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LOFT EXPERIMENTAL MEASUREMENTS UNCERTAINTY ANALYSES VOLUME XIV LOFT DRAG DISC—TURBINE TRANSDUCER UNCERTAINTY ANALYSIS

SANDOR SILVERMAN

November 1978

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF ENERGY

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LOFT DRAG DISC-TURBINE
TRANSDUCER UNCERTAINTY ANALYSIS

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ABSTRACT

An uncertainty analysis on the loss-of-fluid test drag disc-turbine transducer was performed to establish the total uncertainty during single- and two-phase flows for this measuring device.

SUMMARY

One of the basic quantities of interest during a loss-of-coolant experiment (LOCE) is the primary system mass flow rate. Presently, there are no transducers commercially available which directly measure this parameter. Therefore, a transducer was designed at Idaho National Engineering Laboratory (INEL) by EG&G Idaho, Inc., which combines a drag disc and turbine into a single unit[a]. The basis for the design was that the drag disc would measure momentum flux (ρV^2), the turbine would measure velocity, and the mass flow rate could then be calculated from the two quantities by knowing or assuming a flow profile. A development program was required before a meter was obtained which operated satisfactorily in the loss-of-fluid test (LOFT) environment.

The drag disc-turbine transducer (DTT) consists of three transducers mounted in series: (a) a drag disc first, (b) a thermocouple second, and (c) a turbine last. The drag disc force is translated to an output using a torsion bar and variable reluctance transducer, while the turbine uses an eddy current transducer for a pickup. Special electronics are used for the thermocouple.

A variety of different models are in use for data reduction of the DTT during two-phase flow. These models require knowledge of slip and void fraction. Currently, the Rouhani model appears to be best and is used in this analysis for two-phase flow.

The major sources of uncertainty in the DTT are the calibration and linearity/repeatability. A summary of the DTT uncertainty analysis is presented later in Tables I and II of the Introduction.

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[a] Hereafter, the combined meter is denoted as drag disc-turbine transducer (DTT).

The requirements specified for both the turbine and drag disc uncertainties are 5% reading with a response of 1 ms. Neither the turbine or drag disc is capable of meeting any of the specifications. The estimated accuracies for the turbine and drag disc during two-phase flow are, respectively, 5.5 and 19% range for plenum-type drag discs and 16% range for piping drag discs. The response of the turbine (based on Tests L1-2, L1-3, L1-3A, and L1-4) is 50 ms; the response of the drag disc is 10 ms.

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LOFT DRAG DISC-TURBINE TRANSDUCER UNCERTAINTY ANALYSIS

I. INTRODUCTION

The loss-of-fluid test (LOFT) drag disc-turbine transducer (DTT), designed at Idaho National Engineering Laboratory (INEL), is presently being employed at various locations in the LOFT system to measure both velocity and momentum flux. The mass flow rate can then be calculated from these quantities once the velocity profile is known or assumed. Unfortunately, the state-of-the-art is such that it is not known precisely what the drag disc or turbine measure in transient, two-phase flow. The only two-phase flow data available are contained in Reference 1. In this report, factors known or suspected of affecting the drag disc and turbine accuracies are reviewed. Estimates for the various factors are made and an overall uncertainty estimate is calculated. The results for the turbine may be seen in Table I while those for the drag disc are presented in Table II.

TABLE I

DTT TURBINE UNCERTAINTY ANALYSIS

Parameters	Uncertainty (2σ ± %) Single-Phase (range)	Uncertainty (2σ ± %) Two-Phase (range)
Calibration	1.90	5.0
Linearity and Repeatability	1.40	1.4
State of Knowledge of Measurement Principle	0.70 (est.)	1.4
Miscellaneous (Irradiation, pressure, temperature, etc.)	1.50	1.4
Measurement Channel (RSS)	2.80	1.4
DAVDS (MFM)	0.96	1.4
TOTAL (RSS)	3.00	5.6
Response (10 to 90% rise time)		220 ms (L1-1) 50 ms (all other tests)

The above uncertainty applies to both plenum and piping turbines and both single-phase liquid and two-phase steam/liquid flow.

The uncertainties listed are valid for the ranges tested which were generally less than the full design ranges of the DTT (see Sections V-7, V-8, and V-10).

Some uncertainties could not be evaluated (see Section VI).

TABLE II

DTT DRAG DISC UNCERTAINTY ANALYSIS

Parameters	Uncertainty (2σ ± %)			
	Piping Type (Type B)		Plenum Type (Type A & C)	
	Single-Phase (1) (Range)	Two-Phase (Range)	Single-Phase (1) (Range)	Two-Phase (Range)
Calibration	10	10	10	10.1
Linearity/ Repeatability	10	11	6.1	16
Pressure	1.0	1.0	1.0	1.0
State of Knowledge of Measurement Principle (est.)	2.0	2.0	2.0	2.0
Electronics	1.0	1.0	1.0	1.0
Miscellaneous (Temperature, mounting, etc.)	1.5	1.5	1.5	1.5
Measurement Channel (RSS)	15	16	12	19
DAVDS (MFM)	0.96	0.96	0.96	0.96
TOTAL (RSS)	15	16	12	19
Response (10 to 90% rise time)	10 ms (est.)			

All water only; there are no data available for all steam flow.

The uncertainties listed are valid for the ranges tested which were generally less than the full design ranges of the DTT (see Sections V-7, V-8, and V-10).

Some uncertainties could not be evaluated (see Section VI).

II. DESCRIPTION OF DRAG DISC-TURBINE TRANSDUCER

The DTTs to be used for the LOFT nonnuclear and nuclear tests are being produced for LOFT by EG&G Idaho, Inc. There are two basic transducer designs, one denoted "plenum" and the other denoted "piping". For these two designs, both the drag disc and the turbine portions of the DTT have different dimensions. The differences between the designs result from different "range" requirements at the various installation locations. A complete and current description of DTT designations and ranges may be found in the measurement capabilities list (MCL)[2]. Figures 1 and 2 illustrate typical installations for plenum and piping DTTs, respectively. Detail drawings of the transducers are given in Reference 3. An instrumentation schematic of the electronic system is given in Figures 3 and 4.

The DTT has three detectors mounted in series in a 1.5-in.-diameter shroud 6 in. long. In the forward flow direction, the drag disc is first, the thermocouple second, and the turbine last.

The drag disc is linked mechanically to a variable reluctance transducer; the associated electronic system generates an output voltage proportional to the displacement of the drag disc, proportional to the force on the drag disc. The polarity of the output voltage indicates the direction of the fluid flow.

The turbine consists of the turbine and an eddy current transducer which senses the passing of each turbine blade. The electronic system generates an alternating voltage with a frequency equal to the frequency of the passing turbine blades and also an analog signal proportional to this frequency. Friction in the turbine bearings determines the measured minimum fluid velocity, approximately 0.46 m/s for water.

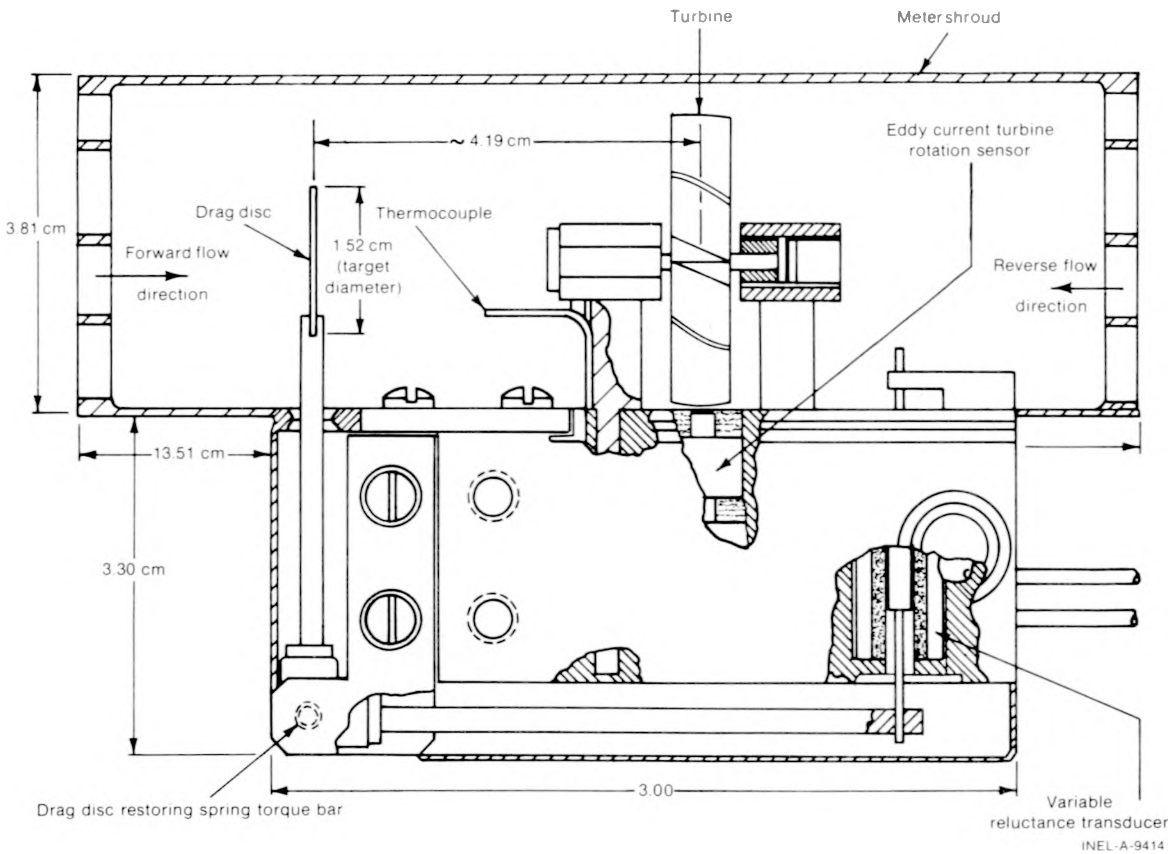

Fig. 1 DTT for installation in outlet plenum or downcomer stalk.

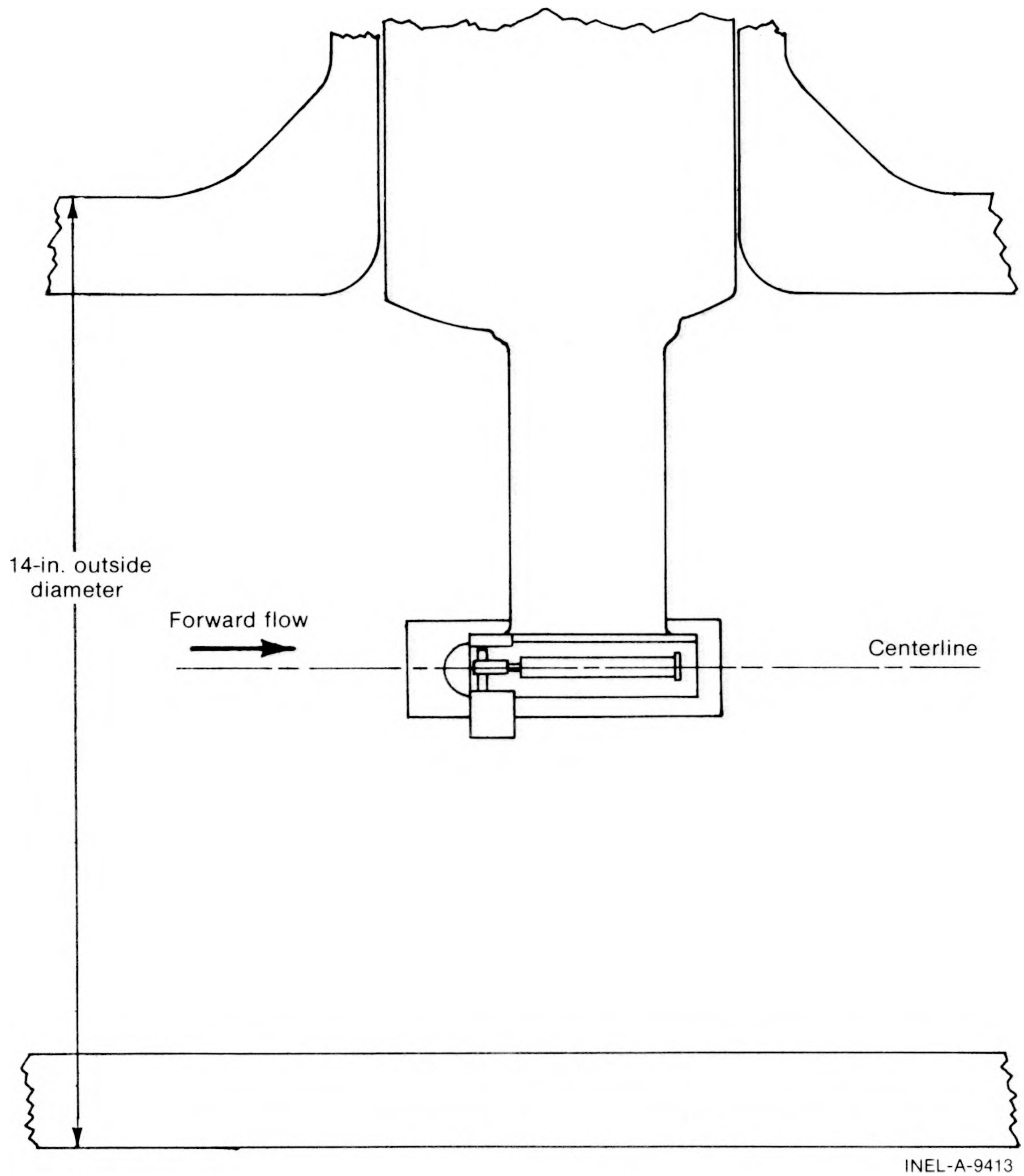

Fig. 2 Schematic - piping instrument flange showing the DTT location in the pipe.

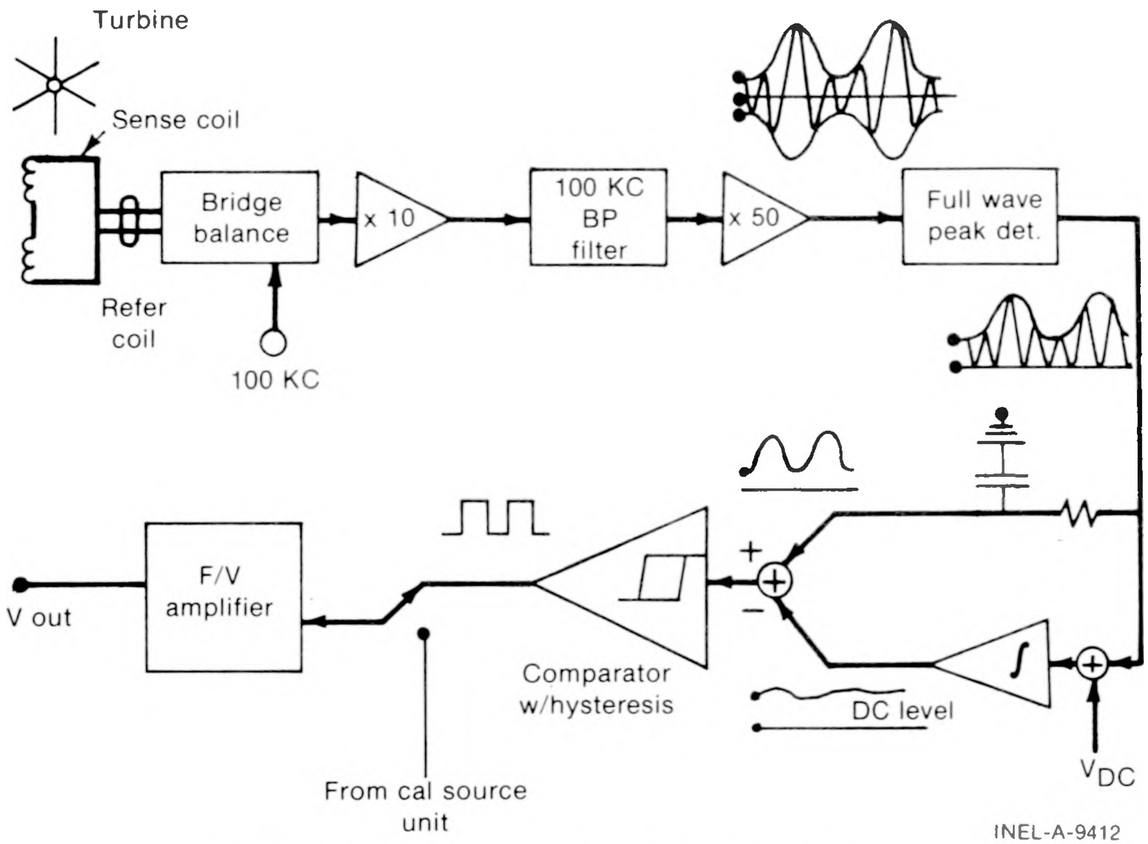

Fig. 3 Schematic of DTT turbine electronics.

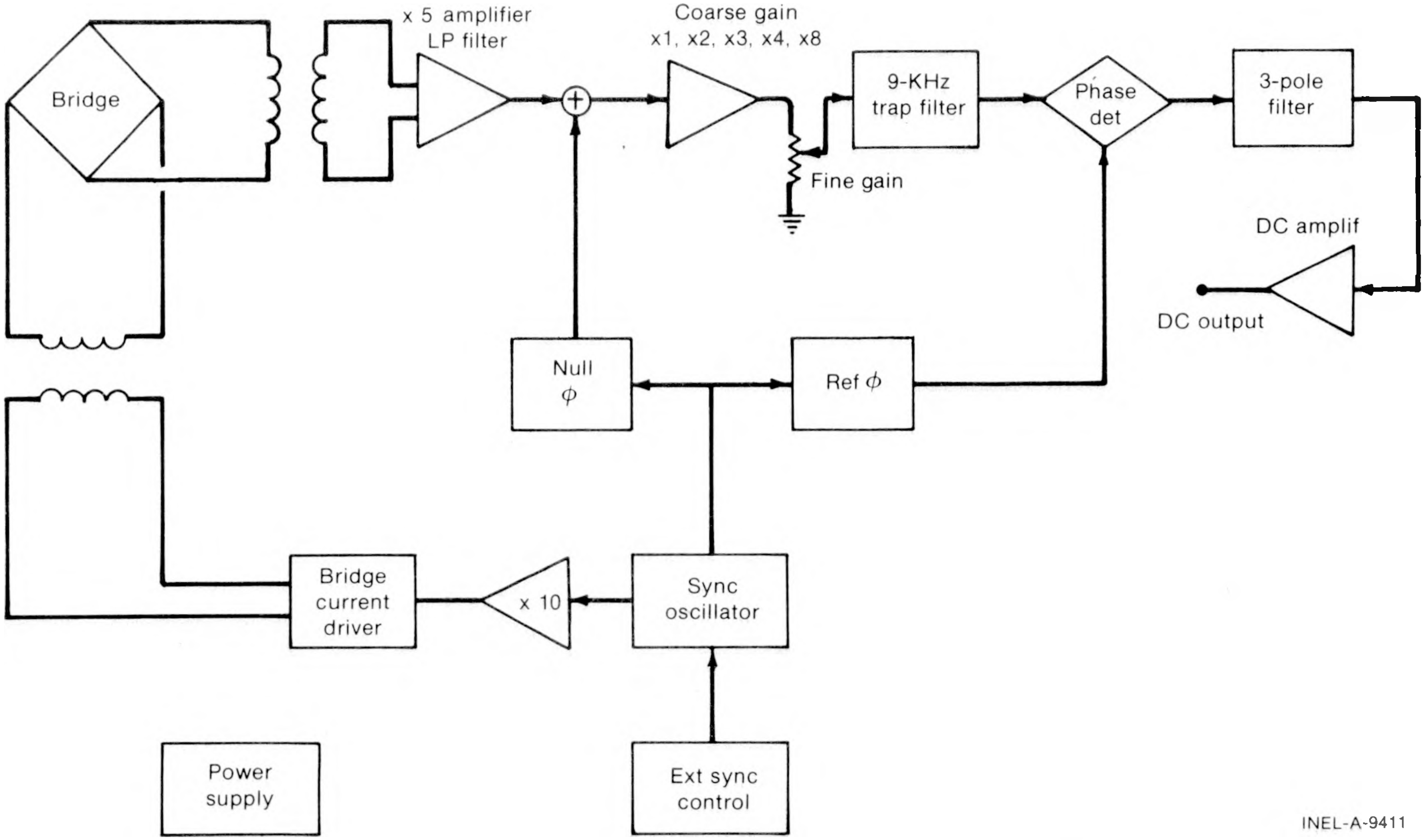

Fig. 4 Schematic of DTT drag disc electronics.

III. MEASUREMENT PRINCIPLE

The following discussion outlines the reasoning initially used to select a transducer having both a drag disc and a turbine meter. Subsequent investigations indicated that the principles of two-phase flow operation of both the drag disc and turbine are not as well understood as initially thought.

A comprehensive study of the performance characteristics of flow-meters in water is reported in References 4 and 5. These papers and the discussions following the papers should be read by everyone interested in turbine meters. References 6 through 11 also contain information and are listed for completeness.

The application of the drag disc to measuring momentum flux appears to be unique to LOFT. In single-phase flow, the principles of operation of the drag disc have been applied to measuring drag forces on various objects. Reference 12 indicates that a turbine in two-phase flow is sensing volumetric flow rate.

It is assumed that the turbine output may be expressed as

$$V_{ot} = C_1 V$$

where

V_{ot} = the output voltage of the turbine

C_1 = a calibration constant

V = some average velocity for the fluid/steam passing through the turbine.

The drag disc output is assumed to be in the form of

$$V_{od} = C_2 \rho V^2$$

where

V_{od} = the output voltage of the drag disc

C_2 = a calibration constant

ρ = some average density for fluid/steam passing through the turbine.

The mass flow rate through the turbine can be calculated as

$$M_t = \rho V A_t$$

where A_t is the flow area of the turbine.

Substituting from the above two equations into the equation for M_t yields

$$M_t = \frac{V_{od}}{C_2 V} A_t = \frac{C_1}{C_2} A_t \frac{V_{od}}{V_{ot}} \quad .$$

Thus, from steady state calibration data, transducer test output, and flow area through the turbine, the mass flow rate through the turbine may be calculated and for the case of a uniform flow distribution over the cross section, the total mass flow rate may be calculated as

$$M = M_t \frac{A}{A_t}$$

where A is the total flow at the transducer location.

For nonuniform flow over the cross section, the nature of the flow must be known before the total mass flow rate can be predicted. If it is not known, then all that can be determined is the flow rate through the meter. In this report, only this "point" measurement through the DTT will be considered; therefore, the uncertainty associated with nonuniform flow over the cross section is not evaluated.

IV. TRANSDUCER SPECIFICATIONS

The DTT design requirements are discussed in Appendix A. Since it was determined that commercially available turbine meters could not meet the requirements, the turbine portion as well as the drag disc portion of the DTT was specially designed.

V. TESTS PERFORMED AND RESULTS

1. INTRODUCTION

A considerable amount of testing has been performed on the DTTs. The information obtained has resulted in useful calibration data, a better understanding of what the turbine meter and drag disc actually "see", and a definition of problem areas. Because the overall test program was of a developmental nature, changes were continuously being made in the meters, with the result being that the data from one series of tests may not agree with the data from another series. Descriptions of the tests follow.

2. AUXILIARY REACTOR AREA (ARA) AT INEL

The air-water tests were conducted as "proof-of-concept" tests to characterize the performance of the DTT in two-phase mixtures. Air and water were chosen because of the availability and the absence of boiling and condensing problems. The specific intent of the tests was to check the consistency of the DTT calibration over a wide range of two-phase mixtures and to determine fluid density from the drag disc and turbine outputs.

The tests were performed with DTT 005 oriented in the horizontal plane and installed in the free-field configuration. Flow was in the forward direction. The results showed that some rather large errors exist between the predicted and measured densities.

The drag coefficient of the disc changes for different air-water mixture densities, indicating that the coefficient is dependent upon Reynolds number.

Since the test loop was oriented in the horizontal plane and the cross flow dispersal bars and diffusing screen may not have been effective[a], the data are of limited value for uncertainty analysis.

3. AUXILIARY REACTOR AREA HOT- AND COLD-WATER DENSITY PROFILE TESTS AT INEL

The purpose of the density profile tests was to investigate the fluid behavior as it passed through the meter and to obtain all water calibration constants for DTTs 011 and 012. A vertical, full-flow test configuration was employed.

Turbine output voltage for all water flow is presented for DTT 011 and 012 for hot (366 K) and cold temperatures and forward and reverse flow directions. The results of these tests showed that the turbine was temperature sensitive. This problem was subsequently corrected with eddy current coil compensation.

The effect of water temperature on drag disc output was not as great as that of the turbine. These tests were proof-of-concept tests and the results are not relatable to uncertainty analysis.

4. ARA PRESSURE AND THERMAL SENSITIVITY TESTS AT INEL

The DTT contains parts that could be sensitive to the changes and conditions of pressure, temperature, and fluid present during the LOFT

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[a] It is known that it is very difficult to obtain a homogeneous fluid condition.

loss-of-coolant experiments. The tests described demonstrate (a) the pressure and temperature sensitivity of the transducer body and, in particular, the turbine eddy current transducer (ECT) sensor coil and the variable reluctance transducer (VRT) coil associated with the drag transducer and (b) the adequacy of the method used to install these coils in the transducer body. Prototype transducers 01, 03, 04, and 05 were used for the thermal sensitivity of the transducer body and Numbers 13, 14, 15, 16, and 18 were used for the pressure sensitivity tests.

4.1 Thermal Sensitivity Tests

The purpose of these tests was to measure the sensitivity of the ECT and the VRT coils to temperature step changes. Because the DTT is to yield accurate data while subjected to a hot water-steam environment that is rapidly changing temperature, the turbine ECT and the drag disc torsion bar and VRT must not be excessively affected by changes in temperature. Thermal sensitivity tests were run at temperatures between room temperature and 616 K in an air furnace. Thermal sensitivity was measured by putting the DTT and about 5.5 m of cable in a box air furnace and measuring the shift in signal as the furnace is heated to 616 K in 311 K steps. The DTT was placed on its side in the furnace, electrical connections were made, and the electronics for each sensor adjusted for null of bridge outputs.

Temperature sensitivity data were obtained for four different prototype DTTs (Serial Numbers 01, 13, 04, and 05). Figure 5 shows the turbine bridge output versus temperature for the four probes and Figure 6 shows the VRT drag disc signal-conditioner null output as a percent of full scale VRT output versus temperature.

As Figure 5 illustrates, the drift of the turbine bridge output is essentially the same for all units (2.16 mV/K). The reverse direction of the 03 transducer data is due to nulling the electronics at 616 K and taking the data while the temperature was being decreased. The source of the drift is that the two coils of the ECT pickup do not view

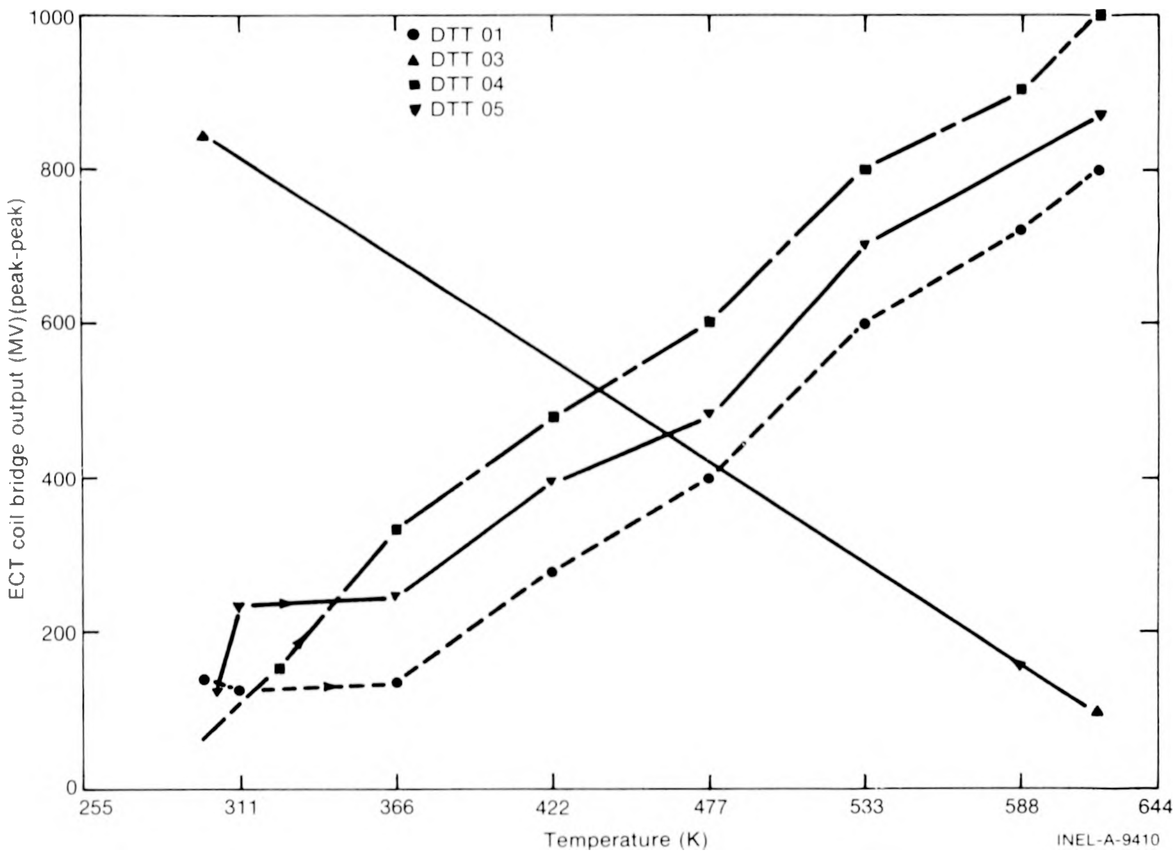

Fig. 5 Temperature sensitivity tests - turbine eddy current transducer bridge output versus temperature.

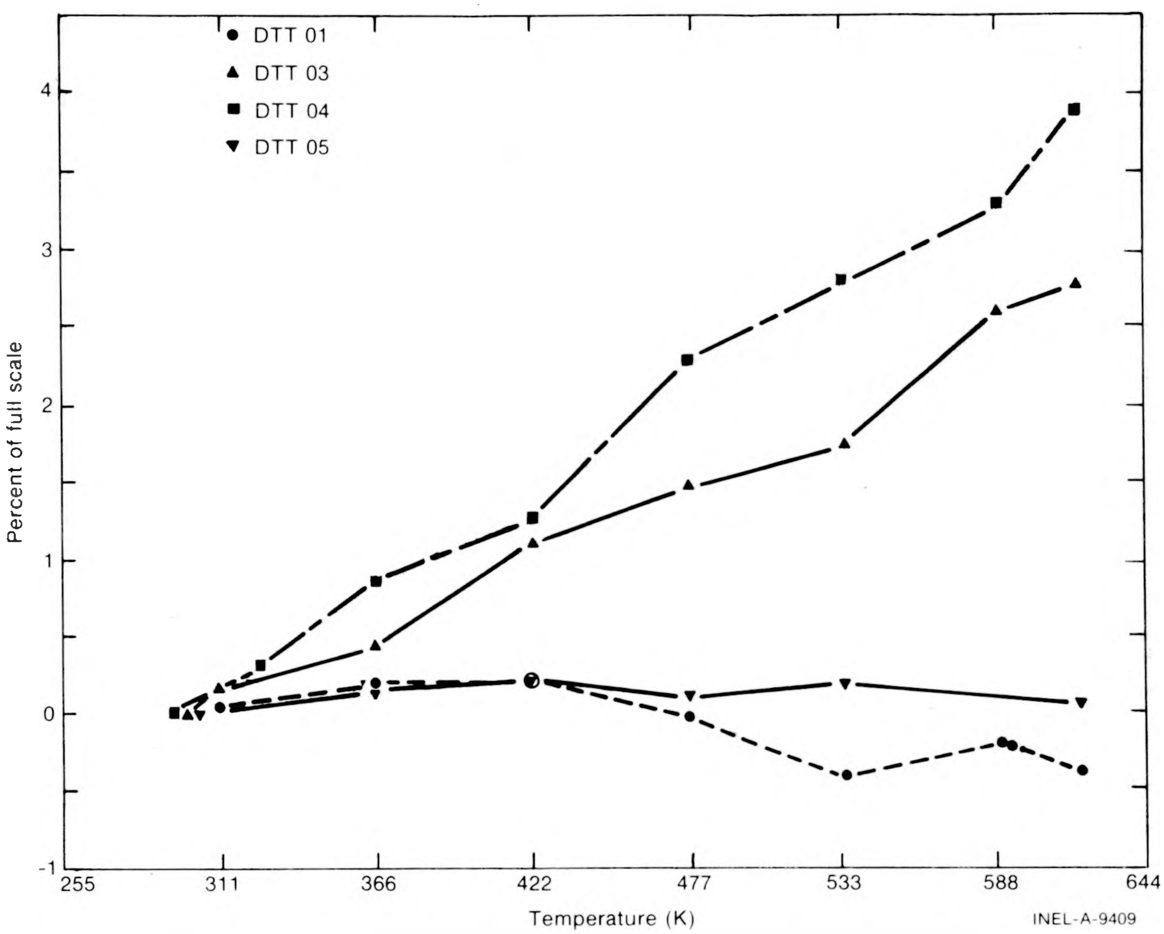

Fig. 6 Drag disc VRT signal conditioner output versus temperature.

identical "targets". The "sense" coil is immediately adjacent to a 0.025-cm-thick diaphragm, while the compensation coil is not adjacent to a metal target. The change in conductivity of the diaphragm with temperature causes the temperature drift. The drift during a blowdown would only be 222 x 2.16 = 480 mV p/p, and the eddy current conditioner auto compensation circuitry will tolerate up to 1.5 V p/p null unbalance when properly adjusted.

The VRT null drift is very low and quite acceptable (less than 0.5% of full scale at 575 K) when the signal conditioner reference phase adjustment is set in the proper manner.

4.2 Pressure Sensitivity Tests

Tests to ensure that the ECT and VRT coils and mechanical portions of the DTT were not excessively sensitive to pressure were performed by placing the DTT units in autoclave and then blowing down the autoclave. The following results were reported for DTT plenum production units 013, 014, 015, 016, and 018.

The DTT and about 18 ft of the instrument leads were placed inside the blowdown autoclave at ARA and the leads brought out to electronic instrumentation. Any signal change during pressurization or the blowdown decompression is then from stresses in the VRT or the leads.

The autoclave was blown down to atmospheric pressure from 16.55 MPa in 20 to 60 s. The 16.55-MPa cold pressurization sensitivity of the turbine ECTs tested is shown in Figure 7. The maximum pressure sensitivity is about 25% of the design maximum allowable of 0.54 V rms or 1.5 V p/p for the bridge nulling capability. The VRT had a maximum pressure sensitivity of 0.1% full scale (0 to 16.55 MPa) for cold pressurization tests.

The subcooled blowdown part of the autoclave test lasted for approximately 250 ms. During this subcooled part of blowdown (16.55 to 12.41 MPa), the turbine ECTs tested showed a maximum pressure sensi-

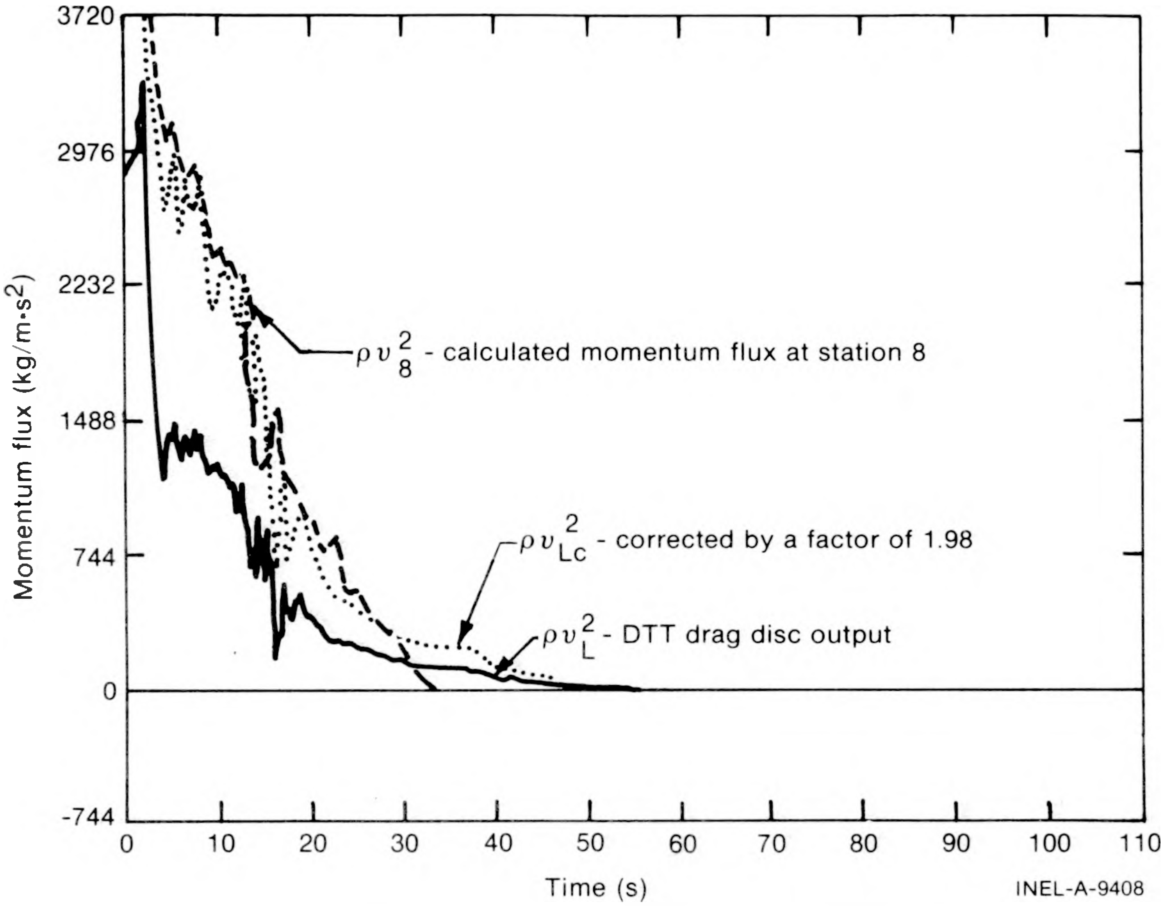

Fig. 7 Turbine ECT bridge output versus pressure.

tivity of 2 mV rms for 4.14-MPa change. The VRTs showed a maximum pressure sensitivity of 0.25% full scale for 4.14-MPa change.

The VRT sensitivity is only real in the cold pressurization case and during subcooled blowdown. The VRT was not locked up and could be moved by flow during the depressurization and the saturated blowdown phase of the test (approximately 12.41 to 0 MPa).

5. BETTIS FLASK TESTS AT INEL

The Bettis Flask tests were performed as part of a series of tests primarily intended to evaluate the method that is being used to weld the thermocouples to the LOFT fuel rod cladding. DTT 012 was installed in the blowdown nozzle of the test system for (a) determining the response of the DTT to transient two-phase flow conditions and (b) obtaining information on the ability of the transducer to withstand blowdown transients. Data were obtained for LOFT single-rod heater tests 1111, 1112, 1113, and 1114. These tests were the only dynamic tests conducted for the DTTs. Scheduling has been such that only the data for test 1111 have been investigated. Analysis of the data indicated that the DTT output approximately agreed with ρV^2 calculated from a mass balance when the DTT output is multiplied by 1.98 (see Figure 8). The results are encouraging since they indicate that the turbine response may not be overly complex.

6. EXXON FRET TESTS

Fretting tests were done on the LOFT drag disc-turbine transducer. These tests were included in LOFT fuel assembly fretting tests conducted by Exxon Nuclear Company at the facilities of Battelle Northwest Company in Richland, Washington. The primary purpose of these tests was to

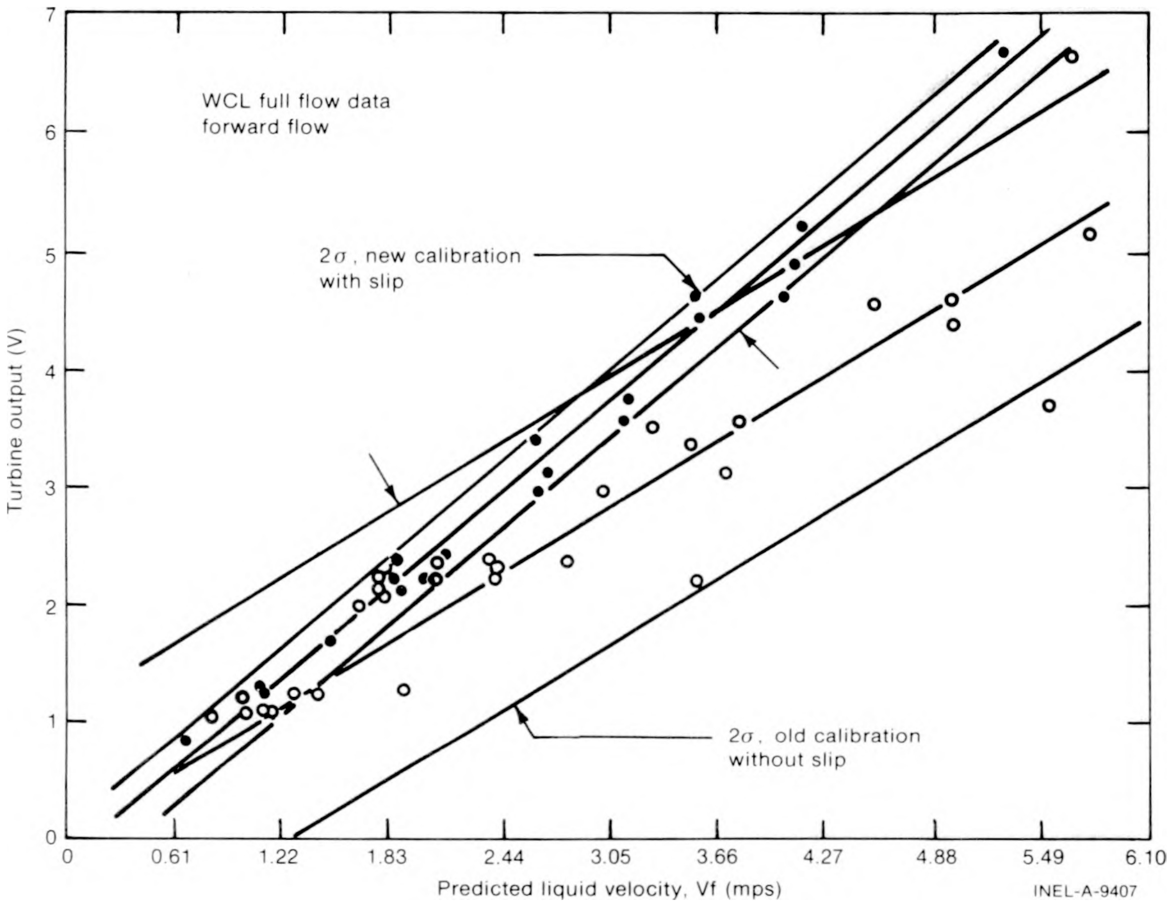

Fig. 8 Temperature sensitivity tests - turbine eddy current transducer bridge output versus temperature.

determine how the DTT withstands expected environments. A secondary goal was calibration and error analysis of the DTT.

The complete investigation includes a calibration of the transducer, in terms of transducer output versus flow rate. This calibration is in exactly the same geometries as were used in these tests. It does not constitute a general velocity calibration of the turbine or a general momentum flux calibration of the drag disc, because accurate velocity and momentum flux values are not known for these experiments. For that same reason, the uncertainty analysis was restricted to studying reproductivity of the transducer readings, and it did not include the effects of constant errors, such as calibration errors. Two points must be emphasized in connection with this error analysis. First, a lot of the data was taken under conditions outside of the design range of the transducers. Second, the "standard" with which these DTT data are compared in the error calculations - that is, the Battelle loop instrumentation - may have significant, unknown errors.

The test series were useful since the DTTs were set up in a real LOFT-type configuration and problem areas were disclosed. Unfortunately, because of the uncertainty in the flow conditions, the data are not usable for calibration purposes and are of questionable use for determining the reproducibility of the transducer.

7. WESTINGHOUSE CANADA, LTD. (WCL) FULL-FLOW TESTS

Tests were conducted with the LOFT DTT 012 in the full-flow configuration to characterize the transducer performance in two-phase, steam-water flow. Steam-water flow rates were separately metered and then combined in a steam-water mixing device. The full-flow configuration was chosen to eliminate the transducer bypass flow variable and to require the DTT to experience flow which can be better correlated with gamma densitometer data.

The tests were performed in the SWIFT flow loop located in the laboratory of the Atomic Power Division of Westinghouse, Canada, Ltd., Hamilton, Ontario, Canada.

In a preliminary analysis it was assumed that the flow was always homogeneous. The results showed considerable scatter in the data. In an effort to reduce the scatter in the turbine calibration data, further analysis of the data was accomplished. A new calibration procedure was developed for the DTT turbine and is reported in TREE-NUREG-1109[13]. The old and the new calibration equations[a] are

$$V_f = 25.31\ V_o + 0.61 \pm 0.15 \qquad r^2 = 0.9904 \qquad S = 0.4186 \text{ (New)}$$

$$V_f = 34.78\ V_o + 0.17 \pm 0.83 \qquad r^2 = 0.8562 \qquad S = 2.15 \text{ (Old)}$$

The reduction in the scatter can readily be seen in Figure 9. From the above equations, the uncertainty has been reduced by a factor of five.

8. WESTINGHOUSE CANADA, LTD., FREE-FIELD TESTS

The purposes of the WCL free-field tests were as follows:

(1) To determine the single- and two-phase water operability for the plenum DTTs (Serial Numbers 011 and 012) and the pipe DTT (Serial Number 051) under free-field, two-phase flow conditions similar to the expected operating window for the LOFT drag disc-turbine transducers.

(2) To determine if the two plenum DTTs perform as in Item 1.

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[a] The equations are presented in English units, since all calibration data were obtained in English units and have not been translated to SI units.

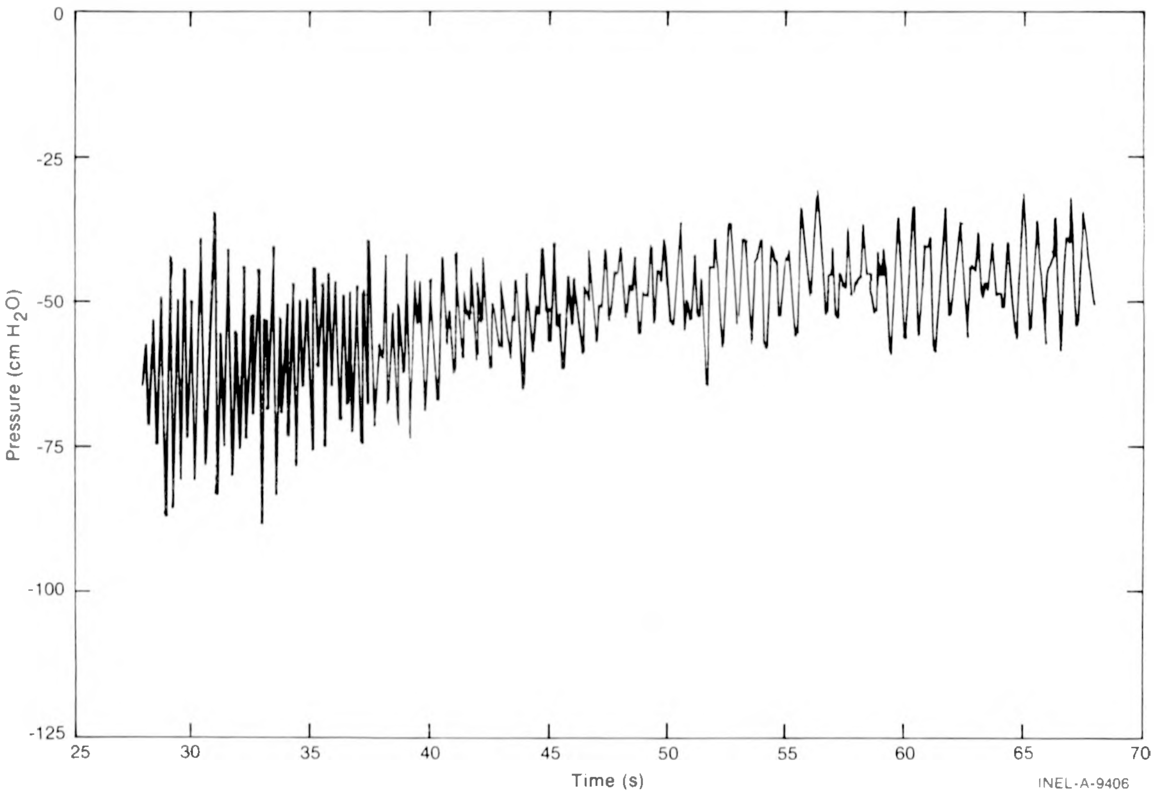

Fig. 9 Turbine output versus liquid velocity.

(3) To determine the effect of the flow direction on the turbine transducer performance.

(4) To determine the relationship between the single- and two-phase calibration equations for both types of DTTs.

(5) To determine the repeatability of the DTTs.

Tests of the LOFT DTT in single- and two-phase, steam and water flows were conducted at Westinghouse Canada, Ltd., from October 13 to November 16, 1973. Steam and water flow rates were separately metered and then combined in a steam-water mixing device.

8.1 Results

A total of 196 data points was obtained. Initially 30 single-phase points were taken with plenum DTT 012. These 30 points were taken at approximately 0.3, 0.9, 1.8, and 3.05 m/s, 328 K and 1.93 MPa, nominal. The 166 single- and two-phase points were taken with plenum DTTs 012 and 011 and piping DTT 051. The latter 166 points were taken at nominal pressures of 2.07, 3.45, and 6.21 MPa. The range of velocities and densities tested covered the range over which the transducers were designed to operate in the LOFT LOCEs -- within the capabilities of the test facility.

For a given velocity, the output of the turbine in the free-field tests is about 10% lower than for identical full-flow test conditions while that for the drag disc is about 40% of the full-flow output. This difference also occurs when comparing Wyle free-field tests with ARA full-flow tests. Investigation indicates that an accurate evaluation of the flow areas accounts for a large part of the difference. That is, the initial calibration was based upon a nominal rather than an actual velocity.

The results of the two-phase tests showed large errors in two-phase flow, due to the difficulty in establishing a density standard. The density measured by EG&G Idaho (diametrial gamma densitometer) differed significantly from the density computed by WCL from a heat mass balance. This was caused by two things:

(1) WCL's assumption of no slip (homogeneous flow)

(2) Density distribution in the pipe with the resulting difficulty in interpreting densitometer output.

An attempt was made to predict the flow regime at each of the test conditions. The techniques developed led to some improvement in agreement between EG&G Idaho and WCL densities; it did not eliminate the problem. With the use of densities and velocities modified for flow regime, the error in the DTT was not significantly reduced.

8.1.1 <u>DTT 012 Turbine Transducer Single-Phase Results</u>. The calibration curves, data points, and 2σ error band for single-phase water tests showed that in the forward flow direction, the turbine is accurate to ±0.088 m/s (95% confidence) over a range from 0.3048 to 3.048 m/s. The design operating range of the plenum turbine transducer is 0.610 to 6.10 m/s. If the forward and reverse flow data points are taken together, the error is increased to only 0.094 m/s (95% confidence), a statistically small increase in error. One concludes that in single-phase, subcooled flow, the flow direction has no effect on the turbine transducer output.

8.1.2 <u>DTT 012 Drag Disc Single-Phase Results</u>. In the 30 initial single-phase tests, the DTT drag disc quite frequently failed to operate freely, and the test section had to be jarred to free it. The uncertianty analysis was done using the transducer output after it had been jarred, if it was suspected that the drag disc was stuck. In the forward flow direction, the drag disc was accurate to ±279 $kg/m{\cdot}s^2$ (95% confidence) over a range from 87.8 to 3348 $kg/m{\cdot}s^2$; while in the reverse flow direction, the transducer was accurate to within 71.4 $kg/m{\cdot}s^2$ over a range from 92.3 to 3300 $kg/m{\cdot}s^2$. The design specifications call for an operating range of 260 to 5208 $kg/m{\cdot}s^2$.

8.1.3 DTT 012 Turbine Transducer Two-Phase Results. The data and the 2σ error bands for DTT 012 in the reverse flow direction for all points showed that WCL calculated, homogeneous densities were greater than 200 kg/m^2. The data scatter about the best fit line with a 2σ error is ±0.49 m/s over a range from 0.914 to 3.96 m/s. The error is substantially increased (±1.62 m/s; range 0.914 to 5.79 m/s), if the low density (below 200 kg/m^3) points are included.

In the forward flow orientation, the 95% confidence limits are ±0.427 m/s over a range from 0.914 to 2.74 m/s.

When forward and reverse flow data are considered together, the 2σ error is ±0.488 m/s, which is not a statistically significant increase in error. Thus, as in single-phase flow, there is little difference in the DTT performance for forward and reverse two-phase flow. Comparing the single-phase calibration equations obtained in the all-water tests with the two-phase calibrations obtained above, the two calibration curves are almost identical. Thus, single-phase calibration is adequate for two-phase flow with density greater than 200 kg/m^2. Table III contains a summary of the errors and calibration equations for all DTTs tested at WCL. For DTT 012 in vertical forward two-phase flow, a new calibration curve was generated based upon the technique described in Reference 13. A lack of time prevented the application of the technique to the remaining data. A reduction factor of five in the uncertainty was obtained by employing this procedure.

8.1.4 DTT 012 Drag Disc, Two-Phase Results. The output of the drag disc is assumed to be governed by the following equation

$$\text{Output} = \frac{KA\ \rho v^2}{2g_c} .$$

For the transducer to be useful, the drag coefficient C_D must be constant or a predictable value. For a disc in single-phase flow, the drag coefficient is a constant (about 1.17) for Reynolds numbers greater than 100,000.

The data were best correlated ($\rho < 320$ kg/m^3) with the equation

$$\text{Output} \cong \rho_f \, V^2.$$

This is probably due to the lighter steam going around the drag disc and the heavier liquid water striking the drag disc. However, a calibration of this form is not useful as it does not enable one to compute the mixture density because the drag disc transducer is responding to liquid rather than two-phase fluid density.

Considering the equation

$$\text{Output} = A\rho V^2 + B.$$

The error in forward flow is ± 847 kg/m·s^2 and in reverse flow is ± 794 kg/m·s^2 (95% confidence). Table IV summarizes the calibration equations for all DTTs tested at WCL.

8.1.5 DTT 011 Turbine Transducer Results. The tests performed on DTT 011 were not as extensive as the tests performed on DTT 012 because the units should be identical in construction. In single-phase, subcooled flow, DTT 011 is slightly more accurate than DTT 012 with a 95% confidence limit error of ± 0.058 m/s in forward and reverse flow over a range from 0.914 to 3.048 m/s. As with DTT 012, there is no direction effect on the turbine transducer output. When compared with DTT 012, it was found that the two transducers display similar performance. As shown by the data in single-phase, subcooled water flow, the two plenum DTT turbine meter calibration equations agree within 3% (Table III).

8.1.6 DTT 011 Drag Disc Results. Enough points were taken in single-phase, subcooled flow to establish a single-phase calibration. The 95% confidence error in forward flow is ± 372 kg/m·s^2 over a range up to 2950 kg/m·s^2; in reverse flow, the error is from ± 476 to 3163 kg/m·s^2. Referring to the calibration equations given in Table IV,

TABLE III

WCL FREE-FIELD TESTS - DTT TURBINE TRANSDUCER CALIBRATION EQUATIONS[a]

Transducer	Flow Direction	Flow Type	Calibration Equation[b]	95% Confidence Error (ft/sec)[b]
012 (Plenum)	F	1ϕ	Vel = 31.75 V + 0.45	±0.29
012	R	1ϕ	Vel = 28.74 V + 0.74	±0.25
012	F & R	1ϕ	Vel = 31.06 V + 0.53	±0.31
			26.48 V + 0.16[c]	±0.12
012	F	1ϕ & 2ϕ	Vel = 28.57 V + 0.97	±1.41
012	R	1ϕ & 2ϕ	Vel = 35.21 V - 0.57	±1.61
012	F & R	1ϕ & 2ϕ	Vel = 32.24 V + 0.19	±1.62
011 (Plenum)	F	1ϕ	Vel = 31.55 V + 0.49	±0.21
011	R	1ϕ	Vel = 31.95 V + 0.38	±0.12
011	F & R	1ϕ	Vel = 31.74 V + 0.46	±0.19
011	F	1ϕ & 2ϕ	Vel = 32.79 V + 0.62	±1.46
011	R	1ϕ & 2ϕ	Vel = 34.84 V - 0.59	±1.22
011	F & R	1ϕ & 2ϕ	Vel = 33.56 V + 0.18	±1.49
051 (Piping)	F	1ϕ	Vel = 100.2 V + 0.13	±1.32
051	R	1ϕ	Vel = 93.13 V + 0.82	±0.55
051	F & R	1ϕ	Vel = 95.25 V + 1.23	±0.93

TABLE III (continued)

Transducer	Flow Direction	Flow Type	Calibration Equation[b]	95% Confidence Error (ft/sec)[b]
051	F	1ϕ & 2ϕ	Vel = 109 V - 0.34	±2.24
051	R	1ϕ & 2ϕ	Vel = 131 V - 1.60	±1.76
051	F & R	1ϕ & 2ϕ	Vel = 127 V - 1.46	±2.13

[a] The approximate maximum values for the tests are as follows:

	DTT 11	DTT 12	DTT 051
ρv^2 lbm/(ft-sec^2) tests	5900	2200	18,500
ρv^2 max. design valve	3500	3500	70,000
Velocity, fps, tests	14	20	39
Velocity, max. design valve	30	30	200

[b] These units are presented in English units, since the original data are only available in English units.

[c] This equation was obtained using the procedure outlined in TREE-NUREG-1109. For this equation $r^2 = 0.9753$ and $s = 0.38$.

TABLE IV

WCL FREE-FIELD TESTS - DTT DRAG DISC CALIBRATION EQUATIONS[a]

Transducer	Flow Direction	1 or 2 Phase	Calibration Equation[b]	95% Confidence Error[b] (lbm/ft sec^2)
012 (Plenum)	F	1	$\rho V^2 = 5,192\ V - 256$	± 188
012	R	1	$\rho V^2 = 6,438\ V + 370$	± 48
012	F	1 & 2	$\rho V^2 = 3,503\ V - 328$	± 569
012	R	1 & 2	$\rho V^2 = 5,410\ V + 212$	± 534
011 (Plenum)	F	1	$\rho V^2 = 5,476\ V - 739$	± 215
011	R	1	$\rho V^2 = 7,472\ V + 281$	± 320
011	F	1 & 2	$\rho V^2 = 4,549\ V - 660$	± 559
011	R	1 & 2	$\rho V^2 = 6,123\ V + 267$	± 562
051 (Piping)	F	1	$\rho V^2 = 90,900\ V + 7,327$	±1282
051	R	1 & 2	$\rho V^2 = 227,600\ V + 16,788$	±1343
051	F	1 & 2	$\rho V^2 = 106,700\ V + 10,651$	±2471
051	R	1 & 2	$\rho V^2 = 496,300\ V + 36,640$	±8337

[a] See Table III for test ranges.

[b] These units are presented in English units, sicne the original data are only available in English units.

notice the difference in the slope of the calibration curve for DTTs 012 and 011. Therefore, the calibration equations for one plenum drag disc is not adequate for other plenum drag discs.

In the two-phase tests, the plenum transducers drag disc was accurate (2σ) to within ± 833 kg/m·s^2 over a range up to 3125 kg/m·s^2. As observed in the single-phase tests, the calibration equations for forward and reverse flows differ significantly.

8.1.7 DTT 051 Turbine Transducer Results. The drop off in turbine output at low densities was even more pronounced with the piping transducer (DTT 051) than with the plenum transducer because of the smaller blade angle. In several of the low-density tests, the turbine stopped altogether. Since the turbine operation was erratic at points with densities less than 200 kg/m^3, the low-density points were not considered in the data analysis. This left only seven two-phase points for the data analysis. With these points plus ten single-phase points, the error (95% confidence) was ± 0.649 m/s over a range from 0.914 to 5.79 m/s, considering forward and reverse flows together. The transducer calibration equation is given in Table IV.

8.1.8 DTT 051 Drag Disc Results. In reverse flow, the piping DTT drag disc is located 0.025 m behind the turbine bearing hub. The turbine hub is 0.0076-m-OD nominal, and the drag disc is 0.0076-m-OD nominal. Thus, considerable "shadowing" existed in the WCL tests and can be expected in LOFT. The difference in slopes for the different directions is due to the shadowing. This transducer is designed to operate from 3720 to 74 400 kg/m·s^2; however, due to loop limitations, it could only be tested up to 26 784 kg/m·s^2. The 2σ error was ± 3677 kg/m·s^2 in forward flow and ± 12 405 kg/m·s^2 in reverse flow. The larger error in reverse flow is due to the small drag disc behind the bearing hub. Inspection of Table IV shows that a ρV^2 of 744 000 kg/m·s^2 is required to cause a full-scale deflection. The large discrepancy between the design maximum (83 328 kg/m·s^2) and the indicated maximum is due to the drag disc operating the wake behind the turbine bearing hub.

9. ENGINEERING TEST REACTOR (ETR) M-3-3 IRRADIATION TEST AT INEL

Several of the DTT probes are to be built for installation in various locations in the LOFT reactor where they will experience neutron and gamma irradiations as well as exposure to 616 K, 15.2 MPa hot water. A radiation test was required to determine the ability of the DTT to perform properly to a specified integrated flux. A combination test was conceived late in 1971 to place pressure transducers, a liquid level probe, thermocouples, and accelerometer, and the DTT in an environment simulating that in LOFT.

For a radiation environment, a pressurized-water, 0.152 x 0.152-m flow loop located in the M-3 position in ETR was found to be available. Proper water chemistry was attainable. The irradiation level of the M-3 location was sufficient for gamma and thermal neutrons to equal 2000 effective full-power hours (EFPH) in LOFT in a reasonable time[a]. The decision was made to run in the M-3 location for two cycles to obtain the necessary gamma and thermal neutron exposures, even though the fast flux was low.

9.1 LOFT Transducer Irradiation Requirements

The irradiation requirements for the transducers used in the LOFT test program are given

$$\text{Total neutron flux} = 7.2 \times 10^{18} \text{ nvt}$$

$$\text{Total gamma flux} = 2 \times 10^{10} \text{R}.$$

Different materials respond differently to neutron radiation, with the response for a given material being dependent upon the energy level

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[a] Actual radiation was less than the requirements. (See Table V in Section V-9.3.)

of the radiation. For this reason, a plot of maximum neutron flux versus neutron energy level should be determined for the LOFT core. In addition, the attenuation of neutrons of various energy levels with distance from the core would be useful. Then, for example, exposure of the DTT in the ETR could be compared with the expected exposure in LOFT. Presently, all that is specified is that the total neutron exposure is 7.2×10^{18} nvt.

9.2 DTT ETR Irradiation Exposure

The LOFT transducer test capsule was placed in the ETR prior to ETR test cycle 117, which started September 14, 1972, and was discharged from the reactor at the conclusion of test cycle 118A. The capsule was irradiated through cycles -17A, B, C, D, and E for a total of 10,416 MWD (megawatt days) and through 2417 MWD in cycle 118A. Average reactor power during this time was 167 MW. The total test time for the capsule was therefore

$$t_d = \frac{10{,}416 \text{ MWD} + 2417 \text{ MWD}}{167 \text{ MW}} = 76.84 \text{ d}$$

$$t_h = 76.84 \text{ d} \times 24 \frac{\text{h}}{\text{d}} = 1844 \text{ h}$$

$$t_s = 1844 \text{ h} \times 3600 \frac{\text{s}}{\text{h}} = 6.64 \times 10^6 \text{s}.$$

The location of the DTT is 0.71 m above the ETR reflector piece. The neutron and gamma exposure of the transducer can be calculated

Thermal neutron flux level

$$\phi th = 1.2 \times 10^{11} \text{ n/cm}^2\text{s}.$$

Total thermal neutron exposure

$$\phi th \text{ (total)} = 1.2 \times 10^{11} \text{ n/cm}^2\text{s} \times 6.64 \times 10^6 \text{ s}$$

$$= 8 \times 10^{17} \text{ n/cm}^2.$$

Fast neutron flux level

$$\phi_f = 7.0 \times 10^9 \text{ n/cm}^2\text{s}.$$

Total fast neutron exposure

$$\phi_f \text{ (total)} = 7.0 \times 10^9 \text{ n/cm}^2\text{s} \times 6.64 \times 10^6 \text{ s}$$

$$= 4.7 \times 10^{16} \text{ n/cm}^2.$$

Total gamma exposure

$$\gamma(t) = 6.8 \times 10^6 \text{ R/h} \times 1844 \text{ h} = 1.2 \times 10^{10} \text{ R}.$$

A summation of the radiation exposure values for the DTT and the anticipated LOFT equivalent values is given in Table V.

As shown by Table V, the DTT received less than LOFT 2000 EFPH irradiation in all three varieties of radiation. The principal reason was that the spacing selected between devices to avoid flow stagnation and the flow straightener in front of the drag disc-turbine transducer forced the DTT test away from the ETR core.

TABLE V

ETR IRRADIATION TESTS - IRRADIATION EXPOSURE OF THE LOFT DRAG DISC-TURBINE TRANSDUCER

	Thermal Neutrons	Fast Neutrons	Total Neutrons	Gamma
ETR-M3-3 actual	$0.8 \times 10^{16} \frac{n}{cm^2}$	$0.047 \times 10^{18} \frac{n}{cm^2}$	$0.847 \times 10^{18} \frac{n}{cm^2}$	1.2×10^{10}R
LOFT requirements	-----	-----	$7.2 \times 10^{18} \frac{n}{cm^2}$	2×10^{10}R
Percent of requirements	-----	-----	11.8	60.0

9.3 Results and Conclusions

The VRT dc and eddy current pulse rate output was recorded at monthly intervals for full reactor power at 204, 273, and 337 ℓ/min loop flow rates. The results are discussed in the following paragraphs.

9.3.1 Effect of Irradiation on Turbine Operation. Table VI separates the data of the test into three sections, each section at one of the three different loop flow rates. As can be noted from the data and from the dates given, the seven sets of readings in each of the three sections were taken at full reactor power on dates spread through the extent of the radiation test. The turbine results are summarized in the column entitled K_{cal} (Turb), which is the ratio of the eddy current output pulse rate divided by the loop flow in ℓ/min. This ratio is about unity in value. The mean value for the 21 values of K_{cal} (Turb) is 1.106. The maximum deviation of the data from the mean value is +4 and -6%. No trend exists in the data that can be meaningfully correlated with the radiation exposure which was accumulating as the test proceeded.

9.3.2 Effect of Irradiation on Drag Disc Operation. The drag disc raw data are listed under column entitled VRT (mV) of Table VI. Because the drag disc offset corrected data are proportional to ρV^2, a means of evaluating the drag disc performance is to remove the v^2 dependence by dividing by v^2 to obtain what should be the same constant for each of the 21 data points as long as the loop fluid density is constant. The column entitled K_{cal} (VRT) is the ratio of the offset corrected VRT millivolt output divided by the square of the appropriate eddy current pulse hertz value. The variation of K_{cal} (VRT) versus flow is an indication that the drag disc did not respond exactly proportionally to the square of velocity.

The constancy of the value of K_{cal} (VRT) versus time for each of the three flow rates is direct verification that radiation has had no deleterious effect on the drag disc VRT operation. The increase in value of K_{cal} (VRT) in the February 5, 1973, data versus all previously

TABLE VI

ETR IRRADIATION TESTS - DRAG DISC-TURBINE IRRADIATION DATA (REFERENCE 20, Table III)

Test 14 Data (54 gpm), N_F

Date	VRT (mV)	Eddy Current (dc mV)	Eddy Current (Pulse Hz)	K_{cal} (Turb)	Loop (MPa)	Loop (K)	K_{cal}[b]
10-16-72	720	140	57	1.06	13.5	509	0.21
11-29-72	690	90	58	1.07	13.6	552	0.20
12-21-72	35[a]	103	60	1.11	13.6	552	[a]
12-28-72	35[a]	104	59	1.09	13.6	547	[a]
1-4-73	36[a]	100	59	1.09	13.6	544	[a]
1-4-73	760	111	62	1.15	13.5	519	0.19
2-5-73	820	99	59	1.09	13.5	529	0.23

Seven point K_{cal} (Turb) mean value is 1.094.

Test 14 Data (72 gpm), N_F

Date	VRT (mV)	Eddy Current (dc mV)	Eddy Current (Pulse Hz)	K_{cal} (Turb)	Loop (MPa)	Loop (K)	K_{cal}[b]
10-16-72	1040	170	82	1.14	13.5	509	0.15
11-29-72	1000	120	81	1.113	13.6	552	0.15
12-21-72	48[a]	142	80	1.11	13.6	552	[a]
12-28-72	49[a]	142	79	1.10	13.6	547	[a]
1-4-73	48[a]	136	75	1.04	13.6	544	[a]
1-24-73	1050	145	82	1.14	13.5	518	0.15
2-5-73	1120	130	76	1.06	13.5	529	0.19

Seven point K_{cal} (Turb) mean value is 1.100.

Tests 14 and 15 (89 gpm), N_F

Date	VRT (mV)	Eddy Current (dc mV)	Eddy Current (Pulse Hz)	K_{cal} (Turb)	Loop (MPa)	Loop (K)	K_{cal}[b]
10-16-72	1360	190	101	1.13	13.5	509	0.13
11-29-72	1345	137	102	1.15	13.5	552	0.13
12-21-72	66[a]	182	101	1.13	13.6	552	[a]
12-28-72	65[a]	179	99	1.11	13.6	547	[a]
1-4-73	68[a]	172	98	1.10	13.6	544	[a]
1-24-73	1420	188	102	1.15	13.6	518	0.13
2-5-73	1440	168	98	1.10	13.5	529	0.15

Seven point K_{cal} (Turb) mean value is 1.124.

Twenty-one point K_{cal} (Turb) mean value is 1.106.

[a] VRT electronics functioning improperly.
[b] Corrected for 25.7 mV VRT offset.

constant values occurred sometime during a time span of 12 days in the 111-day test and is not viewed as being caused by radiation. This change can be partially explained by the fact that K_{cal} (Turb) is lower than the mean of the corresponding set of seven data points, causing an increase in K_{cal} (VRT) proportional to the square of this ratio change. The remainder of the change in K_{cal} (VRT) is viewed as most likely due to an unrecorded adjustment in the VRT electronics between January 24 and February 5, 1973.

9.3.3 Conclusions. No radiation-induced changes in operation of the DTT turbine or drag disc are identifiable from the data obtained in the ETR irradiation test. The turbine operated within +4, -6% of the mean. Because the loop flow was assumed to be perfectly reset each time in obtaining these numbers, actual DTT turbine performance was probably better than this.

With the exception of the February 5, 1973, set of data, the DTT drag disc calculated constant K_{cal} (VRT) reproduced itself at each of the three loop flow rates to $\pm 5\%$ of the mean. The inconsistency of the February 5, 1973, data is not likely due to nuclear effects, since only 25% of the total irradiation exposure occurred from the previous data point where no evidence of degradation was evident.

Because the drag disc evaluation "constant", K_{cal} (VRT), has had the velocity dependence extracted by dividing by the square of the velocity, and because it agrees with itself so well at a given loop flow rate, most of the turbine +4, -6% nonrepeatability is due to slight missettings of the loop flow rate at each of the data points. Insufficient information exists to determine if this is so.

The DTT was exposed to about one-eighth of the total neutron flux of 2000 LOFT EFPH and 60% of 2000 LOFT EFPH gamma irradiation. These low exposures were due to the physical limitations in the experimental assembly and its location and the ETR being shut down for long-term major modifications, thereby terminating the test. For the exposures experienced, both the drag disc and turbine meter appeared to operate properly and were not affected by the exposure.

10. WYLE TESTS AT WYLE LABORATORIES

The purpose of the Wyle tests was to obtain water calibration data for 14 DTTs that are to be used in the LOFT experiments; the calibration equations are summarized in Table VII.

TABLE VII

WYLE TESTS - DTT CALIBRATION SUMMARY[a]

DTT Type S/N	Turbine Equation Velocity = (ft/sec)[b]	Goodness of Fit, r^2	Variance S(x, y)	S(0)	S(1)	Drag Disc Momentum Flux (ρV^2) = $\frac{lbm}{ft\ sec^2}$ [b]	Goodness of Fit, r^2	Variance S(x,y)	S(0)	S(1)
12	$11.11E_o + 1.08$	0.9877	0.80	0.20	0.21	F $4450E_o - 0.05$	0.9957	223	91.46	84.22
						R $5616E_o + 4.17$	0.9946	277	101.91	117.72
13	$11.37E_o + 0.18$	0.9994	0.17	0.05	0.05	F $2300E_o - 81.63$	0.9989	105	42.64	23.87
						R $3633E_o - 9.72$	0.9965	213	82.08	64.73
14	$11.26E_o - 0.13$	0.9985	0.26	0.08	0.08	F $1930E_o - 63.52$	0.9969	48	30.55	40.58
						R $3223E_o - 34.94$	0.9992	103	39.72	27.66
15	$11.29E_o + 1.32$	0.9894	0.73	0.18	0.20	F $2048E_o - 191$	0.9994	40	18.90	15.93
						R $3520E_o + 190$	0.9993	100	33.64	25.82
16	$12.42E_o + 0.52$	0.9919	0.64	0.19	0.21	F $2385E_o - 894$	0.9911	72	77.07	85.43
						R $4065E_o + 1874$	0.9969	198	59.76	72.16
17	$11.61E_o + 0.06$	0.9978	0.33	0.10	0.10	F $1940E_o - 160$	0.9959	49	35.56	46.88
						R $2957E_o + 40.30$	0.9981	155	59.98	41.30
18	$12.48E_o + 0.17$	0.9977	0.35	0.10	0.11	F $1953E_o + 0.96$	0.9998	12	6.96	9.30
						R $3348E_o + 203$	0.9991	28	13.36	33.22
19	$10.38E_o - 0$	0.9975	0.35	0.10	0.09	F $2213E_o + 393$	0.9888	77	40.00	83.32
						R $2562E_o - 238$	0.9977	41	26.23	43.77
55	$39.43E_o - 0.36$	0.9971	0.38	0.11	0.38	F $2867E_o - 976$	0.9917	311	131.02	75.82
						R $4236E_o + 498$	0.9907	369	127.55	123.83
56	$38.08E_o - 0.98$	0.9962	1.97	0.46	0.36	F $44,170E_o - 2949$	0.9820	7228	2971.41	1658.37
						R $86,551E_o - 12,964$	0.9974	2379	770.21	1041.88
57	$38.95E_o - 2.63$	0.9899	3.06	0.67	0.56	F $46,141E_o - 6638$	0.9910	3393	1019.12	863.39
						R $90,300E_o - 807$	0.9974	2744	850.85	1181.92
58	$34.75E_o - 0.20$	0.9879	3.45	0.71	0.55	F $42,720E_o - 6997$	0.9925	3350	1213.08	990.50
						R $88,926E_o + 8788$	0.9948	3198	741.30	1398.86

TABLE VII (continued)

DTT Type S/N	Turbine Equation Velocity = (ft/sec)[b]	Goodness of Fit, r^2	Variance S(x, y)	S(0)	S(1)	Drag Disc Momentum Flux $(\rho V^2) = \frac{lbm}{ft\ sec^2}$ [b]	Goodness of Fit, r^2	Variance S(x,y)	S(0)	S(1)
59	$35.74E_o + 0.18$	0.9935	2.53	0.54	0.41	F $51{,}569E_o - 3265$	0.9959	2717	666.82	659.08
						R $94{,}454E_o - 3648$	0.9843	6786	2169.04	3078.10
60	$35.64E_o + 0.23$	0.9888	0.74	0.20	0.67	F $2823E_o - 363$	0.9935	68	47.03	80.82
						R $3770E_o + 205$	0.9889	77	45.52	141.04

[a] The approximate maximum values for the tests are as follows

	Plenum DTTs (low numbers)	Piping DTTs (high numbers except 55 and 60)
ρv^2, lbm/(ft sec^2) tests	12,000	150,000
ρv^2, maximum design value	3500	70,000
Velocity, fps tests	23.0	100.0
Velocity, maximum design value	30.0	200.0

[b] These units are presented in English units since the original data are only available in English units.

VI. SPECIFIC UNCERTAINTIES FOR THE DTT TURBINE

1. INTRODUCTION

The variables which may affect the output of the turbine during calibration tests and/or LOCEs include the following:

(1) State of knowledge of the measurement principles
(2) Temperature
(3) Pressure
(4) Irradiation
(5) Mounting misalignment
(6) Hysteresis
(7) Pipe dynamics
(8) Fluid transients
(9) Electronics
(10) Fluid kinematic viscosity
(11) Flow pattern within meter
(12) Entrance flow pattern
(13) Orientation of the meter, horizontal versus vertical
(14) Angular position of the pickup
(15) Retarding forces, electromagnetic and bearing
(16) Dynamical response and vibration of the turbine blades
(17) Cavitation.

Each of the above uncertainties is considered in the following, while the data are summarized in Table I.

2. STATE OF KNOWLEDGE OF THE MEASUREMENT PRINCIPLES

Since the principles of operation of the turbine meter in two-phase flow are not well understood, there is uncertainty attributable to misinterpretation of the calibration data. For example, assume that the other 15 variables listed are completely controlled during a calibration test series, and that the principles of operation of the turbine are not thoroughly understood. Then the calibration data may be incorrectly plotted and errors will result from the lack of understanding.

Calibration equations and measurement uncertainties are summarized in Tables III and VII. The two-phase flow data in Table III indicate that the uncertainty for the plenum type turbine varies from

$$\frac{\pm 0.37 \text{ fps}}{9.14 \text{ fps}}^{[a],[b]} = 4.06\% \text{ to } \frac{\pm 0.49 \text{ fps}}{9.14 \text{ fps}} = 5.4\%$$

which is a factor of 1.33 difference. Increasing this factor to 2.5 for conservatism, the uncertainty for the plenum meters is estimated as

$$\frac{2.5 \times 0.0366}{9.14}^{[c]} = \pm 1\% \text{ of full scale.}$$

It is assumed that this uncertainty is also valid for the piping meters.

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[a] The decreased uncertainty due to the new calibration procedure for DTT 012 in forward, two-phase flow is not considered, since it is desired to establish the range in the uncertainty for the "old" calibration procedure.

[b] The 9.14 fps in the denominator is the maximum range requirement for the turbine for Ranges A and B.

[c] The 0.0366 fps is obtained from the application for the new calibration procedure to the WCL free-field, forward, two-phase flow data. (See Table III.)

3. TEMPERATURE

To determine the effect of temperature on the turbine output calibrate for different fluid temperatures and temperature transients. Thus, the total effect of temperature on electronics, turbine bearings, flows patterns, etc., would be obtained.

Tests on the effects of temperature are reported in Section V-4. The effects of temperature are minimal. However, the tests should have been conducted in water instead of air to better simulate the LOFT environment.

The results of the air tests showed the temperature effects were within the design limits. Uncertainties due to temperature will probably be minimal.

4. PRESSURE

The effects of transient pressure on the DTT turbine output are reported in Section V-4.2. The entire DTT was placed within an autoclave, along with 5.49 m of instrument leads, with the turbine blade locked in place. The autoclave was pressurized to 16.6 MPa and then blown down. Results from these tests showed the uncertainty due to pressure and pressure transients is essentially zero, since the bridge remained in balance.

5. IRRADIATION

Irradiation tests were reported in Section V-9. Total neutron exposure was about one-eighth of the design requirements. For the tests, no radiation-induced changes in operation of the turbine were identified. Therefore, the irradiation effect on uncertainty is considered to be small.

6. MOUNTING MISALIGNMENT

There are no data available on the effects of mounting misalignment on the DTT calibration, so it is not possible to obtain an accurate estimate of the uncertainty. The conclusion is that the error is negligible for the small misalignments that might be found in practice.

7. HYSTERESIS

There appears to be no methodical investigation of hysteresis effect in the turbine. The WCL data have hysteresis effects within them, but the effects are hidden within the scatter and were not specifically addressed in the test program; therefore, zero uncertainty is attributed to hysteresis.

8. PIPE DYNAMICS

There are no data in the effect of pipe dynamics on turbine output. The large acceleration forces predicted (up to 5 g) may have a significant effect on output since the fluid, the turbine, and all the electronics, including cabling, will be undergoing motion. The posttest examination of the output of the various transducers may yield some insight into the magnitude of the problem, but there may be a problem even if no such spikes exist. Because of a lack of data, the uncertainty caused by pipe dynamics is not estimated.

9. FLUID TRANSIENTS

The Bettis Flask tests are the only tests available concerning the response of the turbine meter to fluid transients. Unfortunately, the tests are of limited value since the flow through the turbine is not well known. In addition, the analysis of the test data is only of a preliminary nature. (Refer to V-5.) There have been both theoretical and experimental investigations of the response of turbine meters to water transients — the transient response obtained to a step change in fluid velocity[6] and an analytical and experimental investigation of the calibration of a flowmeter for sinusoidally perturbed flow. The theory reported in Reference 6 was employed to obtain an estimate of the turbine response[13].

For water, the 10 to 90% response time is estimated as 0.033 s for the plenum meter (the piping DTT has a faster response). Using a density of

$$\frac{0.373\ \text{kg}}{0.1869\ \text{m}^3}$$

(this is an approximate minimum during a LOCE), the 10 to 90% rise time in steam flow is estimated as 14 s. These values are approximate as the response time varies with fluid density and velocity. The response time in water is approximately one-third that specified in the MRD[14], and the response time in steam exceeds the MRD value by a significant amount. Testing to verify these estimates is recommended.

10. ELECTRONICS

As long as the bridge is in balance, the uncertainty due to the electronics is zero. Pressure and temperature changes could cause sufficient unbalance, such that double pulsing or no pulsing (zero output) could occur. The pressure and temperature effects are discussed separately.

During an investigation of the response of the turbine electronics, a step change in frequency to the turbine ECT coil, simulating a step change in fluid velocity, was input. It was determined the 10 to 90% rise time of the electronics is 220 ms, this is greater than the desired 1 ms response time[1]. Therefore, the turbine response time is fast enough that there is zero uncertainty associated with it, but the electronics has a large unknown uncertainty associated with it, since its response time exceeds the MRD[14] requirements.

11. FLOW PATTERN WITHIN METER

The actual state of fluid flowing through the DTT may cause additional uncertainty. Numerous flow regimes have been identified for two-phase flow, but only a few have been investigated in the tests conducted to date. Thus, the uncertainty due to the flow regime cannot be evaluated.

12. REMAINING VARIABLES

Variables (10) and (12) through (17) are known to affect turbine output. (See References 4 and 5 for additional discussion.) In general, the effect of each of these variables appears to be small but, since none of them has been investigated, the uncertainties cannot be estimated accurately. Turbine blade dynamics is known to affect output, but it is felt that for the LOFT DTT, the effect will probably be negligible.

VII. SPECIFIC UNCERTAINTIES FOR THE DTT DRAG DISC

1. INTRODUCTION

The variables that may affect the output of the drag disc during calibration and/or LOCEs include variables (1) through (10) and (15) listed for the turbine and variable (16) of "turbine blades as replaced by disc." (Refer to VI-1.) Each of these variables is considered in the following, while a summary of the uncertainties may be found in Table II.

2. STATE OF KNOWLEDGE OF THE MEASUREMENT PRINCIPLES

The calibration equations and measurement uncertainties are summarized in Tables IV and VII. The two-phase flow calibration has a reasonably good chance of being improved through application of the measurement principles discussed in Reference 13 to the data available. This has not yet been accomplished, so the uncertainty attributed to this is estimated from Table IV (WCL free-field tests) as

$$\frac{847}{5208} = \pm 16.3\%$$

of full scale for the plenum-type DTT and

$$\frac{12\ 405}{104\ 160} = \pm 11.9\%$$

for the piping-type DTT. These uncertainties are the total for the WCL free-field tests. Within these values, it is estimated that the uncertainties due to the state of knowledge of the measurement principles are about $\pm 2\%$ range.

3. TEMPERATURE

The best way to determine the effects of temperature on drag disc output is to calibrate at different fluid temperatures. Then the total effects of temperature on electronics, flow patterns, and differential expansion of mechanical hardware would be obtained. A preliminary calibration of this nature is discussed in V-3. It is concluded that the water temperature was not hot enough (366 K) and the tests not controlled well enough to use the data to determine uncertainty. Further tests on the effects of temperature in air are reported in V-4.2. Results from these tests indicated the drift with temperature was less than 0.5% range at 575 K.

4. PRESSURE

The effects of transient pressure on the DTT output are reported in V-4.2. The DTT was placed within an autoclave, pressurized to 16.6 MPa, and then blown down. The DTT VRT shaft was free to move, so the data are probably valid only for the initial pressurization and subcooled portion of the blowdown. After the subcooled blowdown, flow may move the VRT shaft and invalidate the data. The uncertainty is $\pm 1/4\%$ full scale for a pressure change of 4.14 MPa. For a LOCE, the uncertainty is estimated as four times this uncertainty since the pressure change will be about four times higher, which is $\pm 1\%$ of full scale.

5. IRRADIATION

Irradiation tests are reported in V-9. With the neutron exposure level attained, no detrimental effects were observed. The conclusion is that radiation-induced changes, even for the full exposure requirement, are small.

6. MOUNTING MISALIGNMENT

There are no data available on the effects of mounting misalignment on the drag disc calibration, so it is not possible to obtain an accurate estimate of the uncertainty. The conclusion is that the error is negligible for the small misalignments that might be found in practice.

7. HYSTERESIS

Hysteresis effects are inherent within the calibration data, so zero uncertainty is attributed to it. No methodical investigation of these effects was undertaken nor is one warranted.

8. PIPE DYNAMICS

There are no data on the effects of pipe dynamics on drag disc output. It is likely that the accelerations predicted during a LOCE will affect the output. Posttest examination of all the transducer output may yield insight into the problem. Large spikes in output indicate a possible problem, but there may be a problem even if no such spikes exist. A test program to determine the effects of pipe dynamics on output is recommended. Because of a lack of data, the uncertainty caused by pipe dynamics is not estimated.

9. FLUID TRANSIENTS

The Bettis Flask tests are the only dynamic tests conducted on the DTT. Unfortunately, the tests cannot be used to evaluate the uncertainty in drag disc response, since the flow is not well known. An analysis of the disc response to a step change in flow is reported in Reference 13. The response time of 4 ms is much less than that required in the MRD[14], so the drag disc should accurately follow any expected transient. There have been no analysis or tests conducted to determine the response of the drag disc electronics to a transient.

10. ELECTRONICS

The uncertainty associated with the drag disc electronics has not yet been experimentally evaluated. It is estimated that the maximum uncertainty is 1% of range. This value will be updated when the data become available. There have been preliminary tests to determine the response of the drag disc electronics to a transient[a]. The results indicate that the 10 to 90% rise time is 10 ms. Therefore, the drag disc electronics should follow any expected transient.

11. FLUID KINEMATIC VISCOSITY

The kinematic viscosity influences the Reynolds number, which in turn influences the drag coefficient. As long as calibration covers the

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[a] The tests involved pulsing the LVDT in an attempt to obtain a step input and then observing the output.

same range in Reynolds number that the test data do, viscosity is accounted for. Therefore, zero uncertainty is attributed to viscosity.

12. FLOW PATTERN WITHIN METER

The actual state of fluid flowing through the DTT may cause additional uncertainty. Numerous flow regimes have been identified for two-phase steady flow, but only a few have been investigated in the tests conducted to date. Thus, the uncertainty due to the flow regime cannot be evaluated.

13. RETARDING FORCES, ELECTROMAGNETIC AND BEARING

These forces will influence both the static and dynamic response of the drag disc. If the forces never change, then the calibration already accounts for them. Unfortunately, there is no guarantee that the forces are constant and there have been numerous cases where the drag disc output was influenced by friction during test. The uncertainty due to these forces cannot be estimated.

14. REMAINING VARIABLES

Variables (12) through (14), (16), and (17) may affect the drag disc output, but the effect is probably small. However, since none of them has been investigated, the uncertainties cannot be estimated.

VIII. SUMMARY OF UNCERTAINTIES

The major sources of uncertainty in the DTT are the calibration and linearity/repeatability. A summary of the DTT uncertainty analysis is presented in Tables I and II.

The Measurement Requirement Document (MRD)[14] requires 5% reading with a response of 1 ms for both the turbine and drag disc uncertainties. Neither the turbine or drag disc are capable of meeting any of these specifications. The estimated accuracies for the turbine and drag disc during two-phase flow are respectively 5.5% and 19% range for plenum-type drag discs and 16% for piping drag discs. The response of the turbine (based on Tests L1-2, L1-3, L1-3A, and (L1-4) is 50 ms, the response of the drag disc is 10 ms.

IX. CONCLUSIONS

The DTT does not meet the specified accuracy requirements. It is believed that this may be more a result of the state of knowledge of measurement principles and data reduction techniques as opposed to basic transducer design. The response of neither turbine nor the drag disc meets the MRD[14] specified requirements.

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APPENDIX A

VELOCITY, DENSITY, FLOW DIRECTION DETECTOR ENVIRONMENTAL REQUIREMENTS

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VELOCITY, DENSITY, FLOW DIRECTION DETECTOR ENVIRONMENTAL REQUIREMENTS

The LOFT experimental measurements will include ten velocity, density, flow direction detectors in the reactor vessel, and primary and blowdown loop piping. The following sections provide data on the operational and environmental requirements for these detectors.

I. COOLANT FLOW REQUIREMENTS

1. COOLANT VELOCITY

The steady state and transient flow requirements are given for each of the LOFT experimental flow detectors in the MRD[A-1]. The instrument range required to meet the transient flow measurements is also provided in Reference A-1. This range is based on an anticipated flowmeter rangeability of 30 to 1. The range will clip the higher velocity peaks in some velocity measurement locations.

2. MOMENTUM FLUX MEASUREMENTS (ρV^2)

Momentum flux will be measured at each of the ten coolant flow measurement locations. The anticipated steady state and transient momentum flux ranges are given in Reference A-1. The document also provides the range of the ρV^2 detector to most adequately cover the anticipated operating range. The instrument range is based on an expected instrument rangeability of 20 to 1. This will mean that in some instances very small readings and momentum flux peaks will be clipped by the instrumentation.

The specified uncertainties and response are as follows:

Detector Uncertainty		System Response
Velocity	±5% range	10 to 90% in 1 ms
Momentum Flux	±5% range	±5% range

System temperature and pressure requirements are specified below:

Normal Operation	565 - 588 K
Maximum	810 K
Normal Operation	15.5 MPa
Design Maximum (hot)	17.24 MPa
Design Maximum (cold)	25.8 MPa

Shock Resistance - Subcooled Decompression $\Delta\rho/\Delta t$ = 69.0 MPa/s

Shock Resistance - Saturated Decompression $\Delta\rho$ Δt = 5.52 MPa/s.

TABLE A-I

SUMMARY OF PRIMARY COOLANT SPECIFICATIONS (Temperature above 394 K)

Parameter	Preconditioning (WEC[a] and LOFT)	Nonnuclear Operation LOFT Nonnuclear Test	Nuclear Operation (WEC-specified and tentative LOFT values)
pH @ 298 K	10.0 to 10.5	9.8 to 10.2 if boric acid is not specified	Not applicable
		When boric acid present the values are dependent upon the boric acid and alkali concentration. The values may range from 4.2 (high boric acid concentration) to 10.5 (low boric acid concentration) measured at 298 K	Same as LOFT nonnuclear test
Electrical conductivity	15 to 70 micromhos/cm	15 to 40 micromhos/cm at 298 K if boric acid is not specified	Not applicable
		With boric acid present, the values will vary as with pH; expected range is 1 to 40 micromhos/cm at 298 K	Same as LOFT nonnuclear test
pH control agent (^7LiOH)	0.9 to 2.2 ppm lithium-7[b]	0.22 to 2.2 ppm lithium-7	0.22 to 2.2 ppm lithium-7
Boric acid	Not required[c]	As specified	4000 ppm boron
Oxygen (max)	0.1 ppm	0.1 ppm	0.1 ppm[d]
Chloride (max)	0.15 ppm	0.15 ppm	0.15 ppm
Fluoride (max)	0.15 ppm	0.15 ppm	0.15 ppm
Hydrogen[e]	Not required	25 to 35 cc/kg	25 to 35 cc/kg
Total suspended solids (max)	1.0 ppm	1.0 ppm	1.0 ppm

[a] Westinghouse Electric Corporation.

[b] Lithium hydroxide (in the natural state, not enriched in the lithium-7 isotope) may be used for nonnuclear operation.

[c] It is assumed that boric acid will be required for chemical shim control. The exact concentration will be specified later. The 4000 ppm represents the maximum specified by WEC. At this time it is estimated that LOFT will specify on the order of 350 ppm boron.

[d] Oxygen concentration in the primary coolant need not be determined during nuclear operation so long as a positive hydrogen concentration is maintained.

II. CORROSION RESISTANCE

All materials used in the fabrication or attachment of the velocity, density, flow direction detectors in the primary system must be capable of operation for the specified core life without failure due to LOFT coolant corrosion. LOFT coolant specifications are given in Table A-I for preconditioning, nonnuclear and nuclear operation. Additional coolant conditions are as follows.

(1) Post-LOCE Coolant - The post-LOCE coolant will be high boron content water (up to 4000 ppm boron) with chemistry similar to the nuclear operation primary coolant.

(2) Refueling Conditions - During the refueling operation the primary system will be exposed to the atmosphere allowing absorption of air into the primary coolant. The temperature of the coolant during this operation will be less than 311 K.

(3) Primary Loop Decontamination - The problem of decontamination of the primary system has been deferred without selection of a decontamination solution.

III. IRRADIATION ENVIRONMENT

The velocity, density, and flow direction detectors will be designed to provide data within the specified accuracies after neutron and gamma exposure equal to the following maximum values:

<u>Neutron Flux</u>

Normal Operation	1.0×10^{14} nv
Total Exposure (Maximum)	7.2×10^{20} nvt

<u>Gamma Flux</u>

Normal Operation	1×10^{9} R/h
Total Exposure	2×10^{12} R

IV. DESIGN LIFE

The 2000 effective full power hours for the reactor means the detectors must survive for a longer but undefined period of time at operating temperature and pressure. The design objective will be for an operational life at temperature and pressure of 10,000 hours with 3000 hours as a minimum acceptable standard. The number and type of transients the ρV^2 detector will be subjected to during the design life are defined in Reference A-2.

V. CONFIGURATION

The velocity, density, and flow direction detectors will be located in the upper plenum; specific locations for each experiment may be found in the MCL[A-1]. The transducers will be designed with enclosures to secure all transducer components in the event of a transducer failure. Stainless steel sheathed MI cable will be provided for transmission of the transducer signals through the upper plenum and instrumentation penetration in the reactor vessel head. The detectors in the upper plenums will be mounted inside of the fuel assembly support columns. For fuel assemblies 1 and 3, this support has a cylindrical cross section with an inner diameter of 0.076 m. Fuel assembly 5 support column has a support with a square cross section with an inside dimension along each side of 0.197 m.

VI. SIGNAL READOUT

The output signals from the velocity, density, and flow direction detectors will be transmitted to the medium bandwidth FM multiplex system for data recording and display.

The specifications for the medium bandwidth system are as follows

(1)	Accuracy	$\pm 3\%$ range
(2)	Frequency response	dc to 1 kHz
(3)	Fixed input levels	± 2, ± 5, ± 20, ± 50, ± 200, ± 500, ± 2000 mV full scale
(4)	Output level	Adjustable ± 1 to ± 10 V
(5)	Signal-to-noise ratio	48 db

The velocity, density, and flow direction detector shall be designed to provide signals compatible with the data system input requirements.

VII. EFFECT OF FAILURE

1. SIGNAL LOSS

The data from the coolant velocity, density, and flow direction detectors will be used for the following purposes

(1) To evaluate the WHAM Code predictions for subcooled blowdown

(2) To evaluate RELAP3 Code saturated blowdown

(3) To provide data for the evaluation of core thermal analysis by the THETA1-B Code

(4) To provide data for the evaluation of ECC and containment spray systems capability

(5) To provide data concerning loss-of-coolant effects not included in any analytical code.

The loss-of-coolant velocity, density, and flow direction data would mean the ability to evaluate the contributions of these parameters or the above codes would be lost. Multiple units are used in the reactor vessel, so loss of a single unit would not result in a total loss of data.

2. HARDWARE FAILURE

Hardware failure resulting in physical separation of components from the mounting structure could result in blockage of coolant flow channels which could cause damage to the core.

VIII. REFERENCES

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