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INSTRUMENTATION FOR LOCALIZED MEASUREMENTS IN TWO-PHASE FLOW CONDITIONS

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ABSTRACT

Three types of instrumentation that have been developed by EG&G Idaho, Inc., and its predecessor, Aerojet Nuclear Company, at the Idaho National Engineering Laboratory to investigate two-phase flow phenomenon in a nuclear reactor at the Loss-of-Fluid Test (LOFT) facility are discussed: (a) a combination drag disc-turbine transducer (DTT), (b) a multibeam nuclear hardened gamma densitometer system, and (c) a conductivity sensitive liquid level transducer (LLT). The DTT obtains data on the complex problem of two-phase flow conditions in the LOFT primary coolant system during a loss-of-coolant experiment (LOCE). The discussion of the DTT describes how a turbine, measuring coolant velocity, and a drag disc, measuring coolant momentum flux, can provide valuable mass flow data. The nuclear hardened gamma densitometer is used to obtain density and flow regime information for two-phase flow in the LOFT primary coolant system during a LOCE. The LLT is used to measure water and steam conditions within the LOFT reactor core during a LOCE. The LLT design and the type of data obtained are described.

THE LOFT FACILITY IS LOCATED at the Idaho National Engineering Laboratory. The facility comprises a scaled down version of a Westinghouse Electric Corporation pressurized water reactor (PWR) and includes a test system consisting of the major components shown in Figure 1. The LOFT facility was designed for the study of thermal-hydraulic behavior in a PWR during a loss of primary coolant. The reactor is monitored by numerous instruments not usually found in a commercial, nuclear PWR plant. The data obtained from a LOCE aid in assessing the analysis techniques employed in the design of nuclear power plant safety features.

To perform a LOCE, the LOFT reactor is brought to normal operating conditions for a PWR: 540 K and 15.5 MPa. The LOCE is initiated by opening two quick-opening blowdown valves that are an integral part of the LOFT primary coolant system. The primary coolant water is thereby allowed to escape from the primary coolant system. The reactor core is automatically shut down by the insertion of the control rods. Due to the sudden loss of cooling water and abrupt rise in core temperatures, the emergency core cooling system (ECCS) engages to cool the reactor core. During the entire scenario, data concerning the performance of the reactor are being recorded for later evaluation.

Three of the instruments developed specifically for the LOFT Experimental Program are the DTT, gamma densitometer, and LLT. These instruments measure mass flow rate-momentum flux, fluid density, and fluid mass balance, respectively. The design of these instruments is complicated by the fact that during transient flow conditions, the fluid in the primary coolant pipes is a nonhomogeneous mixture of steam and liquid water at, or very near, saturation conditions. In addition, water chemistry and radiation level must be given attention when choosing the materials used in fabricating transducers for these instruments.

DESCRIPTION OF INSTRUMENTS

The transducers used in LOFT are unique in that they were developed specifically for two-phase flow measurements. The following discussion describes each of these instruments in detail:

DRAG DISC-TURBINE - The DTT is in actuality a drag disc, a turbine, and a thermocouple assembled together as shown in Figures 2 and 3. The current modular design for these units is employed because of the ease in assembly and repair.

The major components of the turbine transducer are the turbine and the coil as shown in Figure 4. The turbine provides fluid velocity data. It uses self-aligning graphite bearings in the forward and aft posts that support the turbine. These bearings add prolonged useful life to the unit. The turbine consists of six twisted blades mounted on a shaft. The pitch of the blades determines the useful range of the transducer. The coil that is excited by the turbine is housed directly below the turbine and is one-half of a bridge network. The other half is contained in the signal conditioning electronics.

When properly balanced, the bridge output is modulated by the turbine blade passing near the coil, as illustrated in Figure 5. The signal output then passes through a series of amplifiers and filters and finally through a frequency-to-voltage converter. The output from the signal conditioning electronics is a direct current voltage proportional to the number of blades passing the coil per unit of time.

The other portion of the DTT, shown in Figure 6, is the drag disc, which comprises a drag disc, disc post, carrier, core, leaf springs, and a variable reluctance transducer (VRT) coil. The leaf springs are rigidly clamped at the lower end. Each end of the core is rigidly mounted to one spring and passes freely through the VRT coil, shown in Figure 7. When the drag disc is displaced, the position of the core relative to the coil shifts.

The two sides of the coil are driven in a bridge configuration. When the drag disc is in the unactivated position and the core is in the center of the coil, the bridge can be balanced for minimum output, Figure 8. As the core is displaced, the output is amplified and filtered. The resultant output is a direct current voltage level proportional to the drag disc displacement. Due to system phase sensitivity, the direction of flow is easily determined from output polarity.

NUCLEAR HARDENED GAMMA DENSITOMETER - The nuclear hardened gamma densitometer used in LOFT characterizes fluid density and flow regime of the primary cooling medium by use of pulse height analysis rather than the more conventional count rate analysis. Pulse height techniques were chosen because of the presence of a high background flux that must be extracted from the data. The densitometer comprises three subsystems: the detector and shielding assembly, the signal conditioning system, and the data acquisition system.

The detector and shielding assembly shown in Figure 9 has four detectors. They are contained in a tungsten shield. An 11-Ci Cobalt-60 source is tightly collimated for Beams A, B, and C, whereas Beam D is an off-axis beam used to characterize the background. The shielding consists of both lead and tungsten so that an effective shielding of 10.16 cm of tungsten is maintained. The detector assembly in

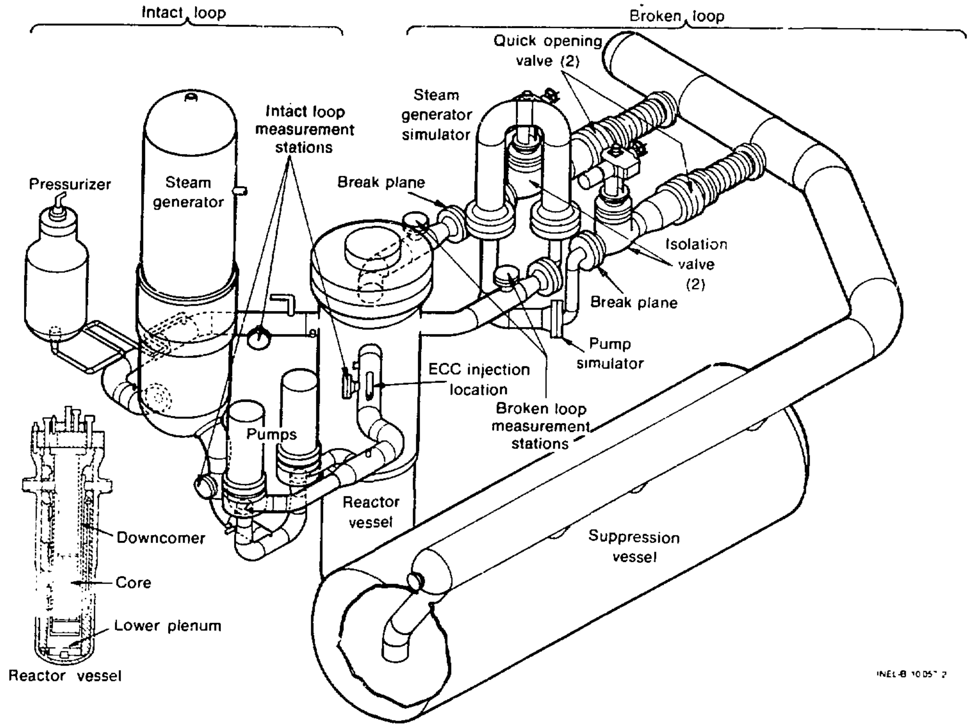

Fig. 1. - LOFT major components

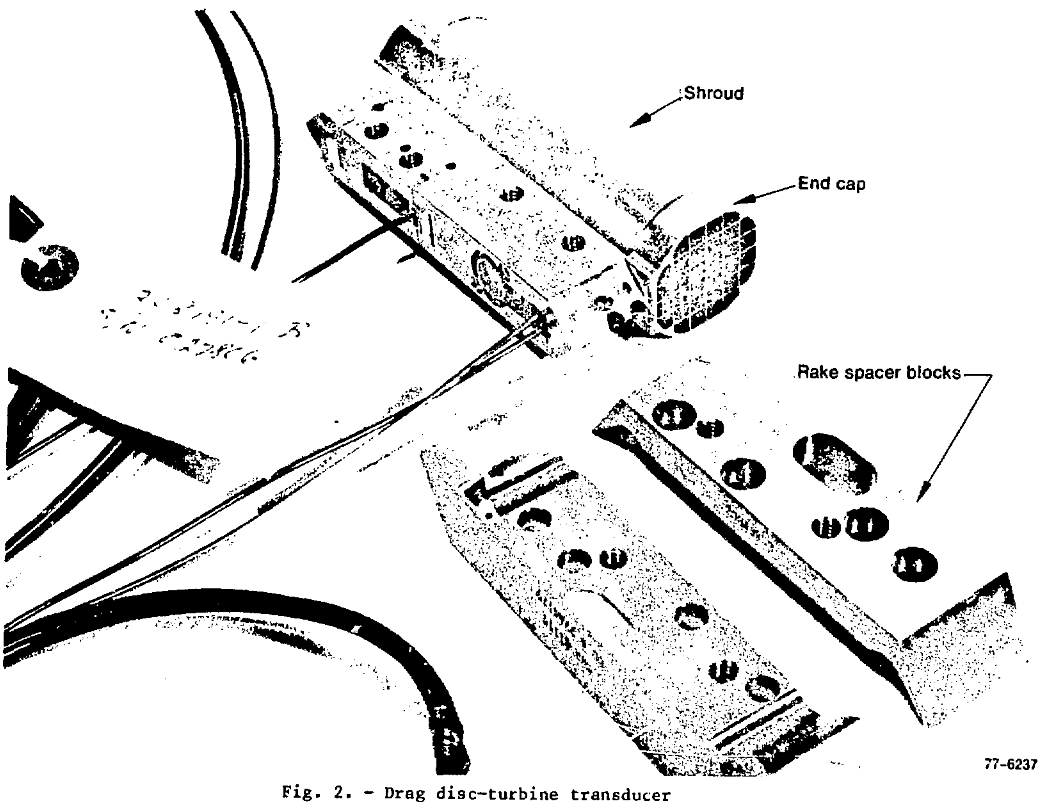

Fig. 2. - Drag disc-turbine transducer

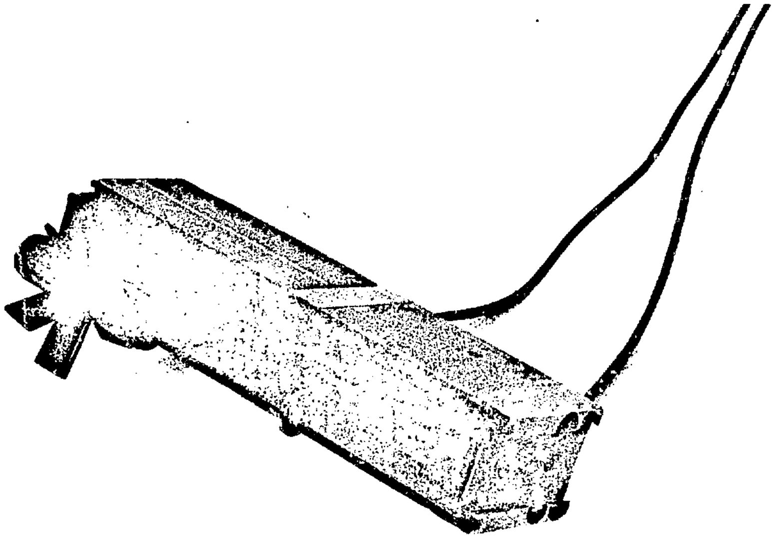

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Fig. 3. - Drag disc-turbine transducer without shroud and end caps

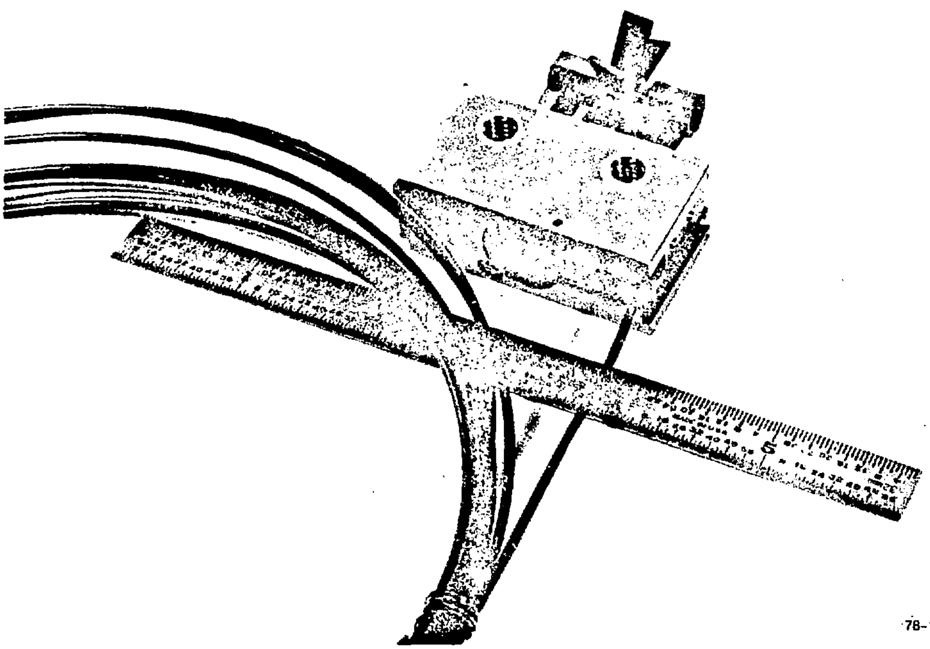

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Fig. 4. - Turbine transducer

Figure 10 consists of 2.54-cm diameter by 2.54-cm long NaI crystal, optically coupled to a photomultiplier tube (water cooled for stability over a wide range of temperatures). The photomultiplier tube output is coupled to a current-to-voltage converter-amplifier stage that provides count rate voltage compensation to the tube. Figure 11 illustrates a typical compensation curve.

The signal conditioning electronics receives the output from the current-to-voltage converter. The electronics shown in Figure 12 comprises four modules per detector, the negative restorer, the single channel analyzer-live timer, the invert-delay-linear gate, and the analog-to-digital converter.

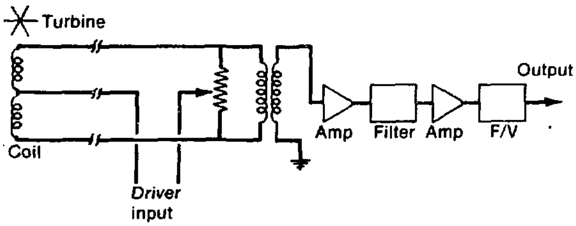

Fig. 5. - Turbine signal conditioning

The data acquisition system (DAS), Figure 13, receives the output from the signal conditioning electronics. The DAS consists of the multichannel analyzer (MCA) memories and scaler subsystem, PDP 11/04 computer, RK05 system software units (disc), Kennedy tape transport, Digital Equipment Corporation (DEC) writer, and a plasma scope. The DAS performs the functions of a MCA, data collection timing, data logging, and operator interface. The DAS is designed to count and store a discrete pulse rate of up to 1.2×10^6 Hz. The MCA memories

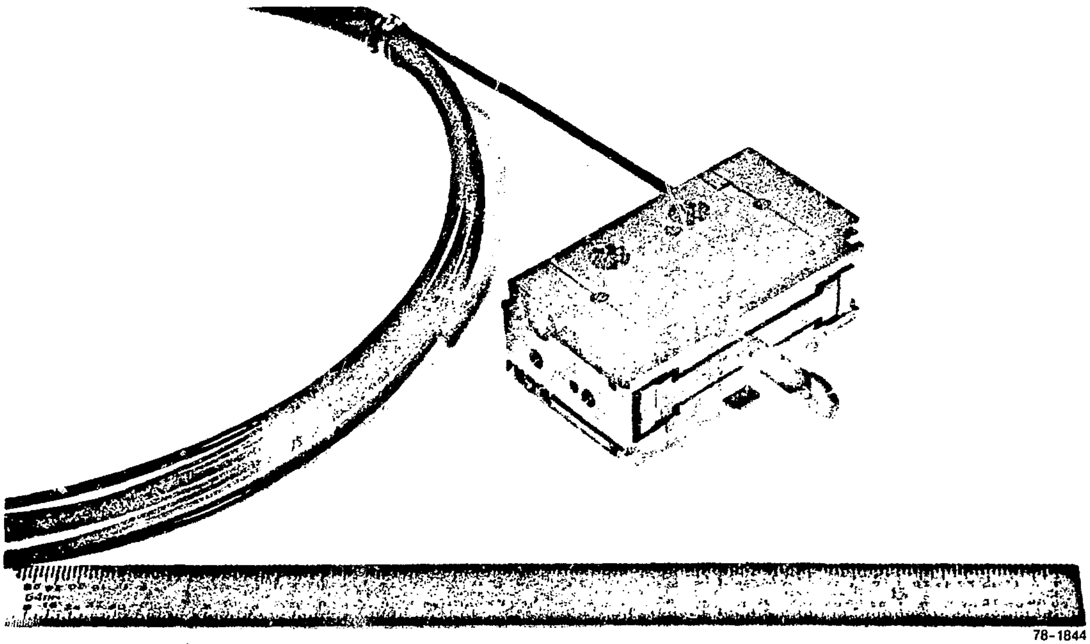

Fig. 6. - Drag disc transducer

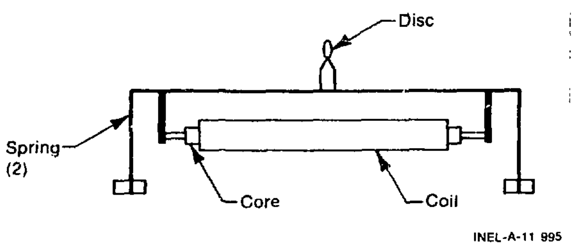

Fig. 7. - Diagram of drag disc

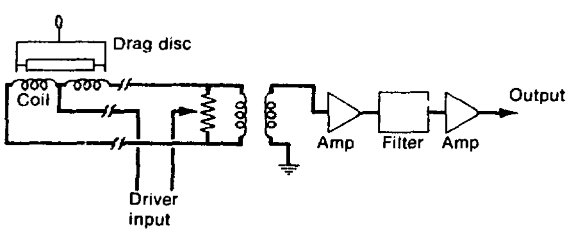

Fig. 8. - Drag disc signal conditioning

accept a six bit word address from the analog-to-digital converter (ADC), addresses the appropriate memory location, fetches the stored word, increments it by one, then stores it back into the same memory location. The address represents a given ADC channel and will be incremented dependent upon the number of counts received in that channel per given time frame. Each channel is double buffered to ensure that continuous data accumulation can occur, that is, Memory A collects data while Memory B is dumping data to tape. Information from Memories A and B is unloaded onto the computer master buss and transferred to tape by means of the tape controller. Data transfer is controlled by the PDP 11-04 minicomputer.

LIQUID LEVEL TRANSDUCER - Several conductivity sensitive LLTs are installed in the LOFT reactor. The four locations are the reactor core, downcomer, upper plenum, and lower plenum. The design of the LLTs at each of these locations differ as to the spacing of the electrodes, the types of ports (slotted or circular) and the type of splash shield. For the purpose of this paper, reference will be limited to the transducer located in the core.

The LLT design, shown in Figure 14, is basically a conductivity sensitive device consisting of a series of electrodes, or probes, that are surrounded by a cylindrical ground plane. The probes are located at a given spacing over the range of the

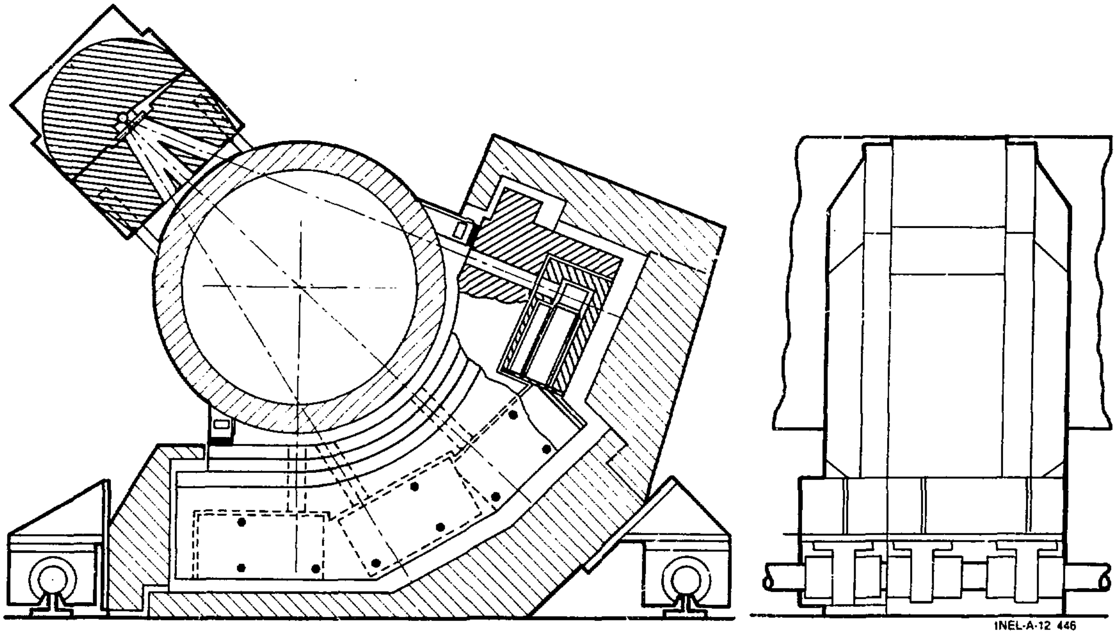

Fig. 9. - Typical shielding assembly

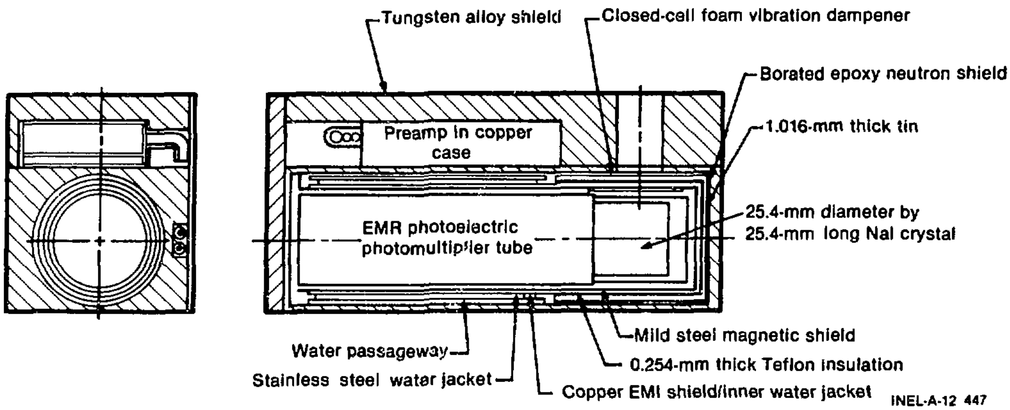

Fig. 10. - Detector assembly and housing

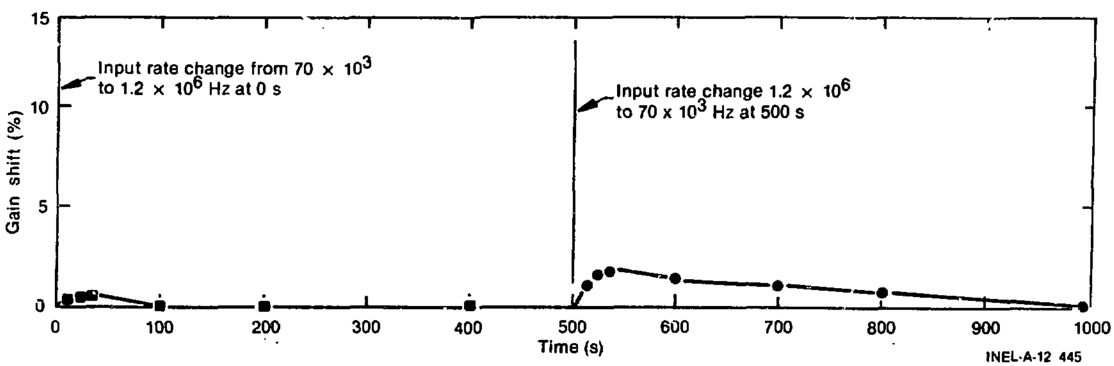

Fig. 11. - Compensated photomultiplier gain shift

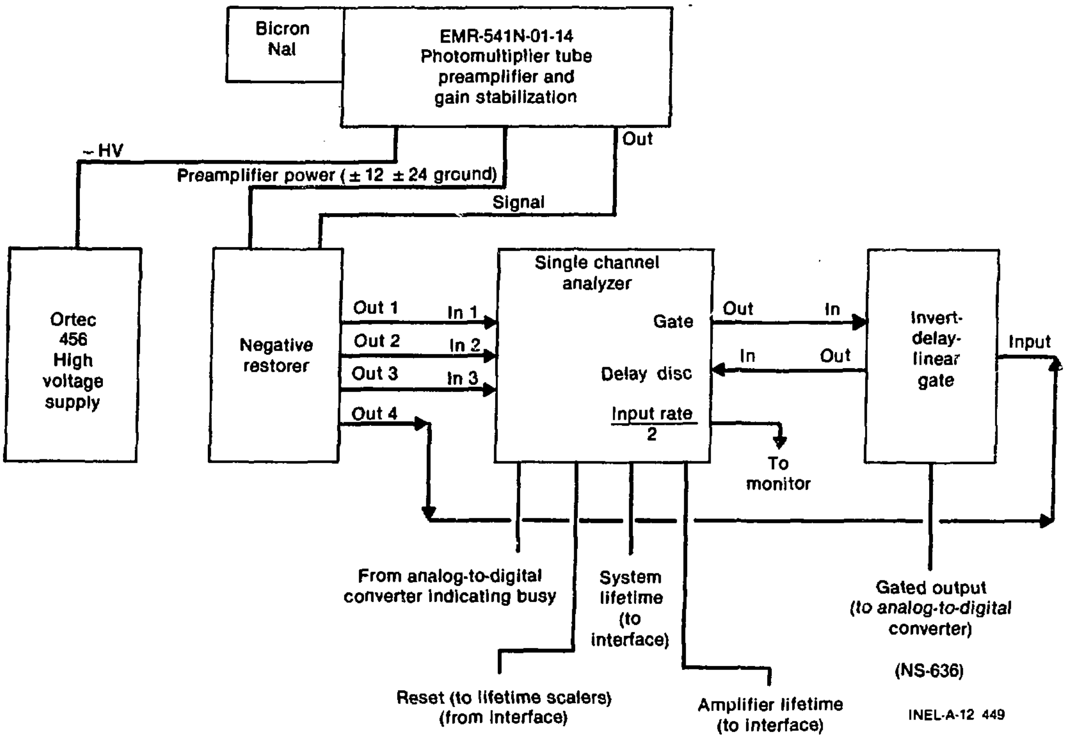

Fig. 12. - Block diagram of LOFT densitometer front end

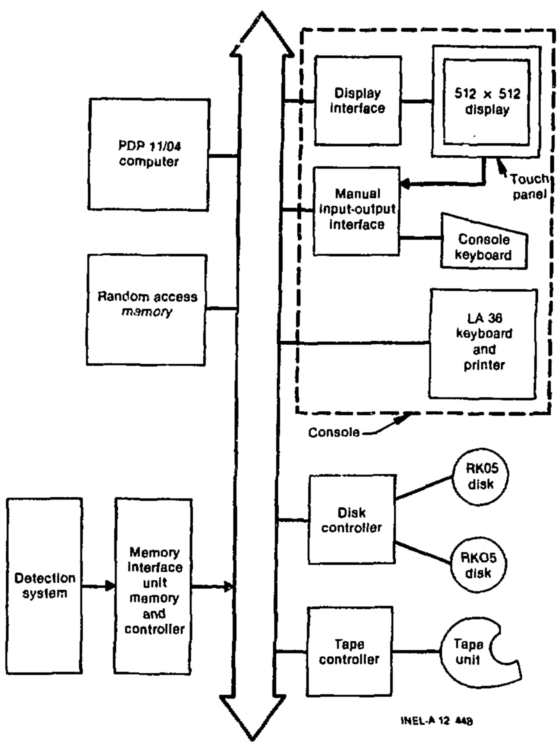

Fig. 13. - Block diagram of DAS

expected water level. Fluid may enter the LLT through slotted or cylindrical ports located over the length of the LLT in the cylindrical ground plane. The slots or ports are designed to prevent splashing of primary coolant on the LLT and thus prevent erroneous liquid level measurements.

A block diagram of the required signal conditioning instruments for the LLT is shown in Figure 15. The electrode is current driven to the ground plane across the fluid impedance. The voltage signal is multiplexed and processed through the signal conditioner. The signal conditioner used is made up of an isolation amplifier, a 60-Hz rejection filter, and a low-pass (2000-Hz) Butterworth filter. The signal conditioner output goes to a peak detector, which supplies the discrete output of each electrode and is used to determine whether the probe is shorted by the presence of vapor or completely open when dry.

Figure 16 is an equivalent circuit for a LLT that has been reduced to a simple network diagram. The network is made up of a 10-V peak and a 10-Hz square wave excitation source with an output resistance of 50 kΩ. For all practical purposes, the effective probe resistivity (R_{eff}) is part of a resistor-divided network in series with 50 kΩ. When the LLT electrode is dry, the R_{eff} is significantly greater than 50 kΩ and the signal output is close to 10 V. However, when the LLT electrode is wet, R_{eff} is significantly less than 50 kΩ and the signal output is effectively 0 V. Should one of the LLT electrodes begin to deteriorate and the maximum dry resistivity approach 50 kΩ, the maximum output voltage will diminish. At a maximum R_{eff} of 50 kΩ, the maximum output voltage could, in fact, assume any value from 0 to 10 V.

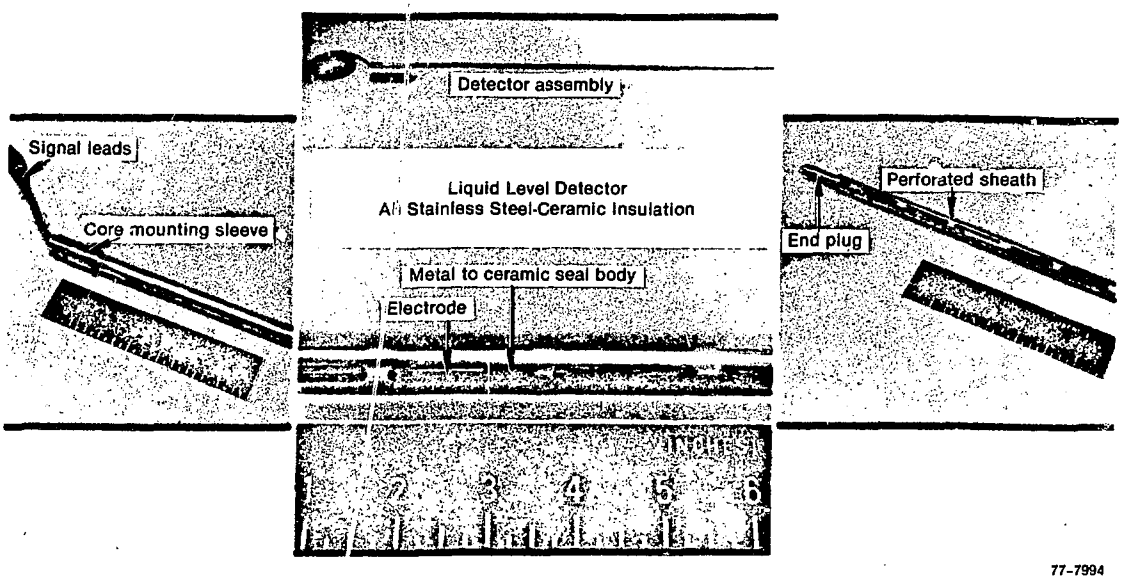

Fig. 14. - In-core liquid level transducer

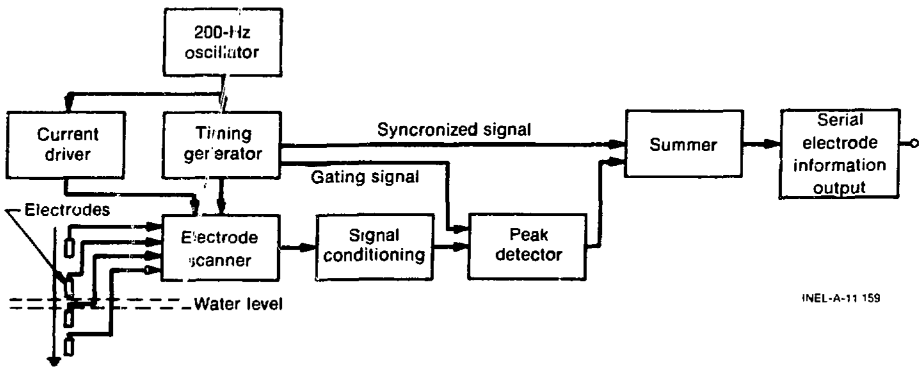

Fig. 15. - Block diagram of liquid level transducer and instrumentation with four electrode probe output signals

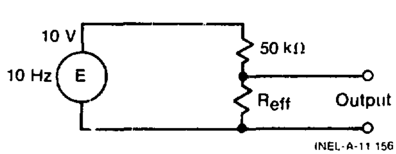

Fig. 16. - LLT basic equivalent circuit diagram

INSTRUMENT CALIBRATION TECHNIQUES

In most cases, the instruments used at LOFT require calibration prior to a LOCE. The DTT, gamma densitometer, and LLT are all subjected to a calibration procedure before each experiment. The following discussion describes the calibration for the three instruments addressed in this paper.

DRAG DISC-TURBINE - The DTT is calibrated prior to installation at the LOFT facility. It is first calibrated by measuring drag disc displacement, or force, versus output at several temperatures. The result is a family of curves giving displacement (mils) versus direct current voltage output (V) at given temperatures. These curves are linear to within 1%, but the zero offset and slope of the curves vary with temperature; the slope generally decreases with an increase in temperature.

The drag disc and turbine are then assembled into a DTT unit and calibrated in a small, single-phase water facility at ambient temperatures under full-flow conditions, that is, no bypass of the water around the shroud. Under these conditions, the DTT is linear with flow velocity to within 1%.

Next, three DTTs are assembled into a rake configuration, see Figure 17, and calibrated in a large, single-phase flow loop at pressures up to 15.5 MPa and temperatures up to 540 K. The flow loop closely simulates the LOFT primary coolant loop.

After installation in the LOFT system, the previous calibrations performed on the DTTs are rechecked by two different methods for those transducers in the primary coolant loop: First, by varying the mass flow rate (by changing pump speed) and comparing the known flow to the output of the DTT. Second, the primary coolant loop venturi data are used to compute the average velocities and

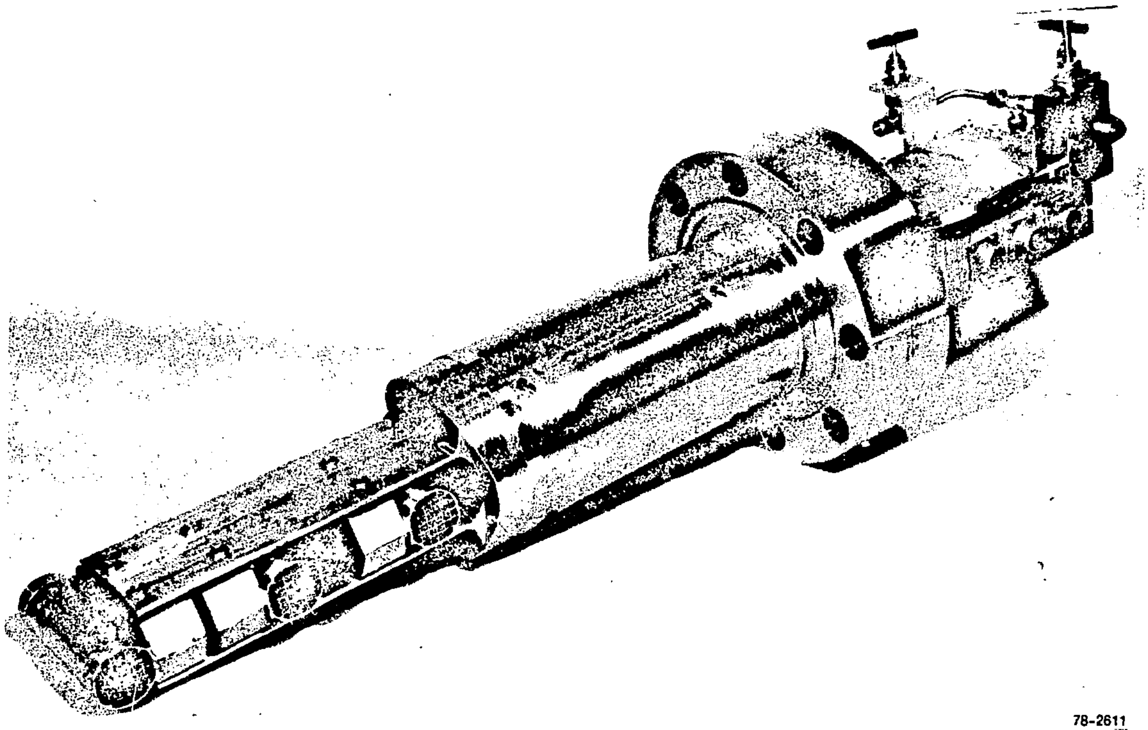

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Fig. 17. - Drag disc-turbine transducer rake

momentum fluxes. These values are compared to the turbine and drag disc outputs to provide a cross-correlation to the calibration. Both checks are performed for a range of temperatures up to the maximum operating temperature of LOFT.

NUCLEAR HARDENED GAMMA DENSITOMETER - The gamma densitometer must have dead-time correction performed as a calibration procedure. The dead-time correction is standard in most spectroscopy and consists of multiplying the spectrum by some constant which accounts for the energy analyzer being "dead" (turned off) during a portion of the data acquisition time. The background subtraction is done to separate the Cobalt-60 peaks from reactor background radiation. This background radiation is extrapolated into the cobalt peak region and subtracted from the total spectrum to obtain the cobalt spectrum. This background radiation shape is obtained from the background channel spectrum.

The background subtraction alone would be simple; however, it must be done in conjunction with the coincidence correction. Coincidence correction is a spectrum-shape correction that becomes necessary because high count rates make coinciding events relatively frequent. These are events in which two or more photons are absorbed by a detector at or near identical times and appear as a single high-energy photon. The effect of this coincidence is to increase the higher energy counts while decreasing the lower energy counts. The result is that the background portion of the observed spectrum is greater than it should be, which causes a large error in the background subtractions; therefore, the coincidence correction must precede background correction. A further problem encountered in the data analysis process is the fact that the actual background radiation intensities are not known at the data channels (Beams A, B, and C). The background channel spectral shape must be assumed to have the same basic shape as the other channels. The intensity at each beam location is then calculated by a successive approximation method that zeros in on a known tactic condition, for example, fluid density at the time of blowdown.

The results of these various corrections yield a single number which represents the intensity of the cobalt. This number then represents the average fluid density and is a linear function of the logarithm of this number.

LIQUID LEVEL TRANSDUCER - The LLT is not calibrated, but rather the signal conditioning electronics receive a calibration by means of adjusting the discriminator level. The discriminator level allows for the electrode to distinguish between a wet or dry condition. During the blowdown phase of a LOCE transient, the discriminator is set at ~15% of the full-scale voltage range. This level remains in effect until the transducer output reaches maximum value.

As part of a LOCE, the emergency core cooling system refloods the reactor core. During this reflood period, the electrode maximum voltage, V_{MAX}, is attained and the discriminator level is reset at ~85% of the full-scale voltage in order to preserve the response. After reflood, the level is reset to 15%. Figures 18 and 19 show examples of individual electrode voltage histories.

A somewhat better understanding of the LLT response is given by:

$$R_{eff} = R_w + \frac{R_c R_s (R_o + R_1)}{R_c R_s + (R_c + R_s)(R_o + R_1)} \qquad (1)$$

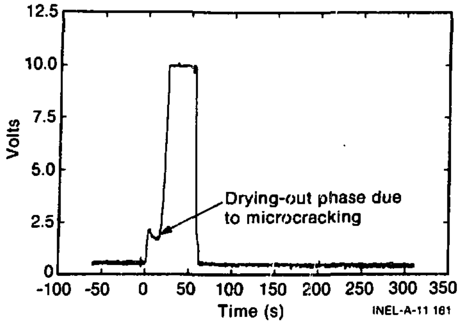

Fig. 18. - Liquid level voltage time history showing dry-out of ceramic seal

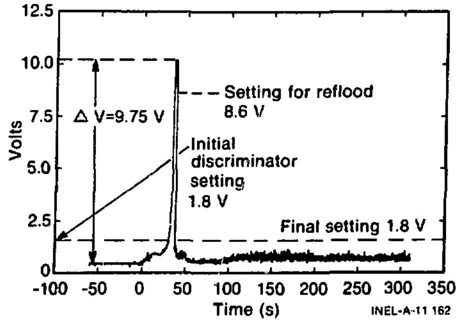

Fig. 19. - Typical liquid level voltage time history

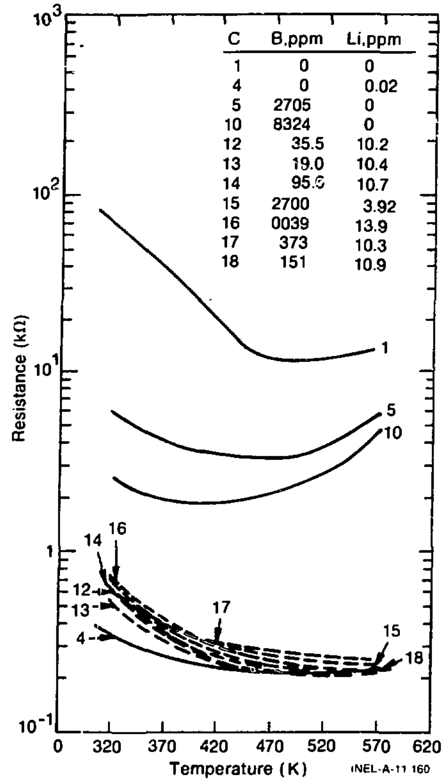

Fig. 20. - Resistance of LLT based on conductivity data

where

R_c = the shunting resistance across the cable insulation which is usually greater than $10^6 \Omega$

R_o = a series resistance due to oxide buildup on the electrodes and ground plane leads

R_w = wire resistance of the signal lead

R_l = resistance of air or liquid between the electrode and ground plane

R_s = the shunting resistance across the seal of the liquid level transducer which changes with aging corrosion.

During exposure to steam environments, the R_l term of Equation (1) increases with a resultant increase in voltage output. By use of a voltage discriminator level in a computer program, the voltage output can be used to determine whether liquid or steam exists at any particular probe. Both the baseline and the 100% void voltage levels may vary with time as R_s, R_l, and R_o vary.

The resistance of the fluid environment surrounding the electrode (R_l), varies as a function of chemistry, temperature, and void fraction. All of these factors can change or shift the transducer baseline voltage. Changes of this type are shown in Figure 20. However, the effect is not as severe when ionizing chemicals such as lithium are combined with water. In addition, the resistance value of R_l is a function of the geometrical distribution of the fluid droplets between the electrode and ground plane. Therefore, the same output voltage can represent a variety of void fractions between the values of 20 and 80% void.

Other factors for determining the discriminator voltage level of the LLT electronics are response time and noise. If the discriminator voltage level is set too high, the desired response of the LLT could be compromised. R_s changes when the reactor vessel conditions change. However, these values do not change instantly. Therefore, the discriminator level must be preset.

INSTRUMENT ACCURACY AND RELIABILITY

Due to the nature of the LOFT experiments, some mention must be made as to the transducer accuracy and reliability. Although every effort has been made to assure accurate methods of measuring data, some factors are difficult to control.

DRAG DISC-TURBINE - In the past, the reliability of the DTT turbines had been reduced significantly because the gold bearings that support the turbine shaft tended to freeze up due to oxidation buildup. Usually this buildup would occur between LOCEs when the LOFT facility was shut down and the primary coolant system was without flow. The current turbine bearings are being fabricated from graphite and the turbine shaft is being machined from stainless steel. Test results of this new bearing material indicate that the life of the turbine transducer will be greatly extended.

The mechanical sticking problem of the drag disc has been eliminated with a new leaf spring design. Presently, temperature sensitivity is the major problem. However, any offset in the outputs can be corrected with the calibration data. Studies are presently being performed to determine whether a modification to the signal conditioning can reduce this effect.

The accuracy of the turbine is considered to be within ±6% of full scale. The drag disc accuracy is within ±12% of full scale during steady state and within ±18% of full scale during a transient. Significant improvements in the accuracy is expected due to improvements in the transducers and electronics.

NUCLEAR HARDENED GAMMA DENSITOMETER - Due to the recent development of the nuclear hardened gamma densitometer, it will only be briefly mentioned.

The gamma densitometer data shown in this paper are considered to be accurate to within ±7%. No reliability data exist at this time.

LIQUID LEVEL TRANSDUCERS - The output from the LLT is sensitive to several factors such as changes in the electrode performance characteristics due to aging, mounting, or response limitations. Any change to the fluid medium such as the temperature or chemistry would also affect the electrode output. In addition, any splashing that occurs during blowdown or reflood would cause erroneous output from the electrode. Therefore, the data are considered to be accurate to within ±3%.

DATA PRESENTATION

This section presents data recorded during a LOCE. In the case of the DTT and the gamma densitometer the data are from the first LOFT nuclear experiment (LOCE L2-2).

DRAG DISC-TURBINE - The DTT data were acquired from measurements in the cold leg of the broken loop of the primary coolant system. The configuration for a DTT rake in this loop is vertical.

Figures 21 through 26 are typical data graphs obtained from the output of each transducer as a function of time, where time zero is the start of the transient. As can be seen in these figures, the turbine meters in the broken loop experience zero flow until the quick-opening blowdown valves are opened. At time zero, all turbine meters record a high positive peak that rapidly decays corresponding to the mixture of steam and water exiting the broken loop.

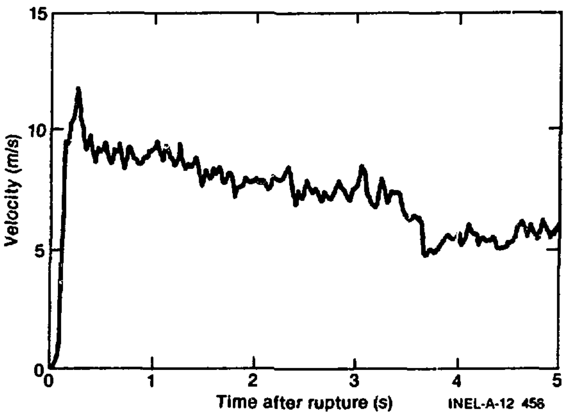

Fig. 21. - Top turbine output during LOCE

The data in Figures 21 through 26 indicate that the transducers survived the blowdown of the primary coolant system, with the exception of the turbine in the DTT located in the middle of the rake assembly. This turbine was stuck and not turning prior to the blowdown. The data obtained from the two functioning turbines and the three drag discs correlate fairly well, indicating that the flow and fluid density were uniform across the profile of the pipe. The outputs of the center and lowermost drag discs were higher due to temperature sensitivity.

Figures 27, 28, and 29 for the top, center, and bottom DTTs, respectively, display how fluid density is derived by dividing the drag disc output ($kg/m{\text -}s^2$) by the square of the turbine output (m/s^2). Due to the failure of the center turbine during the blowdown, only one point at 3 s after rupture has been computed.

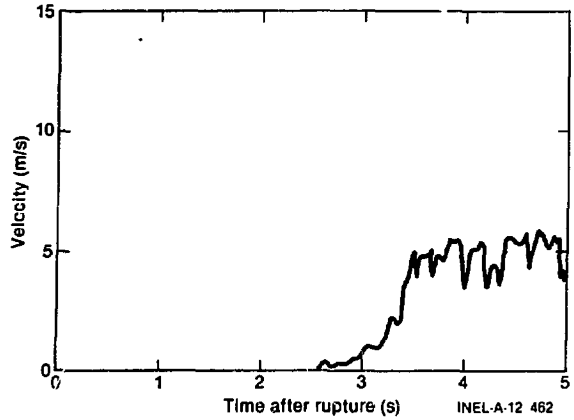

Fig. 22. - Middle turbine output during LOCE

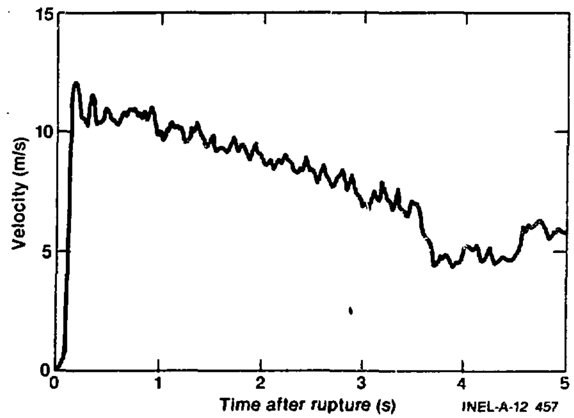

Fig. 23. - Bottom turbine output during LOCE

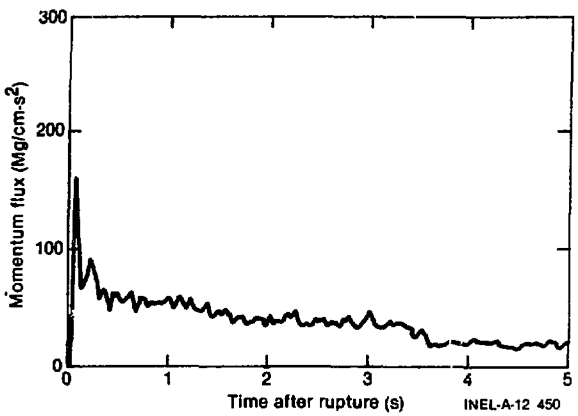

Fig. 24. - Top drag disc output during LOCE

NUCLEAR HARDENED GAMMA DENSITOMETER - The data graphs for the densitometer are shown in Figures 30, 31, and 32. These plots show good agreement among all three beams, indicating that the fluid density was uniform throughout the period that the densitometer outputs were being recorded.

The density graphs from the uppermost DTT and the gamma densitometer agree quite closely. The outputs from the middle and lower DTTs do not agree nearly as well. This lack of agreement is considered

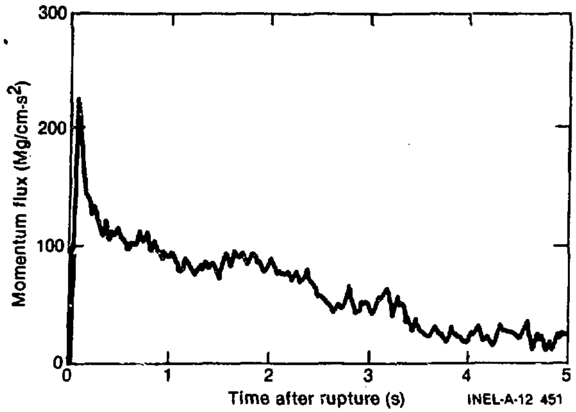

Fig. 25. - Middle drag disc output during LOCE

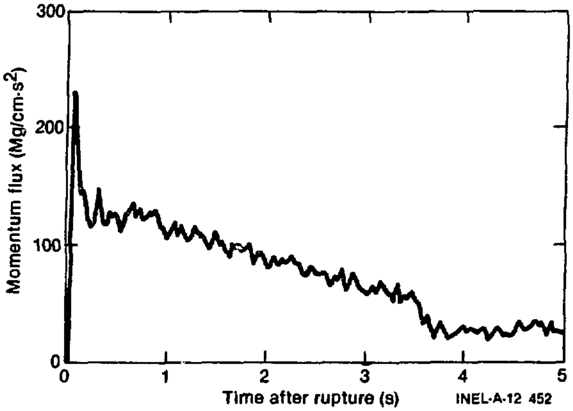

Fig. 26. - Bottom drag disc output during LOCE

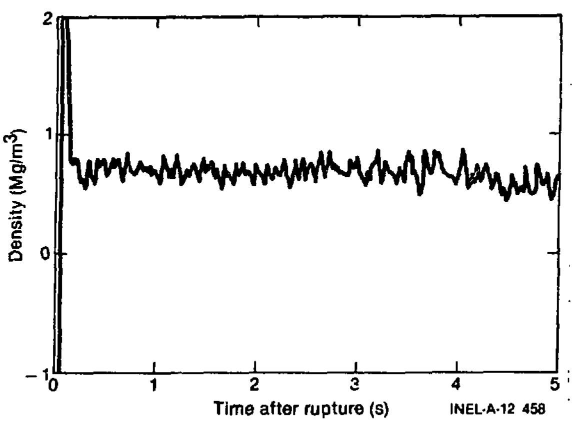

Fig. 27. - Calculated density during LOCE for top DTT

to be due to the temperature sensitivity of the drag discs at these locations.

LIQUID LEVEL TRANSDUCERS - The LLT data graphs shown in Figures 33 and 34 are from a previous nonnuclear LOCE. The data were recorded from an in-core transducer. Figure 33 is a bubble plot, where the "Xs" indicate fluid and the blank areas indicate voids. However, this one plot cannot be interpreted as a complete void of the reactor core.

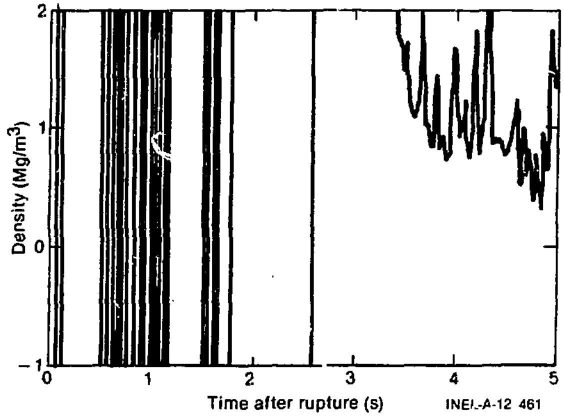

Fig. 28. - Calculated density during LOCE for middle DTT

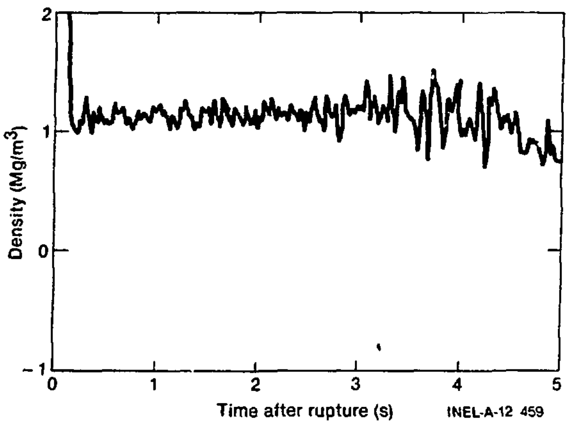

Fig. 29. - Calculated density during LOCE for bottom DTT

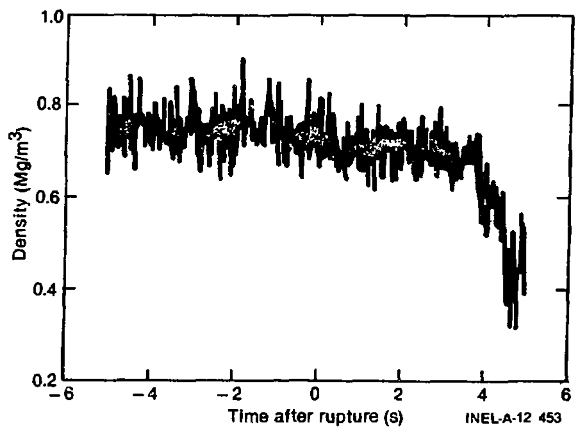

Fig. 30. - Gamma densitometer Beam A output during LOCE

Figure 34 displays exactly how the LLT can be used for fluid mass balancing within the reactor after a LOCE.

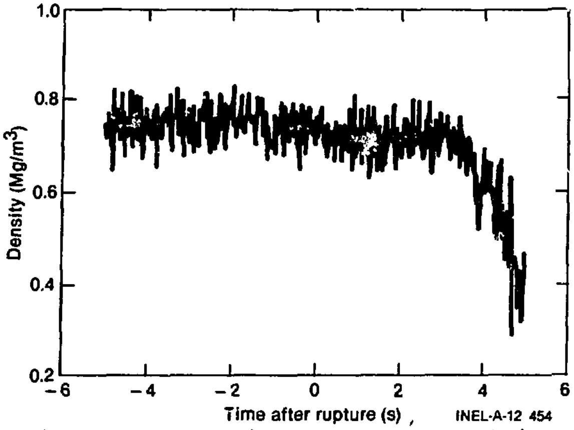

Fig. 31. - Gamma densitometer Beam B output during LOCE

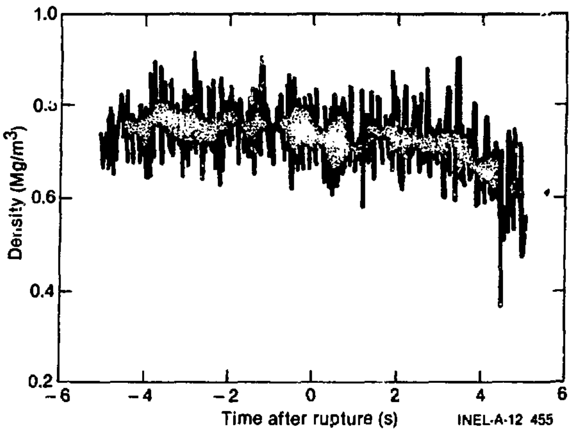

Fig. 32. - Gamma densitometer Beam C output during LOCE

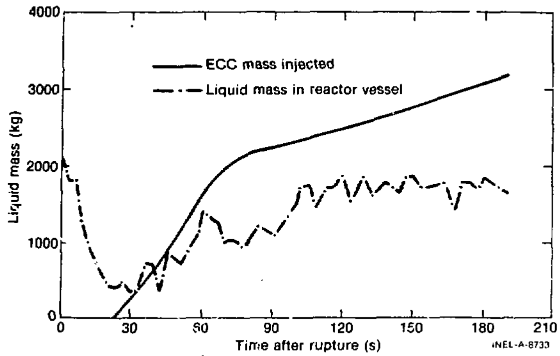

Fig. 34. - Liquid mass in reactor vessel and injected by the emergency core coolant system during LOFT LOCE L1-4

CONCLUSIONS

The types of tranducers being used at LOFT are surviving the various LOCEs and are providing data sufficiently accurate for analysis of the effects of a postulated loss-of-coolant accident on a PWR. The DTT turbine reliability has been greatly increased through the use of graphite bearings. The drag disc continues to supply data on fluid momentum flux that aids in explaining two-phase flow conditions during a LOCE. However, a problem does exist with temperature sensitivity causing higher than normal transducer outputs. Additional studies are being performed on the drag disc with expectations that this problem will be resolved.

The nuclear hardened gamma densitometer has shown increasing value in obtaining data on two-phase flow conditions in the primary coolant piping during a LOCE. The density profiles obtained are expected to prove invaluable when correlated with the drag disc-turbine data.

The LLT is currently providing relatively accurate data on the voids that occur in the LOFT reactor during a LOCE. However, significant improvements are considered achievable through electrode design changes. Currently, there is a test plan being developed that will explain some of the erroneous signals that have been produced by the LLT electrodes. However, these occasional erroneous signals do not necessarily deter the capability of the LLT to distinguish between a void or full reactor core.

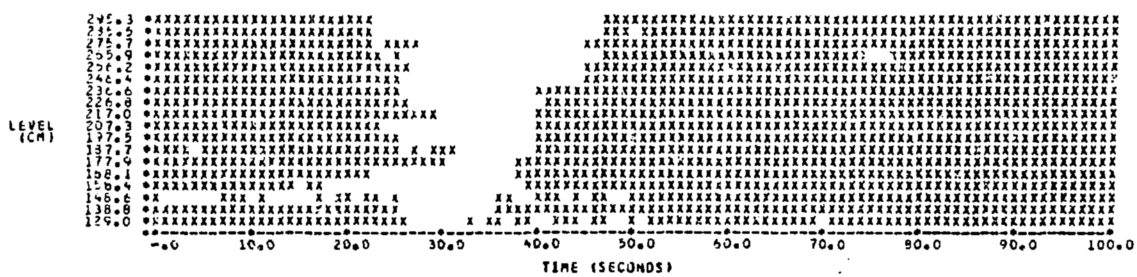

Fig. 33. - Typical bubble plot