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ABSTRACT

     The theory of the method of measurement of liquid level by measure-
ment of the resistance of a heated wire is developed, and it is applied to the
design of a liquid-nitrogen-level indicator having a power dissipation of 3.4
milliwatts per inch of length and a deviation from linearity in the calibration
of less than 0.1 inch over its working length of 2.0 inches.

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INTRODUCTION

A number of ways have been developed for controlling the level of low-boiling liquids as applied to automatic filling of cold traps. Of the proposed devices, perhaps the simplest is a commercial bimetallic thermoregulator[1] used to control a solenoid valve. Most of the other devices measure the change in resistance of a wire or a carbon resistor when immersed in the liquid.

Equipment for measurement of level, rather than an on-off indication, may use the change in resistance of a wire,[2] the change in capacity of a condenser having the two-phase fluid as dielectric,[3] or the scattering of x-rays.[4] Of the above methods, the measurement of change in resistance is perhaps the simplest.

The sensing element is usually a fine wire heated by a small electric current so that it rides at a temperature slightly above ambient temperature. The magnitude of this temperature difference between the wire and the medium is a function of the thermal properties of the medium surrounding it; and for a liquid-vapor interphase, it is a definite function of the liquid level.

The variations in average temperature of the wire with variations in liquid level are reflected in changes in the resistance of the wire, which can be measured with a sensitive bridge circuit, or can give a direct indication of level if an unbalanced bridge is used.

THEORY

Consider a section of heated wire dissipating a certain amount of heat, q, surrounded uniformly by a fluid of heat-transfer coefficient h. From a heat balance on a section of the wire, we can write

[1] M. Lounsbury, Rev. Sci. Instr. 22, 533 (1951).
[2] A. E. Wexler and W. S. Cox, Ibid., 941 (1951).
[3] W. E. Williams, Jr. and E. Maxwell, Ibid. 25, 111 (1954).
[4] J. E Jacobs and R. R. Wilson, Electronics 24, 172, 176, 180, 184, 188, 192 (October 1951).

$$\frac{\partial U}{\partial \theta} + \frac{q}{\rho C_p A_c} - \frac{A_s h}{\rho C_p A_c} U + \frac{K}{\rho C_p} \left(\frac{\partial^2 U}{\partial x^2}\right) = 0, \qquad (1)$$

where

U = temperature difference between wire and medium,
θ = time,
q = heat dissipation per unit length,
ρ = density,
C_p = specific heat,
A_c = cross-sectional area,
A_s = surface area per unit length,
h = heat-transfer coefficient of the fluid,
K = thermal conductivity of the wire,
x = distance along wire.

For steady-state conditions we have $(\partial U/\partial \theta) = 0$, and the equation simplifies to

$$\frac{\partial^2 U}{\partial x^2} - a^2 U = -b, \qquad (2)$$

where $a^2 = A_s h/K A_c$ and $b = q/K A_c$.

For a semi-infinite wire, with one end clamped so that at $x = 0$ $U = 0$, Eq. (2) can be integrated to

$$U(x) = U_\infty (1 - e^{-ax}), \qquad (3)$$

$$U_\infty = b/a^2 = q/A_s h, \qquad (4)$$

where U_∞ is the steady-state temperature difference between the wire and the medium at $x = \infty$.

For a finite wire of length L, with both ends clamped, $U = 0$ at $x = 0$ and at $x = L$,

$$U(x) = U_\infty \left(1 - \frac{1}{1+\alpha} e^{ax} - \frac{\alpha}{1+\alpha} e^{-ax}\right), \qquad (5)$$

where

$$\alpha = e^{aL}, \qquad (6)$$

and the average temperature of such a wire is given by

$$U_{av} = U \infty \ (1 + \frac{2}{aL} \ \frac{1 - a}{1 + a}). \tag{7}$$

The general case, when a wire of length L is immersed in liquid to a depth l, requires separate equations for the vapor and liquid phases, which have to meet the following boundary conditions:

$$
\begin{array}{llll}
x & = & 0 & \qquad U & = & 0 \\
x & = & L & \qquad U' & = & 0 \\
x & = & 1 & \qquad U & = & U' \\
x & = & 1 & \qquad dU/dx & = & dU'/dx,
\end{array}
$$

and the resulting coefficients for equations of the form

$$U = U \infty + C_1 e^{ax} + C_2 e^{-ax} \tag{8}$$

are functions of L, l, a, a', U ∞, U' ∞, where the primed quantities apply to the vapor phase.

Design considerations, however, require only the solutions for the finite and semi-infinite wires surrounded by a uniform medium.

DESIGN CONSIDERATIONS

The liquid-level indicator was required to indicate liquid level to better than 0.1 inch, in a total span of 2 inches, with a very small power dissipation.

Table I is a comparison of calculated values for several possible sensing elements, operating on the system acetone-air at room temperature.

The sensing elements were compared under conditions which gave the same values of temperature difference between the element and the fluid, conditions which also yield approximately the same values for the heat-transfer coefficients.

Under these conditions, Eq. (4) indicates that the power required to obtain a given temperature difference at a large distance from one of the terminals is directly proportional to the surface area; thus we see it is advantageous to operate with a very fine wire.

The sensitivity of the liquid-level indicator, however, depends not only on the power dissipated, but also on the ratio of heat transferred to the fluid to heat transferred longitudinally along the wire--a factor which appears exponentially in Eq. (3) through (8). This factor "a" was calculated for the different sensing elements and appears in Table I together with its reciprocal, which for the semi-infinite wire is the distance along the wire necessary for a 63 percent approach to U ∞. On the same table appears the average temperature that the 2-inch sensing element would assume in contact with air under the same conditions.

Table I

Characteristics of different liquid-level indicators for the
system acetone-air at room temperature

Sensing Element	$(U)_L$ (°C)	$(U)_G$* (°C)	q (watts/in.)	a ft^{-1}	"Sharpness" ($1/a$ in.)	$(U_{av})_G$
No. 40 copper wire	1	39	1.1×10^{-3}	8.3	1.45	5.2
2-mil platinum wire	1	39	7.1×10^{-4}	24.4	0.51	19.8
1-mil quartz, silver-plated	1	39	2.6×10^{-4}	46.8	0.25	29.2
1-mil platinum wire	1	39	2.6×10^{-4}	34.5	0.35	25.5
0.5-mil platinum wire	1	39	1.8×10^{-4}	48.9	0.25	29.2
platinum ribbon 0.001 by 0.002 in.	1	39	2.5×10^{-4}	61-81.0	0.19-0.15	31.6

* Calculated using h = 1 Btu/hr x sq. ft. x °F, which is approximately the gas-film heat-transfer coefficient.

Thus it appears that either a 0.0005-inch platinum wire or a platinum ribbon would be the most advantageous sensing elements. The 0.5-mil wire requires a smaller power input than the ribbon to maintain the same temperature difference, but the ribbon gives a more linear response near the ends of the filament, an effect which is more noticeable in short sensing elements. The platinum wire should not be silver coated (Wollaston wire), however, because the thermal conductivity of silver is about six times that of platinum, thus offsetting some of the advantage of the small diameter.

A platinum ribbon approximately 1 mil x 0.2 mil was used as the sensing element and was made by rolling 3-mil Wollaston platinum wire into a ribbon 1 mil thick. This ribbon was wound on a glass tube and the silver dissolved with nitric acid. The resulting ribbon has a resistance of about 22 Ω/inch at room temperature and is very uniform throughout its length.

The liquid-level indicator was mounted as indicated in Fig. 1 and its resistance was measured by means of the bridge circuit shown in Fig. 2. The 20-μa full-scale meter was calibrated directly in inches.

Although the bridge was operated with rectified ac, it is shown battery-operated, because the reading is very sensitive to variations in operating current and battery operation probably would be more satisfactory.

CALIBRATION AND RESULTS

The instrument is calibrated by adjusting the Helipot R-4 so that ME-1 reads zero when the sensing element is completely immersed in liquid, then, by adjusting the current and the sensitivity, the 20-μa meter can be made to read full scale when totally outside the liquid. It may be necessary to readjust the settings until the meter reads correctly at the two ends of the scale.

The calibrating procedure given above is satisfactory when the instrument is to operate always in the same liquid and the same gas, under identical conditions of temperature and pressure; however, it was desired to obtain a method of calibration whereby the instrument could be calibrated rapidly, without resort to visual indications, and under widely different conditions of pressure, temperature, and composition of the phases.

The procedure adopted, which gave satisfactory results for the systems acetone-air at room temperature and liquid nitrogen-nitrogen vapor at 1 atmosphere pressure, is as follows:

(a) Adjust R-5 for maximum sensitivity.
(b) With the sensing element totally immersed in liquid, and the lowest current (about 1.5 ma), adjust the Helipot R-4 to balance the bridge, Record the Helipot reading, R_1.
(c) Gradually increase the current and plot bridge unbalance versus sensing-element current, Curve A in Figs. 3 and 4.
(d) Plot bridge unbalance versus current with the sensing element completely in contact with the gas, Curve B in Figs. 3 and 4.

(e) Note the current I_1 at which the bridge gives full scale in the gas, and from the plot read the corresponding reading in the liquid, L_{liq}. Extrapolate curve B for the gas until $L_{gas} = L_{liq} + 2$ (the 2 being the full-scale reading desired).

(f) Reduce the current until the reading in the gas is the same as L_{liq} mentioned under (e).

(g) Adjust the Helipot R-4 until bridge is balanced (zero) and record the Helipot reading R_2.

(h) Set the Helipot at the intermediate value $(R_1 + R_2)/2$ and adjust the current to obtain full-scale deflection in the gas.

(i) Record the current I_2. This is the correct operating current for the sensing element.

The instrument is then adjusted to read correctly at the two ends of the scale for the given liquid and gas phases.

The above procedure is especially advantageous when the heat-transfer properties of the liquid phase change slowly with pressure, temperature, or composition, since it is then possible to prepare a family of curves of bridge unbalance versus current for the liquids, and variations in the properties of the gas phase can be taken care of by individual calibrations under the different conditions. Step (h) of the calibration procedure gives rise to some error, especially at the higher pressures, when the deflection-versus-current curves are more nearly parallel and a higher operating current is required.

The linearity of the sensing element is satisfactory, as can be seen in Fig. 5, which compares the platinum ribbon with 1-mil platinum wire, showing that, as predicted, the ribbon gives a more linear response. The data were obtained in the system acetone-air at room temperature, with the power dissipated by the wire about four times as great as the power dissipated by the ribbon.

Also shown in Fig. 5 is the response of the 1-mil platinum wire under nonisothermal conditions such as would be obtained in measuring the level of liquid nitrogen in an open container, where appreciable temperature gradients exist in the gas phase. The deviations from linearity are then quite appreciable.

The scatter in the experimental data shown is due to variations in the operating current, and a part of the deviations from linearity could be adscribed to the difficulty in obtaining a perfectly taut filament out of such fine wire.
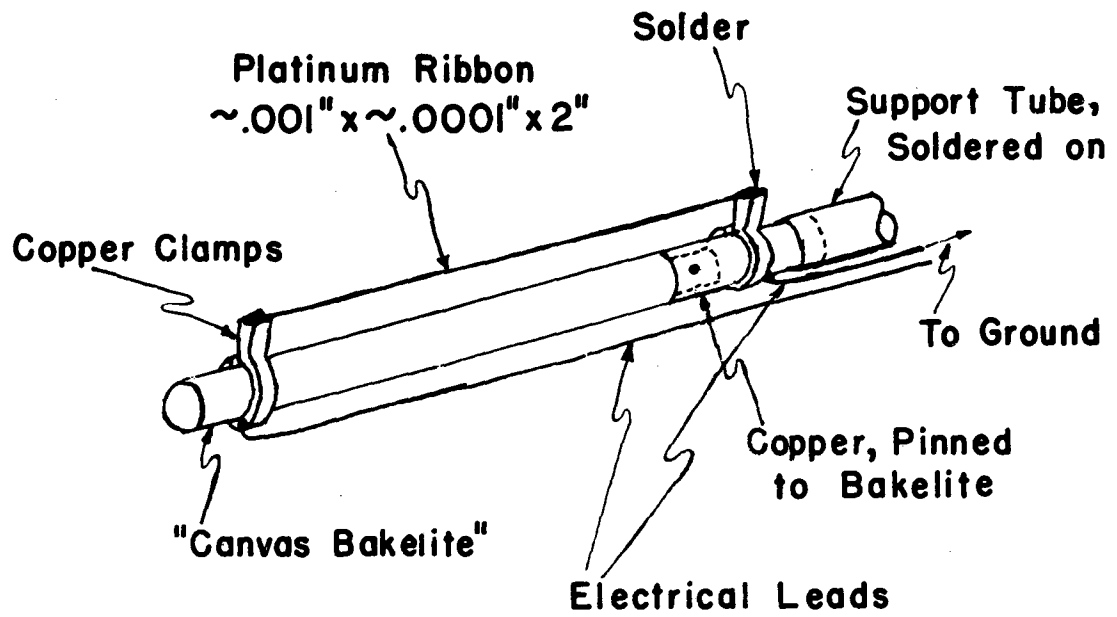
The power dissipation of the liquid-level indicator under operating conditions at liquid nitrogen temperatures was about 3.4 milliwatts per inch or 6.8 milliwatts for the total length.

The calibrating procedure given above was found to be fairly reliable at low pressures or for operation with pure nitrogen vapor. Thus reliable results were obtained with pure nitrogen at 100 psig; however, if hydrogen is added to the vapor phase it increases the heat transfer coefficient of the vapor to the point where the above calibrating procedure was not reliable at operating pressures of about 300 psig, with hydrogen concentrations in the vapor of the order of 75 percent.

ACKNOWLEDGEMENTS

Platinum Ribbon
~.OOI"x~.OOOI"x 2"

Solder

Support Tube,
Soldered on

Copper Clamps

To Ground

Copper, Pinned
to Bakelite

"Canvas Bakelite"

Electrical Leads

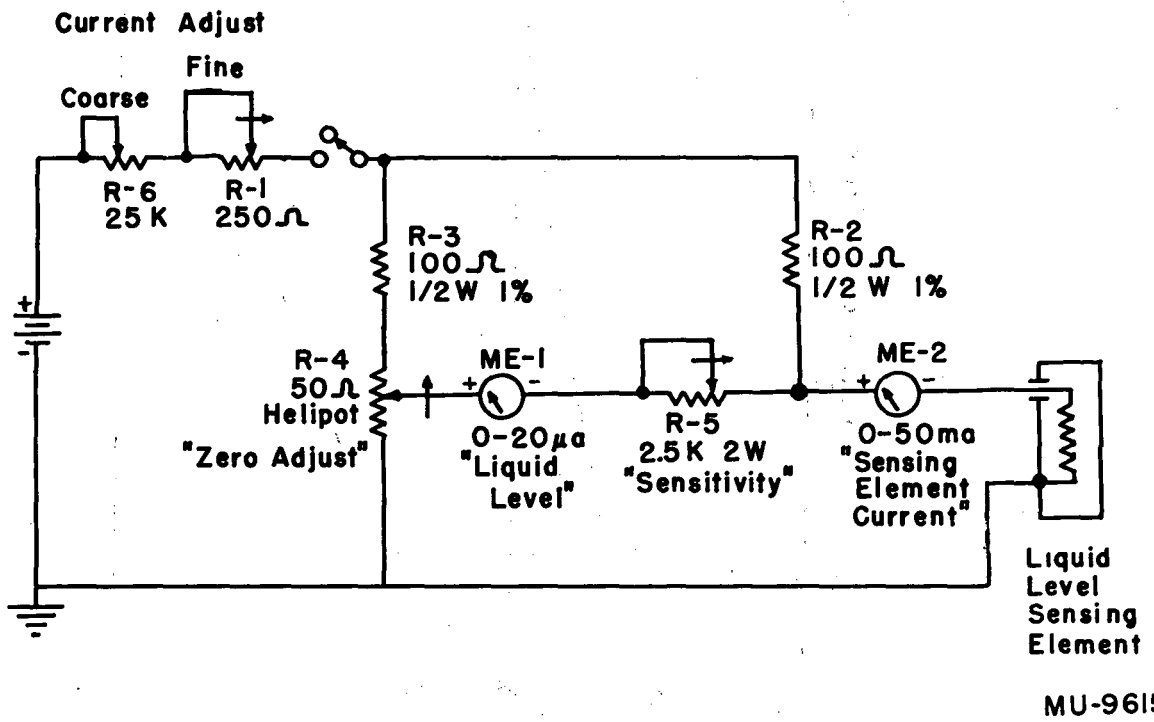MU-9616

Fig. 1. Liquid-level indicator.

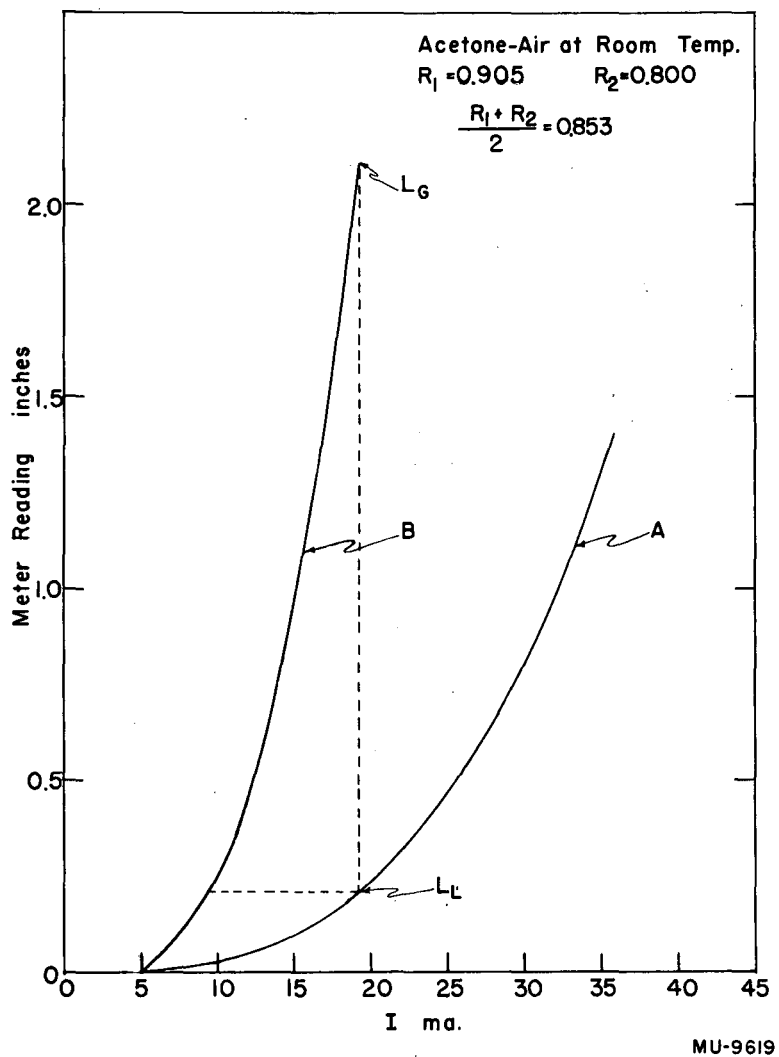Fig. 2. Circuit diagram for liquid-level indicator.

Fig. 3. Curve for calibration of liquid-level indicator,
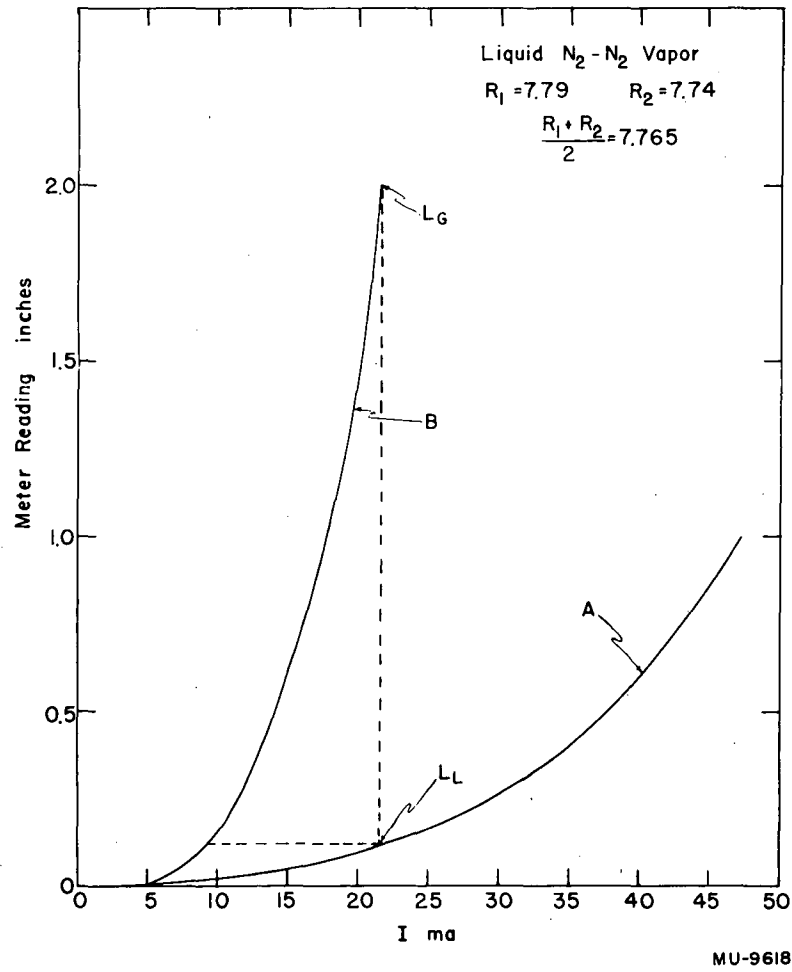acetone-air at room temperature.

Fig. 4. Curve for calibration of liquid-level indicator,
liquid nitrogen-nitrogen vapor at 1 atmosphere.

The chart shows Meter Reading, in. (y-axis, from 0 to 2.0) versus Length of wire exposed to gas, in. (x-axis, from 0 to 2.0), with a legend:

□ I Mil Platinum Wire, Isothermal
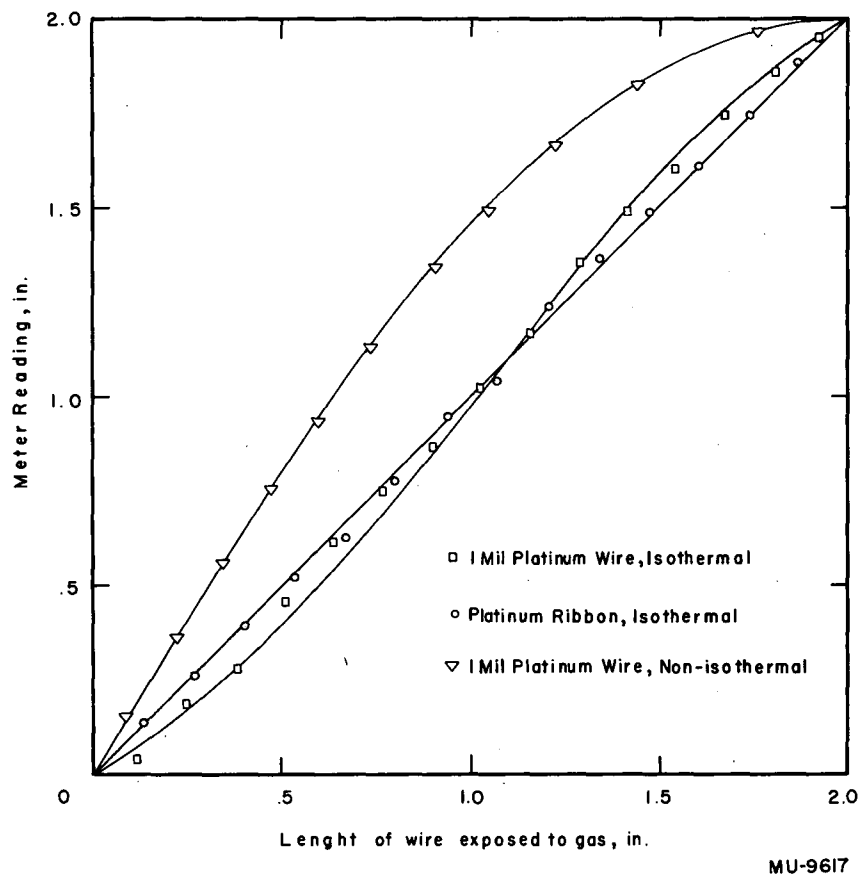
○ Platinum Ribbon, Isothermal

▽ I Mil Platinum Wire, Non-isothermal

MU-9617

Fig. 5. Linearity of liquid-level indicator.