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CAPACITANCE MASS SENSING

OF

BOILING PROPELLANTS

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ABSTRACT

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No pressurizing gas is introduced into the propellant tanks of the Centaur vehicle during engine firing. The consequent pressure decay causes the propellants to boil and the resulting gas bubbles change the effective density of the propellants. For liquid hydrogen in the Centaur this change is 1.4 percent and would show up as an error in any level-sensing propellant-utilization system. A perforated capacitance probe shows a net 1/2 percent error because the bubble population is not the same inside and outside the probe. However, a manometer-type capacitance probe senses propellant mass without a bubble-induced error. The paper outlines the theoretical background for this effect and presents the results from medium-scale tests in a general form applicable to vehicles other than Centaur. Author

SYMBOLS

A	area
C	capacitance
ΔC	change in capacitance caused by the substitution of a dielectric for a vacuum
δC	capacitance change due to temperature
c_s	specific heat at saturated conditions
d_b	bubble diameter
G	a constant
g	acceleration
H	propellant depth
ΔH	height change due to bubbles
H_v	heat of vaporization
h	dielectric height
K	a constant in the Clausius-Mosotti relation
K'	a constant defined by equation 5
k	a parameter defined by equation 18
M	mass
M_i	indicated mass
ΔM	mass error due to bubbles
δM	mass measurement error
P	pressure
$\dot{Q}_x$	external heat flow to liquid
T	temperature
t	time to empty tanks

u_b	bubble velocity
V	volume
$\dot{V}$	gas volume flow rate through the liquid surface (assumed equal to propellant use rate)
ϵ	dielectric constant (relative to vacuum)
ρ	density
ρ_o	nominal Centaur propellant density
$\Delta\rho$	change in density due to bubbles
ϕ	saturated gas density at reference pressure

CAPACITANCE MASS SENSING OF BOILING PROPELLANTS

INTRODUCTION

An advanced propellant-utilization system for the Centaur vehicle was being studied in the spring of 1963. A basic decision was needed on the sensing method. Other liquid-hydrogen-liquid-oxygen vehicles, such as S-II, S-IV, and S-IVB, were to employ capacitance systems, while past experience by many persons at General Dynamics/Astronautics indicated that a point-sensor system should be used. The choice was further complicated by the Centaur tank pressurization procedure which allowed boiling to occur. Tests were planned at General Dynamics/Astronautics in May and were conducted at Lewis Research Center, Cleveland, Ohio, in June and July to determine which (if either) system would perform properly under Centaur conditions. The tests showed that with care either type could be used but that the capacitance system had the edge.

These tests and the basic sensor analysis are the subject of this paper.

BACKGROUND

Capacitance Sensors

A capacitance sensor, either a continuous probe or a point sensor (liquid-level detector), relies on the very small change in capacitance caused by the difference in dielectric constant between gas and liquid. The capacitor is very nearly a perfect mass sensor; it almost "counts molecules" regardless of the density. While mass sensing is of the greatest importance in a P/U system, other advantages are the continuous analog signal and the relative simplicity of the in-tank hardware. The major problem concerns gas density, since the probe reading is a sum of liquid _plus_ gas mass.

Most early aircraft capacitance gaging systems were quite sensitive to stray capacitance. The wide spread use of the "three-terminal capacitor" has reduced this problem to insignificance. Any capacitance to ground (see Figure 1) appears only as a load on the source (i.e., the transformer) or as a load on the amplifier input (normally kept at ground potential by the servo system).

Centaur Tank Conditions

The Centaur uses boost pumps, rather than the introduction of pressurizing gas, to assure that the propellant delivered to the main engine pumps is well below saturation. The Centaur boost pumps, which provide roughly a 20-psi head, can function satisfactorily with a relatively low-quality mixture (i.e., lots of bubbles).

Since the Centaur propellant tanks are not artifically pressurized, boiling will occur as the liquid is withdrawn, even if the external heat input is zero. The propellants and the ullage gas are initially at (or near) saturation and, as the tanks are emptied, the ullage pressures tend to fall. But this means that the liquids tend to become superheated and that they will boil to maintain equilibrium. This boiling will counteract the reduction in pressure. The net result is a constantly decaying pressure and a constantly decaying saturation temperature. If the external heat input to the tank is high enough, the ullage pressure can be maintained constant during firing; but, of course, this too requires boiling, albeit of a different pattern, early in flight when most of the heat enters the liquid. Vehicles using pressurized tanks, may also have boiling due to external heat input.

An alternate way to visualize the Centaur situation (when the external heat input is small) is the following. The LH_2 tank is initially almost full of liquid at perhaps 25 psia and finally full of gas at roughly 17 psia. During the 450 seconds of engine firing all of the liquid is removed from the tank at a nearly constant-volume flow rate and consequently ullage space (or gas volume) is added at a constant-volume flow rate. Since the pressure changes by only about 30%, most of the gas must be evolved through boiling and does not come simply from gas expansion. A mathematical description of this process including the effects of external heat input is covered in a following section.

In Centaur the gas mass problem is particularly acute, since the ullage gas will tend to be near saturation and therefore very dense. At 19 psia the boiling point temperature for LH_2 is 21.1°K and the ratio of liquid density to saturated gas density is only 42/1. The actual gas temperature and density will, of course, depend on the heat input during the flight in question -- values which are very hard to predict accurately. Figure 2 shows the relative error caused by the gas density. Since the capacitance system measures total mass and since the mass of GH_2 in the Centaur tank at the end of flight may be as large as 120 pounds (2.4% of full tank), knowledge of the actual gas mass is imperative. The rough assumption of saturated vapor is not sufficient; flight measurements will be made in order to trim the P/U system to its optimum efficiency.

In vehicles using "hot" gas for pressurization this problem is reduced, but it may, as Figure 2 indicates, still be bothersome.

ANALYTICAL CONSIDERATIONS

The Manometer Effect

In-tank capacitance systems (including aircraft fuel and missile P/U) prior to Centaur have generally used perforated probes to assure that the liquid level within the probe is the same as that in the rest of the tank. For the Centaur system a manometer-type probe (i.e., one open only at the top and bottom with no lateral holes) was conceived in order to improve the measurement of the propellant mass in the tank. The advantages of the manometer probe over the perforated probe are:

1. Elimination of the error caused by the fluid (including liquid, gas, and mixtures) density within the probe not being characteristic of that in the rest of the tank and
2. Elimination of undesirable slosh effects by the use of an inertia tube (see Reference 1).

These two advantages are pertinent in any mass-sensing system but are overwhelming when the liquid is boiling.

Figure 3 shows a stylized tank and manometer-type capacitance probe. The condition for hydraulic balance for this system is

$$\rho_1 h_1 + \rho_2 h_2 = \rho_1' h_1' + \rho_2' h_2' \tag{1}$$

This is another way of saying that the mass in the tank between the manometer taps is proportional to the mass in the manometer. Thus,

$$M' = (A'/A)\, M \tag{2}$$

So only the question remains, "Does the probe really sense M?"

The Clausius-Mosotti Relation

For a homogeneous dielectric (for example, the gas only)

$$\Delta C = G\,(\epsilon - 1)\, V \tag{3}$$

where ΔC = change in capacitance caused by the substitution of the dielectric for a vacuum,

G = constant of proportionality,

ϵ = dielectric constant, and

V = volume of the dielectric material.

From Clausius-Mosotti:

$$\epsilon - 1 = \frac{3K\rho}{1 - K\rho} \tag{4}$$

where K = constant — about 1/1000 (cc/gm) for H_2 — and

ρ = density.

Equation 4 for H_2 is plotted in Figure 4. A straight-line approximation may be made as shown below.

$$\epsilon - 1 \cong \frac{3K\rho}{1 - K\rho_o} \cong 3K'\rho \tag{5}$$

where ρ_o = nominal Centaur density (70gm/liter for H_2) and

$K' \cong 1/930$ (liter/gm) for H_2

From equations 3 and 4 we can write:

$$\Delta C = G\left(\frac{3K\rho}{1 - K\rho}\right) V = GM\left(\frac{3K}{1 - K\rho}\right) \tag{6}$$

where M = mass ($=\rho V$) and from the identity of equation 5:

$$\Delta C = 3K'GM\left(\frac{1 - K\rho_o}{1 - K\rho}\right) \tag{7}$$

If we assume simply that the ΔC is exactly proportional to mass,

$$\Delta C = 3K'GM_i \tag{8}$$

where M_i = indicated mass; and the measurement error (δM) introduced by density variation is

$$\frac{\delta M}{M} = \frac{\rho - \rho_o}{(1/K - \rho)} \tag{9}$$

If this error is sufficiently small, then the answer is "Yes, the probe really does sense M".

For Centaur the magnitude of the error was determined for two cases: the error associated with variations in liquid density about ρ_o, and an error which is inherent in any gas measurement when using this approximation. The LH_2 density variations about ρ_o will be no more than ± 1.5 gm/liter (corresponding to a maximum tank pressure variation of ± 6 psi) and from equation)9 the consequent error is ± 0.15%. Note that this error is a percentage of point value -- not of full tank. As the tank empties, the error in pounds decreases to zero. The error in GH_2 mass measurement increases to a maximum value of 8% at the end of flight but this represents only eight pounds (the probe is only 4/5 the height of the tank). Further this gas error is partly systematic and can be largely eliminated by proper system bias adjustment based on the gas mass prediction for the particular flight.

Segmentation

Segmentation of the manometer-type probe and electrical removal of the upper element late in the flight could actually increase the ullage gas error, because of the manometer effect. Details on segmentation may be found in the Appendix.

Bubble Theory and Background

The bulk density change in a simple cylindrical tank is

$$\Delta\rho = \rho \frac{\Delta H}{H} \tag{10}$$

where $\Delta\rho$ = change in density,

ρ = density with no boiling,

ΔH = change in surface level relative to the condition of no boiling, and

H = propellant depth.

An expression (equation 11) for the change in surface level, ΔH, in this tank can be written for the following assumptions.

1) Constant-volume boil-off rate. 2) Boil-off rate is equal to the propellant use rate.	Only approximately true over the entire Centaur flight; but early in flight when the bubble effect will be the greatest, it is very nearly correct.
3) No external heat input.	Heat input is negligible for many Centaur flights.
4) Bubbles formed uniformly on the vertical surfaces. (For simplicity the bottom is ignored.)	An almost infinite number of nucleation points are available.
5) Uniform bubble size.	Small bubbles tend to coalesce; large bubbles tend to break-up. Nucleation also restricts the size range. (Reference 2).
6) Initially saturated propellant.	Time on ground between tanking and launch assures this condition for Centaur.

The expression is

$$\triangle H = \frac{H}{2u_b A'} \left(\frac{V_p}{t} \right) = \frac{H}{2u_b A'} \dot{V} \tag{11}$$

where u_b = bubble velocity,

A' = tank area,

V_p = propellant volume,

t = time to empty the propellant, and

$\dot{V}$ = gas volume flow rate through the liquid surface.

The velocity of rise of single spherical bubbles in an unrestricted medium may be found by equaling the drag and buoyant forces. When the Reynold's number is between about 100 and 200,000, the flow around the bubble is turbulent and the coefficient of drag is almost constant and the velocity of rise is almost independent of the medium. The Reynold's numbers in LH_2, LO_2, and LN_2 are in this range for bubbles of the size expected during Centaur firing and their velocity is given by*:

$$u_b = 1.74 \sqrt{g d_b} \tag{12}$$

where u_b = bubble velocity

g = acceleration

d_b = bubble diameter

* Reference 3.

Equation 12 is plotted in Figure 5 at one-g acceleration over the range of d_b expected during a Centaur firing. Approximate test data from motion pictures of boiling LH_2 is plotted above the calculated curve. Two effects probably explain why the test data is 60 to 70% above the calculated velocity: a decrease in drag would occur, if there is circulation inside the bubbles; and an increase in veloicty could result from the presence of other bubbles (the calculation was made for a single bubble).* One might expect an increase in u_b proportional to $\sqrt{g}$ from a first inspection of the expression for u_b. However, d_b probably decreases as the acceleration increases so that u_b should be expected to vary with g to some power less than one-half.

The LH_2 motion pictures indicated a bubble velocity between 8 and 20 inches/sec for corresponding bubble diameters of 0.02 to 0.12 inches. Applying these rough estimates and Centaur LH_2 tank geometry to equations 11 and 10 the surface shift is between 3.75 and 1.5 inches and the density variation between 2.5 and 1 percent. The values found in the tests were 2.2 inches and 1.4% respectively.

Scaling

Since the tests were to be conducted in a non-Centaur tank without the capability to remove liquid at anything like Centaur flow rates, methods were developed for scaling boundary conditions and test results. The geometrical scaling was based on equation 11. We stipulated the same ΔH in the model (i.e., at LeRC) as in the Centaur, therefore:

* Reference 4.

$$\Delta H_m = \Delta H_c = \frac{H_m}{2u_b A'_m} \dot{V}_m = \frac{H_c}{2u_b A'_c} \dot{V}_c \qquad (13)$$

or

$$\dot{V}_m = \frac{H_c A'_m}{H_m A'_c} \dot{V}_c \qquad (14)$$

where the subscrips m and c refer to the model and to Centaur respectively. The nominal flow rate for LH_2 in the Centaur is 2.7 ft^3/sec and for LO_2 0.85 ft^3/sec. Assuming that both Centaur tanks are cylindircal:

	H_c*	H_m	A'_c	A'_m	$\dot{V}_c$	$\dot{V}_m$	
	inches	inches	ft^2	ft^2	ft^3/sec	ft^3/sec	cc/sec
LH_2	157	70	78	4.9	2.7	0.32	10,700
LO_2	54.4	70	74	4.9	0.85	0.043	1,220

The figures in the last column of the above table were used as nominals during the tests with excursions to either side to obtain bracketing data.

The condition of boiling implies a heat input, but this can be misleading. The heat required to vaporize the liquid can certainly come from an external source, but for most Centaur flights the more important heat source is internal — the heat liberated by the reduction in temperature of the liquid mass. The relation between a constant-volume flow rate through the liquid surface (i.e., a constant-volume boil-off rate), the heat input, and the ullage pressure is outlined below:

* At start of P/U control.

$$M\dot{H}_v = - c_s M\dot{T} + \dot{Q}_x \tag{15}$$

(heat used in boiling) = (heat supplied)

where $\dot{M}$ = mass flow rate of gas through the surface,

H_v = heat of vaporization,

c_s = specific heat at saturated conditions,

M = total liquid mass,

$\dot{T}$ = time rate of change of liquid temperature, and

$\dot{Q}_x$ = external heat flux to liquid.

From equation 15 we get the differential equation:

$$c_s M(0.17) \frac{dP}{dt} + \frac{\phi \dot{V} H_v}{P_o} P = \dot{Q}_x \tag{16}$$

where ϕ = saturated gas density at reference pressure and

P_o = reference pressure

The solution of 16 is

$$P = P_o \left[\frac{\dot{Q}_x}{\phi \dot{V} H_v} + \left(1 - \frac{\dot{Q}_x}{\phi \dot{V} H_v} \right) e^{-k\dot{V}t} \right] \tag{17}$$

$$\text{where} \quad k = \frac{\phi H_v}{c_s M(0.17) P_o} \tag{18}$$

Equation 17 clearly shows the effect of the external heat input to the liquid, $\dot{Q}_x$. Figure 6 illustrates equation 17. If there is no external heating, equation 17 reduces to

$$P = P_o e^{-k\dot{V}t} \tag{19}$$

Equation 19 can be differentiated and P set equal to P_o to find the initial slope, $\dot{P}_o$.

$$\dot{P}_o = -P_o k\dot{V} = \frac{\phi H_v}{c_s M(0.17)} \dot{V} \tag{20}$$

Over "short" times the slope is very close to this initial value. Note that the depressurization rate for the tests, $\dot{P}_o$, is proportional to the volume flow rate, $\dot{V}$. Depressurization rates during the tests were many times greater than the 1.2 psi/min rate actually existing during Centaur flight in order to simulate propellant outflow. The important thing is that $\dot{V}$ and hence the quantity of bubbles in the liquid were scaled to Centaur flight conditions.

TESTS

LeRC Facility

All tests were conducted at Lewis Research Center, Cleveland, Ohio, in June and July, 1963. The test tank was a vacuum insulated, 30-ft^3 container sunk into the ground to make the top readily accessable. See Figure 7. All equipment was suspended from the lid which could be removed in about two hours. Calibrated carbon resistors were used as temperature sensors. Liquid level was measured with Honeywell ring-type, capacitance point sensors or visually with a spike in a stillwell. Three sets of sensors and spikes were mounted on a rod which could be moved vertically by a lead screw accurate to $\pm$ 0.01 inches. However, a tight packing gland greatly limited the utility of the level measuring system when the screw had to be moved very fast during depressurization cycles. (Considerable manual effort was required.) Various plumbing connections allowed for control of pressure, fill and drain, etc. The total heat leak (with a balsa wood insulator attached to the bottom of the lid) was about 100 watts, making the $\dot{Q}_x$ of equation 17 essentially zero. A 2000-watt electric heater was used to heat the liquid. A temperature rise rate of about 0.3° K/min could be maintained in full tank of LH_2 with this heater. The rigidity of the tank was demonstrated by a drop in level of only 0.09 inches for a sudden pressure increase of 19 psi (most of this decrease was due to the compressability of LH_2).

Four Bistol strip-chart recorders were used to record the tank ullage pressure and the three probe signals. Resolution and accuracy for pressure measurements were better than 1% and for the probe read-out about 0.1% of the liquid to gas capacitance change. Temperatures were recorded on a remote computer system called CADDE. Shortly after each test run tabulated temperature data accurate to about 0.05°K were available.

Capacitance Probes

Three probes made by Honeywell were tested in June anf five probes made by Liquidometer were tested in July.

Honeywell Probes

The Honeywell probes were concentric stainless-steel tubes, 70 inches long, with inner and outer diameters of one and two inches respectively. Their nominal capacitances were 155 $\mu\mu f$ in GH_2, 190 $\mu\mu f$ in LH_2 and 222 $\mu\mu f$ in LN_2. Each had a 4-inch diameter flat plate 1/2 inch below the bottom as a shield against rising bubbles. These three probes were distinquished as follows:

1) Manometer probe - open only at the top and bottom.

2) Polished probe - identical to the manometer probe except that the annular space was highly polished.

3) Perforated probe - identical to the manometer probe except that the outer tube was perforated with six 1/4-inch holes per vertical inch (a total of 372) spaced in a spiral pattern.

The polished probe was included in the tests in the (not very enthusiastic) hope that nucleation points could be eliminated and thus boiling eliminated within the probe (see Reference 5).

The control units provided with the probes employed an electromechanical servo system ultimately driving a 5000-ohm wire-wound potentiometer with a resolution slightly better than 0.1%. A d-c voltage was supplied across each potentiometer with a zero wiper voltage indicating an empty probe and a full-scale voltage indicating a probe full of liquid.

Liquidometer Probes

After the June tests with the Honeywell probes demonstrated the utility of the manometer-type probe, similar tests were made with five probes from the liquidometer corporation. These probes were all of the manometer-type and 70 inches long. The electrode diameters were varied as the following table indicates.

Probe	Inner Electrode Outside Diameter (D_{in}) (inches)	Outer Electrode Inner Diameter (D_o) (inches)	$\frac{D_o}{D_{in}}$	$\frac{D_o - D_{in}}{2}$	Nominal H_2 Capacitance ($\mu\mu f$) Empty	Full
1	1.87	2.93	1.56	.55	225	274
2	1.25	1.93	1.54	.34	230	281
3	0.63	0.95	1.51	.16	245	300
4	2.26	2.93	1.30	.34	380	464
5	0.25	0.95	3.75	.35	78	95

These variations were planned to detect the presence of either of the following effects:

1) a systematic bubble distribution which, in the non-linear electric field of concentric cylinders, would cause a capacitance error or
2) a restriction to bubble flow which would cause an error in column height.

Liquidometer supplied a multiple control unit similar to the Honeywell devices except that their resolution was about 0.2%. Since only three recorders were available the probes were tested in sets of three. Especially of interest were 1, 2, 3 (same diameter ratio but different gaps) and 2, 4, and 5 (same gap but different diameter ratios).

Procedure and Data Reduction

The key to the test procedure is the operation called a depressurization cycle or simply a "DC". Omitting the mechanical details, a "DC":

1) started with saturated liquid at P_o (24.7 psia);
2) continued with a pressure decay determined by equation 21; and
3) terminated with an abrupt pressure increase of several psi.

Figure 8 displays this description graphically. During the ramp pressure decay the volume boil-off rate was constant. The liquid level rose as the boiling began, then fell at a nearly constant rate because mass was lost through boil-off and because the liquid contracted due to cooling. The bulk density decreased and (although the liquid level fell) remained nearly constant until the pressure was raised and the bubbles collapsed. During this operation the ullage pressure and the three probe outputs were continuously recorded, and exact level measurements were made before and after the "DC" with as many as possible level measurements made during the ramp itself. Because the pressure control at the start of the "DC" was very poor, most level and probe data were taken at the end of the ramp.

Various depressurization rates were used in the tests to obtain bracketing data about the value which would exactly simulate Centaur. Tests with both LN_2 and LH_2 were performed following the same basic procedure. Tests were conducted with the probes completely immersed in order to relate the change in density within the probe to that in the tank and at lower levels to measure the net indicated mass change.

Since $\dot{Q}_x$ was negligibly small, equation 20 applied. P_o was 10 psig or 24.7 psia, and k for a full tank of LH_2 was 3.06×10^{-7}. Equations 19 and 20 can be rewritten as

$$P = (24.7)e^{-3.06 \times 10^{-7}\dot{V}t} \tag{21}$$

$$\dot{P}_o = -7.55 \times 10^{-6}\dot{V} \tag{22}$$

Since $\dot{P}_o$ is a function of mass, and since various levels and hence masses were used, it was not a constant.

Note that the nominal depressurization rate was <u>not</u> the same as that occurring during a Centaur engine firing; the actual test value was the rate required to produce the same liquid-level change as occurs during firing. Equation 14 relates the tank geometry to the desired boil-off rate and equation 19 relates the pressure decay to the boil-off rate. The basis of the simulation, equation 13, required that the ΔH in the tests be the same as in Centaur and as a consequence and $\Delta M/M$* are proportional to 1/H. For LH_2 the test values must be multiplied by $\frac{70}{157}$ or 0.446 and for LN_2 (simulating LO_2) by $\frac{70}{54}$ or 1.3. All mass measurements, ΔM, inferred from the probe output are expressed in percent of the full tank liquid mass.

Results and Discussion

General

The test results were generally as expected; there were few surprises. The Honeywell and Liquidometer equipment worked very well — a compliment to both compnaies, since each designed, built, and delivered their equipment in one month. The GD/A procedures worked well with virtually no changes. With the exception of the pressure control system the LeRC equipment caused no significant problems. While the pressure control was eventually satisfactory, it caused several delays and was never as good as we would have liked. Vendor and NASA personnel were almost universally cooperative. The LeRC mechanics and technicians were especially hard working and helpful.

* Assuming that the difference in density between the probe and the tank in general is not a function of tank size.

The temperature data handled by the CADDE system were not used explicitly in determining the test results. However, they have been carefully evaluated and found to agree quite accurately with the vapor pressure temperature during each "DC". At other times the temperatures showed gradients, stratification, equilibrium, etc., in agreement with the condition existing at that time. The thermometer time lag in liquid was less than 12 seconds.

The following several sections present details of the LH_2 testing. In Figures 9 through 15 the abscissa is the volume flow rate, $\dot{V}$. Although the very randomness of the boiling phenomena was probably contributory, the wide data scatter was mostly caused by the unevenness of the pressure control. Since the effects in LN_2 are similar but of much lower magnitude, the LN_2 data is only summarized.

Level and Density Changes (LH_2)

During the June tests the initial emphasis was placed on measuring the changes in LH_2 of level, bulk density (i.e., general tank density), and probe density (i.e., that within the probes). Tests were conducted primarily at levels of 95%, and 105%, (i.e., with the probes almost and completely immersed) at various depressurization rates. Figure 9 shows the level changes measured in the tests. The straight lines are fitted by the least square method. The values at 10,700 cc/sec are also the values expected in a Centaur firing — see equation 13. In the test tank at 100% (nominal) and 10,700 cc/sec ΔH was roughly 2.2 inches representing a density change of 3.1% (a Centaur equivalent of 1.4%). These values fall within the brackets predicted by the prior analysis.

Figures 10 and 11 show the Honeywell and Liquidometer probe density for the 105% level. Here no level compensation could take place and the probe output was directly proportional to density. The $\Delta\rho$ at 10,700 cc/sec was roughly 3.7% in the probe (1.65% scaled to Centaur) — significantly higher than that in the tank in general.

Perforated vs Manometer Probe (LH_2)

In the test just described the probes were completely covered and each probe output was thought of as a measure of density, since the volume within the probe could not change. When the liquid level was below the top of the probe, the measured liquid volume could change and the output became a function of both density and volume. Since the system is basically a mass sensor, the output was thought of simply as a measure of mass, and the change in output as a change in mass. Figure 12 shows the $\Delta M/M$ data from the 95% level for the vented and manometer probes. At 10,700 cc/sec the perforated probe error was about 0.9% (o.4% scaled to Centaur) while the error of the manometer probe was less than 0.1%, the minimum readout resolution. The contrast is strong. The height within the vented probe must have been the same as that in the tank in general and, since the densities within and without were different, there was an appreciable error. In contrast, compensation between the column height and density took place within the manometer probe and the net error was negligible.

In the case of high external heat input (into Centaur on any other vehicle) the difference between the manometer and perforated probes could be even greater, since all boiling would take place at the tank walls and the difference in density could be much larger than that produced in the tests herein described.

Figure 13 shows similar data for the lower levels. Here probe effects were masked by the mass change of the gas. Each datum was taken at the end of a "DC" — a comparison of the reading just prior to the sudden pressurization to that just after. Although an effort was made to minimize the magnitude of the pressure rise, 4 psi was typical. At the 50% liquid level the pressurizing gas could have caused a maximum indicated mass increase of 0.2% of the full-scale probe output. At 15% level the gas introduction error could have been as big as 0.5% of total mass. Since the pattern of gas stratification and mixing determines the degree to which the probe was affected, no accurate correction to the data could be made; but this effect coupled with the resolution restriction is clearly sufficient to explain the scatter and the trend to a negative $\Delta M/M$.

Polished Probe (LH_2)

The polished probe (Honeywell) generally behaved like the manometer probe. Occasionally there was an indication that there was suppression of boiling but nothing of real significance.

Size Variations (LH_2)

The Liquidometer probes were all of the manometer type but of varying sizes. They generally behaved like the Honeywell manometer probe. Figure 14 indicates that the probes with the larger spacings and outer-tube diameters produced slightly smaller errors, although eleven of the fourteen points fall within the minimum 0.2% resolution limit. Control unit variations may have been responsible, since each probe was always tested with the same control unit. The final design for the Centaur probes has dimensions very similar to probe number 1.

Again, the data at the lower levels were more scattered, as shown in Figure 15, because of the gas-mass changes and limited resolution.

<u>Oscillations (LH_2)</u>

Sharp pressure variations during depressurization cycles often set the manometer probes into oscillations. A sudden increase in pressure would collapse the bubbles, while a sudden decrease in pressure would increase the boiling. Similar pressure variation cannot occur in Centaur; the pressure decay must necessarily be smooth. Some of the singals thus initiated were text book examples of a lightly damped oscillating system. The natural period (for the 95% level) was measured to be about 2.6 sec and the damping roughly 0.05 of critical. The natural period may be calculated as

$$\tau = 2\pi\sqrt{\frac{\ell}{g}} = 2\pi\sqrt{\frac{65}{(32.2)\quad(12)}} = 2.58 \text{ sec} \tag{23}$$

where τ = period in seconds

ℓ = length of liquid column in inches

g = acceleration in inches/sec^2

Reference 1 includes a complete description of the inertia-tube system used to prevent such oscillations in the Centaur P/U system.

<u>Zero Shift</u>

The polished probe (Honeywell) was placed in a sealed can containing helium gas at two atmospheres pressure at room temperature. The can was completely immersed in LH_2 and supported so that its contents could reach LH_2 temperature. Figure 16 shows the probe total capacitance changes* (as indicated by the readout device) and the helium gas temperature (as indicated by the gas pressure). Although the gas temperature changed drastically, the gas density and hence its dielectric constant did not. The capacitance variations then were caused only by geometric changes and possibly by electronic error. As the cooling progressed the capacitance first increased; presumably this was cuased by the outer tube chilling faster than the inner and reducing the ratio of the cylinder diameters. After temperature equilibrium was reached the capacitance stabilized at about minus 0.1%. The negative spike at 60 minutes occurred at the sharp pressure increase of a "DC"; evidently there was some "cross talk".

The capacitance of concentric cylinders is given by:

$$C = \frac{0.614\, L \epsilon}{\log_{10} (r_2/r_1)} \tag{24}$$

where C = capacitance in $\mu\mu f$,

ϵ = dielectric constant (relative to vacuum),

L = length in inches,

r_1 = inner tube radius, and

r_2 = outer tube radius.

Once temperature equilibrium is reached the value of r_2/r_1 should not be changed and the total capacitance change, δC, should be proportional to change in length, δL. For our probe material (CRES 321) $\delta L/L$ from room temperature to LH_2 temperature is about 0.3%. The difference

* In this section capacitance changes are referenced to <u>total</u> capacitance rater than to active (i.e., liquid to gas) capacitance as is used elsewhere in this paper.

between this value and the observed $\delta C/C$ (0.1%) cannot be satisfactorily explained at this time, although the following effects have been considered.

1) Differential radial expansion due to differences in tube material. The maximum $\delta L/L$ variation should not exceed ± 5% in CRES 321. This maximum variation can account for only 0.04% $\delta C/C$.

2) Support variations. Capacitance changes due to changes in the Kel-F supports could account for only 0.01%.

3) End effects. Movement of the bubble deflector could cause only an extremely small effect.

4) Helium gas variations. Doubling the gas density would only account for 0.01%. Following the test the gas was analyzed and found to be 98.9% helium.

5) Electronics drift. A read-out drift of 0.2% in 12 hours was observed in a later test. If drift caused the error discussed here, it must have been 50 times as rapid at first and zero later.

The unaccountable error of 0.2% relative to the total capacitance actually is equivalent to a P/U sensing error of 0.9% — a significant amount. Needless to say, more attention is being given to this problem.

<u>LN_2 Results</u>

Figures 17 through 19 are data taken in LN_2 (simulating LO_2). The general effects are the same as for LH_2; but, because of the lower propellant drain rate and different fluid properties, the magnitude of the effects are lower. At the nominal vent rate of 1220 cc/sec there is essentially no error in ΔH, $\Delta\rho$, or ΔM, and nothing to indicate a preference of one probe type over the other.

CONCLUSION

There is no doubt that a manometer-type capacitance probe can reduce, if not eliminate, the errors caused by the density in the probe not being characteristic of tank in general — i.e., errors caused by radial density variations. Further the manometer probe can be used to eliminate undesired slosh effects by hydraulic rather than electrical filtering. Although the analysis and tests reported here were done for Centaur, they may be helpful in evaluating gaging problems in other vehicles.

REFERENCES

1. Perkins, C. K., Rivinius, F. G., and Wood, G. B.; "Stillwells for Propellant Gaging"; SAE-ASME Meeting, April 1964.

2. Hsu, Y. Y.; "Size Range of Active Nucleation Cavities on a Heating Surface"; ASME Trans-Journal of Heat Transfer; pp. 207-215; August 1962.

3. Harmathy, T. Z.; "Velocity of Large Drops and Bubbles in Media of Infinite or Restricted Extent"; AIChE Journal; Volume 6, Number 2; pp. 281-288; June 1960.

4. Poutanen. A. A.; "Studies of Bubble Formation and Rise"; The Canadian Journal of Chemical Engineering; Volume 38, Number 40; pp. 93-101; August 1960.

5. Tuck, G.; "Zero-G Report: LH_2 Boiling Threshold"; General Dynamics/Astronautics Report No. 55D859-3; 21 May 1962.

APPENDIX

SEGMENTATION OF CAPACITANCE PROBES

With a perforated capacitance probe there is no doubt that "switching out" part of the probe will reduce the gas-density error. The probe does not sense the gas mass in the "switched out" section and this unsensed mass in no way affects the remaining section. Likewise a section of a manometer-type capacitance probe may be "switched out" and the mass in that section is not sensed. But here the "switched-out mass" does affect the remaining section because of the manometer effect.

In the following simple derivation the capacitor is assumed to be a perfect mass sensor. Also the tank is assumed to be cylindrical. Figure 3 describes the system. A further simplifying assumption is that the liquid in the probe has the same density as that in the tank in general (i.e., $\rho_2 = \rho_2'$).

The condition for manometer balance is

$$\rho_2 h_2 + \rho_1 h_1 = \rho_2' h_2' + \rho_1' h_1' \qquad (25)$$

This is another way of saying that mass in the tank between the manometer taps is proportional to the mass in the manometer. Thus,

$$(K/A) M_{ab} = M_{ab}' \qquad (26)$$

After "switching out" the upper segment, the lower segment, ℓ_2, senses:

$$M_b = M_{ab} - \rho_1 \ell_a A \qquad (27)$$

or

$$(A'/A)M_b = (A'/A)M_{ab} - \rho_1 \ell_a A' \qquad (28)$$

But the actual mass in the tank below the segmentation point is

$$M'_b = M'_{ab} - \rho'_1 \ell_a A' \qquad (29)$$

To find the measurement error, δM, we subtract equation 28 from 29.

$$\delta M = M'_b - (A'/A)M_b = M'_{ab} - \rho'_1 \ell_a A' - (A'/A)M_{ab} + \rho_1 \ell_a A' \qquad (30)$$

But,

$$M'_{ab} = (A'/A)M_{ab}$$

Therefore:

$$\delta M = (\rho_1 - \rho'_1)\ell_a A' \qquad (31)$$

SIMPLIFIED CAPACITANCE SENSOR

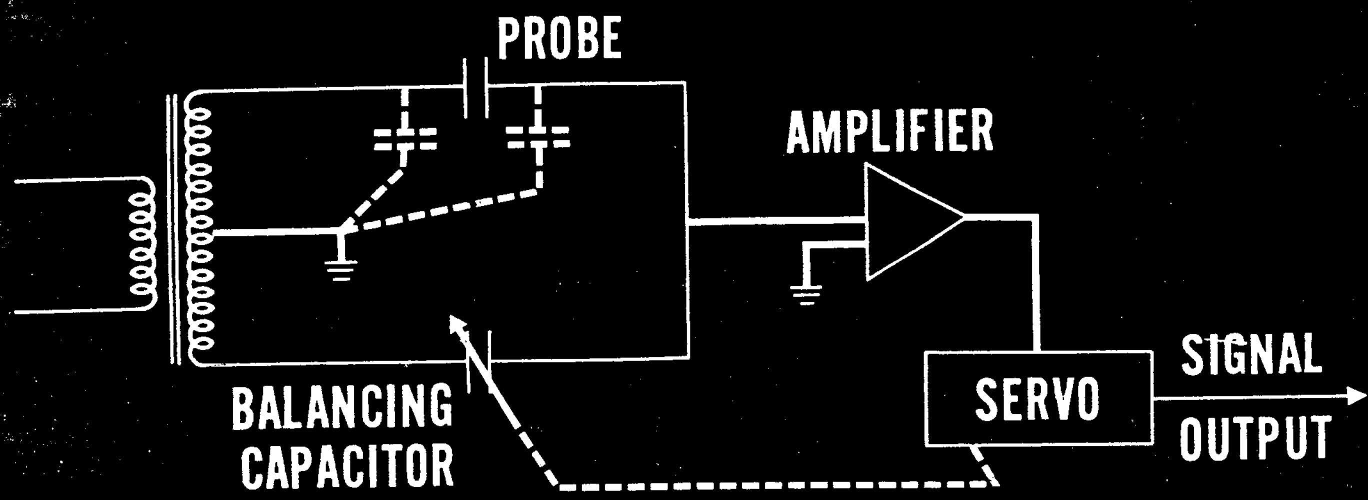


FIGURE 1

GH_2 TEMPERATURE EFFECT ON CAPACITANCE

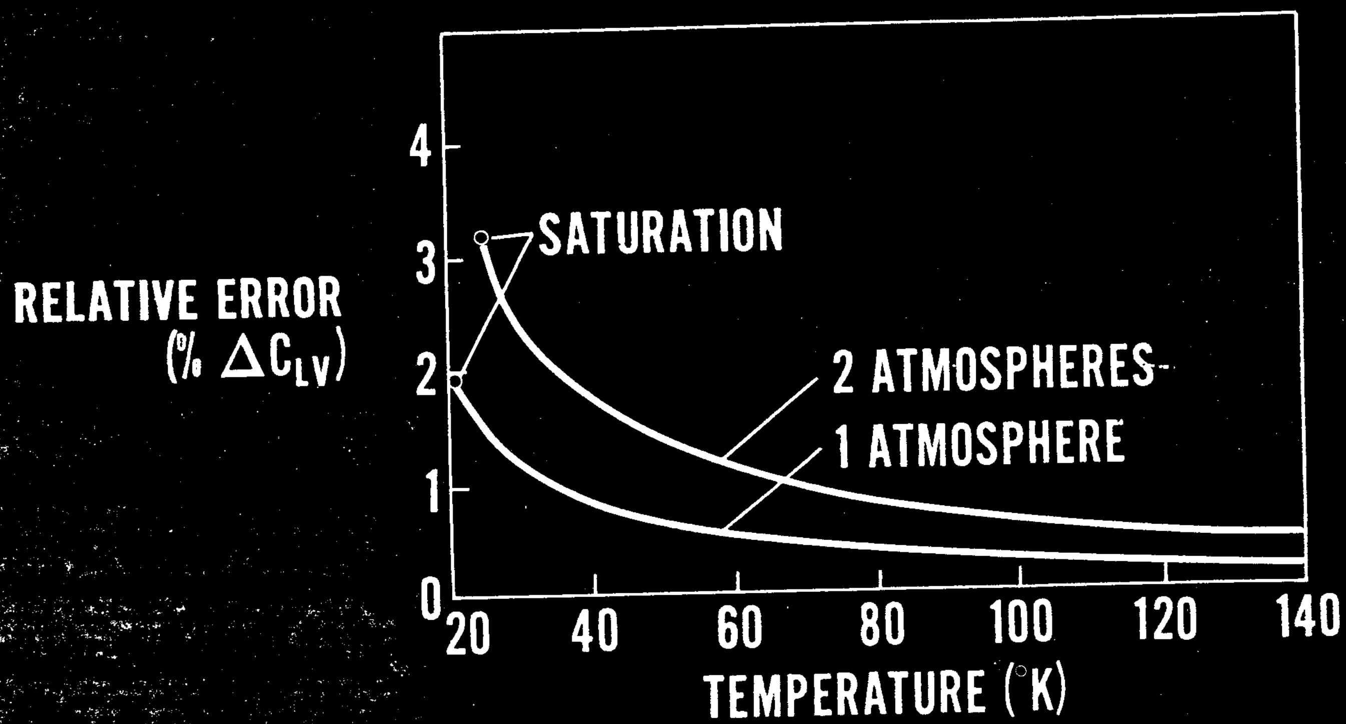


FIGURE 2

STYLIZED MANOMETER PROBE

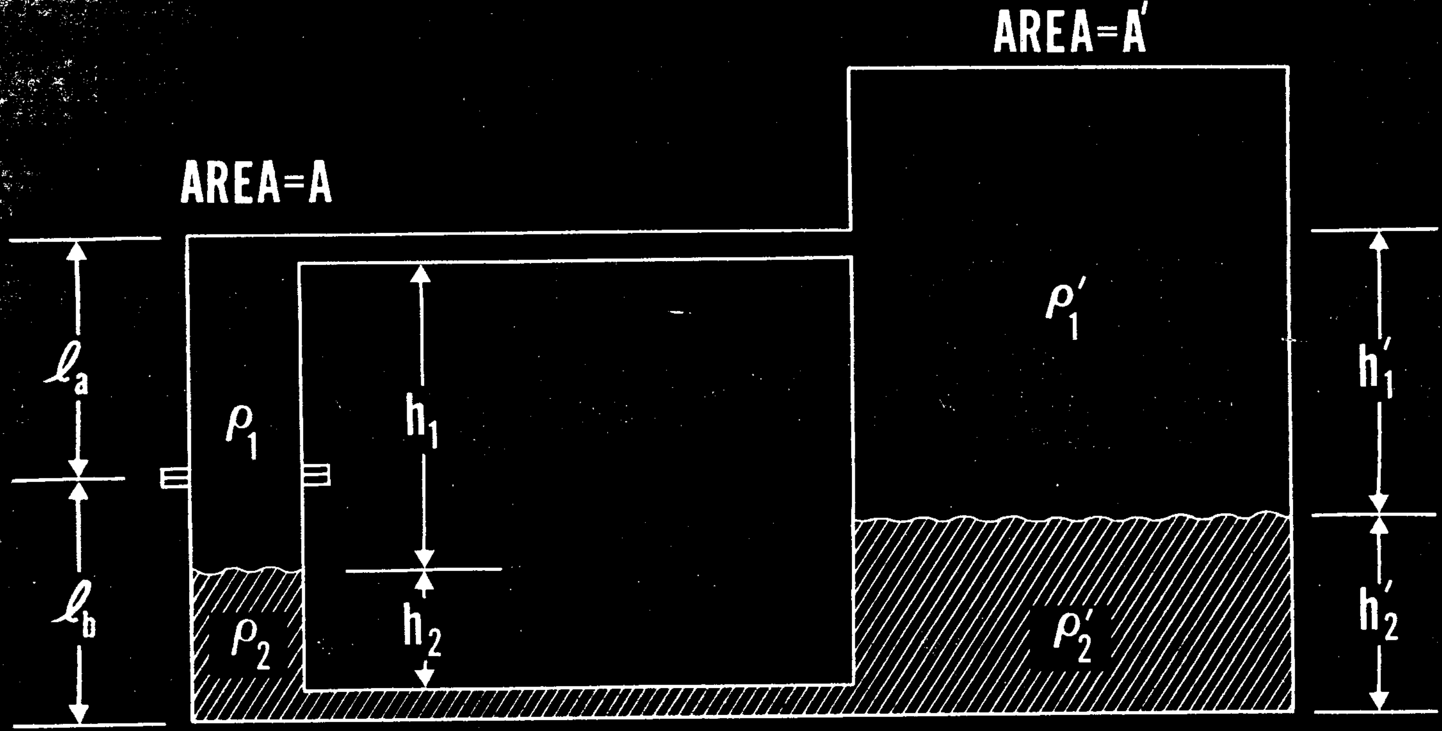


FIGURE 3

CLAUSIUS-MOSOTTI RELATION

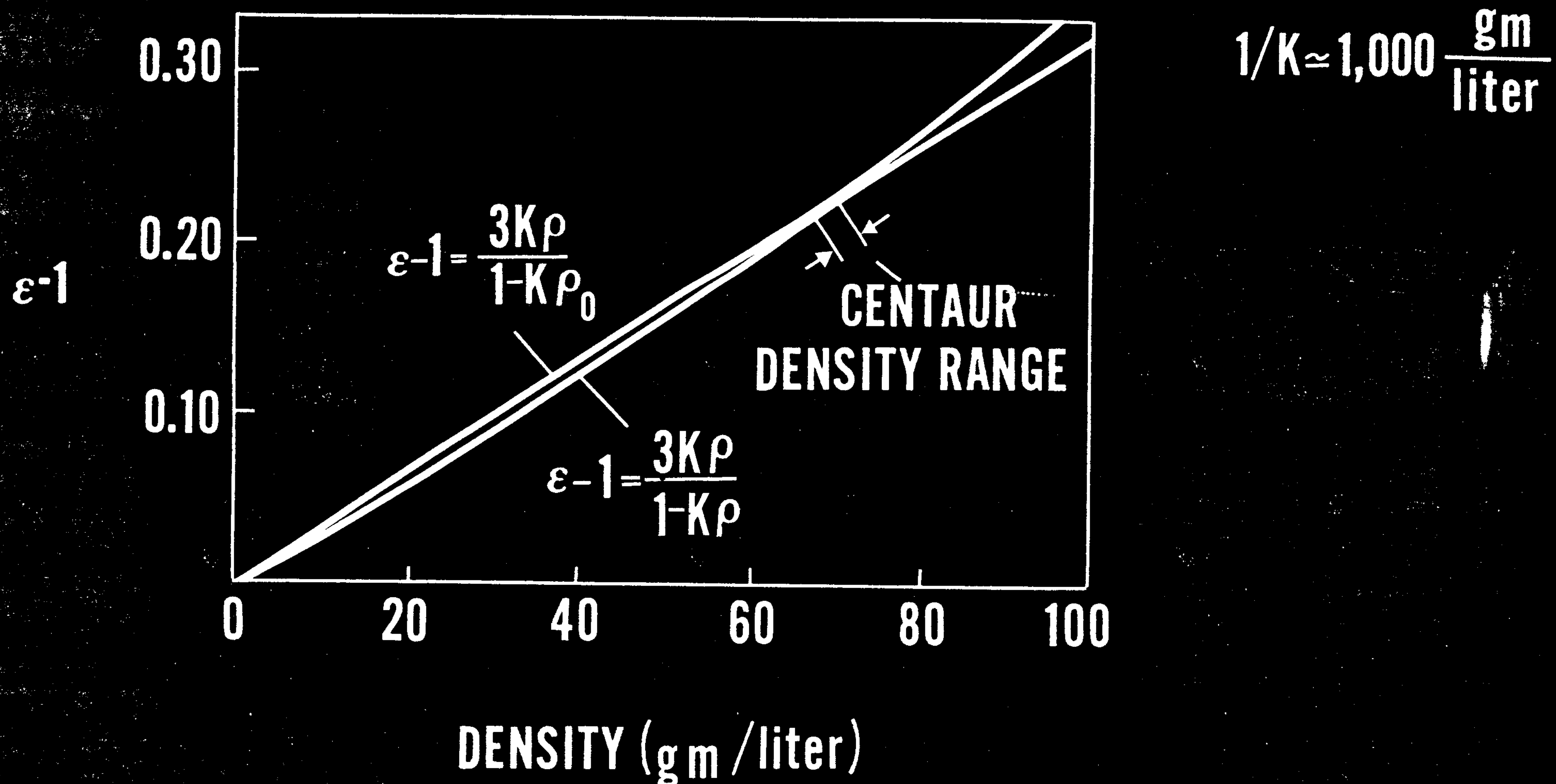
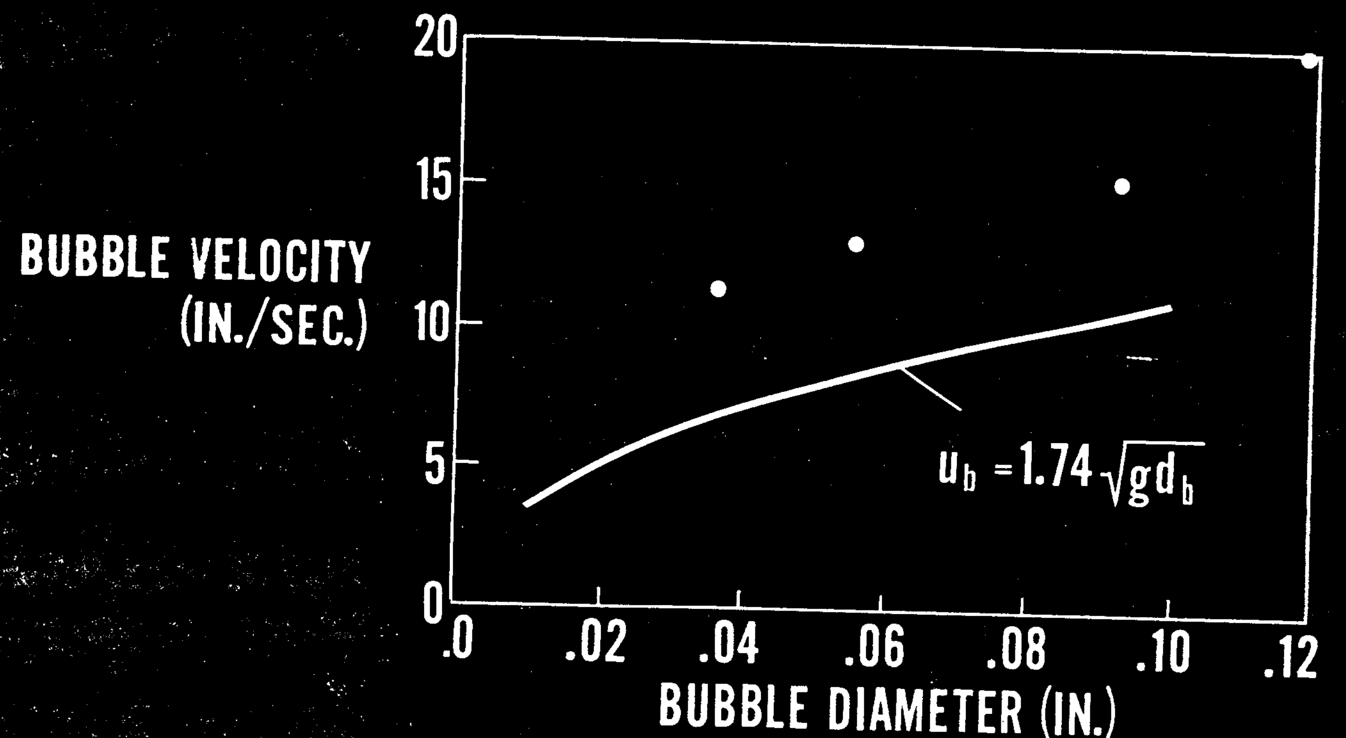


FIGURE 4

BUBBLE VELOCITY IN LH_2



DATA FROM MOTION PICTURES OF LH_2

FIGURE 5

PRESSURE PROGRAM TO MAINTAIN CONSTANT VOLUME FLOW, $\dot{V}$, WITH EXTERNAL HEATING, $\dot{Q}_x$

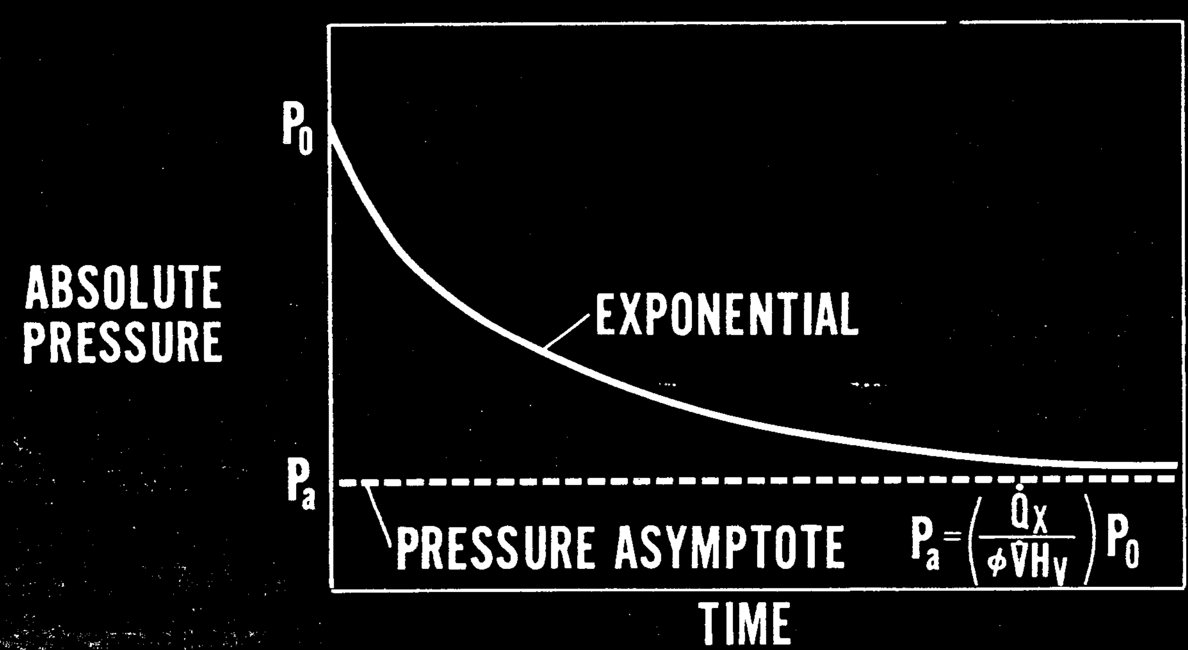


FIGURE 6

LeRC TEST VESSEL

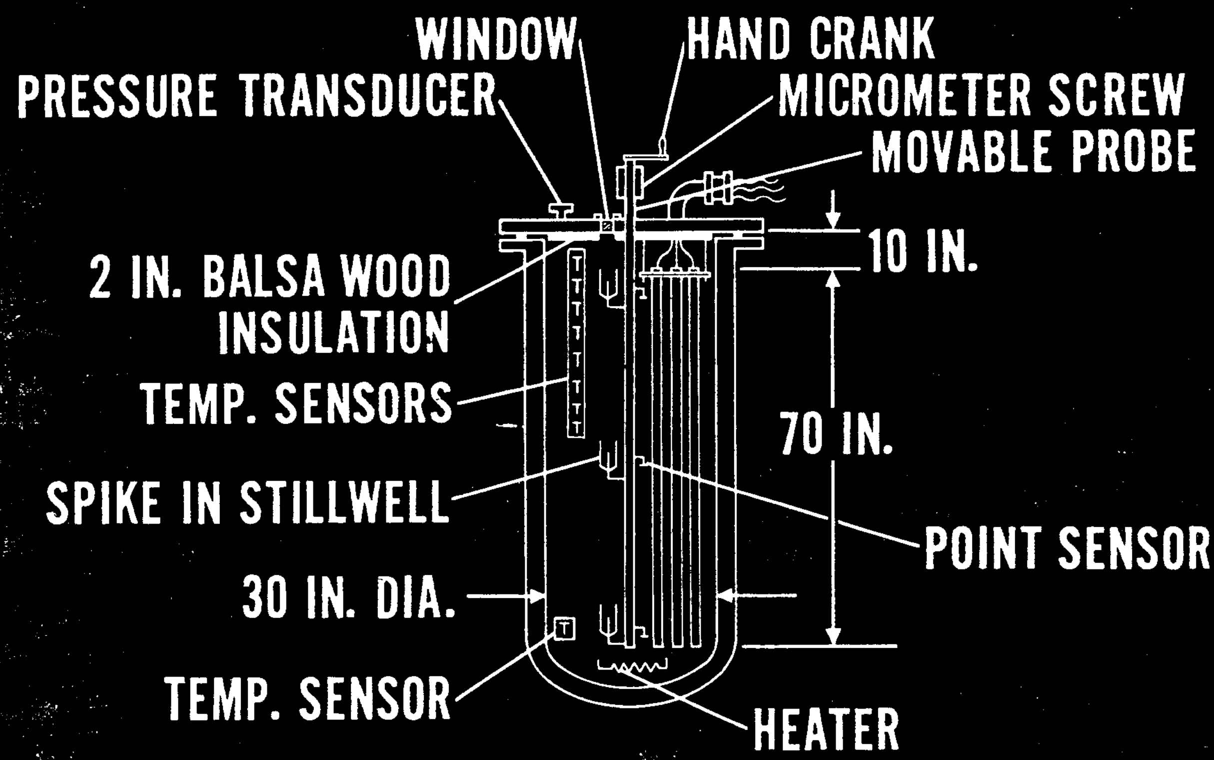


FIGURE 7

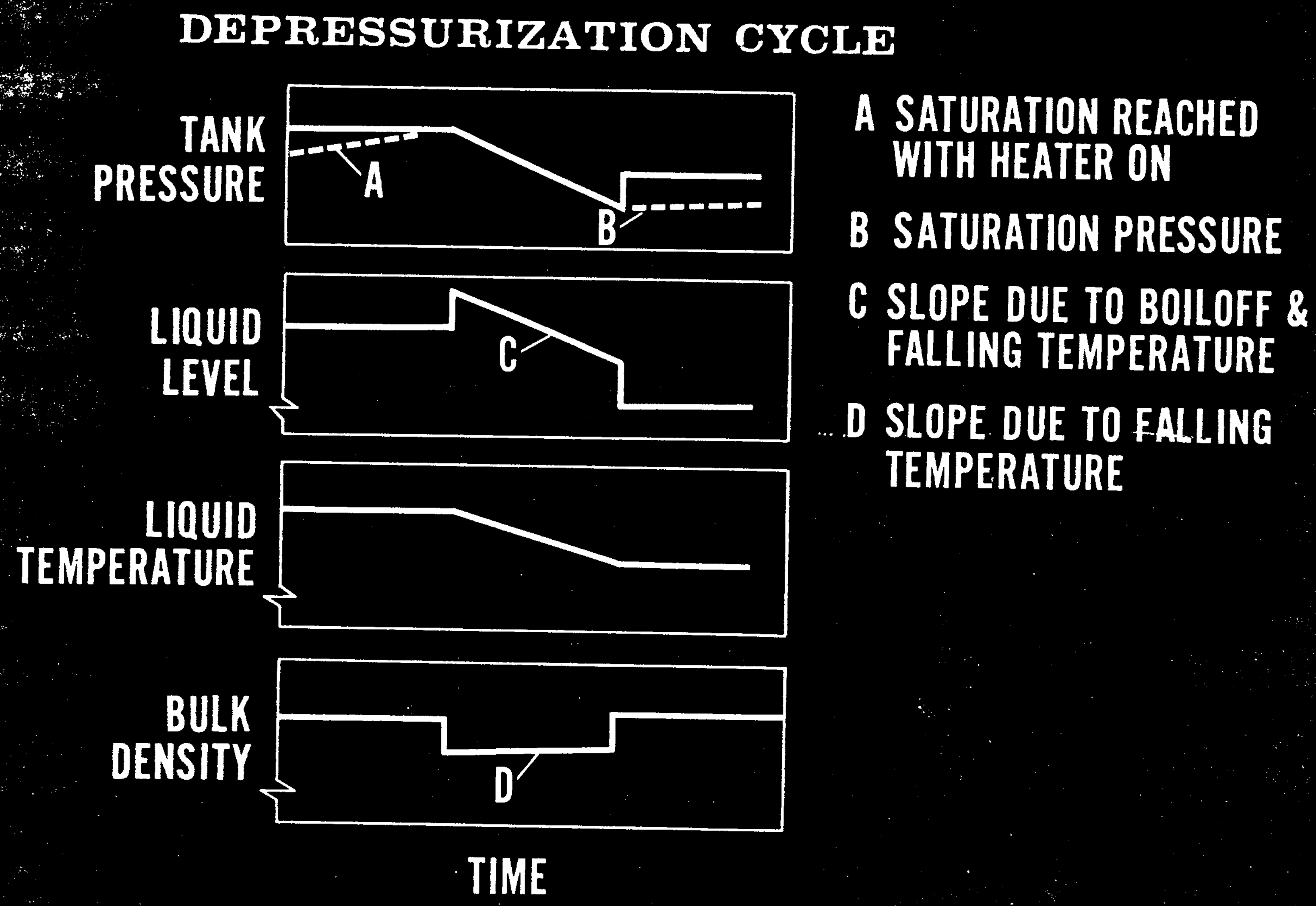

DEPRESSURIZATION CYCLE
TANK PRESSURE
LIQUID LEVEL
LIQUID TEMPERATURE
BULK DENSITY
A
B
C
D
TIME
A SATURATION REACHED WITH HEATER ON
B SATURATION PRESSURE
C SLOPE DUE TO BOILOFF & FALLING TEMPERATURE
D SLOPE DUE TO FALLING TEMPERATURE

FIGURE 8

SURFACE SHIFTS (LH_2)

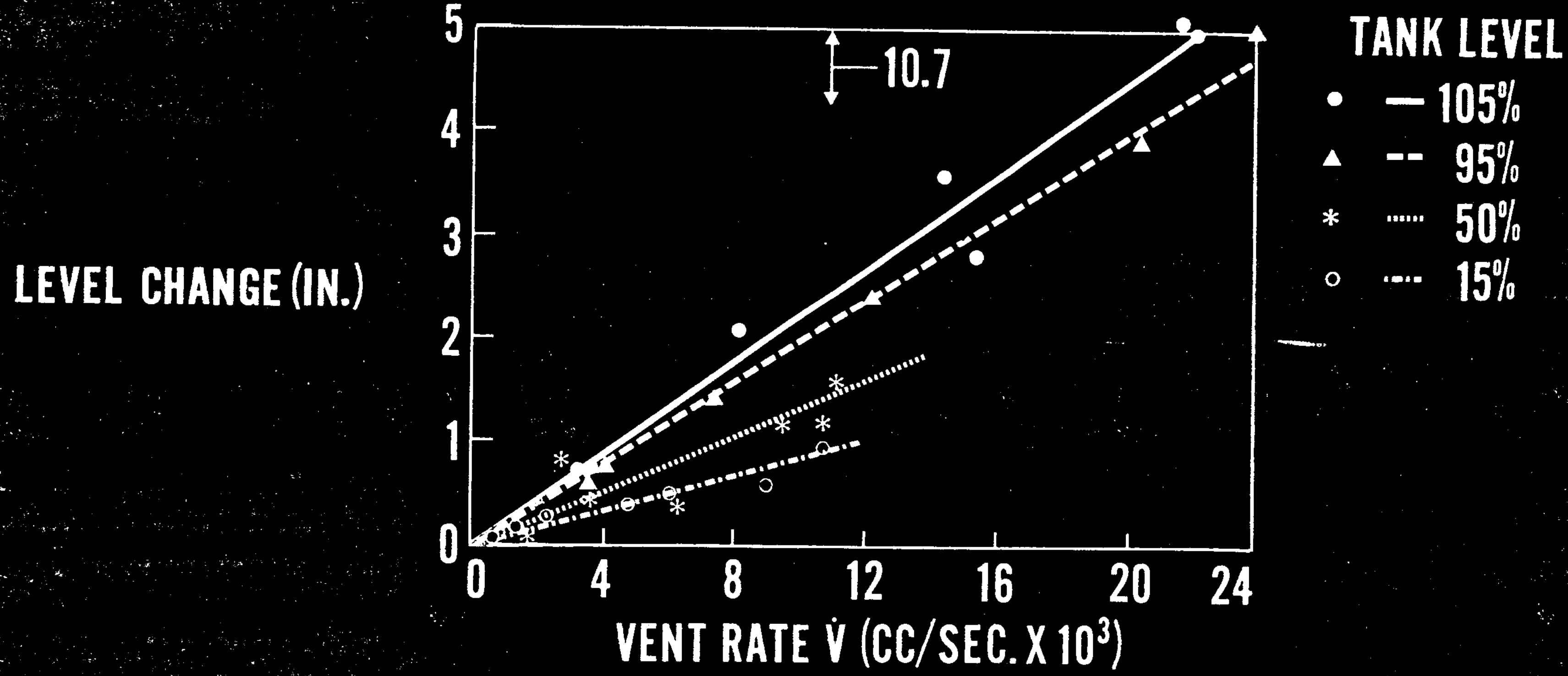
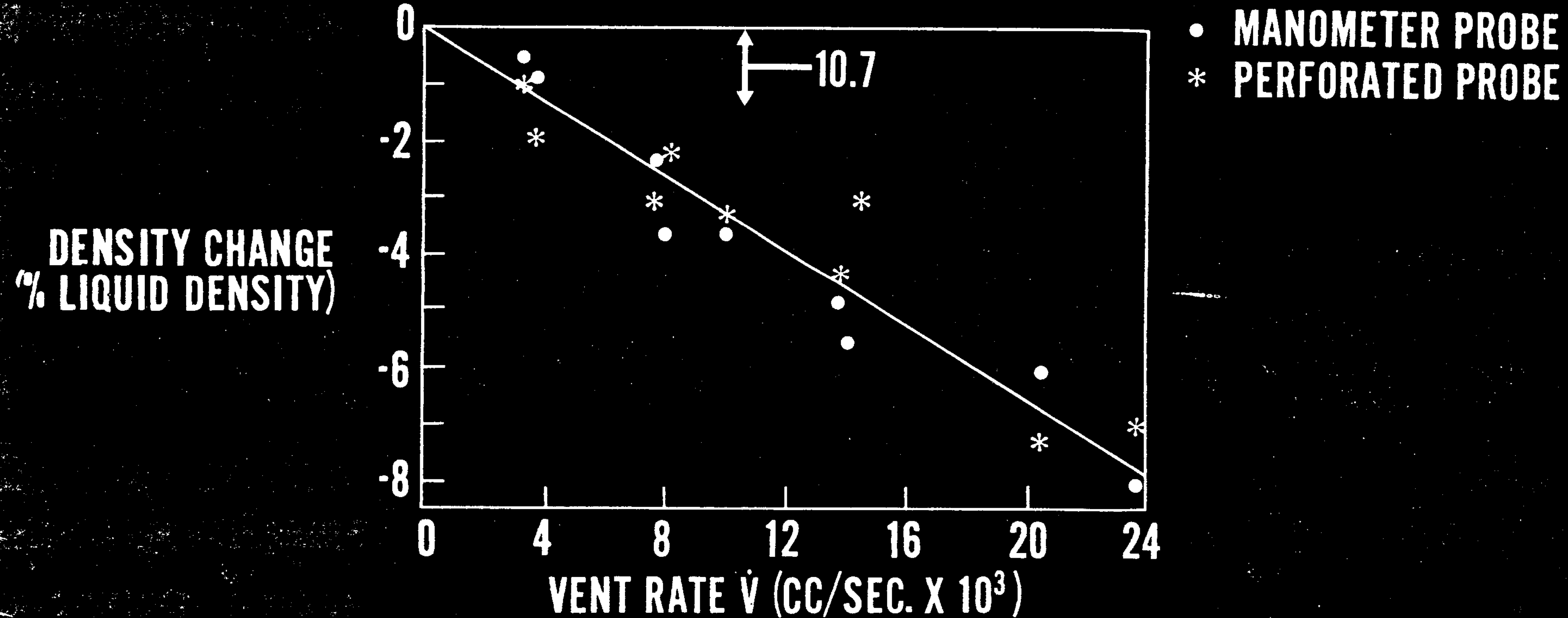


FIGURE 9

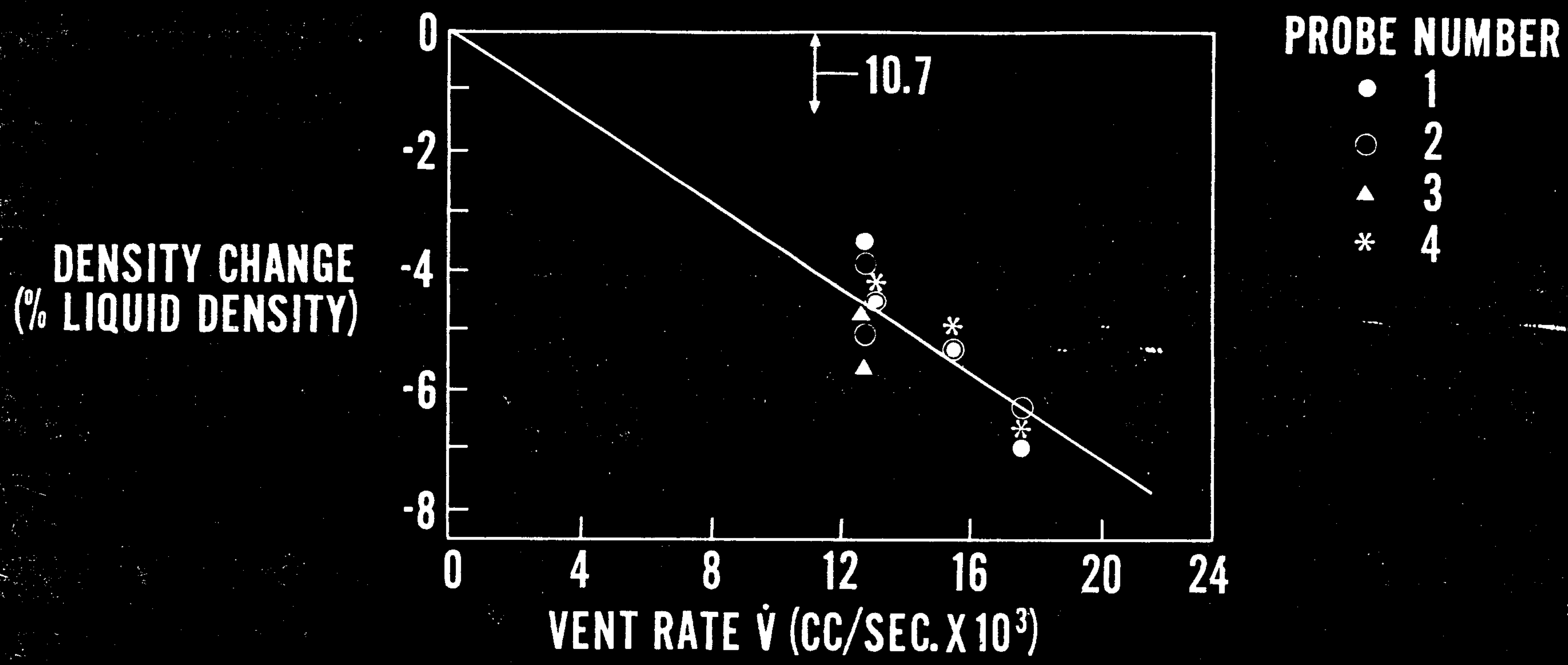
PROBE DENSITY SHIFTS (LH_2)



HONEYWELL PROBES 105% LEVEL

FIGURE 10

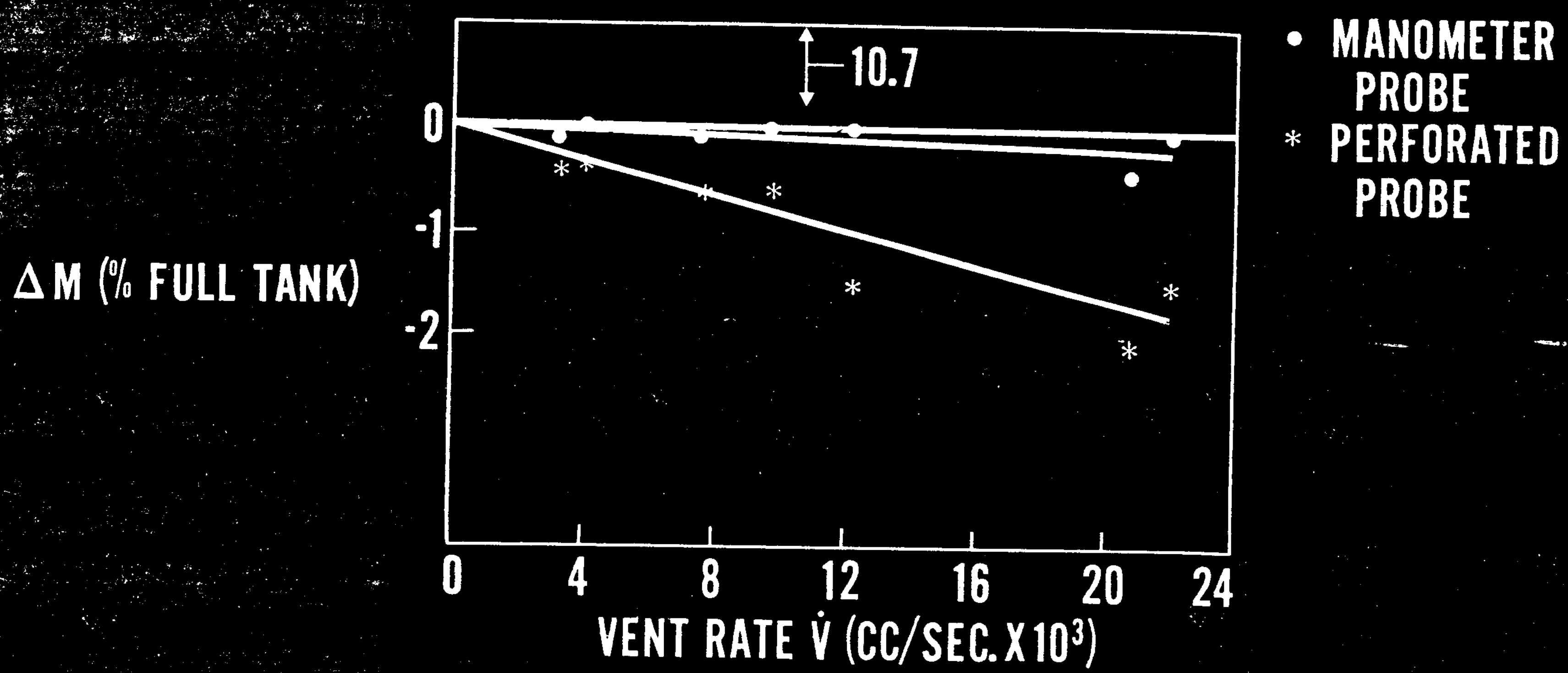
PROBE DENSITY SHIFTS (LH_2)



LIQUIDOMETER MANOMETER PROBES 105% LEVEL

FIGURE 11

MASS ERRORS (LH_2)



HONEYWELL PROBES 95% LEVEL

FIGURE 12

MASS ERRORS (LH_2)

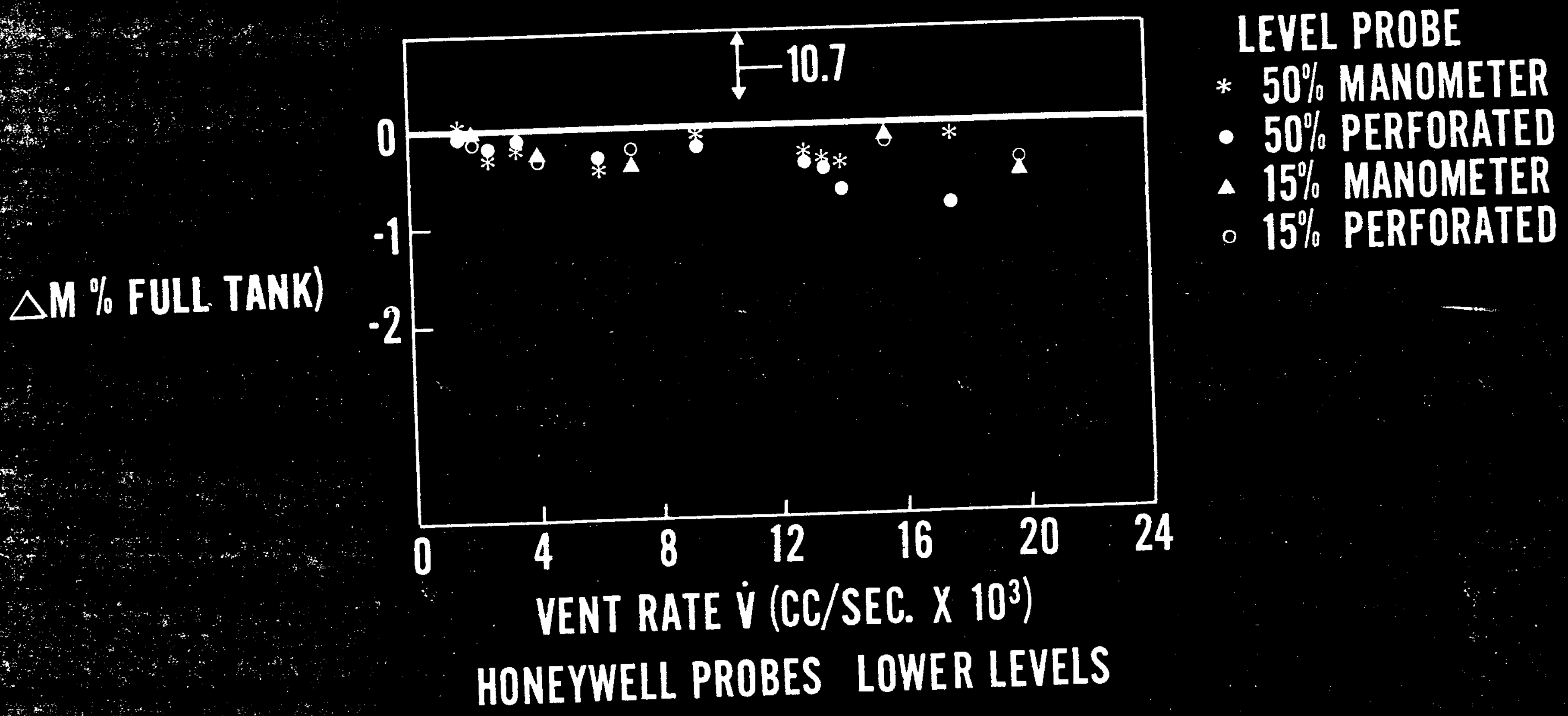


FIGURE 13

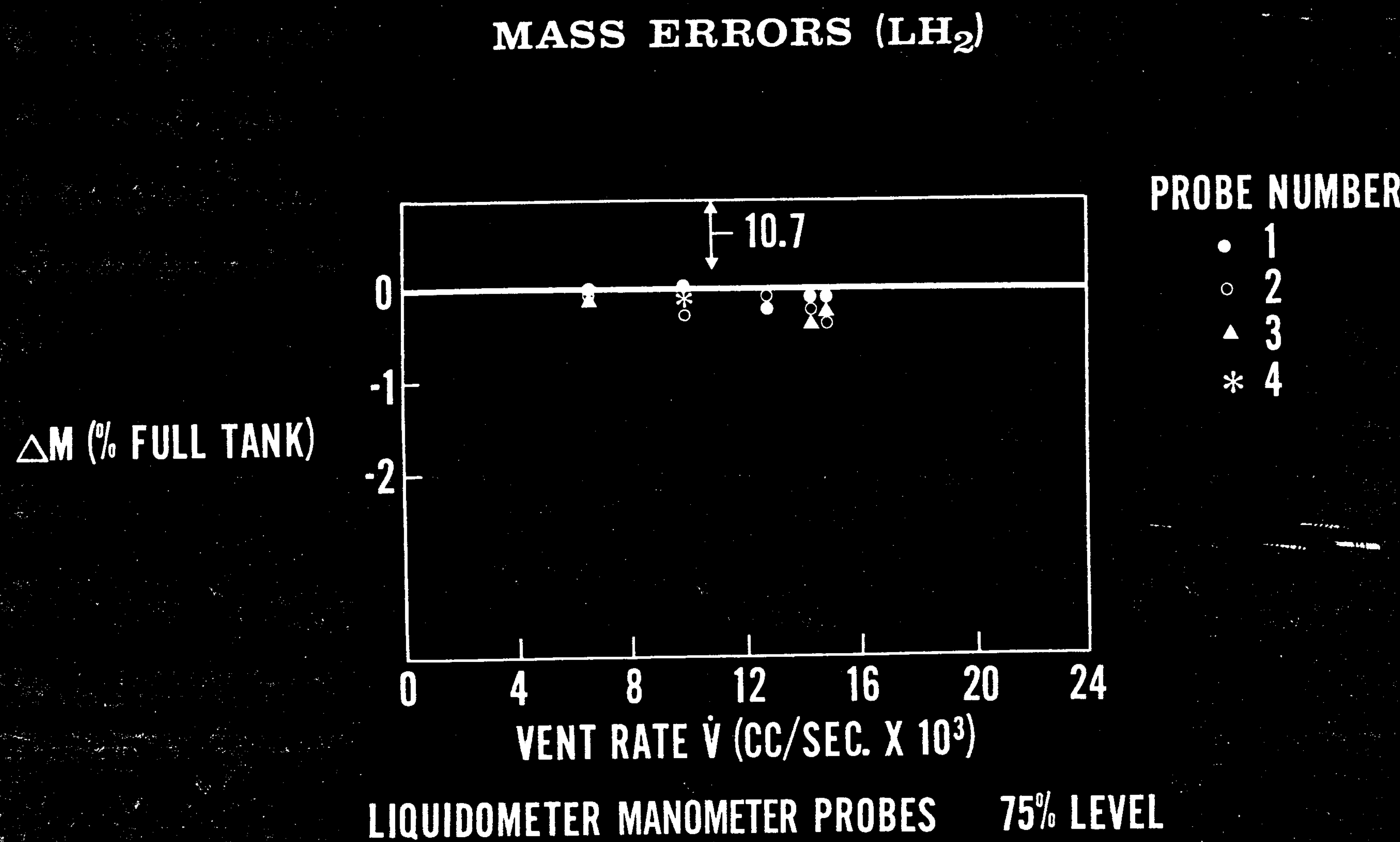

MASS ERRORS (LH_2)
PROBE NUMBER
1
2
3
4
10.7
0
-1
-2
ΔM (% FULL TANK)
0
4
8
12
16
20
24
VENT RATE $\dot{V}$ (CC/SEC. X 10^3)
LIQUIDOMETER MANOMETER PROBES 75% LEVEL

FIGURE 14

MASS ERRORS (LH_2)

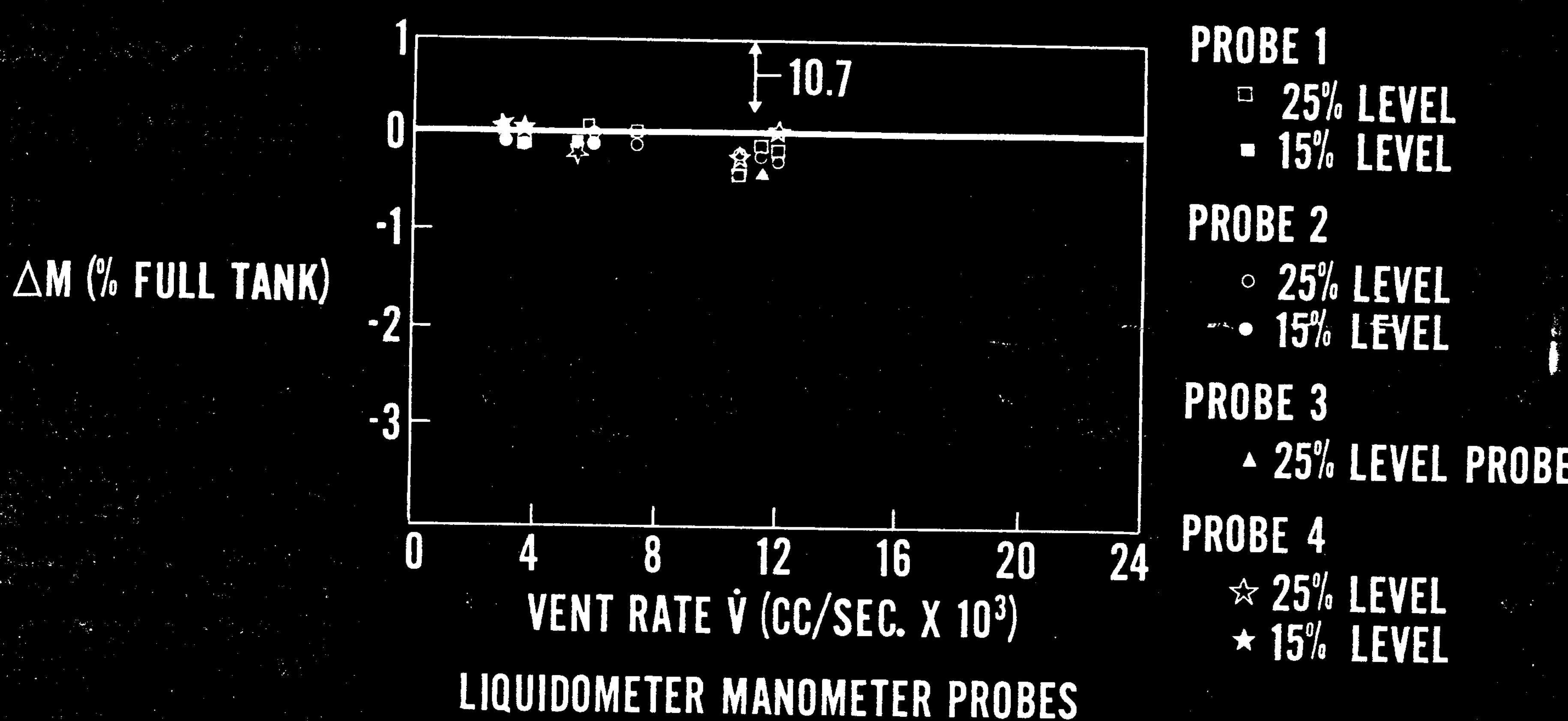


FIGURE 15

ZERO SHIFT WITH TEMPERATURE

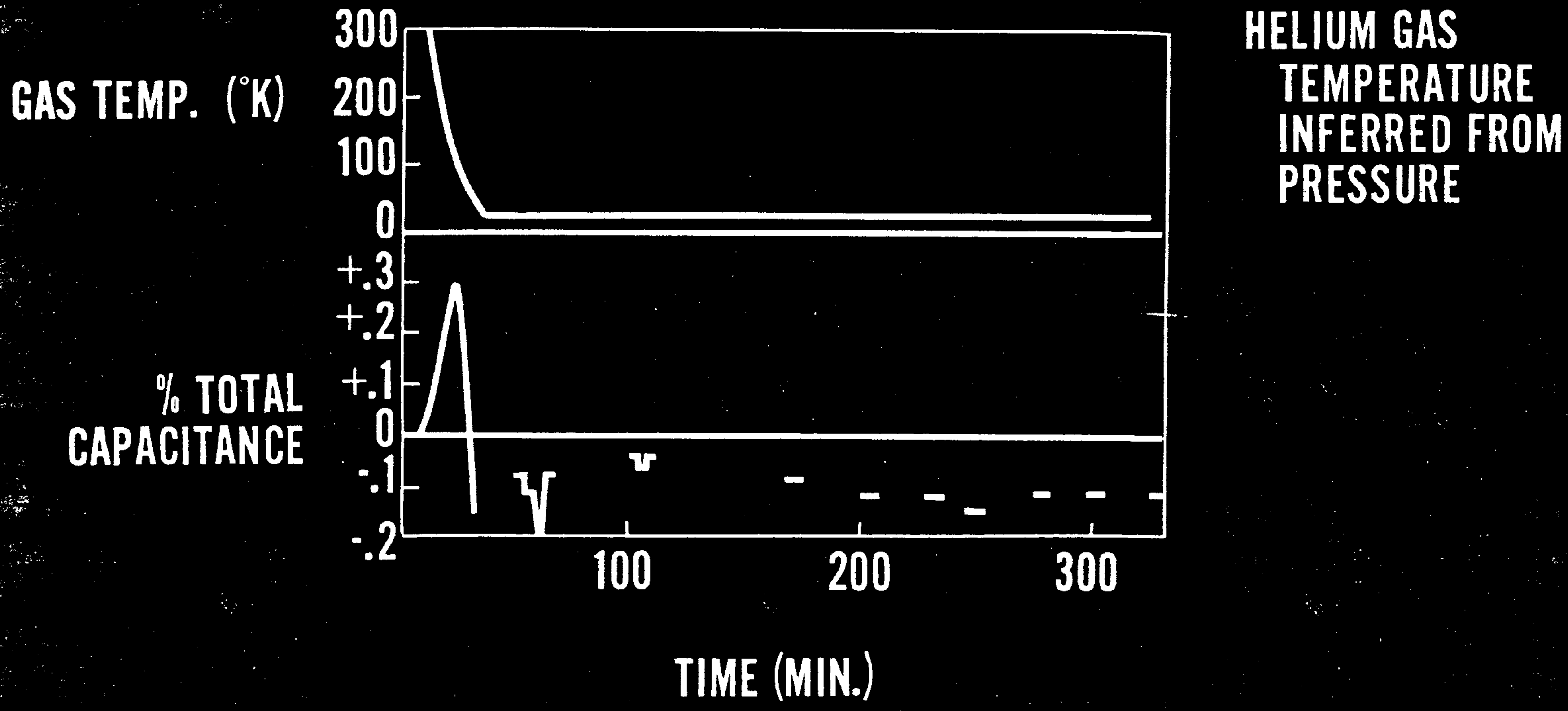
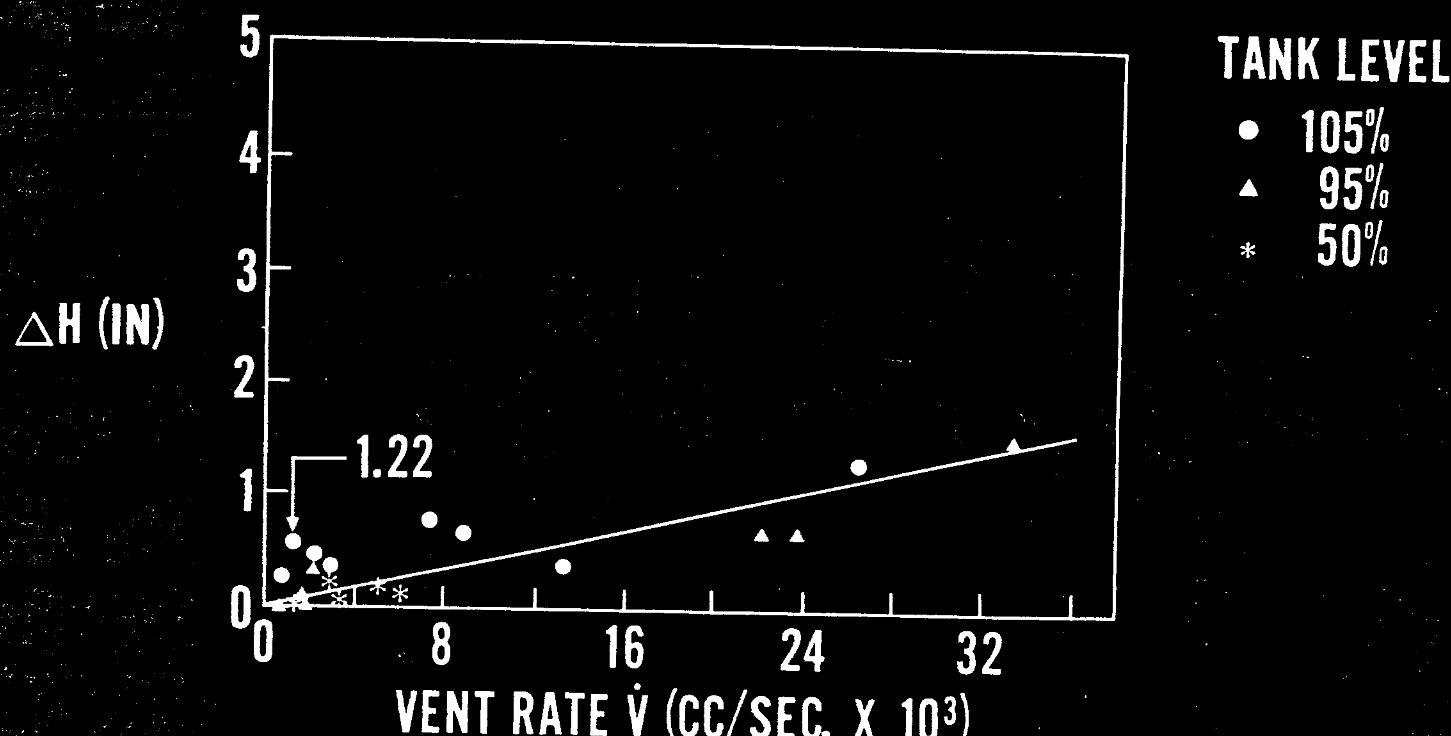


FIGURE 16

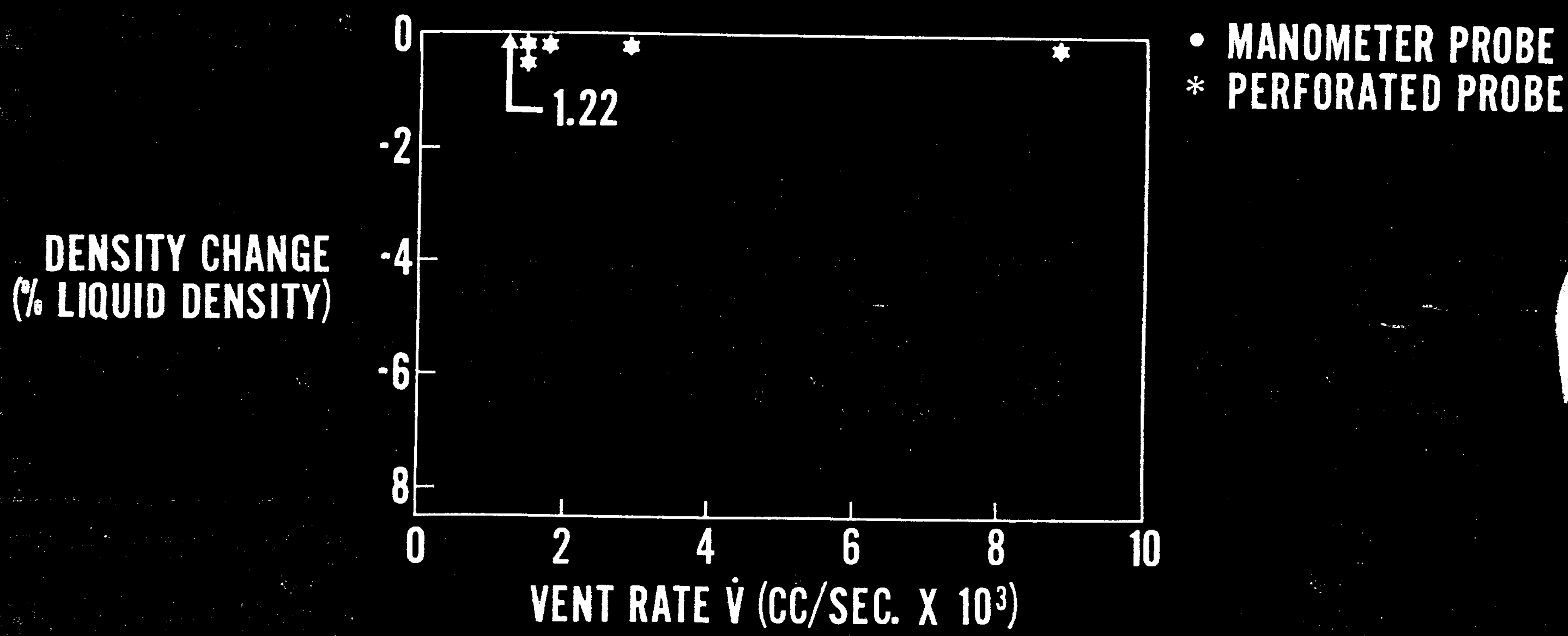
SURFACE SHIFTS (LN_2)



HONEYWELL PROBES

FIGURE 17

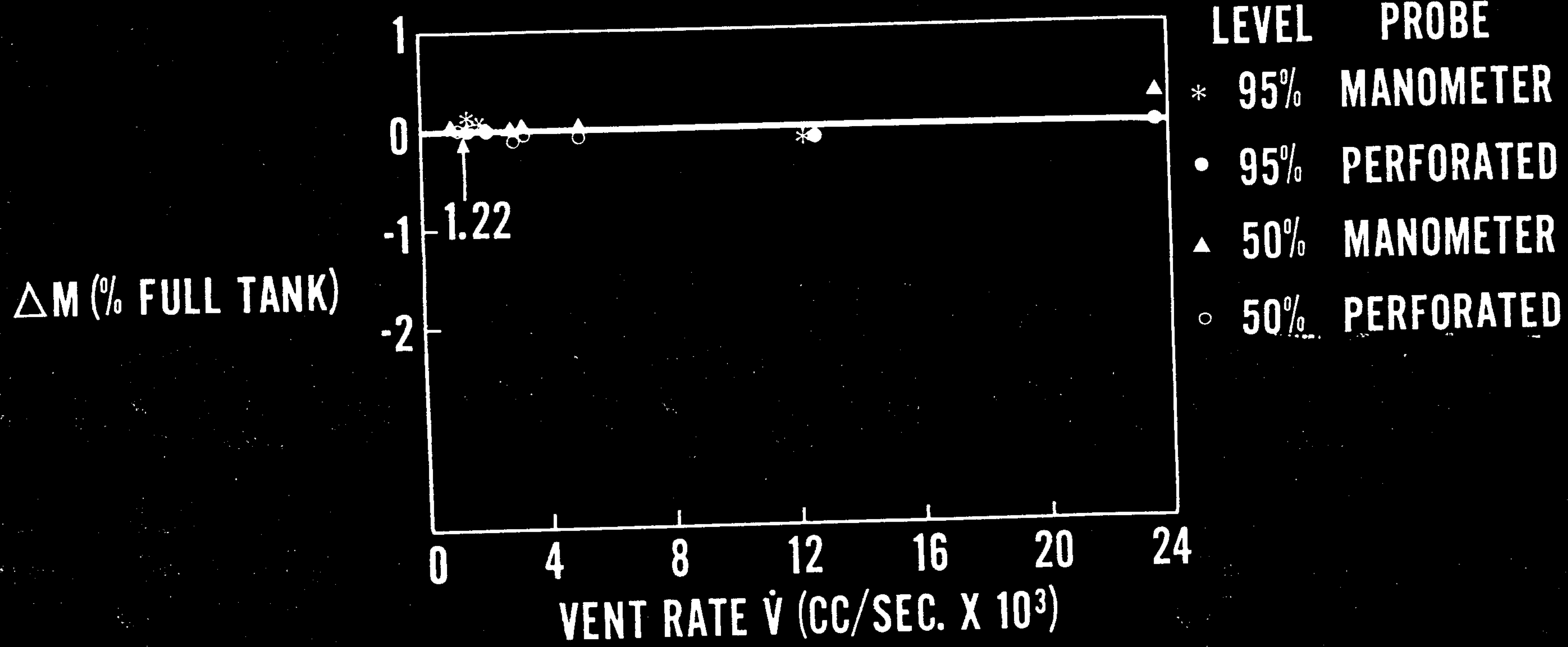
PROBE DENSITY SHIFTS (LN_2)



HONEYWELL PROBES 105% LEVEL

FIGURE 18

MASS ERRORS (LN_2)



HONEYWELL PROBES

FIGURE 19