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DEVELOPMENT OF INSTRUMENTS FOR
TWO-PHASE FLOW MEASUREMENTS

MASTER

Aerojet Nuclear Company

IDAHO NATIONAL ENGINEERING LABORATORY

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Light-Water Reactor
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ABSTRACT

This report presents a state-of-the-art summary on instruments developed or being developed for measuring two-phase flow in the Loss-of-Fluid Test (LOFT) and Semiscale tests conducted by Aerojet Nuclear Company (ANC) for the AEC Water Reactor Safety Program. Brief descriptions of the purpose, measurement principles, design and development bases, designs, and performance are given for instruments to measure fluid velocity, momentum flux, density, and level.

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1. INTRODUCTION

The Water Reactor Safety programs at Aerojet Nuclear Company (ANC) involve several blowdown test facilities that utilize two-phase flow measurements for code verification. This document covers state-of-art two-phase instrumentation that has been developed, or is being developed, by ANC for use in these facilities.

Test facilities used by ANC include a pressurized light-water reactor system (LOFT Facility), a smaller nonnuclear system of similar geometry (Semiscale), and special purpose flow and/or blowdown loops for investigating phenomena associated with postulated loss-of-coolant accidents (LOCA). LOFT, Semiscale, and some of the "separate effects" facilities are designed to operate with pressurized water at pressures of 2500 psig and temperatures of 500 to 700°F. During the loss-of-coolant experiments (LOCE), system depressurization and reflood with emergency core coolant (ECC) produce a wide range of two-phase (steam-water) flow conditions. In order to adequately interpret results from these experiments, accurate measurements of fluid flow and fluid conditions are required. Parameters selected for measurement include flow velocity, momentum flux, density, and liquid level. Transducers such as turbine meters, drag disks, densitometers, and liquid level probes in varying forms are used to measure these parameters.

For the purpose of this report, the discussion is limited to two-phase systems of air-water or steam-water such as encountered in a pressurized water reactor (PWR) loss-of-coolant accident. Flow conditions encountered in a typical test include single-phase water and steam in addition to the two-phase states. Developed instrumentation must then,

of necessity, withstand the conditions of the entire ranges of flow regimes in addition to exposure to high temperatures, high pressures, temperature and pressure transients, blowdown forces, and radiation.

Historically, attempts to measure two-phase flow have at first centered on the use of commercially available instrumentation such as turbine meters, hot wire anemometers, and drag disks. These attempts have been largely unsuccessful in two-phase environments. Modifications of commercial instruments and the design of special detectors have also been of limited success. This has been partly a result of design constraints and limitations in fabrication and materials technologies imposed by the severe application. As an example, one of the major constraints in LOFT is the long-life, single-phase operation associated with the widely separated blowdown experiments. A second factor is the lack of reference measurements for use in evaluating the performance of the devices. This still represents a serious limitation to the development of two-phase flow transducers in that their performance cannot be evaluated and improved upon until reference measurements or standards of performance are available. Thus, to date, most two-phase flow instrumentation has been used in limited and specific applications, and limited success has been obtained in accurately interpreting the data obtained.

In general, development of two-phase flow instrumentation at ANC has followed the approach outlined above. That is, attempts have been made to use commercially available instruments, and in cases where they were found to be unsuitable, specialized devices were designed and developed. The Semiscale program has accumulated rather extensive information on the performance of commercial turbine meters and drag

disks, and on the special drag disks developed by ANC. The LOFT program includes development of a velocity-momentum transducer that incorporates a turbine meter and drag disk in the same unit. Both projects utilize gamma beam densitometers for their two-phase density measurements. Conductivity-type liquid level probes are also used by both projects. Other devices and techniques that have been investigated, but less successfully applied, include ultrasonic probes, pitot tubes, correlation techniques, and several variations on gamma densitometry.

Velocity measurements are made with turbine meters or turboprobes. Various transducing mechanisms are used to transform the flow-induced rotation of a turbine into an electrical signal. Thus, a proportional relationship is developed between the rotational speed of the turbine and the velocity of the media. At ANC, the emphasis has been on the development of turbines for use in the 2500-psia, 650°F PWR environment.

Momentum flux is measured exclusively with drag disks. Such a device when held in a flowing medium experiences a force which is proportional to the product of the drag disk area, fluid density, and velocity. Various unique techniques have been developed to adapt the device to the PWR environment during LOCA, and to convert the drag force into an electrical signal. Again, emphasis has been placed on use in the PWR environment.

Density measurements are made in one of three ways. These are drag disk/turbine transducers, gamma attenuation densitometers, and ultrasonic densitometers. The drag disk/turbine transducer was developed for the LOFT program and as a single unit contains a drag disk, turbine meter, and thermocouple. The unit is designed for use in the free field configuration while immersed in the PWR environment. The turbine uses an eddy

current transducer while the drag disk uses a variable reluctance transducer. The development of this device has been backed by an extensive test and analysis effort.

Gamma densitometers having single, double, and triple beams have been developed for ANC programs. The devices use the measured attenuation of gamma rays in the flowing media to determine the density of the media. By using multiple gamma beams, information concerning the flow regime can also be determined. At the present time, this probably represents the most accurate means available for density measurements under LOCA conditions.

Liquid level measurements in a PWR environment are made with conductivity and ultrasonic probes. Their operation is straightforward and the biggest problem has been in the development of reliable seals (conductivity probe) for use for long periods of time in a PWR environment. These techniques have been thoroughly tested and qualified for single-phase flows and work is continuing to analyze their behavior in two-phase systems.

Ultrasonic densitometers utilize the effect of the fluid density on the propagation of ultrasonic waves in a metallic array to measure average fluid densities in a PWR environment. Although this technique has not been tested as thoroughly as the drag disk/turbine meter, it does show promise and is continuing to be developed.

Transit time flowmeters utilize correlation techniques to sense the velocity of the fluid. Thermal pulses are introduced into the flow, and temperature probes spaced known distances apart downstream are used to detect the arrival times of the thermal disturbances. Although this technique has to date been used only in single-phase applications, its further development for two-phase is being considered.

The following sections of this report discuss each of the above noted measurement techniques and devices. They indicate state-of-art of two-phase measurement techniques currently in use by ANC. Although considerable success has been attained, additional work in the fields of testing and analysis continues.

2. VELOCITY MEASUREMENTS

2.1 Turbine Meters and Turboprobes

The Semiscale program has used specially built, full-flow turbine meters and turboprobes to provide valuable fluid flow information during blowdown and emergency core cooling tests conducted by Aerojet Nuclear Company for the Atomic Energy Commission^[1 through 8]. Volumetric flow rates, mass flow rates, and flow direction are important factors in the analysis of the hydraulic response during blowdown and simulated ECC injection. The experience and technology of various turbine meter vendors has been utilized in the design and manufacture of turbine meters capable of operation in the required test environments and providing data sufficiently accurate to support analysis for the Semiscale program.

2.1.1 Measurement Principles. Turbine meters and turboprobes directly measure flow velocity. The distinction between turbine meters and turboprobes is one of size and configuration rather than operation. The turbine meter, which is more accurately referred to as a full-flow turbine meter, is installed in line to measure the entire flow through an enclosed housing. Turboprobes, on the other hand, consist of a small axial-flow turbine sensing element positioned in the flow stream of a large duct, pipe, or channel by means of a strut.

The measurement principle is based on the proportional relationship between the rotational speed of the turbine and the velocity of the fluid. For full-flow turbine meters, since the turbine is affected by the entire cross-sectional flow, the rotational speed of the turbine is also proportional to the volumetric flow.

2.1.2 Design and Development Bases. Flow Technology, Inc. manufactured most of the full-flow turbine meters and the turboprobes used

in the Semiscale program. These meters were specially made to operate in the environment of the blowdown tests conducted in the Semiscale program. The environmental temperature and pressure requirements are 100 to 700°F and 0 to 3000 psig. Meters with various flow measurement ranges were needed. Table I gives typical meter sizes and ranges used in the Semiscale program.

TABLE I
TYPICAL METER SIZES AND RANGES USED IN THE SEMISCALE PROGRAM

<u>Type of Meter</u>	<u>Size Diameter (in.)</u>	<u>Range</u>
Full flow	2.624	+40 to +800 gpm
Full flow	1.689	+20 to +500 gpm
Full flow	3.777	+40 to +300 gpm
Full flow	0.742	+ 8 to +200 gpm
Turboprobe	0.375	+ 1 to + 30 ft/sec

Response times of 10 msec to step input changes in flow rate were required for the larger turbine meters used in the system.

2.1.3 Sensor Design Description. The basic design of turbine meters and turboprobes consists of a housing containing a propeller or turbine which is rotated by the fluid flowing through the meter. Figure 1 shows a full-flow turbine meter and housing typical of those used in the Semiscale program. The turbine itself is mounted on bearings that are the only mechanical contact between the turbine and its housing. Flow straighteners are used to help establish uniform velocity profiles and reduce swirl components. The rotation of the turbine is sensed by an external "pickoff" mounted on the outside surface of the flow meter

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FIG. 1 FULL-FLOW TURBINE METER AND HOUSING.

body. The pickoff electromagnetically senses the passing of the turbine blades and produces a series of electrical pulses. These pulses are then transmitted through acquisition and processing electronics for amplification and conversion into meaningful information.

2.1.4 Performance Versus Design Bases. Turbine meter performance is dependent on a variety of environmental conditions. The accuracy of turbine meter data is dependent upon velocity profiles of the measured fluid, flow rates, environmental temperatures, homogeneity of two-phase flows, dead bands, and physical similarity between calibration conditions and test conditions. Experience with turbine meters and the use of data obtained during the Semiscale test program has provided information concerning turbine meter performance. The transducer output accuracy is nominally between $\pm 2\%$ and $\pm 3\%$ of transducer full-scale range. Data acquisition and processing have generally added another $\pm 1\%$ to actual data uncertainty. Dead bands of $\pm 5\%$ of transducer full scale have been determined necessary to provide a 95% confidence interval for flows $< 5\%$ of full scale.

The turbine meter pickoff coils have historically been subject to failure at environmental test temperatures and conditions. This problem has been minimized through a joint ANC and vendor effort to develop an improved pickup coil. For some pickoff coil designs the signal strength is reduced enough with temperature increases to cause signal acquisition problems. These problems are overcome through use of appropriate electronics. Turbine support bearing failures have been minimal in Semiscale

use because of the limited test duration. Response times have been within the required limits.

The two main problem areas associated with the use of turbine meter devices to measure volumetric flow rate are as follows:

(1) Low Range -- Generally the turbine meters measure accurately in the upper limit of their ranges but they experience a "dead band" of up to 50 gpm for low flows in the high range units. A device is required that will maintain its accuracy at high volumetric flows and yet measure accurately the low flows as well.

(2) Flow Regime -- The turbine meters have been determined to be accurate when the flow is homogeneous. In nonhomogeneous flow, when two fluid streams of different velocities and densities are flowing (stratified, annular, etc.), no information is available on which to base a determination of the accuracy. This type of information is required in order to determine the applicability of the results from this device.

Figure 2 shows error bands for typical data obtained during Test 1009^[5] of the 1-1/2 loop Semiscale isothermal test program. The error bands shown in Figure 2 were established for homogeneous flow conditions and provide 95% certainty limits on the data.

2.2 Transit Time Flowmeter

The transit time flowmeter (TTF) is for measurement of the velocity of a fluid in a pipe or channel. The TTF has been investigated for possible application in the Semiscale and LOFT programs at ANC. These investigations have included conceptual testing in single-phase water.

FIG. 2 TYPICAL FULL-FLOW TURBINE METER DATA WITH TOTAL PROBABLE ERROR BANDS -- TEST 1009.

2.2.1 Measurement Principles. The TTF operates on the principle of measuring the transit time (t) of a disturbance in the fluid between two sensors. The sensors are separated by a known distance (d) so the velocity is just

$$v = \frac{d}{t} . \quad (1)$$

The disturbance is usually (though not limited to) thermal, and the sensors are usually thermocouples. The approach most often used to measure this transit time is that of cross-correlation. In this approach, thermal noise naturally present in the fluid is utilized. The signal of the upstream TC is correlated with the downstream TC through a variable time delay. The delay that gives the highest correlation is the transit time. This requires a "cross-correlation computer" for the measurement. A simpler approach involves introducing a thermal pulse through a spark gap or similar heater. This thermal pulse is then observed as it passes the downstream TCs and the transit time may be determined directly without requiring correlation of signals.

2.2.2 Design and Development Bases. The work done by ANC on the TTF concept has been limited to feasibility and scoping tests for the purpose of assessing the merits of the technique. As such, most of the instruments were designed for demonstration of principle rather than to meet specific requirements of accuracy or response.

2.2.3 Sensor Design Description. The sensors tested by ANC fall in two groups: those where a thermal pulse was used for the transit time measurement, and those using cross-correlation techniques.

The units employing thermal pulse introduction were designed for ambient temperature single-phase water. They consisted of a spark gap

set in the flow stream with two or three sheathed TCs downstream in line with the spark gap. One unit was built into a tube with a 0.685-inch ID. It employed an automotive spark plug and a capacitive discharge system to introduce a 0.2J energy pulse into tap water. The sensors were 0.020-inch OD sheathed chromel/constantan TCs spaced at 1/2, 1, and 2 inches downstream. The signals were amplified X1000, filtered to 50 Hz, amplified X200, and displayed on an oscilloscope at 0.5 V/cm sensitivity. This gave a 0.075°F/cm sensitivity to the system. The second thermal pulse unit was built into a 0.234-inch ID. It had a spark gap formed from a two-lead glass feedthrough. Spaced 1.5 and 3 inches downstream were two 0.020-inch OD sheathed chromel/alumel TCs. A velonex pulser delivered ~1.4J to the water through the spark gap with each pulse. Electronics similar to that used for the other sensor provided a sensitivity of ~22°F/DIV. Such a TTF is shown schematically in Figure 3.

The unit employing noise correlation consisted of 0.020-inch OD sheathed TCs extending to the center of a 0.938-inch ID tube. The TCs were spaced one inch apart and the upstream TC was formed into a coil in the center of the stream two inches upstream from the junction. This TC was AC-coupled to a 60 Hz power source and when there was not enough thermal noise present in the stream, as is the case when the water is at ambient temperature, it was heated to produce a thermal disturbance. The cross-correlation function from pairs of signals was generated through a Time Data 100 Computer. This last sensor was actually used in hotter than ambient water, although not to PWR primary fluid pressure and temperature conditions.

FIG. 3 TYPICAL THERMAL PULSE TRANSIT TIME FLOWMETER.

2.2.4 Preliminary Test Results. The tests made on the pulsed flow meter showed an accuracy of $\pm 6\%$ between 2 and 5 ft/sec when using the time for the pulse to pass from one TC to the other. Time measured from the pulse gave less accurate flow velocities. It is evident that they function better in small channels, low velocities, and laminar flows than in the opposite conditions. Of course the range of a particular device is determined in large measure by TC spacing. The further downstream from the spark gap, the lower the signal. However, the greater the separation of TCs, the greater the accuracy of the time measurement. Hence, for a given range of velocities, a determination of the optimum tradeoff must be made. Multiranges can be achieved by adding TCs at appropriate distances from the first one. Special spark plugs must be developed to adopt this type of meter to PWR conditions.

The cross-correlation type flowmeter has been studied by ANC only enough to demonstrate the principle. Extensive work has been done by others^[9 through 13] with respect to application of this type of meter to sodium flow measurements. The best sensor developed employs "rakes" of thermocouples, giving enhanced accuracy and the capability of measuring flow profiles. The extension to velocity measurements in two-phase flow appears promising. The thermal disturbances caused by discontinuous phases should produce much sharper correlation peaks than do the thermal eddies in single-phase fluids.

3. MOMENTUM FLUX MEASUREMENTS

In loss-of-coolant experiments performed in the Semiscale apparatus, momentum flux measurements are made with drag disks. These measurements are used directly and in combination with a density measurement to compute the fluid mass flow.

3.1 Drag Disk

Drag disk transducers are used to measure the momentum flux in a given area, determined by the instrument's physical size, within a flowing multiphase fluid.

3.1.1 Measurement Principles. A drag disk consists of a flat circular disk held in its measurement location by a cantilever beam. The beam is deflected by fluid forces on the disk proportional to $A\rho v^2$ where A is the drag disk cross-sectional area, ρ is the fluid density, and v is the fluid velocity. This force is determined by measuring the deflection of the cantilever beam.

3.1.2 Sensor Design Description. Two types of drag disk fluid momentum sensors of 1000, 2000, 7500, and 10,000 lb/ft-sec full scale range were used for the Semiscale test program in a transient pressure and thermal environment.

The first type was a commercially available drag disk sensor utilizing a scheme such as shown in Figure 4. The drag measuring beam also forms the pressure boundary, and the drag deflection sensing strain gages are mounted directly exposed to transients in the fluid temperature. These two design problems lead to large offsets during rapid temperature and pressure changes. Elimination of such effects was a major goal in the development of an instrument for use in the Semiscale experiments.

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FIG. 4 CROSS SECTION OF A COMMERCIAL-TYPE DRAG DISK.

The second type is shown in Figure 5. It was designed to be nearly immune to the pressure and thermal transient problems associated with the first type by utilizing a torsion bar as the disk position restoring element. This torsion bar does not constitute any part of the pressure boundary and the variable reluctance transducer (VRT) is not pressure sensitive to any significant degree. Thermal transient stability results from the following design features:

- (1) The torsion bar is made of Incaloy 903 alloy which has an almost constant modulus as a function of temperature. The torsion bar contacts the rest of the sensor at only one weld location so that differential coefficients of expansion can have no effect.
- (2) The VRT, besides being thermally compensated^[14], is located at a position where it can be water cooled. The angular slant of the VRT axis is such that the VRT core moves axially in the VRT as the drag rod is deflected.
- (3) Water cooling of the VRT portion of the sensor that extends outside the pipe pressure wall prevents "blowdown" of the cooled area and thus prevents false signals that would be induced by rushing water exerting force on the VRT core.
- (4) The drag disk support rod is designed to be balanced about the torsion bar axis so that buoyancy forces do not cause changes in the unit's output.

Results of "blowing the unit down" in an autoclave typically lead to an output change (from just before blowdown to just after blowdown) of about 1 mV out of a full-scale range of 2.5 volts (that is, 0.04% of full scale). Since the water remaining in the autoclave changes

FIG. 5 CROSS SECTION OF SECOND TYPE OF SEMISCALE DRAG DISK.

temperature from 650 to 205°F during a typical 30-second blowdown and the pressure changes from 2200 psi to atmospheric pressure, the test subjects the drag disk sensor to significant pressure and thermal transient.

3.1.3 Performance. The performance of commercial drag disks has been monitored in Semiscale isothermal tests. Figure 6 shows error bands for typical data obtained during Test 1011 of the 1-1/2 loop Semiscale isothermal test series (References 2, 3, 4, 6, 7, 8, 15). The error bands were established for homogeneous flow conditions and provide 95% certainty limits on the data. Nonhomogeneous two-phase flows can cause large errors due to the physical construction of the drag disk.

FIG. 6 TYPICAL MOMENTUM FLUX MEASUREMENTS AND TOTAL PROBABLE ERROR BANDS FROM SEMISCALE TEST 1011.

4. DENSITY MEASUREMENTS

Interpretation of flow, differential pressure, and heat transfer measurements, during an LOCE, is greatly aided with density and/or velocity measurements. Density measurements ideally should be made with minimum perturbation of the flow at key locations throughout the reactor fluid systems. The range of density during an LOCE is from that of all steam to all water; therefore, the transducer should be capable of covering this range.

4.1 Drag Disk Turbine Transducer

A combination drag disk transducer and turbine transducer will be used along with a thermocouple at various piping and vessel locations in the LOFT Integral Test System to measure the fluid velocity, momentum flux, and temperature during the LOCEs. The data from these measurements will then be used to calculate the fluid thermodynamic properties, mass flux, and mass flow rate occurring during the LOCEs. Briefly, the accuracy requirements specified for the measurements of fluid velocity and momentum flux are $\pm 5\%$ of reading over the various ranges predicted at the transducer locations.

4.1.1 Measurement Principles. The measurement principles selected to satisfy the measurement requirements for LOFT involve the use of a turbine transducer to measure the fluid velocity and a drag disk transducer to measure the momentum flux. The basis for this selection involves the suitability of transducers of this type to operate in the LOFT environment and meet the range requirements. Theoretically, the response of the turbine transducer is a function of the fluid velocity (v), and the response of the drag disk transducer is a function of the fluid momentum flux (ρv^2). The intended use of the data obtained from these transducers is to calculate the fluid density and mass flow rate:

$$\rho = \frac{(\rho v^2)_{\text{drag disk}}}{(v_{\text{TURB}})^2} \quad (1)$$

where

ρ = calculated fluid density (lb/ft³)

$(\rho v^2)_{\text{drag disk}}$ = measured fluid momentum flux (lb/ft sec²)

v_{TURB} = measured fluid velocity (ft/sec)

$$\dot{m} = \frac{(\rho v^2)_{\text{drag disk}}(A_f)}{v_{\text{TURB}}} \quad (2)$$

where

$\dot{m}$ = fluid mass flow rate (lb/sec)

A_f = flow area immediately upstream of the transducer (ft²).

The force with which the fluid strikes the drag disk is proportional to the momentum flux (ρv^2) and can be expressed as

$$F = \frac{C_D A_T}{2 g_c} (\rho v^2) \quad (3)$$

where

F = force (lb)

C_D = flow loss coefficient

A_T = area of the disk (ft²)

g_c = gravitational constant (ft/sec²)

ρv^2 = momentum flux (lb/ft sec²).

By combining the calculated fluid density (ρ) with the measured fluid temperature or the measured fluid pressure for the saturated portion of the LOCE, the fluid properties such as enthalpy, entropy, void fraction, and quality can be calculated (assuming a slip ratio of 1). For this reason, a thermocouple is included in the DTT.

4.1.2 Design and Development Bases. Development efforts have been aimed at obtaining an accurate, compact, rugged, integral DTT that has a long operating life. The development criteria include the requirement that the DTT shall be:

- (1) Accurate to within $\pm 5\%$
- (2) Capable of operating for extended time periods (10,000 hours) in the LOFT fluid environment without failure
- (3) Of a size suitable for installation in the LOFT Integral Test System at the specified locations
- (4) Capable of withstanding the LOFT nuclear environment
- (5) Capable of withstanding and measuring the desired parameters with the specified accuracy during the LOFT LOCEs
- (6) Capable of withstanding severe overrange
- (7) Constructed in such a manner that in the event of a transducer failure, the transducer would retain any pieces large enough to block flow passages in the reactor core.

The meter electronics and signals also shall be adaptable to the LOFT data acquisition system. A summary of environmental design requirements is listed in Table II. Performance design requirements are summarized in Table III.

4.1.3 DTT Design Description. The DTT is a turbine transducer and a drag transducer combined on a single body. A schematic diagram of the DTT with representative dimensions is shown on Figure 7. The configuration for the measurement portion of the DTT (the flow transducer and the drag transducer) is the same for all DTTs used in LOFT. Because of the geometry constraints and the installation requirements, however, the mounting method for the "plenum" DTTs, which includes the DTTs mounted in the reactor

TABLE II

DTT ENVIRONMENTAL DESIGN REQUIREMENTS

Temperature		
Normal Operation		557-600°F
Maximum		1000°F
Pressure		
Normal		2250 psi
Maximum (Hot)		2500 psi
Maximum (Cold)		3740 psi
Irradiation		
Neutron Flux		
Normal Operation		1.0×10^{14} nv
Total Exposure		7.2×10^{20} nvt
Gamma Flux		
Normal Operation		1×10^9 R/hr
Total Exposure		2×10^{12} R
Design Life		
Design Goal		10,000 hr
Minimum Acceptable Design		3,000 hr

fuel assembly outlet end boxes, the reactor core simulator (for the non-nuclear tests), and the downcomer stalks, differ from the mounting methods for the "piping" DTTs. The LOFT plenum DTT installation is shown in Figure 8. A DTT installation in a 14-inch pipe is shown in Figure 9.

4.1.3.1 Transducer Functional Description

Drag Disk Operation. The force with which the fluid strikes the drag disk is proportional to the momentum flux. The force causes the drag disk to be displaced which displaces the core in the VRT by means of the torque bar and lever arrangement (see Figure 7). An electrical signal from the VRT, which is proportional to the displacement of the VRT core and to the force on the drag disk and the momentum flux, is sent to the VRT electronics unit.

TABLE III

DTT PERFORMANCE DESIGN REQUIREMENTS

RANGE A		
	<u>Turbine</u>	<u>Drag Disk</u>
Range:	0.4 to 13 fps	35 to 3500 $\frac{\text{lb}}{\text{ft sec}^2}$
Accuracy:	$\pm 5\%$ of reading	$\pm 5\%$ of reading
Response:	100 msec (3.5 Hz)	100 msec (3.5 Hz)
RANGE B		
Range:	0.1 to 20 fps	35 to 3500 $\frac{\text{lb}}{\text{ft sec}^2}$
Accuracy:	$\pm 5\%$ of reading	$\pm 5\%$ of reading
Response:	100 msec (3.5 Hz)	100 msec (3.5 Hz)
RANGE C		
Range:	5 to 150 fps	400 to 40,000 $\frac{\text{lb}}{\text{ft sec}^2}$
Accuracy:	$\pm 5\%$ of reading	$\pm 5\%$ of reading
Response:	100 msec (3.5 Hz)	100 msec (3.5 Hz)

Turbine Operation. The sampled fluid flowing through the turbine shroud (see Figure 7) causes the turbine to turn in the field of the eddy current transducer (ECT). Because the turbine rotates at a speed proportional to the fluid velocity, fluid velocity can be measured by counting the number of turbine blade tips that interrupt the field of the ECT sensor during a specified period of time. The number of blade tip passages per unit of time is counted and converted to an analog voltage that is proportional to the fluid velocity.

4.1.3.2 Electronics Functional Description. The ECT electronics circuitry consists of three somewhat distinct sections: an oscillator or driver, a bridge in which the eddy current transducer forms two of the bridge legs, and an amplifier complex for conditioning the bridge output to that required. All components and wiring on the unit circuit

FIG. 7 DRAG DISK TURBINE TRANSDUCER -- SCHEMATIC DIAGRAM.

FIG. 8 LOFT PLENUM DTT INSTALLATION IN DOWNCOMER STALK.

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FIG. 9 PIPING INSTRUMENT FLANGE SCHEMATIC SHOWING DTT LOCATION IN LOFT PRIMARY PIPE.

board are isolated from the metal container, and the two transformers at the bridge isolate the bridge and the transducer from the circuit board common. Thus, the pulse and DC outputs from the unit are free to be connected to signal recording ground without ground loop problems.

Oscillator. The oscillator serves to drive the bridge formed by resistors and the transducer coils. With turbine blades remote from the eddy current sensing coils and the bridge properly balanced by adjusting null and phase, the fundamental frequency bridge output is zero. As a turbine blade is brought near the eddy current coils, the blade causes a reflected impedance change in the nearest coil and thus unbalances the bridge. During the time a blade is near the sensing coils, a bridge output with large fundamental frequency content occurs. Since the fundamental frequency (100 kHz) is much larger than the maximum turbine revolutions per second, many cycles of fundamental frequency occur while a turbine blade passes the sensing coils.

Amplifier Complex. The amplifier complex amplifies and filters the bridge output, which is then full wave rectified giving a 200-kHz pulse rate during bridge unbalance. The 200-kHz pulse rate is turned into a smooth envelope with a repetition rate equal to the turbine blade passage rate. The 710 discriminator then triggers each time the RC integrated envelope rises above a given level. The output of the 710 discriminator yields a pulse output for each blade passage. DC output proportional to turbine rpm is obtained by using a frequency-to-DC converter module. The 741 operational amplifier furnishes a low impedance output from the frequency-to-DC converter.

4.1.4 DTT Performance Versus Design Bases. Because of the severe environmental and performance requirements for the DTT, extensive testing

has been performed. The DTT was performance tested in (a) the full flow configuration in which all of the flow is directed through the transducer shroud and (b) the free-field configuration in which the DTT is installed in a probe-type configuration and the fluid may flow through and around the transducer. The free-field configuration is used in LOFT. Performance tests were conducted with subcooled water, two-phase steam-water, and air-water mixtures as the flowing fluids. In addition, the DTT was tested in a series of transient blowdowns similar to predicted LOFT blowdowns.

Because there are, in general, two ranges specified for the DTT (that is, one range representative for the vessel or plenum transducers and one representative of the piping transducers), performance tests were conducted on DTTs that were representative of both ranges. The two-phase performance test results indicate that the plenum DTT turbine transducer has a 2σ error band (95% confidence) of approximately $\pm 15\%$ for the full range tested (≈ 3 to 19 ft/sec) and the drag disk had a 2σ error band of approximately $\pm 26\%$ for the full range tested (500 to 2500 lb/ft sec²) with two-phase steam-water as the flowing fluid. Similar tests on the piping DTT indicate the turbine transducer has a 2σ error band of approximately $\pm 11\%$ for the full range tested (4 to 20 ft/sec) and the drag disk transducer, a 2σ error of $\pm 45\%$ for the full range tested (500 to 18,000 lb/ft sec²). Single-phase performance test results indicate the plenum DTT turbine transducer has a 2σ error band of $\pm 3\%$ and the drag disk $\pm 8\%$. Similar tests on the piping DTT indicate the turbine transducer has a 2σ error of $\pm 3\%$ and the drag disk transducer $\pm 22\%$. The greater drag disk error in the piping transducer configuration is due to the smaller target diameter, which is shadowed by the turbine hub. A major

factor in defining two-phase flow errors is the difficulty of defining flow regimes and having adequate standards for calibration and testing.

The 10,000-hour design life objective has not currently been achieved. Current life expectancy is 2,000 to 4,000 hours. The limiting component has been the turbine transducer bearings.

The Bettis flask transient blowdown tests indicate that the DTT operates and is not damaged during successive blowdown tests. These tests also indicate that a correction factor of approximately 1.66 for the turbine and 1.98 for the drag disk must be applied to the full flow water calibration equations to make the data coincide with the velocity and momentum flux obtained from alternate measurements (see Figures 10 and 11).

FIG. 10. COMPARISON OF VELOCITY OBTAINED WITH DTT TURBINE AND THAT CALCULATED -- BETTIS FLASK TESTS.

FIG. 11 COMPARISON OF MOMENTUM FLUX OBTAINED WITH DDT DRAG DISC AND THAT CALCULATED -- BETTIS FLASK TESTS.

The pressure and temperature sensitivity tests show that the DTT sensitivity to these parameters is within the design range. In addition, the irradiation and temperature survivability tests show that the DTT is not adversely affected by either environment.

4.2 Gamma Attenuation Densitometers

Gamma attenuation densitometers serve two purposes: to measure the average density of the fluid in a pipe and to determine the fluid flow regime, or the liquid-gas distribution. The "average density" in this discussion refers to a simple average over the cross-sectional area of the pipe.

4.2.1 Measurement Principles. Gamma attenuation densitometers currently used at ANC utilize either one, two, or three beams of gamma radiation passing through the pipe. The intensity of the transmitted

radiation beam indicates the fluid density averaged along the path of the radiation beam. The radiation beam must be narrow to minimize the effects of scattered radiations. Also, in some cases, a narrow beam is required to allow the use of the simplifying assumption that the density does not vary over the cross section of the beam. Violation of this assumption can lead to "streaming" error. This precludes the use of a single radiation beam broad enough to include the entire pipe cross section.

If the fluid density does not vary across the pipe, then a single beam gives the desired density information. On the other hand, many beams are required to measure unambiguously the density distribution if no assumptions are made about the flow regime. In practice, a compromise is usually made by assuming that the fluid flow is in one of the several commonly considered flow regimes: uniform, stratified, or annular. Only a few beams are required to resolve these flow regimes and to measure with reasonable accuracy the average density and the density distribution of the fluid.

4.2.2 Design and Development Bases. The instrumentation developed to measure the gamma beam attenuation was designed to the requirements given in Table IV.

4.2.3 Design Description. Several variations of gamma attenuation densitometers are in use at ANC. Figure 12 indicates the geometry of a system that is in use on the Semiscale facility. Only one beam is indicated in the figure, but many of the installations in the Semiscale facility use two perpendicular units with the beams intersecting at the center of the pipe. These two beams allow a distinction between uniform and stratified flow. These densitometers are used to obtain density information at frequencies up to 100 Hz.

TABLE IV

GAMMA ATTENUATION DENSITOMETER DESIGN REQUIREMENTS

Range	0.07 to 62.4 lbm/ft ³
Accuracy	$\pm 0.05\%$ FS from 62.4 to 3.3 lbm/ft ³ $\pm 1.0\%$ FS from 3.3 to 0.07 lbm/ft ³
Drift	$< \pm 0.1\%$ FS over one-hr operating period
Life	2000-hr operation minimum with 99% reliability
Frequency response (3 dB)	Single-Beam System - 100 Hz Dual-Beam System - 100 Hz Triple-Beam System - 10 Hz
Signal/noise ratio	66 dB
Amp output voltage	0-10 VDC
Amp output impedance	< 10 ohms
Detector and preamplifier operating environment	50-200°F 20-100% relative humidity
Amp and HV power supply operating environment	68-75°F 30-70% RH
HV power supply output voltage	0-1500 VDC
HVPS line and load regulation	0.001%
HVPS drift	< 10 mV/hr

Figure 13 shows a dual-beam system that is now being conceptually tested for specific application in Semiscale. This geometry allows the system to resolve uniform, stratified, and annular flow regimes in all except a few unrealistic cases. If it is assumed that the flow is in one of these regimes, the average density can be determined with an estimated error of about ± 0.02 g/cc, with a time response of about 0.01 second. Tests indicate that cross-talk between the beams, due to radiation scattering from one beam to the other, is negligible.

FIG. 12 SINGLE-BEAM DENSITOMETER USED IN THE SEMISCALE FACILITY.

FIG. 13 DUAL-BEAM DENSITOMETER UNDER DEVELOPMENT FOR SEMISCALE.

A triple-beam system designed for use in the LOFT program is sketched in Figure 14. Each beam gives density information at frequencies up to 10 Hz with about a 0.05% noise level in the worst case. This system also has negligible "cross-talk" between the beams.

All three of these systems use cooling water in the shields around the detectors. This allows the use of the densitometers with fluid temperatures of at least 600°F. These systems are commonly calibrated before each test to compensate for any possible aging effects in the detector and source and for variations in the background radiation level. The LOFT system includes tungsten shims that can be remotely inserted into and removed from the beam to aid in this calibration. With this occasional recalibration, the gamma attenuation densitometer has an effectively unlimited lifetime.

The single-beam, dual-beam, and triple-beam densitometer systems all utilize the same basic electronic configuration. The gamma rays are detected by a thallium activated sodium iodide crystal that is an integral part of the photomultiplier tube assembly. A current-to-voltage converter and preamplifier are mounted at the photomultiplier tube base, which drives the signal several hundred feet to the signal conditioning amplifier which converts the signal to a 0 to 10 volt level. The high voltage power supply that supplies the photomultiplier tube cathode and dynode voltages is housed beside the signal conditioning amplifier. The solenoid controls for remotely inserting the calibration shims into the gamma beam are also located with the signal conditioner electronics.

The mechanical design of the single- and dual-beam densitometer systems is such that the gamma source is inserted into its collimator from a source cask located several feet away. This is accomplished by means

FIG. 14 TRIPLE-BEAM DENSITOMETER FOR LOFT.

of a teleflex cable controlled by a manual cranking assembly. In the triple-beam system the source cask and collimator are an integral unit. The source is pneumatically moved several inches to the beam ports and electrically latched in place.

The detectors are all physically located inside lead-filled shielding casks to reduce background gamma detection. These shielding casks are maintained at a constant temperature by means of water flowing through cooling coils located inside the lead shielding.

4.2.4 Performance Versus Design Bases. Typical results for a single-beam gamma densitometer, under static conditions, are shown in Figure 15. An overlay of three single-beam density measurements obtained during a Semiscale isothermal test are shown in Figure 16. These data indicate the gamma densitometer in general meets the Semiscale design criteria.

The dual-beam densitometer system has been fabricated and is currently being used during controlled two-phase flow studies being conducted at Westinghouse Canada Limited. Initial performance indicates that all design specifications have been met except the signal-to-noise ratio requirement. This system utilizes a chopper-stabilized preamplifier, which was selected for its high quality temperature drift characteristics. The chopper frequency riding the output signal is filtered out at the recording electronics.

The triple-beam system is being fabricated for use during the forthcoming LOFT tests.

4.3 Ultrasonic Density Transducers

The ultrasonic burst attenuation (UBA) void fraction detector was developed to meet the need for a reliable, rugged sensor to be used in the reactor vessel and piping of the LOFT to measure the density of a steam-water mixture.

FIG. 15 SINGLE-BEAM GAMMA DENSITOMETER STATIC TEST.

FIG. 16 FLUID DENSITY MEASURED BY SINGLE-BEAM DENSITOMETERS IN SEMISCALE BLOWDOWN TEST.

Two types of transducers have been investigated: the first, having a helical geometry, was developed to measure average density; and the second, having a linear geometry, is presently under development and will provide information about density distributions.

4.3.1 Measurement Principles. The UBA technique operates on the principle that the attenuation of a stress wave traveling in a metal helical transmission line is a function of the liquid covering the transmission line. The wavelength of the carrier burst frequency must exceed the wire diameter by approximately a factor of five to obtain void fraction sensitivity when the wire is in a helix. In the straight wire configuration, the stress wave propagates as a nearly pure compressional wave in a guided transmission line with a small attenuation factor under

most conditions. When the surface of the wire is curved into a helical shape, part of the compressional wave is converted into a surface wave. The surface wave attenuation is greatly increased by the presence of a liquid. For a two-phase mixture of water and steam the transmission line sees two media having different acoustical impedances. The attenuation then becomes a function of the steam void fraction in the water.

4.3.2 Design and Development Bases. The UBA detector was designed to provide long-life reliability and a simple, rugged construction. The operating requirements for the detector are as follows:

Temperature Range	200 to 650°F
Pressure	2500 psi
Media	water, air, and/or steam
Void Fraction Range in Density Units	0.1 to 1.0 g/cc
Accuracy in Density Units	± 0.1 g/cc
Response Time	100 msec
Operating Time	2000 hours
Velocity	0-16 ft/sec in vessel, 0-100 ft/sec in piping
Radiation	10^{15} nvt

4.3.3 Transducer Description

4.3.3.1 Detector. The helical-type detector design shown in Figure 17 was selected for use with a 200 kHz compressional wave. The helix is 4 inches long with 6-1/4-inch-diameter turns. This configuration attenuates the amplitude of the stress wave signal approximately 75% as the surrounding media changes from steam to water.

The compressional wave is introduced into the wire with a magnetostrictive transducer. An identical transducer is used as the receiver on the other end of the helix.

FIG. 17 ULTRASONIC VOID FRACTION DETECTOR.

The detector shape is flexible. The helix can be made short to keep the measurement near that of a point measurement. The transducers can be attached at any angle to the helix that is desired. The straight portion of the transmission line can be as long as desired since it is not sensitive to void fraction. The detector will work in other configurations, such as an "S" shape, but a helix is better since it is more insensitive to the direction of flow of the surrounding media.

4.3.3.2 Transducer Design. The transducer is made up of a 1/2-inch-long coil wound on a 1/16-inch-diameter magnetostrictive^[a] stub. This makes a low Q 200 kHz resonant transducer. The coil is wound

[a] The magnetostrictive material is Remendur, which is a metal alloy consisting of 49% iron, 49% cobalt, and 2% vanadium. It is manufactured by Wilbur B. Driver Company, Newark, New Jersey.

with No. 34 copper wire^[a] with ceramic insulation. A schematic of the transducer assembly is shown in Figure 18. The signal-to-noise ratio is increased by biasing the flux level up in the magnetostrictive stub with a magnet attached to the outside of the housing.

The transducer housing is of welded stainless steel construction to withstand the LOFT 650°F, 2500 psi, corrosive steam-water environment.

4.3.3.3 Electronic Instrumentation. A block diagram of the electronic instrumentation system for void fraction measurements is shown in Figure 19. The generator delivers a 2.5 μ sec pulse to the transmit transducers to excite them at 200 kHz resonance. The receive transducers are identical to the transmit transducers. A current sensitive preamplifier amplifies the signal to a one-volt peak amplitude, with a steam environment at the detector, to drive the amplitude-to-analog converter. The converter has blanking and tracking circuits. Blanking is necessary to select the desired cycle of the burst of which the amplitude is to be measured, and tracking is necessary to follow the temperature-dependent time delay of the signal. The converter is a sample-and-hold circuit that tracks the burst signal from the first cycle to the peak of the second cycle and holds that peak until the first cycle of the next signal burst.

4.3.4 Performance Test Results. In development of the UBA void fraction measuring technique, several sources of error were possible and had to be considered:

- (1) Changes in coupling coefficient
- (2) Air and water residual effects

[a] The coil is wound with No. 34 copper wire having ceramic insulation which contains a silicone binder. It is manufactured by Rea Magnet Wire Company, Inc., Fort Wayne, Indiana.

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FIG. 18 MAGNETOSTRICTIVE TRANSDUCER ASSEMBLY.

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FIG. 19 ULTRASONIC VOID FRACTION DETECTOR INSTRUMENTATION BLOCK DIAGRAM.

- (3) Transducer temperature effects
- (4) Instrumentation drift
- (5) Flow effects
- (6) Accuracy of calibration standard.

The coupling coefficient of the ultrasonic energy from the detector to the medium being measured must remain constant. If the medium changes acoustical properties or if the detector has a corrosion buildup, the attenuation will change and new calibration data will be needed. It was determined by extensive tests that the water temperature and pressure changes do not significantly affect the coupling constant. Also, it was determined that when using stainless steel detectors, corrosion effects of the LOFT environment are insignificant.

The air residual effects are present under air-saturated water conditions where air precipitates out of the water as it is warmed up and collects on the detector. Although the air comes off the detector under flow or boiling conditions, in LOFT this effect is of no concern since de-aerated water will be used.

The residual water droplet effect is of no concern under two-phase water-steam conditions. The dynamics of the media prevent the droplets from forming on the detector surface.

The transducer coil characteristics are well behaved up to 700°F. An amplitude versus temperature plot is shown in Figure 20. Between 200 and 650°F the error introduced by temperature variations is less than 4%.

The electronic instrumentation is a key part of obtaining an accurate analog signal proportional to the signal amplitude. Blanking and discrimination techniques are used to select the desired cycle of the signal

FIG. 20 TRANSDUCER TEMPERATURE SENSITIVITY.

of which the amplitude is to be measured. All noise before and after the cycle of the burst to be monitored are blanked out by holdoff and lockout circuitry. DC drift of the analog output is kept to a minimum by keeping all DC levels in the one-volt range.

Flow effects are the largest potential source of error in the void fraction measurement. They are compensated for by defining the calibration curve of signal amplitude versus void fraction for different media velocities at the detector. These effects are generated by a pressure drop across the helix that varies with flow velocity. A two-phase steam-water medium is at saturated stem conditions; therefore, at the upstream surface of the detector, when the pressure increases slightly due to flow, the steam condenses; at the downstream surface of the detector, when the pressure drops slightly below saturation pressure due to flow, the water flashes to steam. The calibration curve as a function of flow is shown in Figure 21. Without knowing the velocity the worst error is 0.2 g/cc. Knowing the velocity, the error is less than 0.05 g/cc from the velocity effect.

Calibration is done in a two-phase flow loop up to velocities of 10 ft/sec and in a blowdown facility for velocities up to 100 ft/sec. A turbine flowmeter that is insensitive to the void fraction is used to measure the velocity. Density is obtained by using as a reference a density detector using gamma-ray attenuation. The accuracy of the gamma density detector is ± 0.05 g/cc.

The ultrasonic burst attenuation void fraction detector is very rugged and compatible with the hostile PWR environment. The ability to withstand the environment is attributed to having all stainless steel welded seals. The simple detector configuration yields a high reliability factor for the 2000-hour operational requirement.

FIG. 21 ULTRASONIC VOID FRACTION DETECTOR CALIBRATION IN TWO-PHASE STEAM-WATER AT AMBIENT LABORATORY PRESSURE.

The accuracy of a measurement depends upon the calibration facilities. Although the principle of operation and physical design of the detector are simple, the calibration of the device is not. Each new detector configuration must be calibrated. Calibration requires a two-phase flow loop with a wide range of velocities and an accurate density and velocity standard.

5. LIQUID LEVEL

One of the pertinent experimental measurements in LOCA blowdown and reflood tests such as LOFT is the liquid level inside the reactor vessel. In order to determine the liquid level, a transducer is required that detects the presence of liquid. The liquid presence can be in the form of a subcooled liquid with a defined level or in the form of an oscillating liquid level with interspersed pockets of vapor. The LOFT and Semiscale programs at ANC utilize conductivity transducers and differential pressure (DP) cells to measure liquid levels. Ultrasonic transducers have been developed as backup.

5.1 Conductivity Liquid Level Transducer

The liquid level transducer (LLT) designed for LOFT is a conductivity sensitive device consisting of multiple electrodes and a common ground plane. Electrodes are located at specific intervals to measure the liquid level with the desired accuracy. LLTs were designed for measuring liquid level in the core, downcomer, and lower plenum.

5.1.1 Measurement Principle. The conductivity LLT is in principle a series of on-off switches; the "on" (effectively closed) or "off" (effectively open) state being determined by the presence or absence of liquid at the "switch" (electrode). The resistance of the switch is measured and the presence or absence of liquid is deduced from the observed state. The conductivity of the liquid varies drastically with temperature and chemistry (see Figure 22), so the "closed" resistance may be very different from zero. To overcome this problem, the step-change in resistance when the switch is submerged or when liquid leaves is measured. Therefore, the absolute resistance is not important so long as the change in state is observable.

FIG. 22 RESISTANCE OF LLD BASED ON CONDUCTIVITY DATA.

5.1.2 Design and Development Bases. The LOFT conductivity LLT consists of electrodes and a common ground plane. Electrodes are located at specified intervals, designated in the Measurements Requirement Document (MRD), to measure the liquid level with the desired accuracy. The design requirements for the LLT are presented in Table V, and the design requirements for the signal conditions are presented in Table VI.

5.1.3 Transducer Design Description. The conductivity LLT consists of electrodes surrounded by a cylindrical ground plane (see Figure 23). Liquid enters the LLT through slotted or circular ports which are located over the length of the LLT. Electrodes are located at a given spacing over the range of the expected water level. Signal leads from each electrode go through a series of spacers to the top of the LLT assembly.

LLTs are of three basic designs: (a) core, (b) downcomer, and (c) lower plenum. The only differences between these designs are the type of port and the electrode spacing (see Table VII). Ports are either slotted or circular. The installation of the LLTs does vary. The core LLT is installed without a splash shield while the downcomer LLT is surrounded by one splash shield and the lower plenum by two splash shields (see Figures 24 and 25). The purpose of these shields is to prevent water from covering individual sensors due to ECC liquid flowing through the downcomer to the lower plenum. With the shields in place, only reflood levels will be indicated.

The downcomer and lower plenum LLTs are installed in the downcomer instrument stalk (see Figure 26) and the instrument stalk is installed in the vessel.

TABLE V

DESIGN REQUIREMENTS FOR THE LOFT LLT

<u>Range</u>	
Core	0-66 in.
Downcomer	0-144 in.
Lower Plenum	0-28 in.
<u>Electrode Spacing</u>	
Core	3.85 in.
Downcomer	12 in.
Lower Plenum	4 in.
<u>Operating Medium</u>	
Lithium-Borated Water	0-4000 ppm boron, 0.22 to 2.2 ppm lithium
<u>Pressure</u>	
Normal	2250 psi
Maximum (hot)	2500 psi
Maximum (cold)	3740 psi
<u>Temperature</u>	
Normal	600°F
Maximum	1200°F
Response Time	<500 msec
<u>Lifetime</u>	
Normal	2000 efph ^[a]
Maximum	10,000 at temperature and pressure
<u>Radiation Environment</u>	
Normal Operation	1.0×10^{14} nv
Total Exposure (2000 efph)	7.2×10^{20} nvt
Gamma Flux	1×10^{11} R/hr
Total Exposure (2000 efph)	2×10^{12} R

[a] Effective Full Power Hours

TABLE VI

DESIGN REQUIREMENTS FOR THE LOFT LLT SIGNAL CONDITIONING

Accuracy	<u>+1%</u> of range
Frequency response	dc to 100 Hz
Output level	Adjustable <u>+1</u> to <u>+10V</u>
Signal to noise ratio	48 dB

Signal conditioning for the LLT (less recording) is shown in Figure 27. Current is driven from the electrode to the ground plane across the fluid impedance by the 200-Hz oscillator; the voltage drop signal is multiplexed and processed through the signal conditioner. The signal conditioner consists of an isolation amplifier, a 60-Hz rejection filter, and a low-pass (2000 Hz) Butterworth filter. The output of the signal conditioner goes to a peak detector which then feeds the two output forms of the LLT instrumentation. These two forms are: (a) discrete (i.e., the impedance of each electrode is obtained to determine whether the probe is shorted by the presence of water, partly shorted, or completely open by the presence of vapor) and (2) a summed output that indicates a summation of the electrodes that are shorted by the presence of liquid.

5.1.4 Performance Versus Design Bases. Performance tests were performed on production and prototype LLTs to determine if the design requirements were met. Performance testing was initially performed in an autoclave under design pressure, temperature, and chemistry. These tests indicated the LLT would perform satisfactorily in a reflood blow-down environment with lithium-boron chemistry. Response testing showed the response was within the 500-msec design requirement.

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FIG. 23 LOFT LIQUID LEVEL PROBE ASSEMBLY.

TABLE VII

COMPARISON OF DIFFERENT TYPES OF LOFT CONDUCTIVITY LLTs

LLT Type	No. of Electrodes	Spacing of Electrodes (in.)	OD of Ground Plane (in.)	Port Configuration, Slotted or Circular	Spacing (in.)	T/C Installed	T/C Spacing (in.)	Splash Shield Ports, Circular or Slotted	Tube Configuration Spacing No.	Instrument Tubes
Core	19	3.85	0.543	Slotted 0.188 x 1.13 to 2.22 in.	---	No	---	N/A	N/A	N/A
Downcomer	12	12	0.543	Circular 0.25-in. dia.	3.375 or 4.0	Yes	24	Slotted		1 ^[b]
Lower Plenum	7	4	0.543	Slotted ^[a] 0.188 x 1.5 in.	0.69	Yes	4	Circular		2

[a] Also has six 0.09-in.-diameter holes in bottom of LLT.

[b] Also has port splash shields.

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FIG. 24 LOFT DOWNCOMER LLT INSTALLATION.

FIG. 25 LOFT LOWER PLENUM LLT INSTALLATION.

FIG. 26 LOFT DOWNCOMER INSTRUMENT STALK.

FIG. 27 BLOCK DIAGRAM OF THE LOFT LIQUID LEVEL DETECTOR AND INSTRUMENTATION.

Lifetime and radiation environment testing was performed in the Engineering Test Reactor (ETR) for 3672 hours at temperature and pressure. Radiation exposure was 1.75×10^{12} R gamma and a total fast neutron dose of 2.7×10^{19} n/cm² and thermal neutron flux of 5.6×10^{20} n/cm². Although the radiation exposure was less than the design requirement, a trend was established that indicated no appreciable damage could be attributed to radiation.

Performance testing in the 1-1/2 loop semiscale system under blowdown transient conditions similar to those that will be present in LOFT showed the ability of the LLT to perform satisfactorily under transient blowdown and reflood conditions. During this test the LLT indicated oscillatory behavior of the fluid and indicated water level, under saturated conditions. Additional reflood testing was performed at the FLECHT-SETS facility. Cold slow reflood using ΔP transducers for reference verified that the LLT met response time and accuracy design requirements. Results from hot reflood tests showed the LLT could indicate the liquid phenomena occurring during reflood; in this case the phenomena were oscillations and voids in the liquid prior to establishing a liquid level. The response time of the LLT for these tests was obtained by comparing the LLT data with the data obtained from the ΔP transducers and movies. This comparison showed that the measured peaks and valleys for the fluid oscillations as measured by the LLT and the ΔP transducer agreed within 500 msec.

A method of reducing and presenting the data was developed and is presented in Figure 28. This method is computerized and is based on observation of the voltage level of each electrode at a given time. If

FIG. 28 LIQUID LEVEL AS MEASURED BY THE LLT.

that level exceeds a predetermined level, the electrode is said to be void of water and no entry is made in the figure. If the electrode's voltage is low (indicating water), then a symbol is entered indicating that water is present. Using this technique, a time history of water level is obtained.

In summary, the testing of the conductivity LLT showed that all design requirements were met.

5.2 Ultrasonic Liquid Level Transducer

An ultrasonic liquid level transducer was developed by ANC for use in the water environment of a PWR. This instrument was developed in parallel with the conductivity LLT.

5.2.1 Measurement Principle. An ultrasonic burst attenuation (UBA) technique was used that operates on the principle that the attenuation of a stress wave in a metal transmission line is a function of the water covering the transmission line.

5.2.2 Design and Development Bases. The design requirements established for the development of the ultrasonic liquid level transducer (ULLT) are presented in Table VIII.

5.2.3 Transducer Design Description. The bar-type detector design shown in Figure 29 was selected for use with 200-kHz shear waves. The length of each section was restricted to maintain good sensitivity. A bar width of approximately $\lambda/4$ was selected to optimize transmission. In the shear mode, the bar configuration is insensitive to thin layers of water or air that can give a residual effect under dynamic conditions. The water on the surface must be a significant portion of a wavelength to cause attenuation of the signal.

TABLE VIII

DESIGN REQUIREMENTS FOR LOFT ULTRASONIC LIQUID LEVEL TRANSDUCERS

Temperature Range	200 to 650°F; 1000°F transients near center of reactor core
Pressure	2500 psi
Media	Water, air, and/or steam
Range	66-in. maximum
Accuracy	<u>+1</u> inch
Response Time	100 msec
Operating Time	2000 hr
Cross Section	<0.5-in. diameter
Radiation	10^{15} nvt

The shear wave is introduced into the bar by a magnetostrictive transducer operating in the compressional mode (Figure 30). At the transducer, detector interface mode conversion to a shear wave takes place. Several options for mode conversion are available (as shown in Figure 31):

- (1) A shear wave coupled directly to the end of the bar, eliminating the need for mode conversion
- (2) A compression wave transducer coupled perpendicular to the bar with mode-conversion-to-shear taking place in the bar as the stress wave starts to propagate along the bar
- (3) An in-line configuration taking advantage of a notch for mode conversion. The configuration of having a compressional transducer perpendicular to the bar provides the most efficient mode conversion. The in-line configuration using the notch is

FIG. 25 25 FT ULTRASONIC LIQUID LEVEL DETECTOR.

FIG. 30 MAGNETOSTRICTIVE TRANSDUCER ASSEMBLY.

FIG. 31 METHODS OF SHEAR WAVE GENERATION.

more compact but has too much temperature sensitivity to meet the 1000°F environmental requirement (see Figure 32). The mode conversion of the notch is only 75% efficient and, as a result, the signal is made up of shear and compressional wave components (see Figure 33).

In the LOFT application, the detector is divided into three sections to cover the 5-1/2-foot range requirement. This is necessary to meet a ±1-inch accuracy. It also has an added advantage of being able to define the void, time characteristics of the core region during blow-down by use of independent readouts.

The transducer is a 1/2-inch-long coil wound on a 1/16-inch-diameter magnetostrictive stub. This makes a low Q 200-kHz resonant transducer. The coil is wound with No. 34 copper wire with ceramic insulation. The signal-to-noise ratio is increased by biasing the flux level up in the magnetostrictive stub with a magnet attached to the outside of the housing.

The transducer housing is a welded construction of stainless steel to withstand the LOFT 650°F, 2500-psi, corrosive steam-water environment. A block diagram of the instrumentation for the 5-1/2-foot range measurement in the LOFT core region is shown in Figure 34. The current drivers deliver 0.5 amp for 2.5 μ sec to the transmit transducer to excite it at 200 kHz resonance. The receive transducers are identical to the transmit transducers. A current sensitive preamplifier amplifies the signal to a one-volt peak amplitude for the amplitude-to-analog converter. Sections 2 and 3 show the same preamplifier. Separation of the burst information is done by time discrimination. Section 2 has a longer transmission time than Section 3.

FIG. 32 ULTRASONIC LIQUID LEVEL DETECTOR WITH TRANSDUCERS IN LINE.

FIG. 33 ULTRASONIC SIGNALS.

FIG. 34 ULTRASONIC LIQUID LEVEL INSTRUMENTATION BLOCK DIAGRAM.

Each converter has blanking and tracking circuits. Blanking is necessary to select the desired cycle of the burst of which the peak amplitude is to be measured and tracking is necessary to follow the temperature-dependent time delay of the signal. The converter is a sample-and-hold circuit that tracks the burst signal from the first cycle to the peak of the second cycle and holds that peak until the first cycle of the next signal burst.

5.2.4 Performance Versus Design Bases. Although extensive tests of the ULLT performance were not conducted, tests performed indicated that the design requirements for accuracy, temperature, pressure, and response time would be readily met. A calibration curve for the ULL is presented in Figure 35. The coil characteristics are well behaved up to 700°F. An amplitude versus temperature plot is shown in Figure 36. The signal-amplitude-versus-temperature effect is within $\pm 4\%$ from 200 to 650°F.

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FIG. 35 ULTRASONIC LIQUID LEVEL PROBE CALIBRATION CURVE.

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FIG. 36 ULTRASONIC LIQUID LEVEL DETECTOR TEMPERATURE SENSITIVITY.

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