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CONTINUOUS LIQUID LEVEL MEASUREMENTS WITH TIME DOMAIN REFLECTOMETRY

by

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ABSTRACT

A time domain reflectometer is considered a closed-loop, one dimensional radar system. Applying the principle of time domain reflectometry to the detection of cryogenic liquid levels, measurements on the order of ±0.3% of total liquid level probe length are possible.

The time domain reflectometer liquid level measurement is independent of liquid density variations and is simple to calibrate and operate. Construction of the liquid level sensing probe is described.

Key words: Coaxial probe; emptying rate; fill rate; liquid level; time domain reflectometer.

CONTINUOUS LIQUID LEVEL MEASUREMENTS WITH TIME DOMAIN REFLECTOMETRY*

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INTRODUCTION

This paper shows how a time domain reflectometer (TDR)[1-4] provides a simple yet accurate method for making liquid level measurements of cryogenic fluids. Measurement of cryogenic liquid levels in storage vessels have generally been performed with discrete sensors arranged in a ladder configuration. The accuracy of this technique is determined by the spacing of the sensors and their response time.

Capacitors have been used both as point sensors and zone sensors. The zone sensor is a large capacitor that samples the entire liquid level and measures the average density of the fluid. The disadvantage in using capacitors for liquid level sensors is that one must know the average density of the sampled fluid. This requires a measurement of the dielectric constant of the fluid and relating this dielectric constant to density with the Clausius-Mossotti equation. This equation is based on simplifying assumptions and may be in error by as much as two percent.

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Capacitance liquid level gages are high impedance devices and can give erroneous readings when subjected to intense nuclear radiation fields[5].

A TDR can be considered to be a one-dimensional, closed loop radar system[4]. This technique involves sending a fast rise time (< 120 picoseconds) pulse down a transmission line. Discontinuities (imperfections) in the line will reflect some energy back to the generator. The amount reflected is proportional to the magnitude of the discontinuity encountered. These transmitted and reflected signals are monitored on an oscilloscope screen.

A time domain reflectometer may be used to make the liquid level and vessel flow (fill or emptying) rate measurements. The measurement depends on an abrupt change in dielectric constant in the sensing probe (a coaxial line). The measurement is not perturbed by variations in liquid density.

Unlike capacitance devices, the TDR system is a low impedance device and is insensitive to high nuclear radiation fields[6]. Furthermore, a TDR provides a visual (oscillographic) display as well as a numerical readout.

A brief history of time domain reflectometry and transmission line theory follows. Sufficient references are given for a reader not familiar with time domain reflectometry or transmission line theory to obtain the necessary background.

TIME DOMAIN REFLECTOMETRY

Time domain reflectometry (TDR) is a state of the art application of established pulse reflection measurement techniques. With the development of fast rise time generators and sampling oscilloscopes, the application of pulse reflection techniques to high frequency transmission systems has become a common practice.

Figure 1 illustrates a TDR system. The step generator launches a voltage pulse down the transmission line toward the liquid surface. When the pulse encounters the liquid surface, part of the energy in the pulse is reflected back toward the step generator where the sampling circuits intercept it and send it to the display. The oscillographic display of the return pulses give an immediate indication of the nature of the reflecting discontinuity which may be resistive, or capacitive, or inductive. The calibrated distance scale of the TDR discloses the location of the reflecting discontinuities.

The TDR displays the characteristic impedance levels of the transmission line. Transmission line theory shows that the characteristic impedance of a transmission line is determined by the cross-sectional dimensions of the line and by the relative dielectric constant, ϵ_r, of the medium between the conductors (we assume negligible resistive losses).

For a right circular coaxial transmission line, as shown in Figure 2 (the kind we use to measure liquid levels), the characteristic impedance, Z_o, is defined by

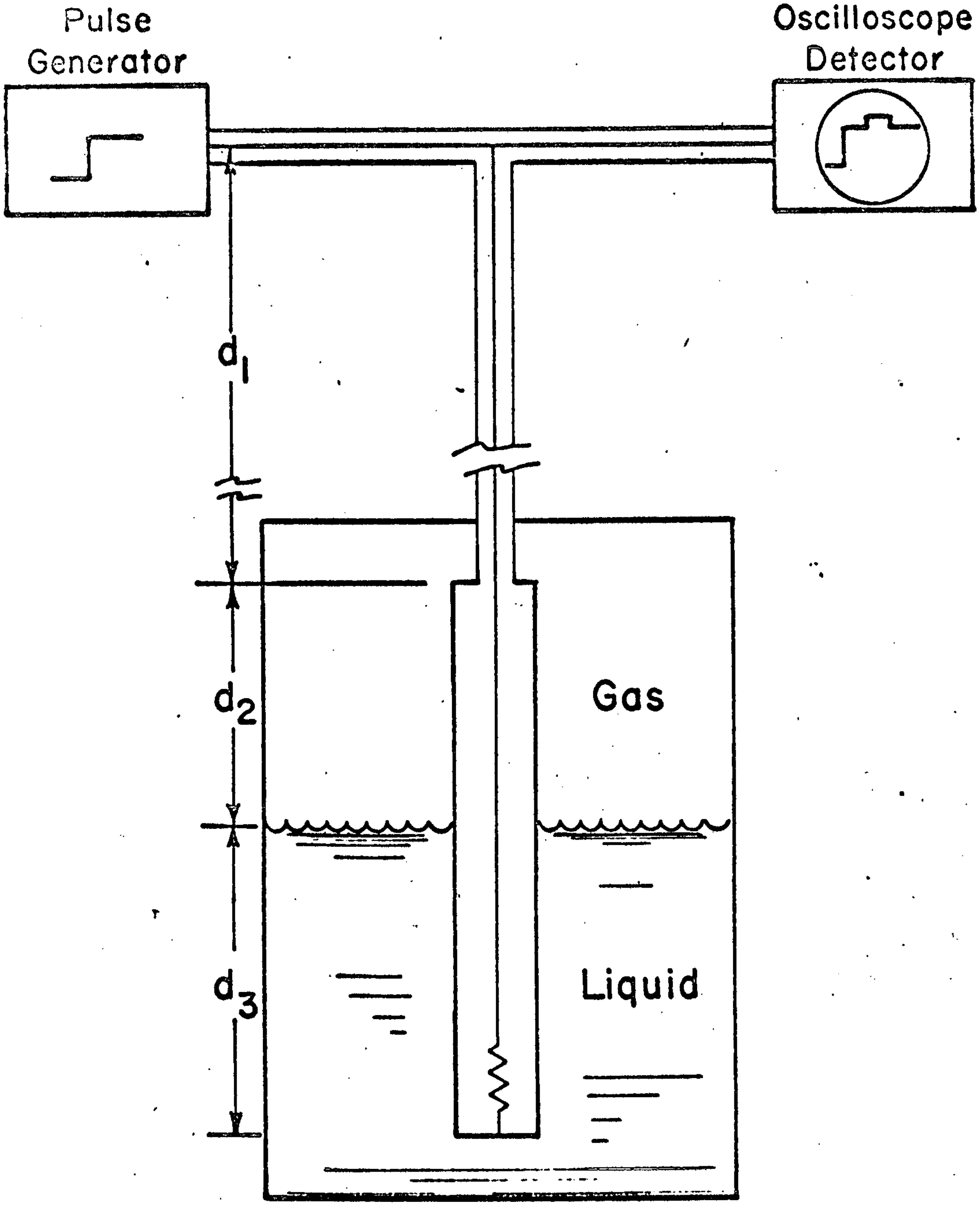

Figure 1. TDR Liquid Level Detection System.

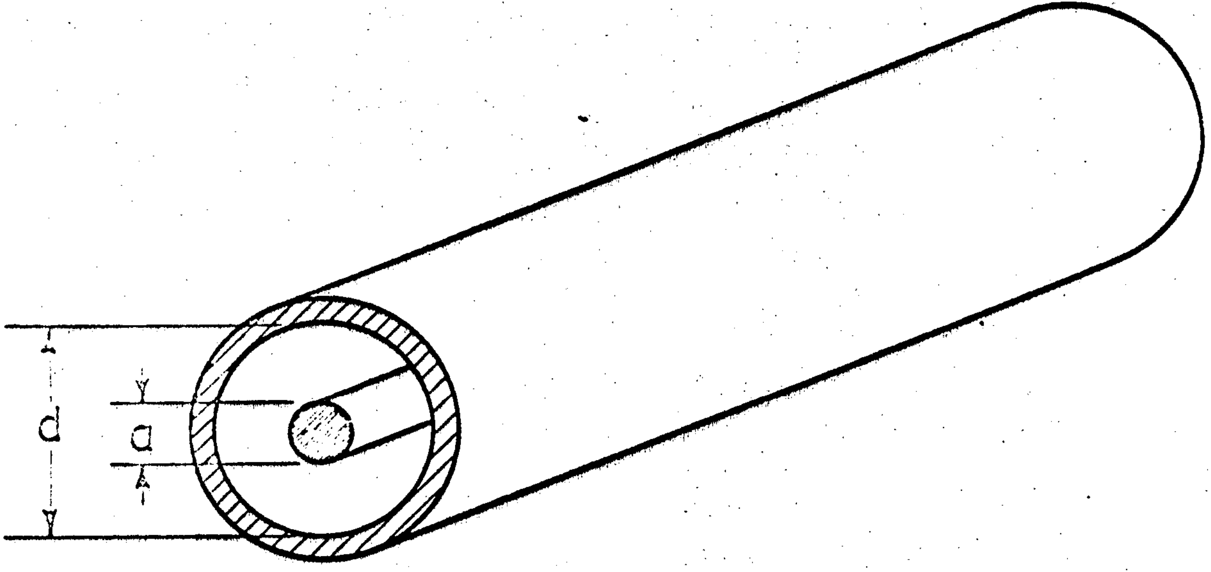

Figure 2. Right Circular Coaxial Transmission Line.

$$Z_o = \frac{60}{\sqrt{\epsilon_r}} \log_e \frac{d}{a} . \qquad (1)$$

Equation (1) shows that the characteristic impedance of the line changes with either relative dielectric constant, ϵ_r, or cross-sectional dimension ratio. It is the abrupt change in ϵ_r at the gas-liquid interface that is used for measuring both liquid level and flow rate.

Clearly, for constant line dimensions, the change in characteristic impedance at a gas-liquid interface is given by

$$Z_{o(\text{liquid})} = Z_{o(\text{gas})} \sqrt{\frac{\epsilon_{r(\text{gas})}}{\epsilon_{r(\text{liquid})}}} . \qquad (2)$$

This characteristic impedance is readily disclosed by the time domain reflectometer.

PROBE CONSTRUCTION

We constructed a 135 cm long right circular coaxial probe. This has holes every 30 cm to allow the liquid to penetrate the region between the conductors. The probe has a characteristic impedance in air of 55 ohms and it has a low temperature coefficient 50 ohm termination.

Figure 1 illustrates a schematic representation of the TDR system including the probe. Distance d_1 is the length of the transmission line from the detector to the probe, d_2 is that part of the probe length with gas dielectric, and d_3 is the probe length with liquid dielectric.

Figure 3 is the oscilloscope display for a typical liquid level measurement. Length d_1 has a characteristic impedance of 50 ohms while

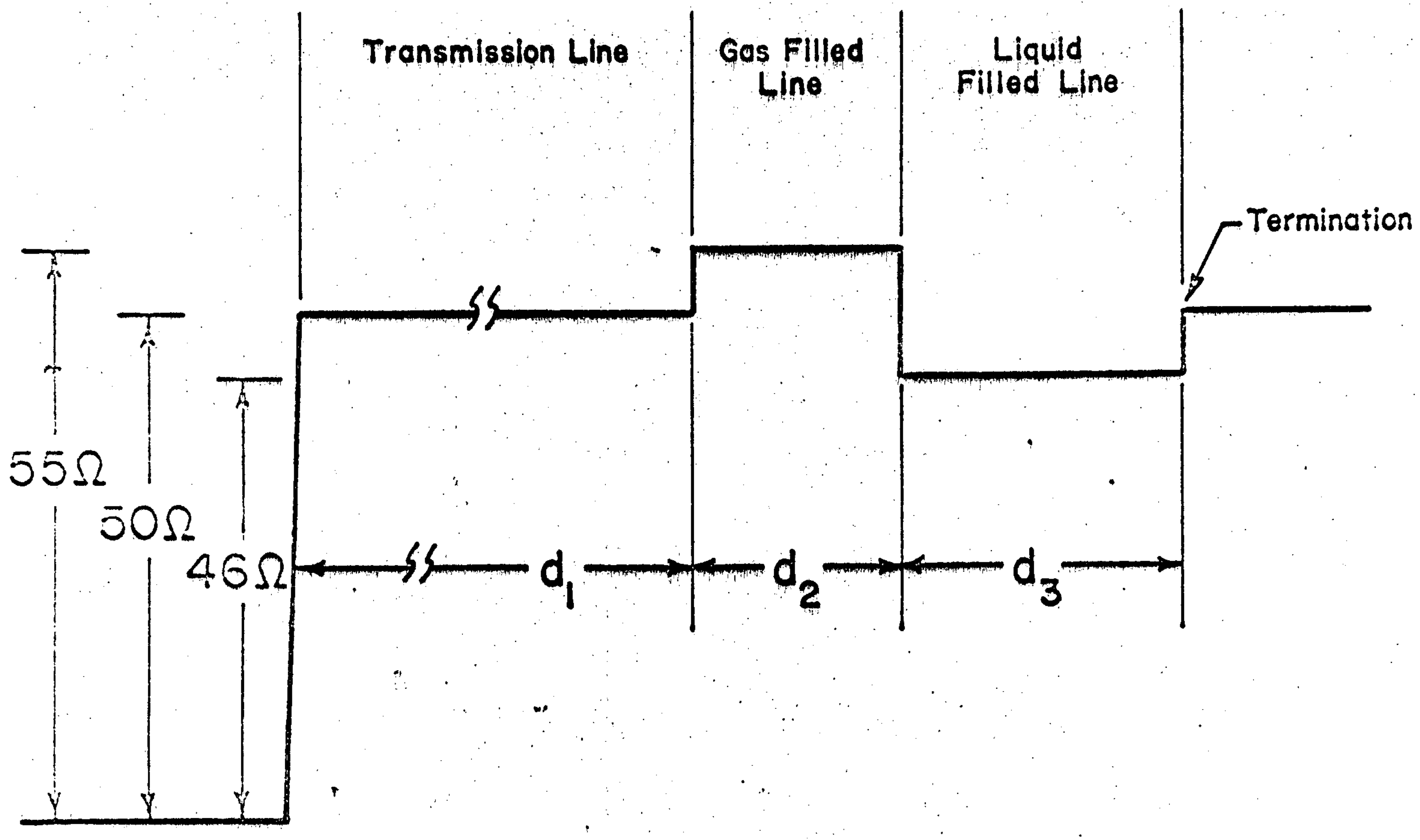

Figure 3, TDR Oscilloscope Display for a Typical Liquid Level Measurement. The distances d_1, d_2, and d_3 Correspond to the Lengths of the Transmission Line Sections Containing Air, Gas, and Liquid.

d_2, the gas filled section, has an impedance of 55 ohms and d_3, the liquid filled length, has an impedance of 46 ohms.

LIQUID LEVEL MEASUREMENTS

Time delay and magnification control on the TDR permit a detailed examination of the probe. See Figure 4.

The horizontal displacement of the oscilloscope trace is proportional to the effective length of the probe, while the vertical displacement is proportional to a characteristic impedance level. The positive slope of the vertical output in the TDR trace is used to start a counter and the negative slope stops the counter. Therefore, the counter indication is proportional to the length of the gas filled portion of the probe. Distance along the oscilloscope display is converted to liquid level in cm as follows.

$$LL = L_o - KP, \tag{3}$$

where LL is the liquid level of the fluid, L_o is the length of the probe, K is determined when the probe is empty, and P is the counter interval time, in milliseconds, of the gas filled length of the probe.

Figure 5 is a liquid level versus counter interval calibration of the 135 cm probe used in the weigh and catch tanks of the liquefied natural gas flow facility. Accuracy of the liquid level measurement is approximately ±0.3% of the total probe length.

THE TDR AS A FLOW INDICATOR

The TDR system has been used as a flow indicator by continuously measuring the counter interval of the gas portion of the probe and plotting

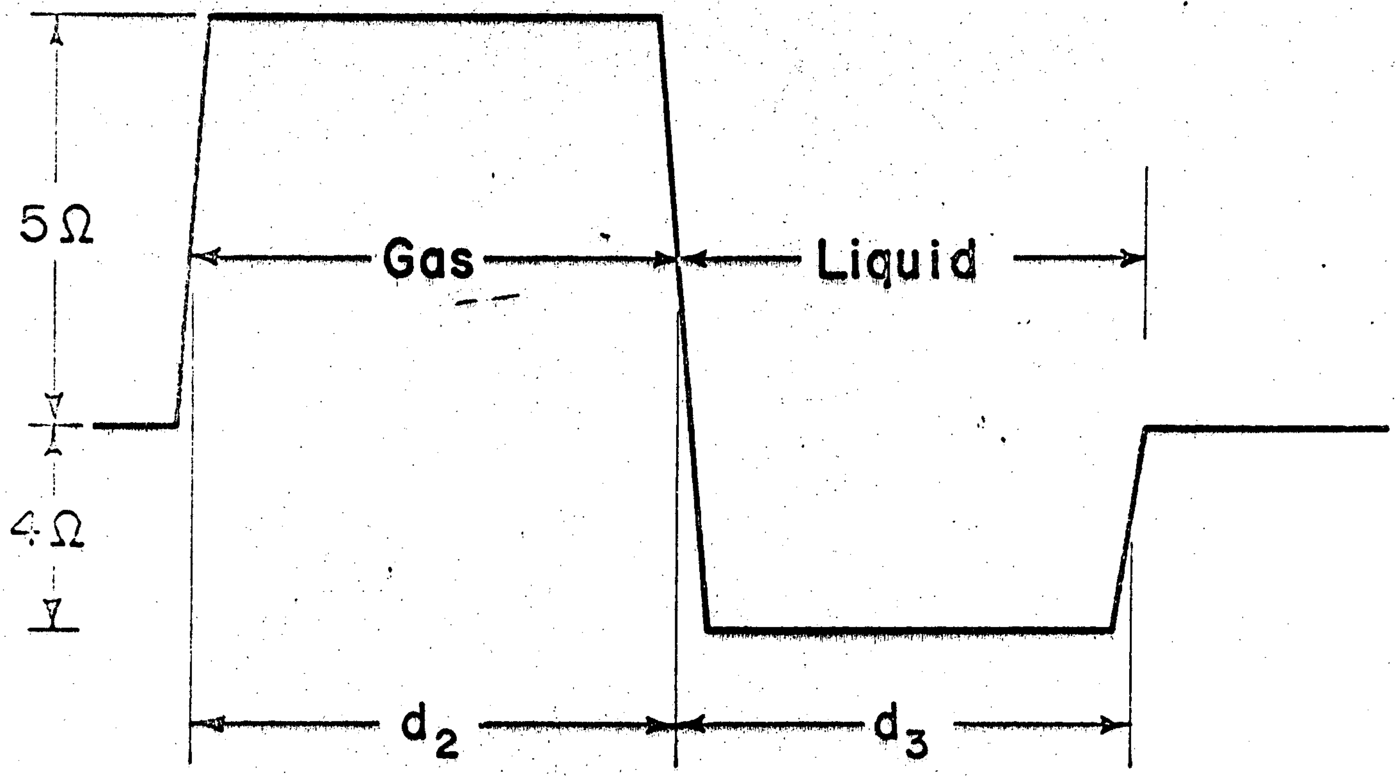

Figure 4. Expanded Display of the Liquid Level Probe.

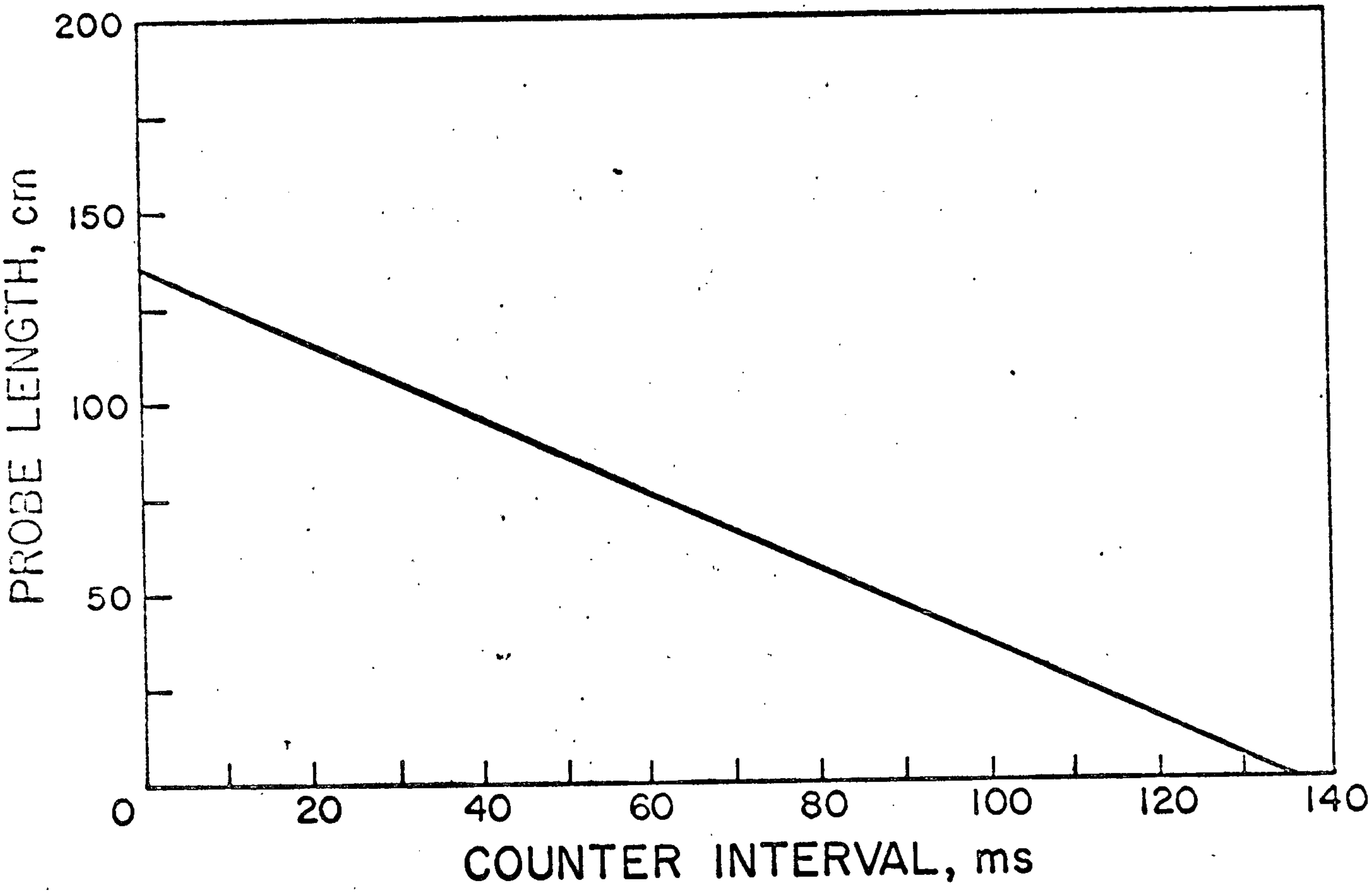

Figure 5. Calibration of Liquid Level Probe in Centimeters vs. Period Measurement in Milliseconds.

this interval or liquid level versus time. Knowing the geometric configuration of the container, the volume flow (emptying) rate out of the container can be calculated and plotted.

Figure 6 is a typical computer plot of liquid level versus time. The geometrical configuration of the container is a cylinder and consequently for a constant flow (fill or emptying) rate the output is linear. These data were obtained from the hydrogen flow loop and are typical of the flow rates obtained using liquid hydrogen.

SUMMARY

Time domain reflectometry is a simple, yet accurate system for continuously measuring liquid levels of cryogenic fluids. The system is independent of liquid density variations and is relatively simple to calibrate and operate. Characteristic impedance calculations of a right circular coaxial probe are straightforward and the probe is simple to construct.

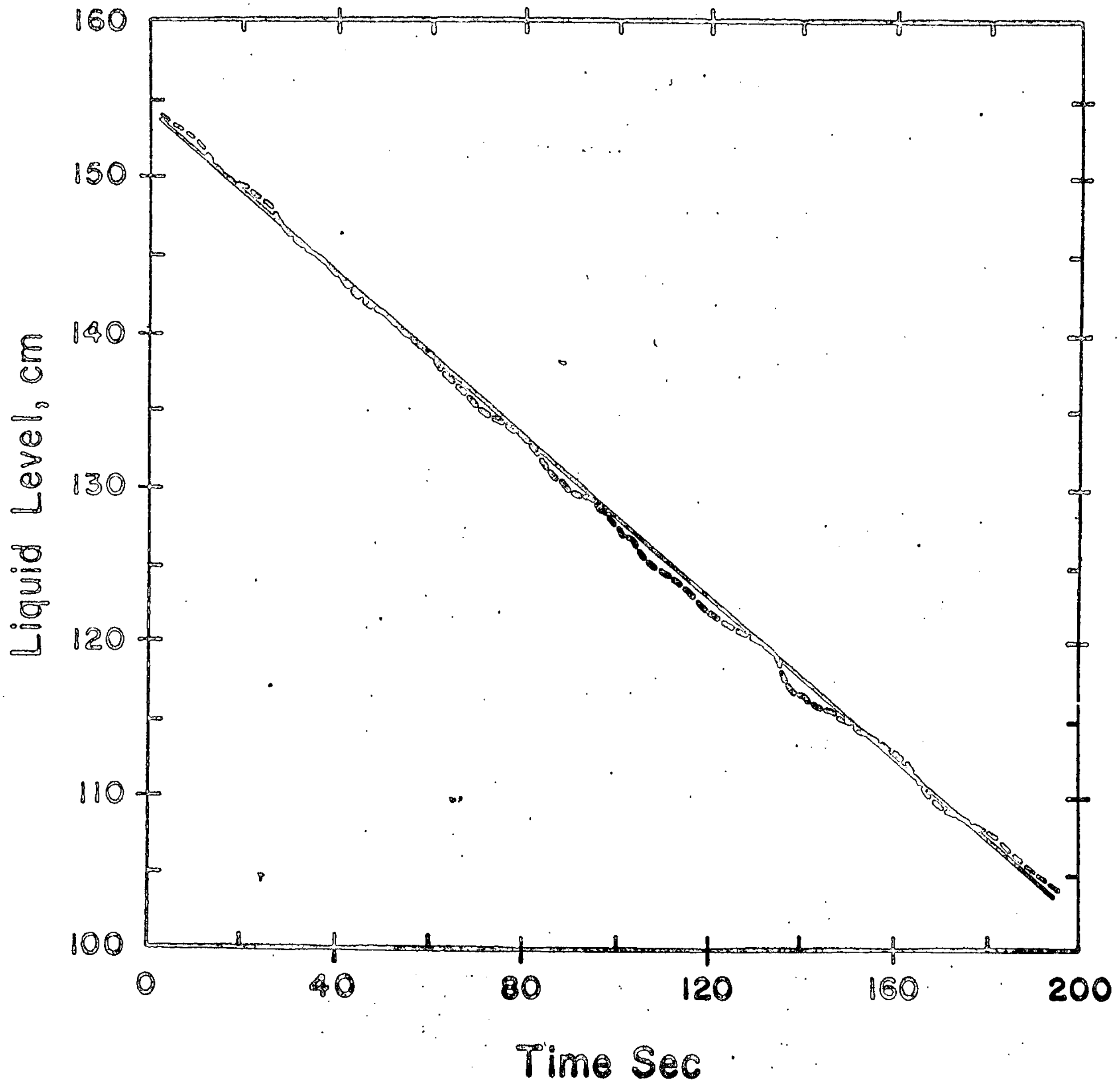

Figure 6. Computer Output of TDR Liquid Level versus Time for Flow Rate Information. Dashed Lines are Data Points and Continuous Line is the Best Fit Curve.

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