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ULTRASONIC LIQUID LEVEL DETECTOR USING SURFACE WAVE ATTENUATION IN A TUBE

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A. E. Arave

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SUMMARY

The ultrasonic liquid level detector was developed for the 200 to 1000°F, 2500 psi corrosive water environment of the Loss of Fluid Test (LOFT) reactor at the National Reactor Testing Station (NRTS). The detector is a new concept in liquid level detection which isolates electrical signals from corrosive environments.

The detector is the wall of a 1/2-inch diameter stainless steel tube. Attenuation of an ultrasonic surface wave as it propagates in the wall of the tube is a function of the water covering the tube. The magnetostrictive transducers for transmitting and receiving the ultrasonic signal are mounted axially in the tube and operate at 250 kHz in the burst mode.

The detector is rugged and meets the tube configuration requirements for compatibility with the reactor core. Testing has shown the detector to be resistant to deterioration by the environment. The sensitivity to liquid level changes is good. But, the temperature sensitivity of the transducer causes the accuracy of the liquid level measurement to be worse than expected. A better design of the transducer and transducer-detector interface would eliminate this problem.

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I. INTRODUCTION

The ultrasonic liquid level detector was developed for the extremely corrosive environment of the reactor vessel in the Loss of Fluid Test (LOFT). The operating requirements for the detector are as follows:

Temperature Range	200-650°F with transients to 1000°F in the reactor core region
Pressure	2500 psi
Media	Water, air and/or steam
Range	2 to 6 ft, depending on the location
Accuracy	±3.5 inches
Rise time	<100 milliseconds
Operating Life	2000 hours
Cross section	<0.5 inch diameter
Radiation	10^{15} nvt

The principle of operation of the detector is based upon the attenuation of an ultrasonic flexural wave in a metal transmission line being a function of the acoustical impedance of the media surrounding the transmission line. The attenuation of the flexural wave is a function of the liquid surrounding the metal transmission line. The closer the acoustic impedance matches the surrounding media the more ultrasonic energy is dissipated.

Various modes of propagation of the ultrasonic signal are possible. The report, "An Ultrasonic Liquid Level Detector Using Shear Wave Attenuation in a Bar"[1], explains some of these modes and the application of them to liquid level measurements.

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[1] IN-1442, by A. E. Arave, November 1970.

II. THEORY OF OPERATION

Attenuation of an ultrasonic surface wave burst in a metal transmission line is a function of the liquid level covering the transmission line. This can be expressed as

$$y = A\,e^{-\alpha x}$$

where

α = attenuation constant,

A = signal amplitude with no liquid surrounding the detector,

y = ultrasonic pulse amplitude,

x = liquid level covering the probe.

The attenuation constant "α" is a function of the transmission line configuration. In this case, when the diameter of tube is increased, the surface area increases and more ultrasonic energy is lost from the transmission line into the surrounding media.

Since the signal amplitude is a logarithmic function of the liquid level, care must be taken to restrict the detector length, "x", to less than "$2/\alpha$" to maintain good liquid level sensitivity. An attenuation curve of signal amplitude versus liquid level for a 1/2-inch diameter tube with a 60-mil wall is shown in Figure 1. In water the tube configuration has high losses. A length of seven inches between transmit and receive transducers was selected to give adequate sensitivity. To detect the level change over a 70-inch region, the liquid probe was divided lengthwise into ten seven-inch detector areas. Transmit and receive transducers were alternately mounted in between these regions. See the block diagram in Figure 2. This not only provided the required sensitivity but it increased the reliability and accuracy.

The circuitry is designed for one preamplifier to receive signals for two seven-inch detector regions. As can be seen in the block diagram of Figure 2, every other transmit transducer is pulsed alternately. The receive transducer alternately receives the ultrasonic burst transmitted through one region and then the one on the other side. Logic circuitry gates the signals into the proper channels for processing.

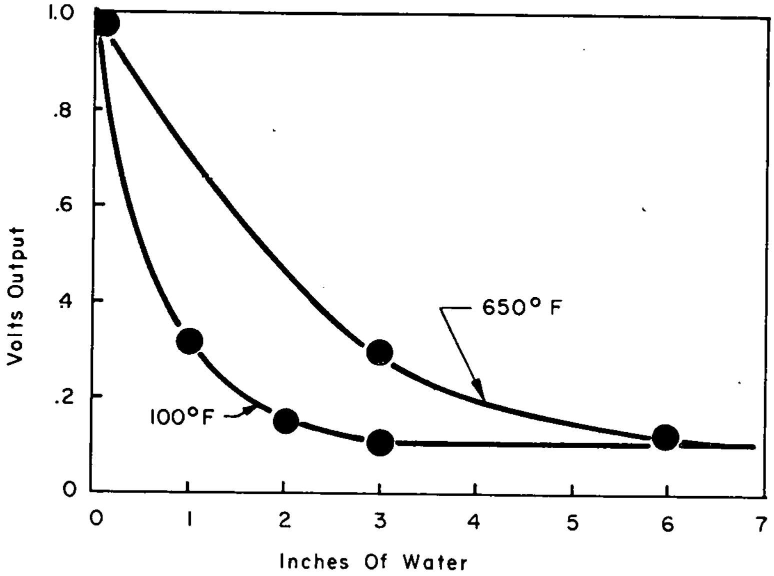

Fig. 1 Ultrasonic liquid level detector sensitivity for 100°F and 650°F water.

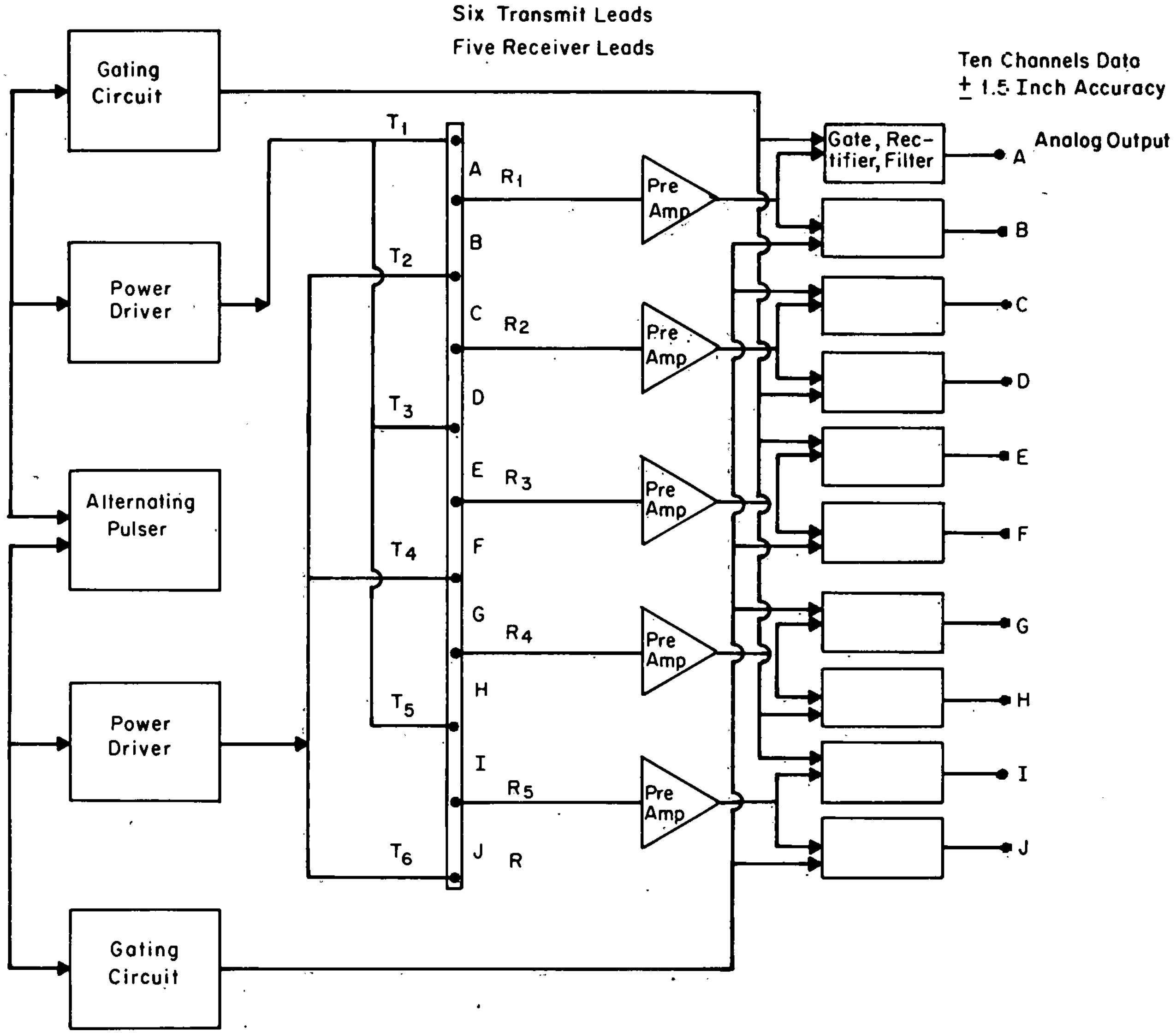

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Fig. 2 Block diagram of the ultrasonic liquid level detector and instrumentation.

III. DETECTOR DESIGN

In order acoustically to attach the transducers to the tubing wall, the tube was split down the center. The transducers are TIG welded to a 30-mil thick, 1/2-inch wide bar and the bar is welded in between the two halves of the split tube. A photograph of the bar before assembly is shown in Figure 3.

Permanent magnets are mounted next to the transducers to bias the magnetostrictive core of the transducer coil for a better flux to strain coupling coefficient. Alnico V permanent magnets have been proven[2] to be good up to temperatures of 1100°F and withstand 10^{22} nvt neutron exposure in a fast flux reactor.

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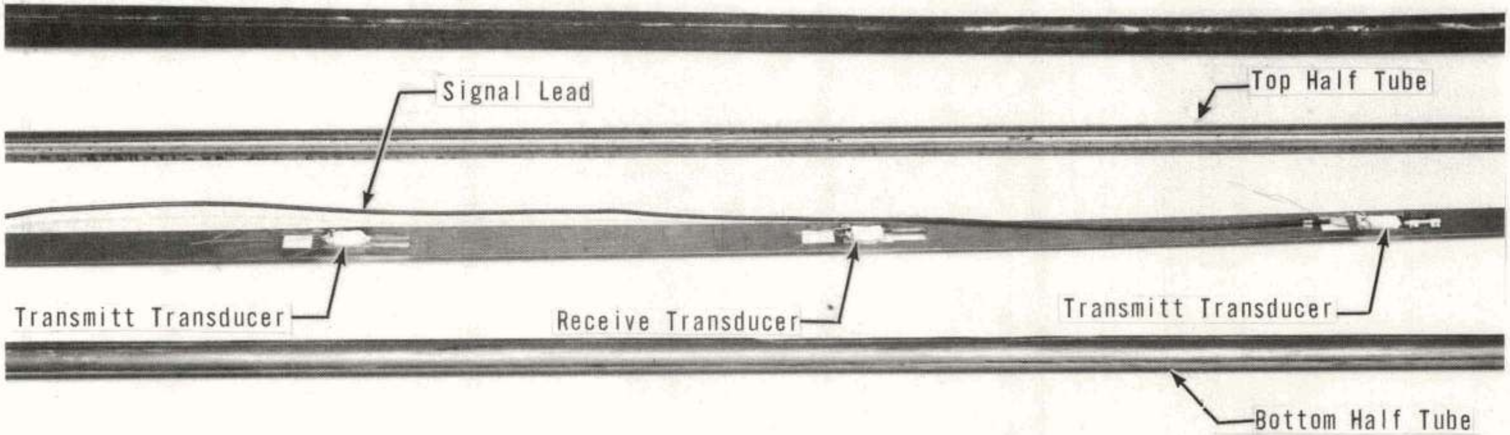
[2] ANL-7705, p. 39 (June 1970).



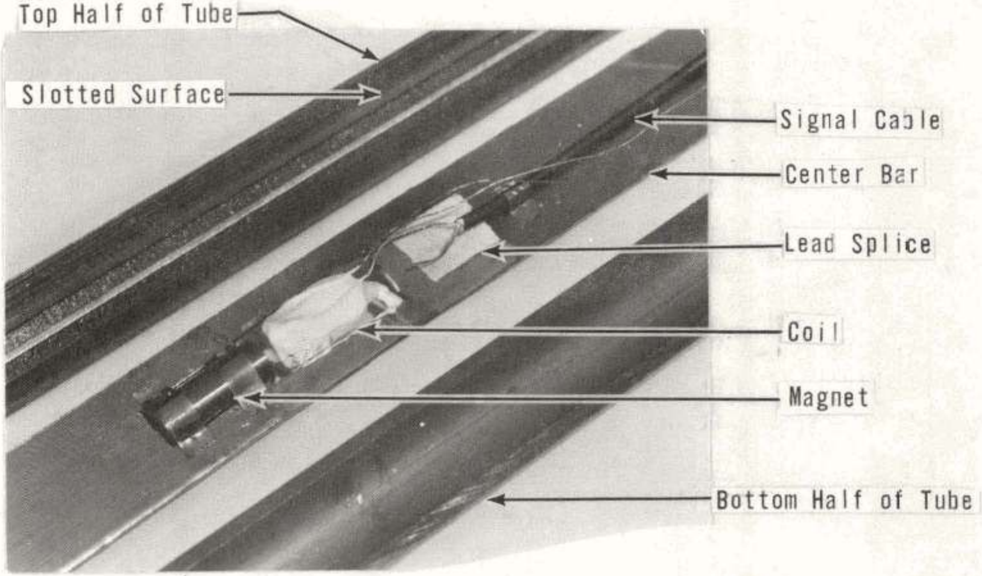


Fig. 3 Ultrasonic liquid level detector assembly.

IV. TRANSDUCER DESIGN

The transducer is a 3/8-inch long coil wound on a 0.04-inch diameter magnetostrictive[3] stub. This stub length generates a low Q 200 kHz resonate signal. The coil is 225 turns of 0.007-inch diameter wire with a ceramic insulation. A photograph of the assembly is shown in Figure 3. The magnetostrictive stub is TIG welded to the 0.030-inch thick stainless steel bar.

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

V. CIRCUITRY DESIGN

Referring to the block diagram in Figure 2, each probe has two pulsers. The pulsers alternately pulse every other transmit transducer. A receive transducer receives signals from the transducers on each side of it. The signals are alternately separated by the gating circuits and then processed. A peak detector provides a dc output proportional to signal amplitude in a preselected window width (see Figure 4). The peak detector output holds at a sampled level until it is reset just before another burst of information is reached. A multiplexer samples each of the peak detector outputs at a 200 Hz rate and provides an output in serial form for recording on magnetic tape.

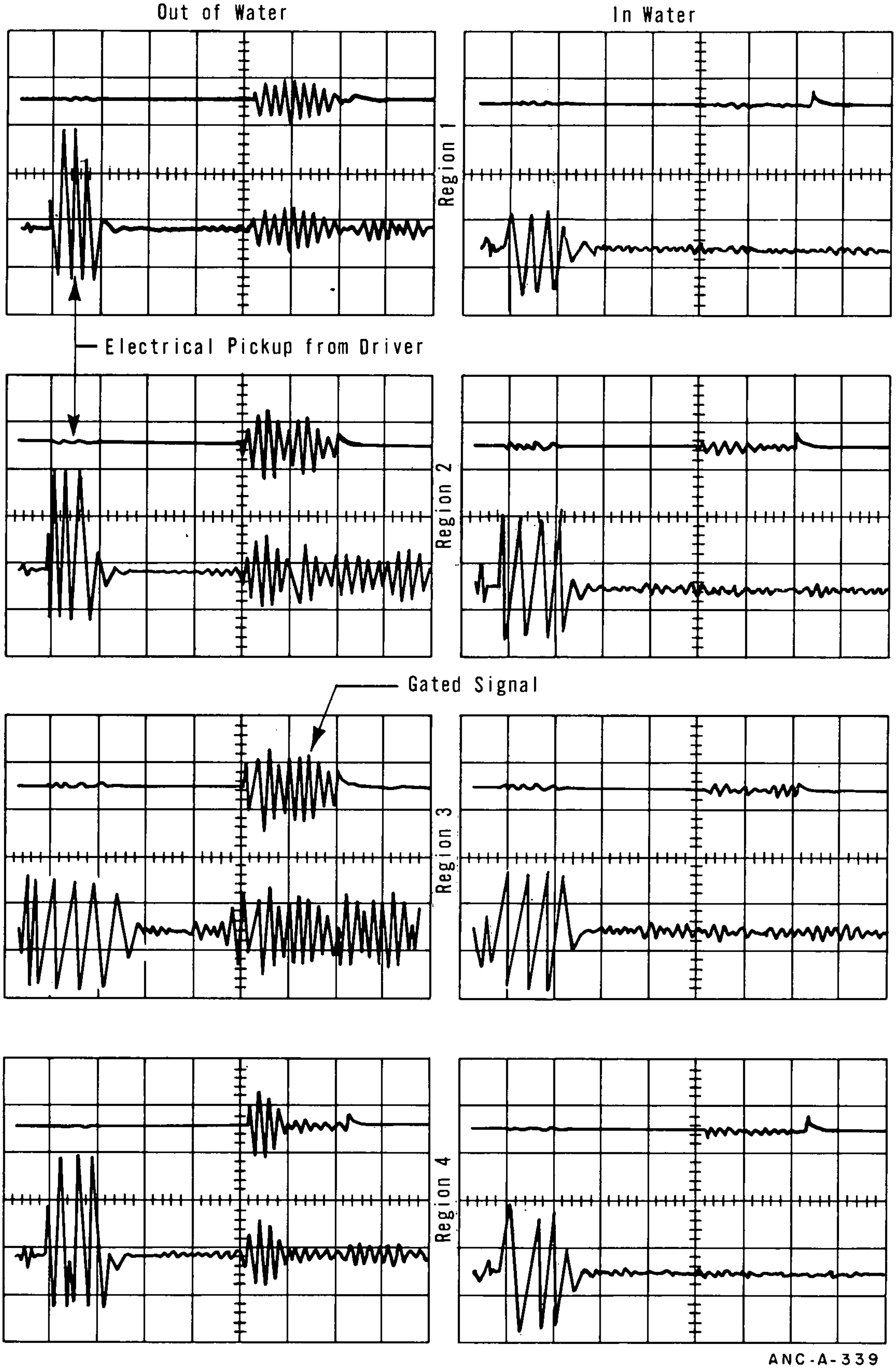

Fig. 4 Ultrasonic signals in and out of water.

VI. LABORATORY TESTING

Detector testing was divided into the following areas:

1. Cold water sensitivity testing
2. Thermal shock tests
3. Dry temperature tests
4. Autoclave testing.

Sensitivity was checked by inserting the liquid level detector into cold water in one inch steps, generating step functions. A typical output response is shown in Figure 5. A plot of output voltage versus inches of liquid covering the detector is shown in Figure 1. As discussed in the theory this attenuation curve changes as a function of media acoustical impedance. The 650°F attenuation curve was calculated at LOFT conditions. The change in sensitivity is discussed below in the section on Errors. At constant water temperature, the attenuation curve was repeatable.

A thermal shock test and surface boiling effect analysis were obtained by heating the probe to 1000°F in the furnace and then immersing it in water. This test was repeated five times without any failure. Figure 6 shows the surface boiling effects on the attenuation seen at the time of immersion in water.

A temperature sensitivity test was obtained by heating the probe to 1000°F, in a tube furnace, over a one-hour period. A thermocouple was attached to the wall of the tube and output was plotted against temperature. The temperature sensitivity was not the same for each detector in the probe. See Figure 7. This variation is attributed to the inconsistency in the magnetostrictive stub to a stainless steel weld. The acoustical coupling at the weld varies from weld-to-weld.

Testing was done at the 650°F, 2500 psi LOFT condition in the autoclave. The autoclave is 36 inches long, 8 inches in diameter, with access through the head into the vessel. See Figure 8. The autoclave was plumbed for blowdown, release of pressure, by rupturing disc-shaped diaphragms in the exit piping. Flooding data were obtained by flooding the autoclave vessel following blowdown. Blowdown data were obtained with the exit at the top and with it at the bottom of the vessel. Blowdown time from the top was 21 seconds with a 30% restriction and 13 seconds from the bottom with a 30% restriction.

Blowdown response curves for a four-level probe are shown in Figure 9.

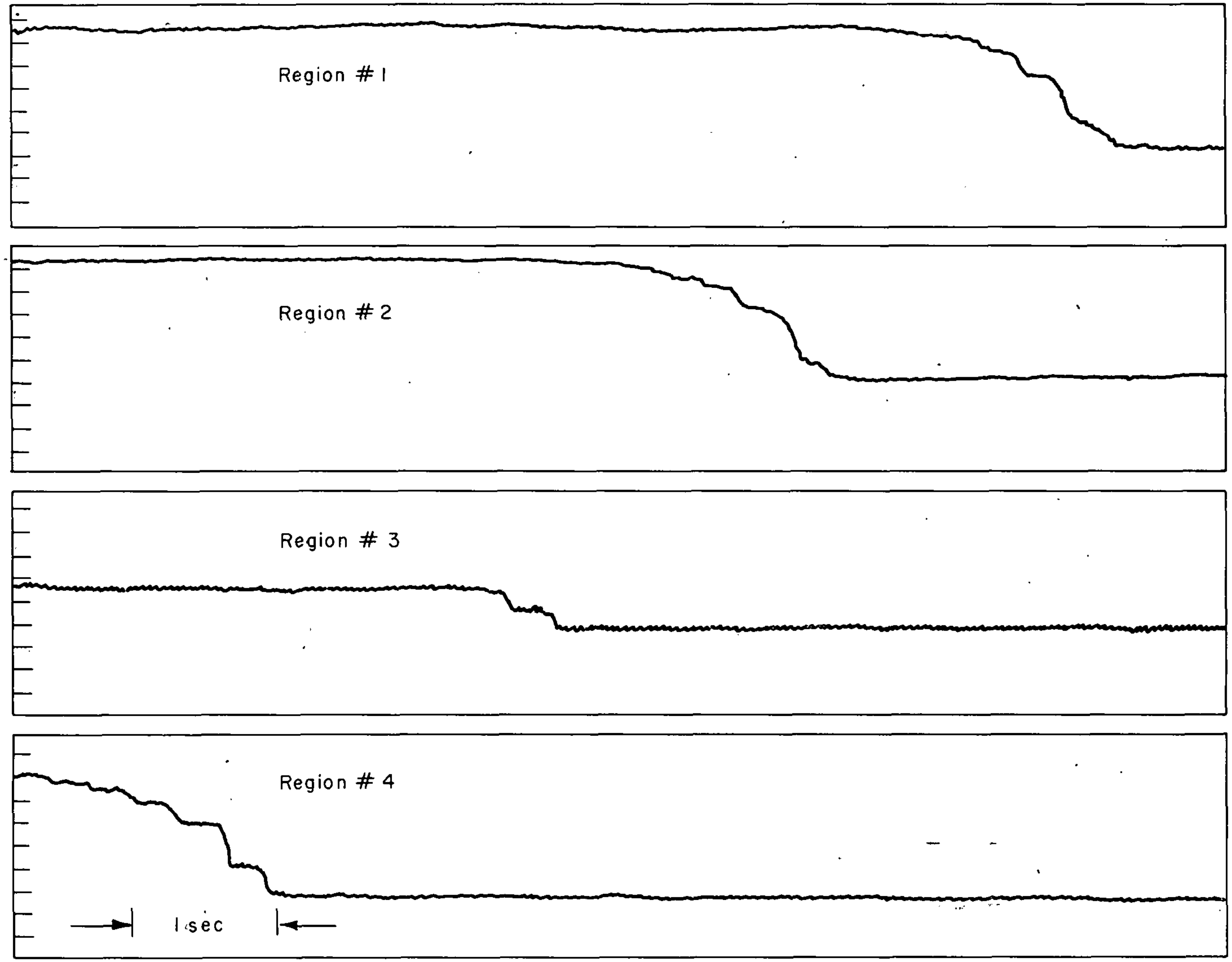

Fig. 5 Step function response.

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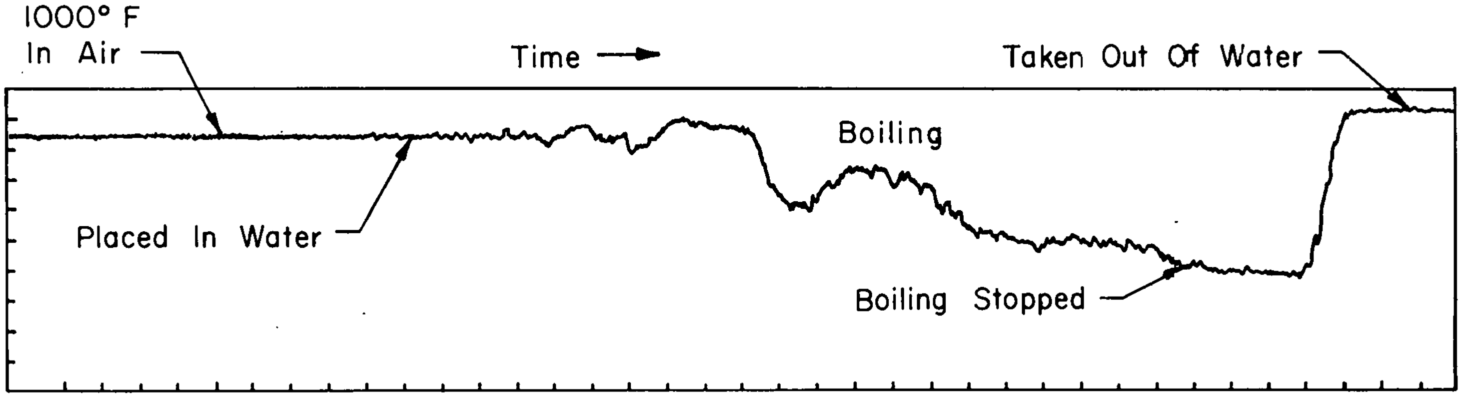

Fig. 6 Response of a 1000°F liquid level detector when immersed in water.

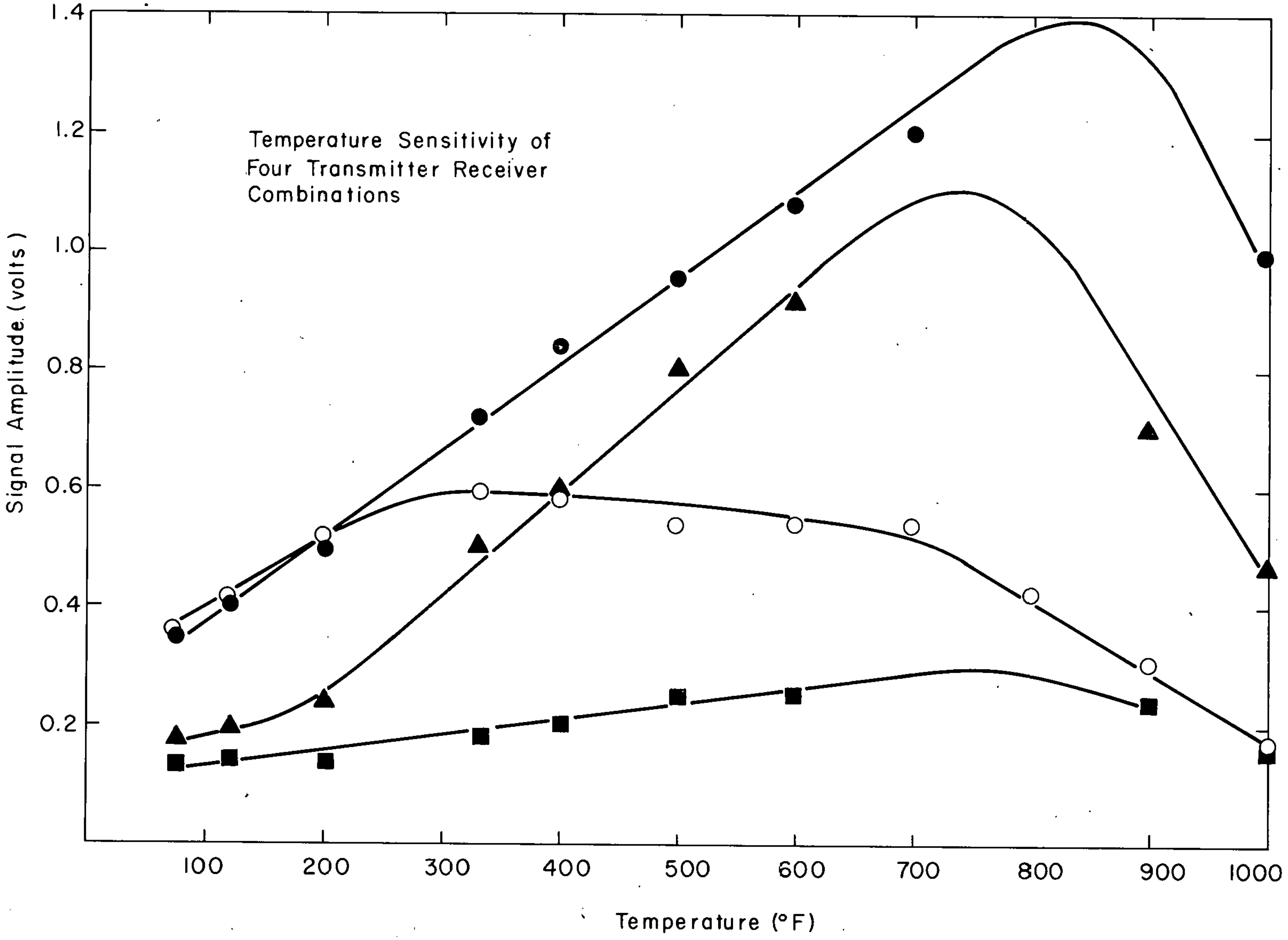

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Fig. 7 Temperature sensitivity curve in air.

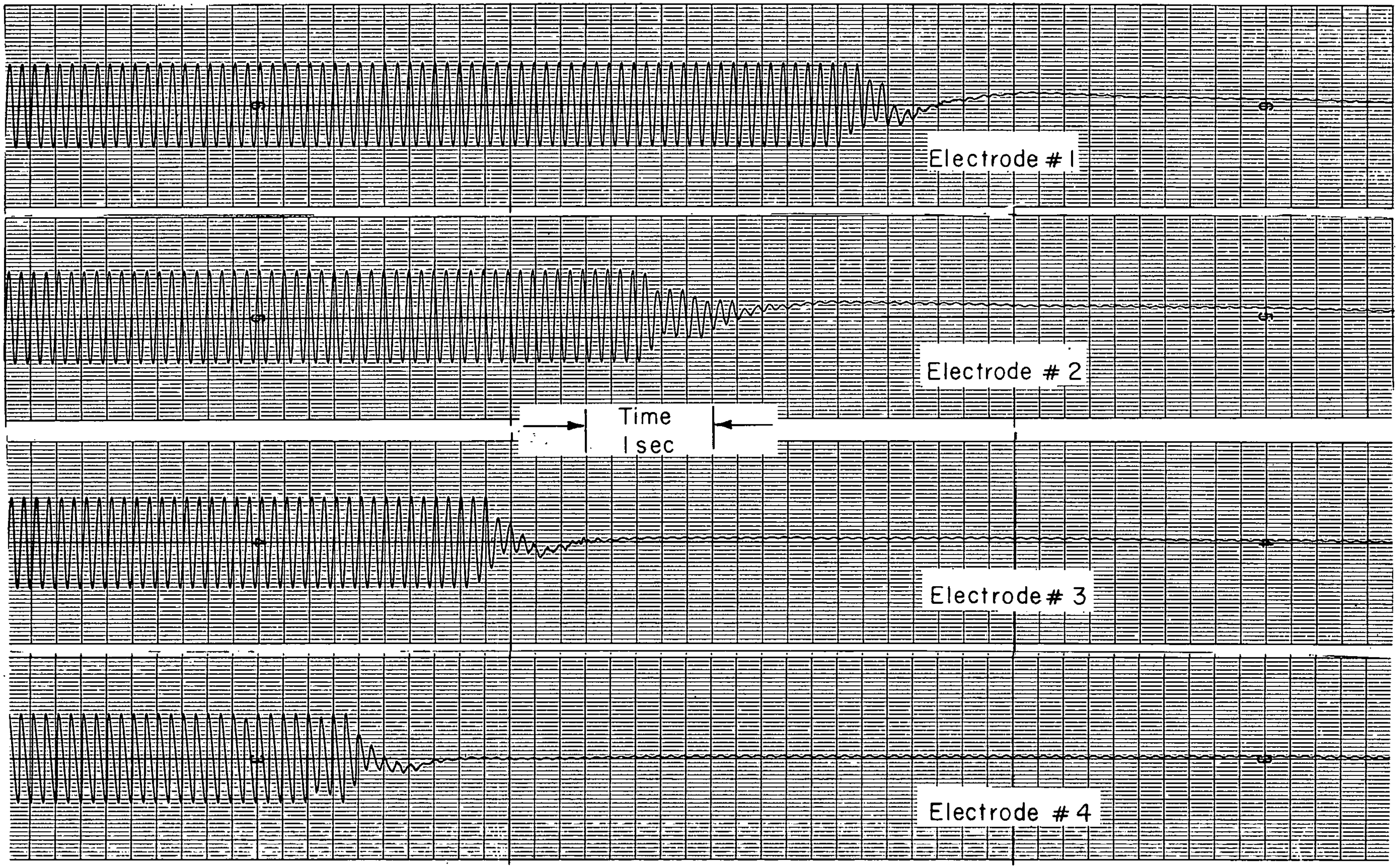

Fig. 8 Autoclave used for environmental testing.

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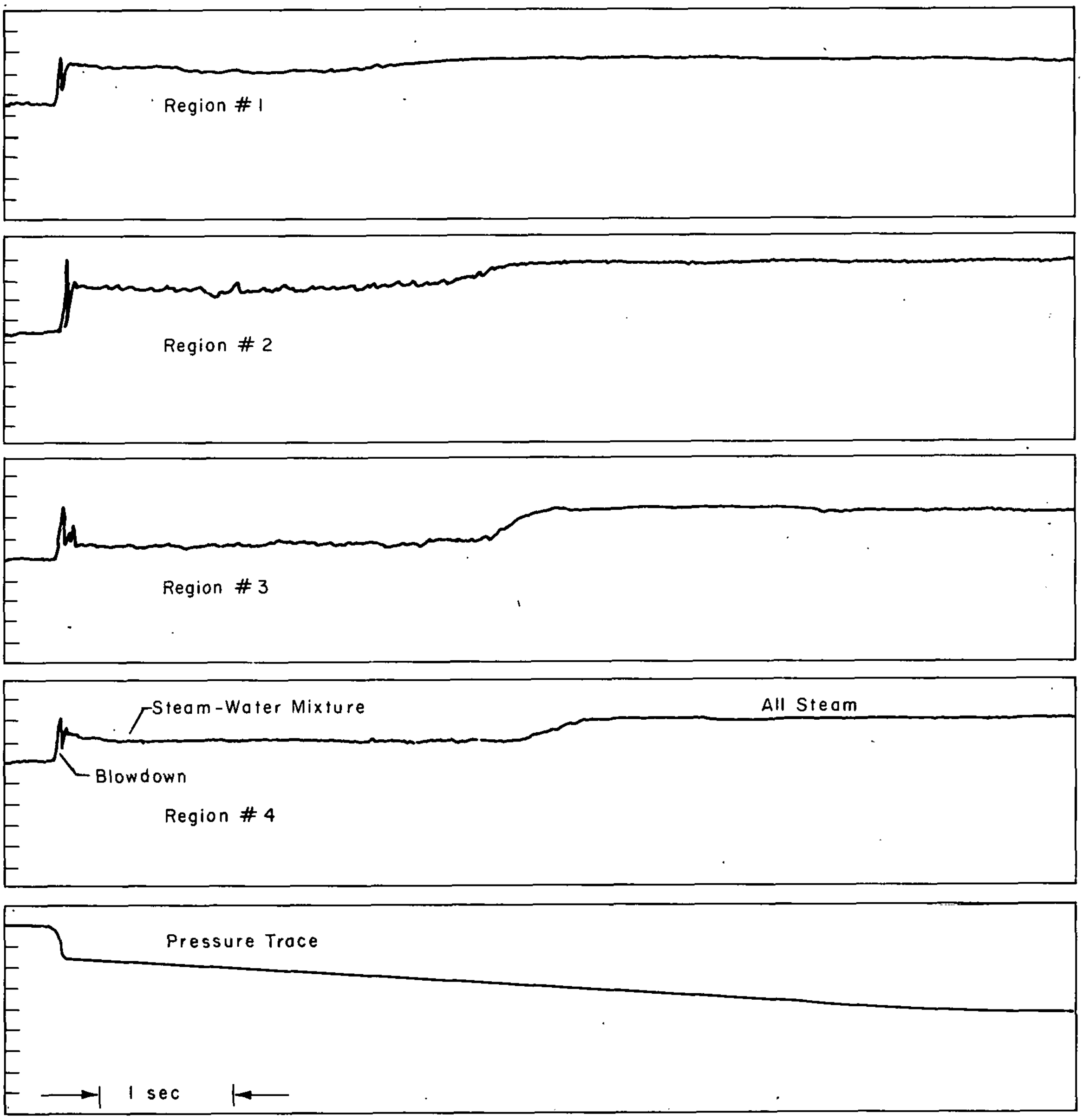

Fig. 9 Blowdown response of a four level probe.

Flooding of the autoclave following blowdown helped to determine the detector sensitivity to a boiling water flooding level. The autoclave was flooded in ten seconds by pumping water into the bottom through a tube extending from the top. Flooding data can be seen in Figure 10.

Autoclave testing was successful and informative. Although it did not simulate exactly the same LOFT conditions expected, it did help to understand what to expect from the detector under dynamic conditions.

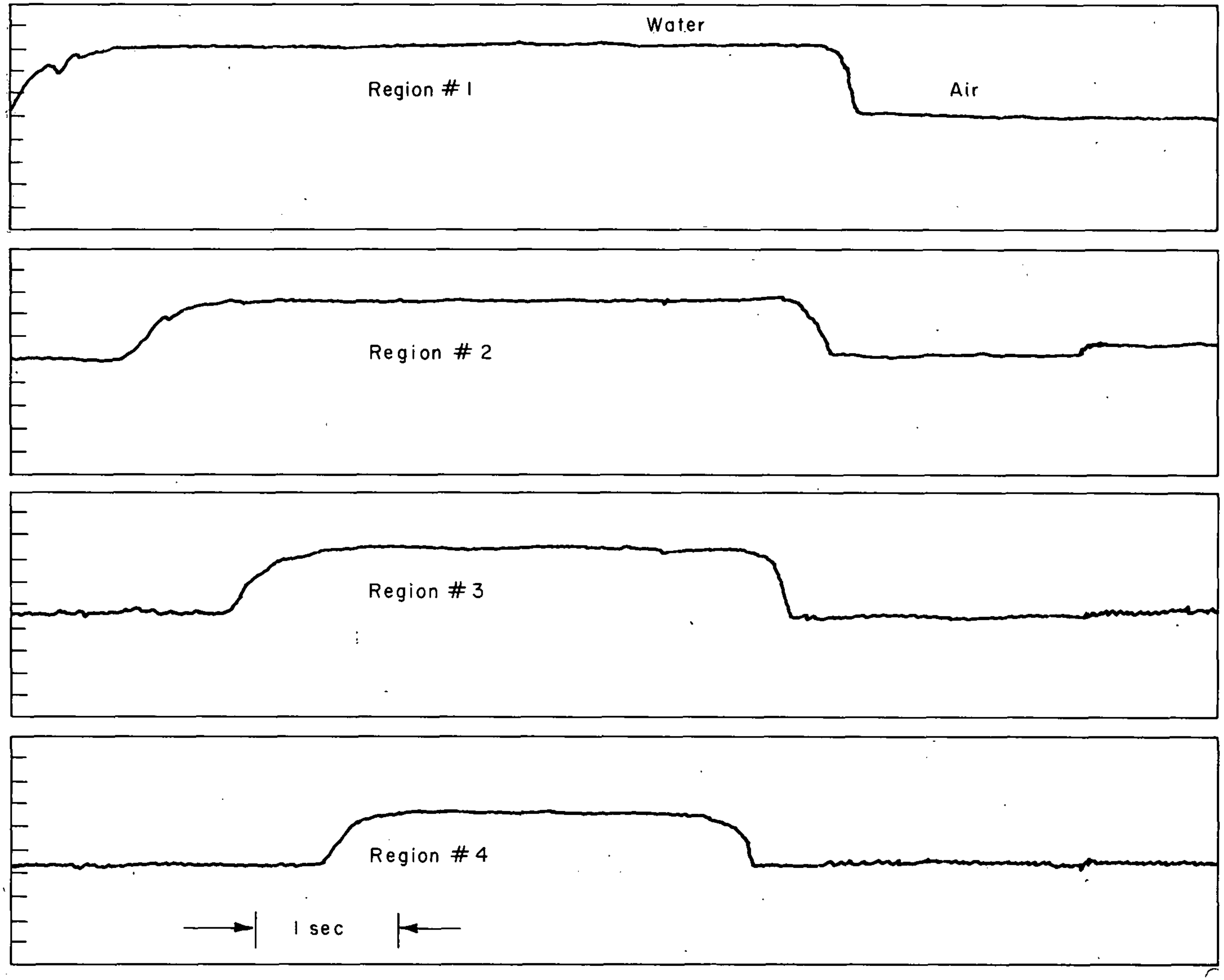

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Fig. 10 Autoclave flooding test.

VII. SOURCES OF ERROR

Several sources of error are present and must be considered:

1. Transducer to detector acoustic coupling is a function of temperature
2. Acoustical coupling from detector to surrounding media is a function of media acoustical impedance and boiling at the detector surface
3. Ultrasonic noise is generated by high velocity steam
4. Output versus water level is a log function.

The interface between the transducer magnetostrictive stub and the detector is a point of acoustical impedance mismatch. The amplitude and mode of ultrasonic energy transfer from transducer to detector depends upon the impedance mismatch of the bonding configuration between the two. This impedance mismatch is a temperature dependent function. The temperature sensitivity of a dry probe is shown in Figure 11. As can be seen the temperature sensitivity varies from transducer to transducer and is hard to control in the cylindrical probe configuration. No attempt was made to compensate for this temperature effect. The error introduced must be considered when temperature effect time constants approach the same value as the liquid level change time constant. When data are taken on a relative basis rather than an absolute basis the temperature effects can be identified in the data and are tolerable.

The ultrasonic coupling coefficient between the detector and the surrounding media is a function of the surrounding media acoustical impedance which changes with pressure and temperature. The acoustical impedance is the product of density and velocity of sound propagation in a media. For water, Figures 12 and 13 plot density of water and velocity of propagation in water as a function of temperature. The product of the two, acoustical impedance, is plotted in Figure 14.

Film boiling on the surface of the detector can take place during blowdown depressurization or during flooding. These effects only last for the short time required to cool the detector surface down to the saturation temperature. Figure 6 shows the boiling effect during flooding and Figure 9 shows the depressurization effect at the time of blowdown. The duration of the film boiling is decreased by slotting the surface of the detector to provide cooling fins.

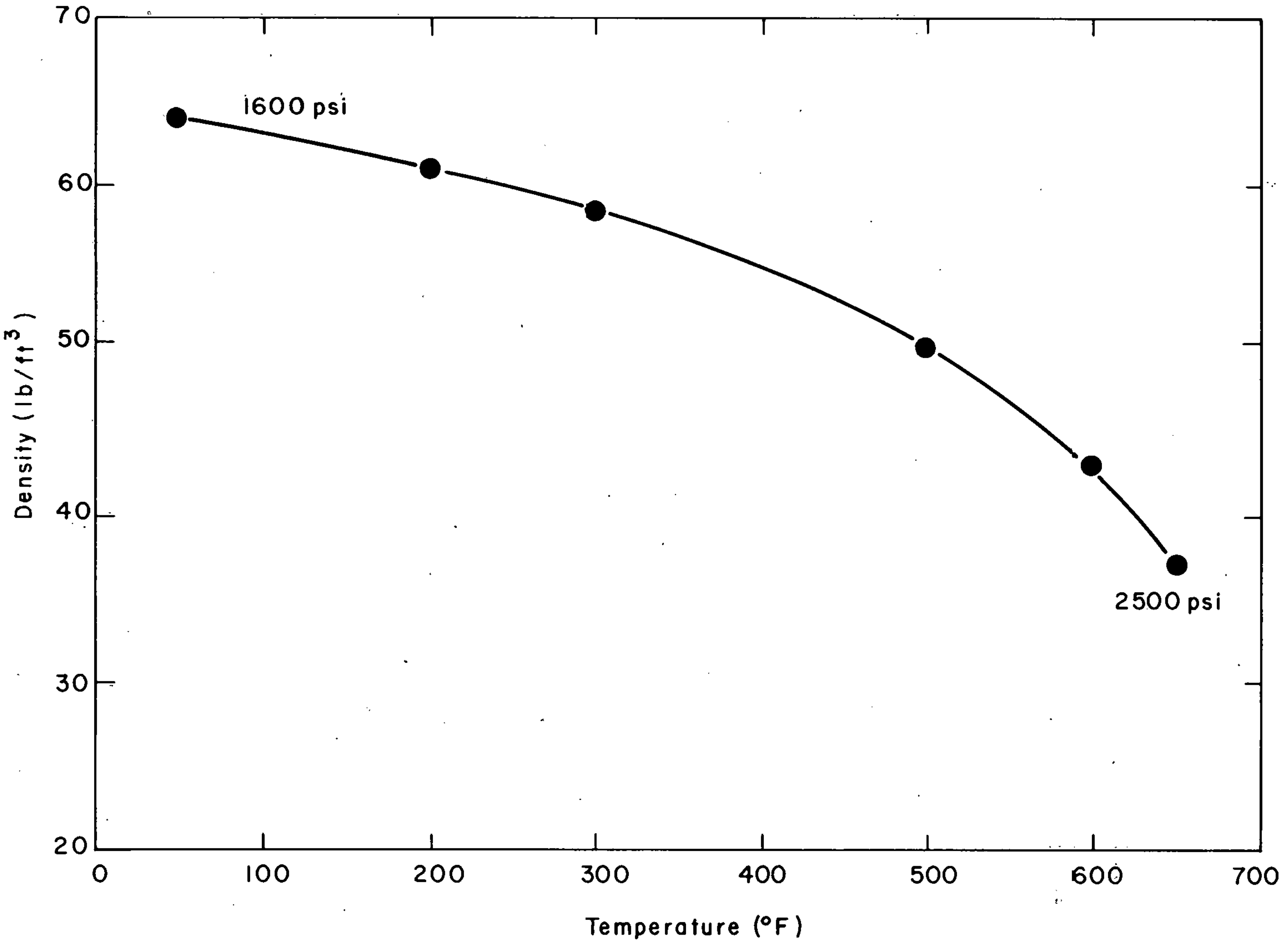

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Fig. 11 Water density curve during autoclave heatup.

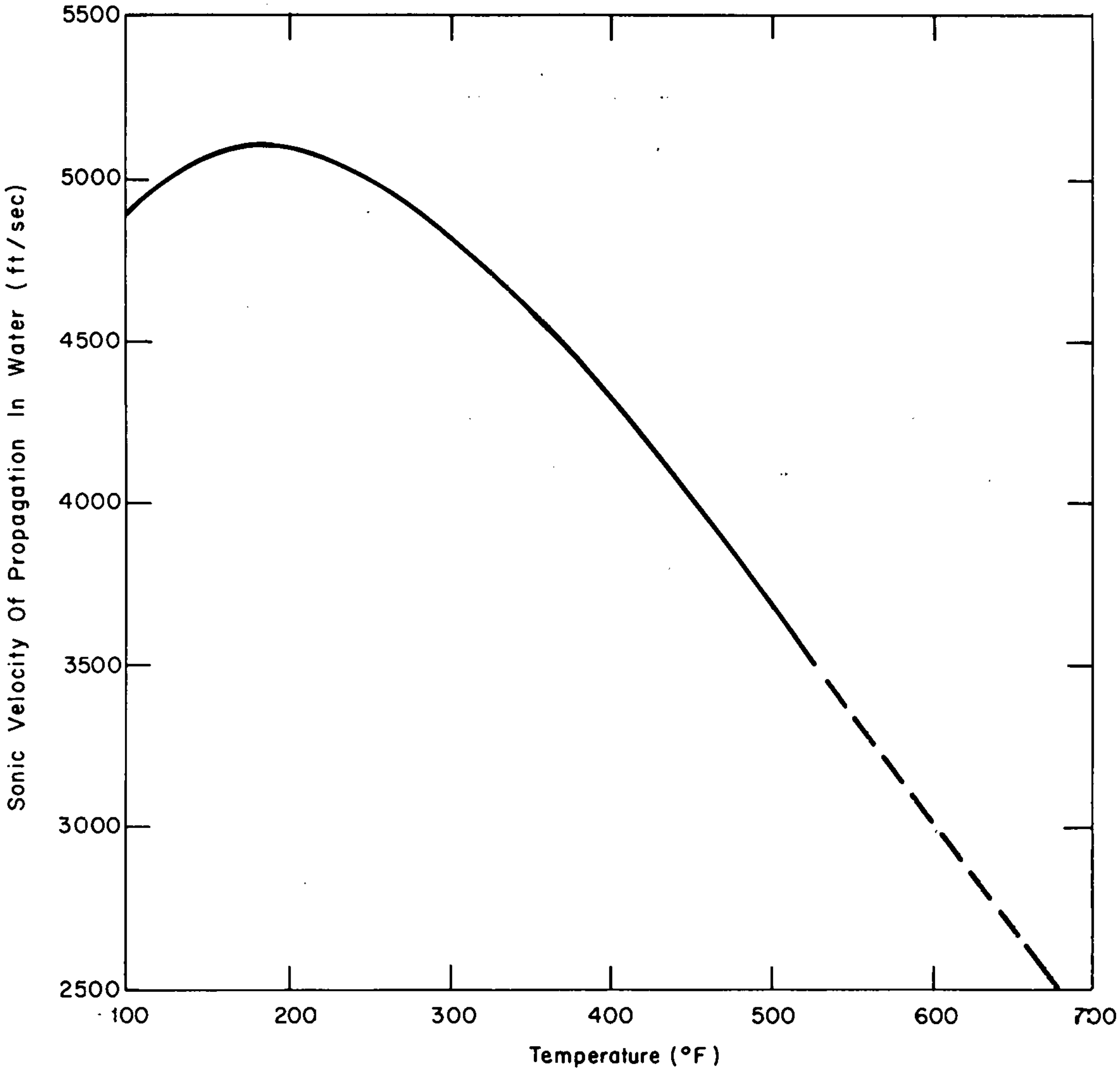

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Fig. 12 Sonic propagation velocity in water versus water temperature.

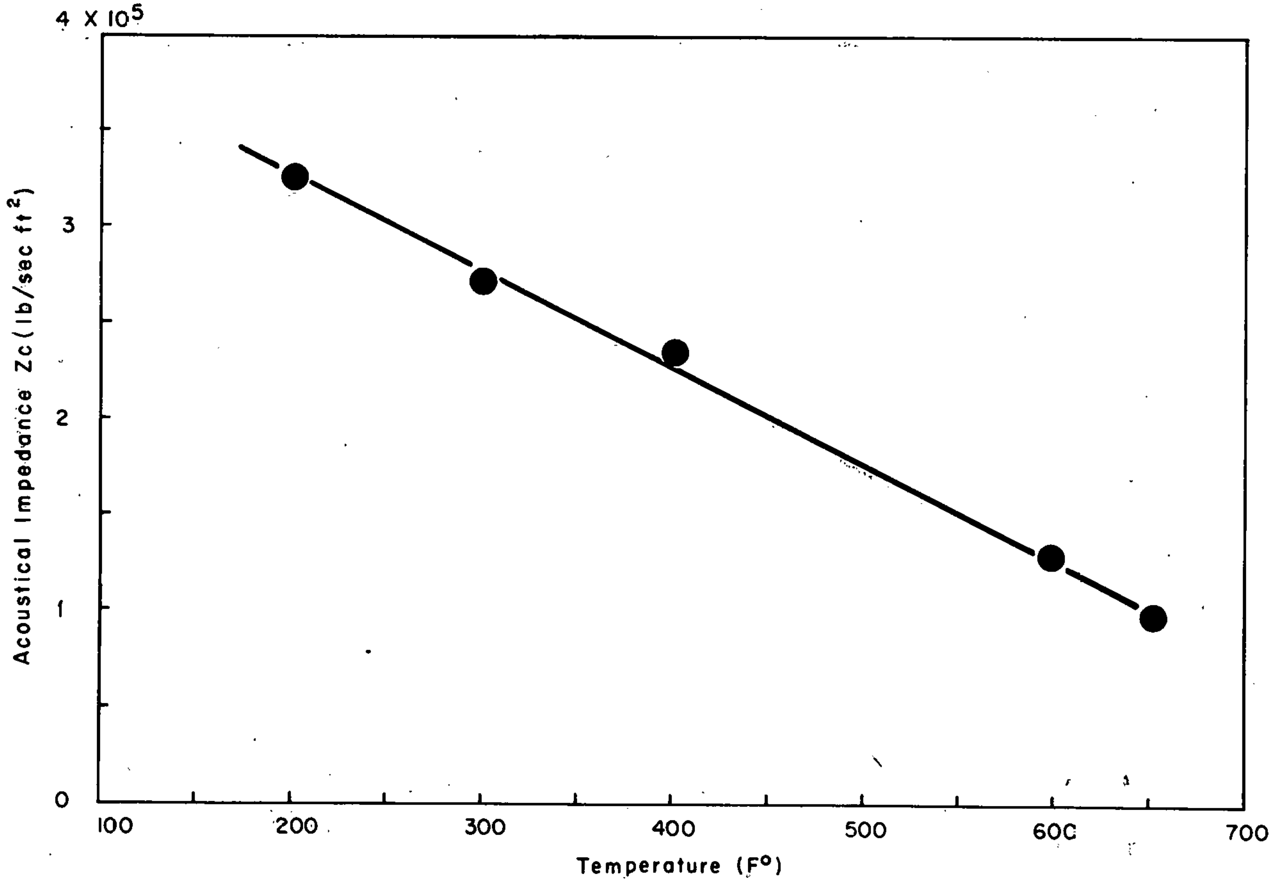

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Fig. 13 Acoustic impedance of water during autoclave heatup.

Some ultrasonic noise is generated at the time of blowdown by high velocity steam and steam bubbles collapsing. Most of this noise is removed by a bandpass filter.

No attempt is made to totalize the errors. The detector was designed with a knowledge of the effects outlined above. Short detection regions provide semi-discrete-continuous output signals that must be analyzed on a comparative basis to adjacent detectors on the longitudinal axis. This type of analysis allows the liquid level to be monitored as it moves from detector to detector. This can be seen in Figures 9 and 10.

VIII. CONCLUSIONS

The ultrasonic liquid level detector described in this report is rugged and compatible with the LOFT environment. With an all stainless steel housing the corrosive hot water environment is no problem. The tube configuration meets the physical requirements of compatibility with the core configuration.

Testing has shown the detector to have good sensitivity to liquid level changes. The temperature sensitivity of the tube configuration is worse than expected. A better design at the transducer-detector interface would greatly reduce this temperature effect.