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Differential Temperature Cryogenic Liquid
Level Sensing System

FINAL REPORT

Contract NAS8-11734

April 15, 1965

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Cryonetics Corporation's Project No. 42-002

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1.0 INTRODUCTION

This report documents the design and development, by Cryonetics Corporation, of the Differential Temperature Cryogenic Liquid Level Sensing System, NASA Contract NAS8-11734. The report contains six (6) sections. The Introduction, Section 1.0, is followed by the Principal of Operation, Section 2.0, which discusses thermodynamic analysis and characteristic curves. Section 3.0 is devoted to sensor design under which is discussed heat transfer in the service media, sensor time response, vibration, shock, service media, proof pressure and sensor fabrication. Section 4.0 is devoted to the electronics. Namely, the level set 6.8 VDC stage, the bridge, the differential amplifier, the double-to-single ended stage, emitter follower driver, switching stage and simulated operation. Performance is covered in Section 5.0 and finally, Section 6.0 contains the projection with recommendations.

2.0 PRINCIPLE OF OPERATION

The main basis for using platinum wire as a liquid level sensor is that 1) its operating temperature for a given power is a function of the heat transfer coefficient between the wire and its environment and 2) that its resistance is nearly a linear function of temperature as shown in Figure 1.

The resistance of a hot wire element is useful as an indication of the medium in which the element is immersed, since the resistance is dependent upon the heat transfer to the surrounding medium. A change in medium is accompanied by a change in resistance. This is useful in liquid level detection, since the change in media occurs between the liquid and vapor phase of a fluid. When immersed in liquid heat transfer from a hot wire is better than in vapor and thus under the same current condition the temperature of the wire is less in liquid than in vapor, resulting in a lower resistance in liquid than in vapor.

In order to have a sensing system which is temperature independent, two (2) sensors are used as follows: one (1) sensor is constructed such that it "thermally sees" the media that surrounds it, be it wet or dry. Another sensor which becomes a reference is encapsulated in a hermetic container filled with low boiling point gas. This sensor always sees "dry". These two (2) sensors are mounted close to each other, such that they are in the same temperature environment. Both sensors are electrically in a bridge circuit which is balanced at all temperatures as long as the open sensor is dry. When the open sensor becomes wet the bridge is unbalanced, which provides an input signal that an electronic circuit uses to provide a switch giving wet indication.

2.1 THERMODYNAMIC ANALYSIS

When immersed in liquid, heat transfer from a hot wire is by means of fluid circulation created by temperature and therefore density gradients (i. e. natural convection) or by nucleate boiling. The mode depends upon the heat being dissipated.

To illustrate the regimes of pool boiling, consider an electrically heated horizontal wire submerged in a pool of liquid at saturation temperature T_{sat} . Figure 2 represents the type of heat transfer data obtained. The ΔT 's given are for pool boiling in water. The shape of the curve, however, is typical for all fluids. As the wire

H₂
K₃

N₂ O₂

ICE
H₂O
R_m

NORMALIZED RESISTANCE
PLATINUM .0005" DIA. 1" SAMPLE

R = 21.1 Ω

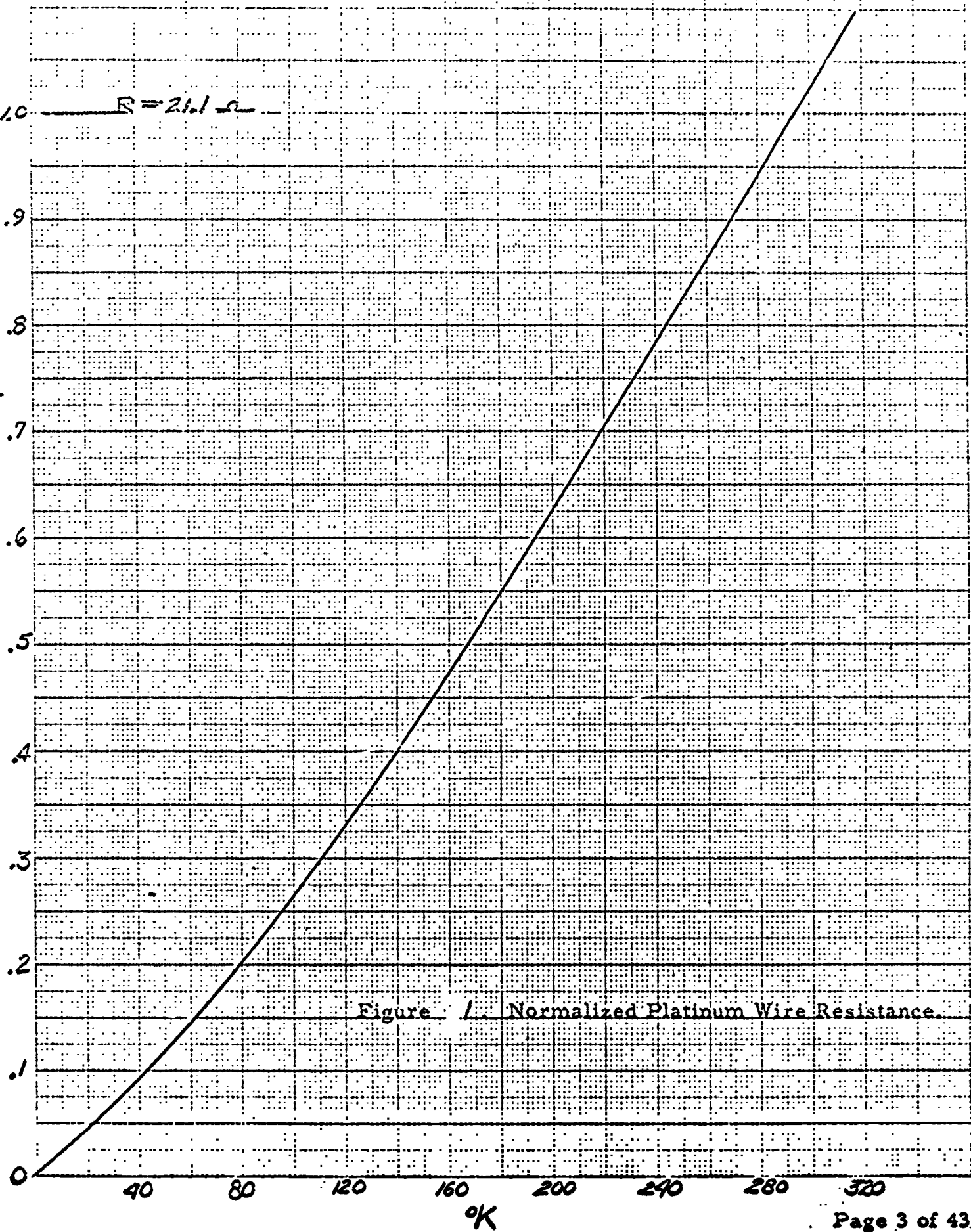
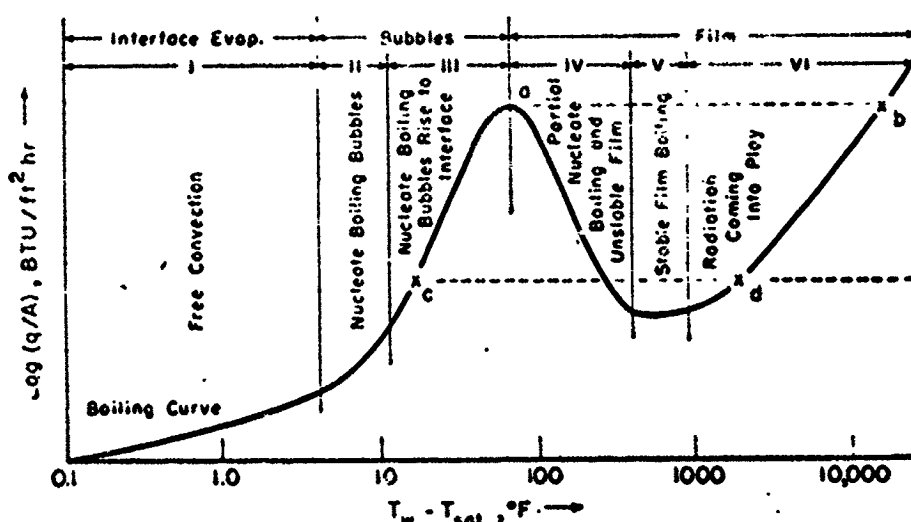


Figure 1. Normalized Platinum Wire Resistance.

surface temperature is raised above the saturation temperature, convection currents circulate the superheated liquid (regime I), and vapor is produced by evaporation at the free liquid surface. Further increase in wire surface temperature is accompanied by the formation of vapor bubbles which rise at favored spots on the metal surface and condense before reaching free liquid surface (regime II). In regime III larger and more numerous bubbles are formed and rise all the way to the free liquid surface. This is called Nucleate Boiling. Beyond the peak of the curve is the transition boiling regime IV; an unstable film forms around the wire and large bubbles originate at the outer upper surface of the film. This vapor film is not stable, but under the action of circulation currents, collapses and reforms rapidly. The presence of this film provides additional resistance to heat transfer and reduces the heat transfer rate. For values of ΔT in the range of 400-1000°F for water, the film around the wire is stable in the sense that it does not collapse and reform repeatedly, but the shape of the outer film surface varies continuously. For values of ΔT beyond 1000°F, the influence of radiation becomes pronounced. In this regime the vapor film is very stable, and the orderly discharge of bubbles suggests that the frequency and location of bubble origination is controlled by factors operating at the outer surface of the film and that favored spots along the wire are without effect. This regime is called stable film boiling.*

FIGURE 2
Typical Pool Boiling Data (Water)



* Ref. : Heat, Mass, and Momentum Transfer: Rohsenow, Warren M., and Choi, Harry; Prentice-Hall Inc., 1961, Curve and paragraph from page 212-213

Operation in liquid corresponds to regime I - III. Operation in vapor is similar to regime VI, in that heat transfer is to a film with a resultant increase in surface to fluid temperature difference ($T_{\text{surface}} - T_{\text{fluid}}$). In vapor, however, heat transfer would most likely be enhanced by a freer circulation, and the $T_s - T_f$ would not be as large as would exist for regime VI of pool boiling.

As previously mentioned, increasing I^2R heating of the wire in regime VI results in an increase in wire temperature necessary to remove the heat. Eventually, the wire temperature will exceed its melting point, and the wire will be destroyed. A similar behavior will also take place in vapor. This destructive condition has been located by Cryonetics Corporation in its tests with various fluids and the data collected has enabled us to design away from these conditions.

Characteristic curves of voltage versus current for platinum wire sensors yield a linear relation in liquid being in regime I as previously described. For operation in vapor the curve is linear at low currents, but voltage increases more than linearly as the current is increased. A simplified discussion as to the origin of these characteristic curves follows.

First the liquid case is considered. The V-I curve is nearly linear since the wire temperature is about equal to the liquid temperature. This holds at low currents and the V-I curve is a straight line whose slope is determined from the R vs T (Callendar-VanDusen relation) curves for the platinum wire elements. Self-heating of the wire in this region is negligible for cryogenic fluid, until one reaches a certain critical current at which "self-triggering" causes the wire to reach its melting point and be destroyed*. A typical curve in this case liquid nitrogen is shown in Figure 3.

For the vapor V-I curves, the heat transfer equation is:

$$\begin{aligned} (1) \quad Q &= hA_s (T_s - T_G) \\ &= I^2R \end{aligned}$$

* Ref: Measurement and Control of the Level of Low Boiling Liquids by A. Wexler and W. S. Corak, Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.

where

I = sensor current

R = sensor resistance at temperature T_S

h = heat transfer coefficient

A_s = wire surface area/mil

T_S = surface temperature of wire, °K

T_G = gas temperature, °K

In equation (1) the heat transfer coefficient, h , the surface area A_s and the gas temperature T_G are constants for any fixed conditions. The desired variables are I and R . R and T are again related through the Callendat VanDusen equation:

$$\frac{R_T}{R_0} = 1 + \alpha \left[T - \delta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right) - \beta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right)^3 \right]$$

where R_T is the element resistance at $T^\circ\text{C}$, R_0 the resistance at 0°C and α , δ and β are characteristic constants for each sensor. This equation is commonly used to describe the R vs T relation as shown in Figure 1.

For this analysis a simplified form given as:

$R = A + \alpha T$ will be used where A is a constant.

Thus

$$I^2 R = h A_s \left(\frac{R - A}{\alpha} - T_G \right) = \frac{V^2}{R}$$

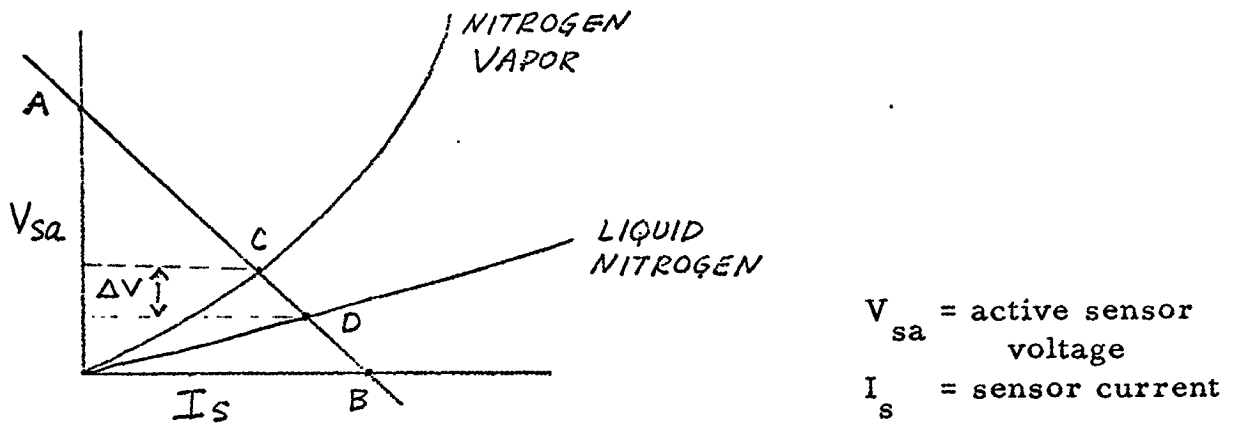
in which R is a function of I and the other parameters are fixed. As power increases and hence current increases, R resistance increases. This gives rise to characteristic vapor curves similar to the one shown for nitrogen in Figure 3.

A detailed description of heat transfer to the service fluids is given in Section 3.1 (Heat Transfer in Service Media).

2.2 CHARACTERISTIC CURVES

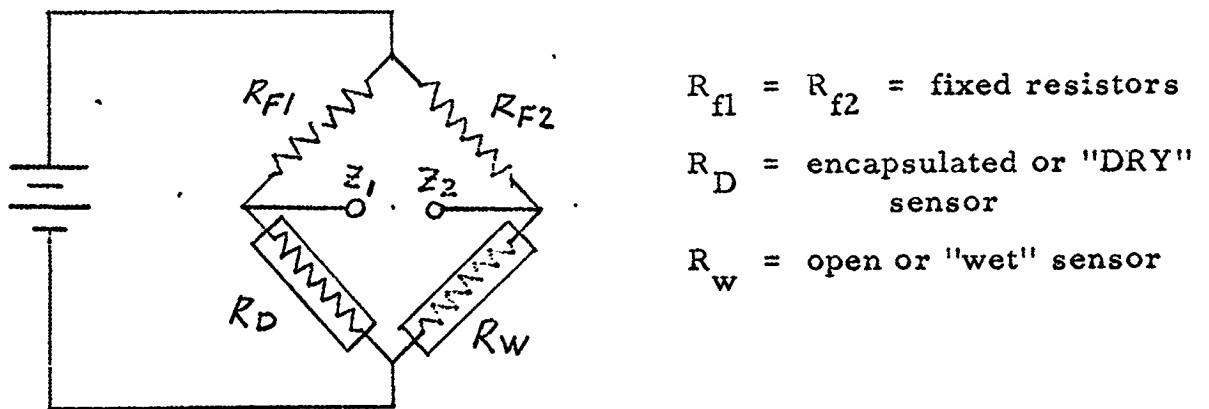
Because the platinum wire temperature sensor is a variable resistance element it is helpful, in analyzing its operation, to use a graphical approach similar to that which is used in analyzing vacuum tubes and transistors. From data obtained by placing a typical platinum sensor in a cryogenic vapor and then immersing it in the liquid, curves similar to Figure 3 may be generated.

FIGURE 3
Generalized V-I Curves



In order to place a "load line" on the curves of Figure 3, let us consider a typical bridge circuit in which platinum wire sensors form two (2) arms of the bridge, Figure 4.

FIGURE 4
Typical Bridge Circuit

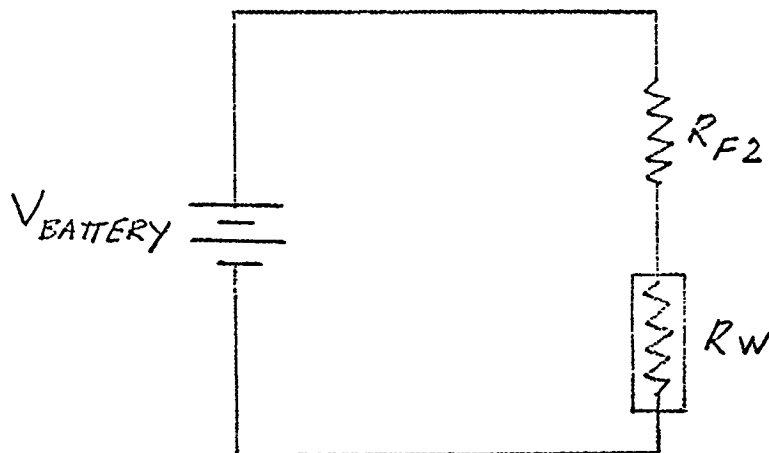


If we assume an equal arm bridge, which is the usual case at room temperature, because of symmetry it is only necessary to examine one-half of the bridge on either side of the dotted line in Figure 4. We will choose the right hand side.

Figure 5 shows the circuit of Figure 4 redrawn for our analysis.

FIGURE 5

Bridge Circuit (re-drawn)



Now considering Figure 5, if R_W were open the current through R_{f2} and R_W would be zero and the point on the V_{sa} axis of Figure 3, would equal V battery or point A. If R_W were shorted the current through $R_{f2} = I R_{f2} = \frac{V \text{ batt.}}{R_{f2}}$ or point B on the I axis of Figure 3.

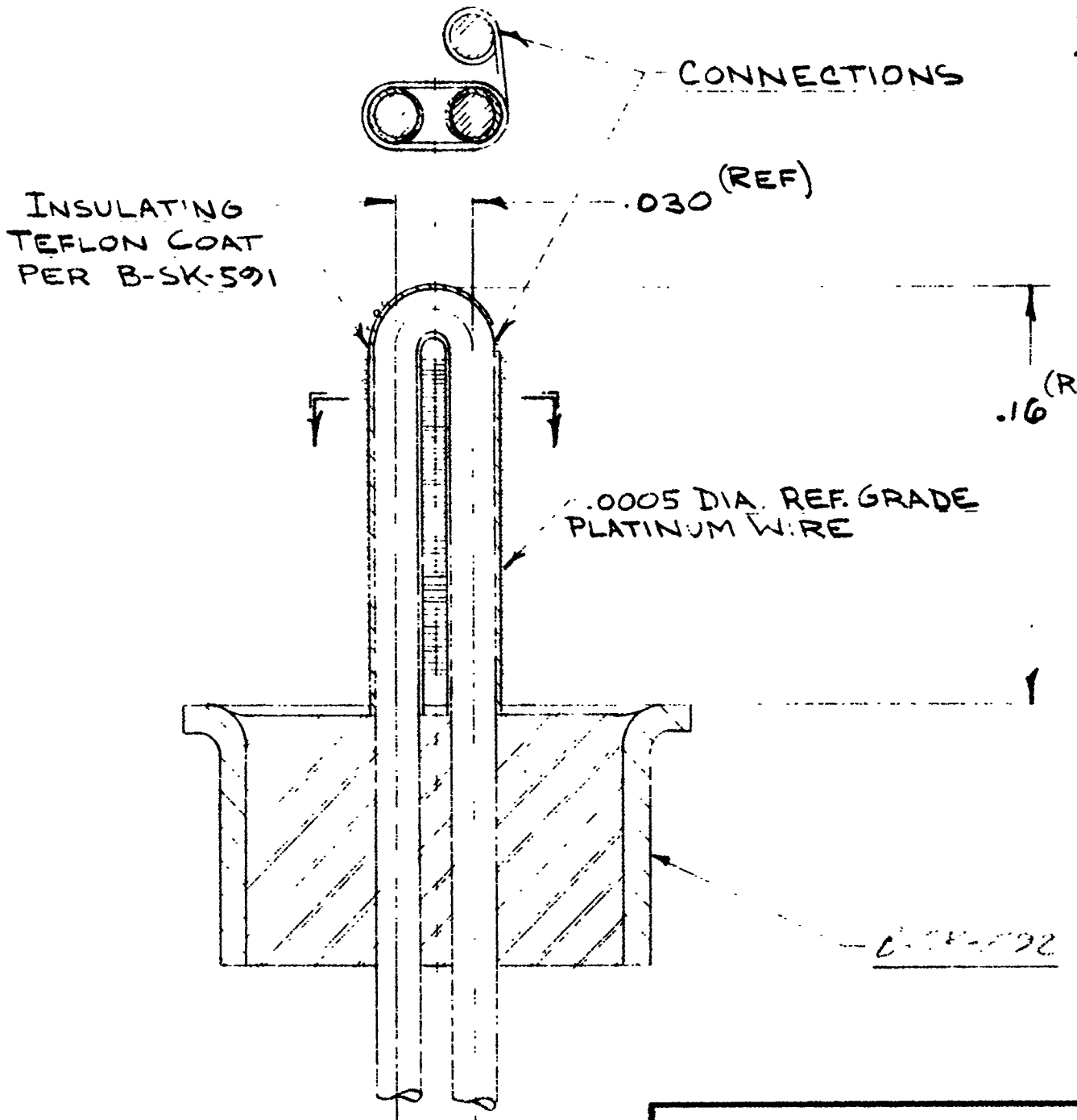
Connecting points A and B establishes the "load line". Therefore, for a given value of V batt. and R_{f2} , the sensor resistance varies between points C and D as it goes from vapor to liquid or vice versa. This change in resistance gives rise to a ΔV which is the signal that appears across the bridge terminals, Z_1 and Z_2 , in Figure 4 and is amplified by a differential amplifier which follows. Because R_D shown in Figure 4 is encapsulated, it "sees" only the vapor temperature. It therefore operates as the reference sensor.

3.0 SENSOR DESIGN

The differential temperature cryogenic liquid level sensing system makes use of two platinum wire sensors, one which is capped to give a signal corresponding to the vapor (whether in liquid or vapor) and the other which is uncapped and gives a signal difference when moved from vapor to liquid. The active or uncapped sensor is shown in SK-593 and the referenced or capped sensor is shown in SK-594.

In the initial concept, the design consisted of a single wire suspended between two posts in the form of a hair spring with an overall length of $\approx .04$ inches. This length resulted in a natural frequency higher than the highest noise or vibration frequency to be encountered. Such a length resulted in a very small signal wet to dry with a potential for difficulties from noise and circuit element tolerances. A multisupport structure was then considered which would allow a longer length of platinum wire to be used. Vibration considerations - to be discussed later in detail- dictated that a simply supported span of .030 inches was desirable. As seen in SK-593, twenty wraps nominal of the platinum wire were used in the final sensor to give an overall wire length of ≈ 2.36 inches with ≈ 1.23 inches of that length actually sensing the wet to dry condition. Pitch of the wire was $\approx .004$ inches which resulted in a compact sensor.

In designing these sensors, three general areas of performance had to be met. The first area was correct thermodynamic performance in all of the required media, ie, water, RP-1 fuel, LOX, LN₂, and LH₂ without any mechanical adjustments of the circuit. The second area is the mechanical design and assembly required to meet the vibration, shock and acoustic vibration specifications. The third area is environmental design, including the sensor service media and operating pressure. A detailed discussion of these design considerations will now be given as well as the fabrication methods used for the sensor.



NOTE:

ASSEMBLY TO BE BAKED IN OVEN
AT 475°F UNTIL FEP 856-200
TOP COAT SOFTENS AROUND
PLATINUM WIRE.

NEXT ASSY. B-SK-594

#1

UNLESS OTHERWISE SPECIFIED
 DIMENSIONS ARE IN INCHES
 TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER 1" ± 1/64	2 PLACE ± .005	± 1/2°
OVER 1" ± 1/32	3 PLACE ± .005	✓

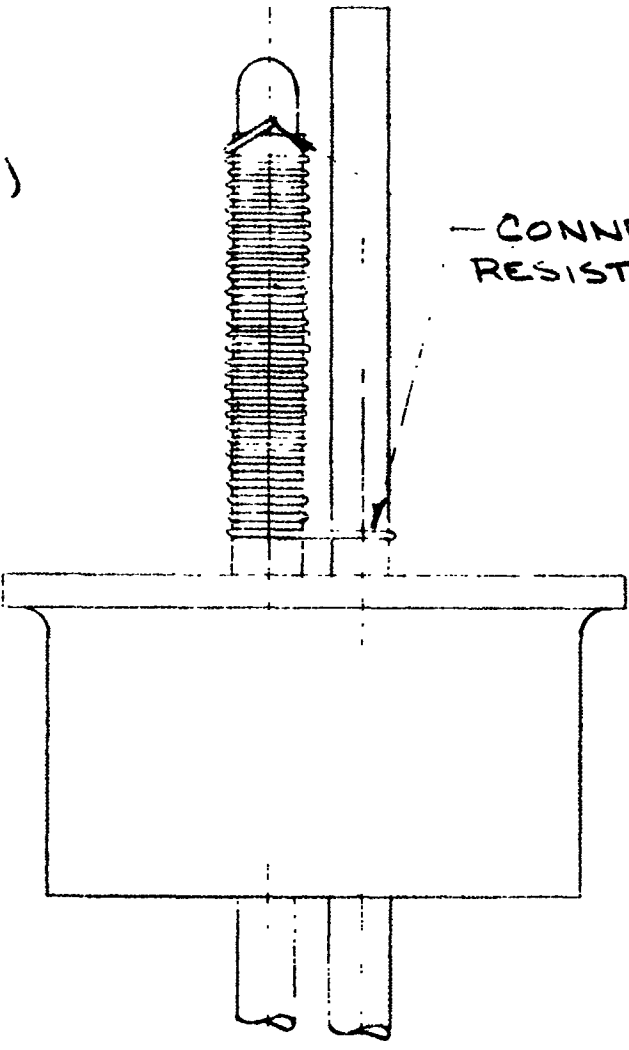
MATERIAL

NOTED

FINISH

REVISIONS

SYM	DESCRIPTION	DATE	APPD
-----	-------------	------	------



- CONNECTIONS
RESISTANCE WELDED

H. STOWE	DATE: 12-7-64
IK	12-10-64
ENGR. APPD <i>J. O'Neil</i>	12-10-64
PROD. APPD <i>Hester</i>	12-10-64

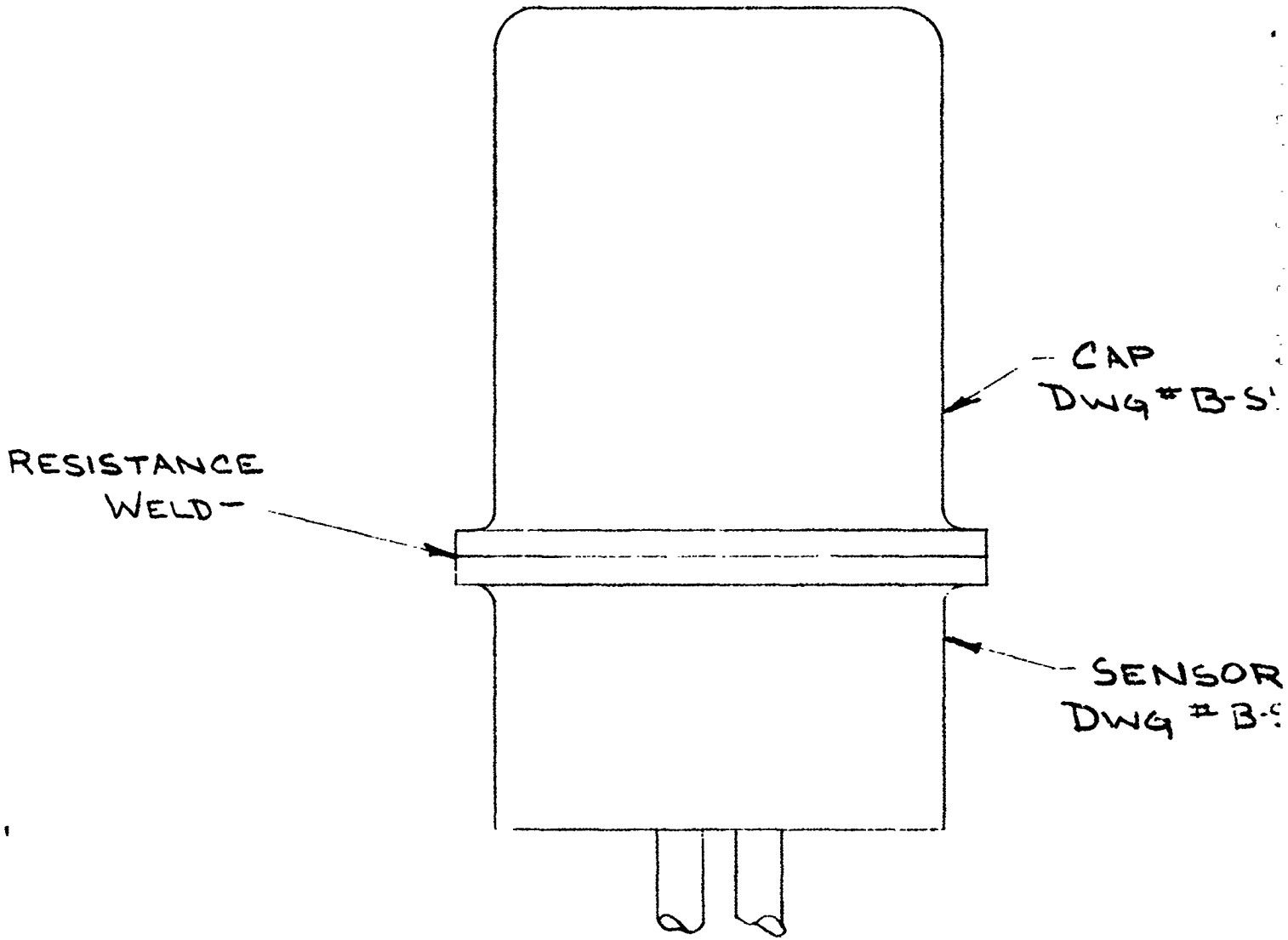
 **CRYONETICS CORPORATION**
BURLINGTON, MASSACHUSETTS

TITLE
SENSOR II ASSEMBLY

CODE IDENT NO.	SIZE B	DRAWING NO. <i>SK-593</i>
----------------	------------------	------------------------------

SCALE <i>16/1</i>	WT	SHEET <i>1 OF 1</i>
-------------------	----	---------------------

#2



NOTE:

- 1.) TO BE PRESSURIZED AT ROOM TEMP. TO 15 PSIA. OR GREATER WITH He⁴
- 2.) SAMPLES TO BE LEAKED CHECKED AT 10⁻⁹ ATMOS cc/SEC

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER 0"	2 PLACE	± 1/8°
± 1/64	± .005	
OVER 0"	3 PLACE	✓
± 1/32	± .005	

MATERIAL

NOTED


FINISH

REVISIONS

SYM	DESCRIPTION	DATE	APPD
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590

1-593

DR H. STOWE	DATE: 12-7-64	 <p>CRYONETICS CORPORATION BURLINGTON, MASSACHUSETTS</p> <p>TITLE</p> <p>SENSOR ASSEMBLY CAPPED</p>		
CHK	12-10-64			
ENGR. APPD <i>J O'Neil</i>	12-10-64			
PROD. APPD <i>R. Weston</i>	12-10-64			
APPROVAL		CODE IDENT NO.	SIZE B	DRAWING NO. SK-594
		SCALE ~	WT	SHEET 1 OF 1

3.1 HEAT TRANSFER IN SERVICE MEDIA

In designing the sensors, it was necessary to generate heat transfer data for all the service media, i. e. water, RP-1 fuel*, liquid oxygen, liquid nitrogen and liquid hydrogen using the final wire (1/2 mil platinum wire with a Callendar-VanDusen alpha constant of 0.003923). Several methods of presenting this data were possible, but a plot of voltage across a one (1) inch sample in liquid and vapor versus current was found to be the most useful. Actual test data for a one (1) inch sample was used to generate these curves for water, JP-4 and nitrogen with the data being shown in Figures 6, 7 and 8 respectively.

Heat transfer to liquid and vapor oxygen will be very similar to that for nitrogen because 1) temperature and therefore resistances are close, i. e. 77°K vs 90°K and 2) heat transfer to either vapor will be about the same when compared to the large difference in "h" occurring between a given liquid and its vapor. Because of the similarity in behavior and temperature, data for nitrogen is considered adequate for oxygen.

Test facilities for liquid hydrogen were not available and it was therefore necessary to generate hydrogen data from test data in the literature or by calculations from heat transfer correlations for other fluids. The most accurate approach was, however, to use published data for liquid hydrogen. Heat transfer data from a 0.001" diameter wire was available in Reference* and was used. The data was for heat transfer from a 72% nickel-28% iron alloy wire. Because of the unknown R vs T characteristic of this wire, it was necessary to revert to the use of the heat transfer coefficient "h" calculated from these tests rather than actual V vs I data. The value of "h" was reported to be 500 BTU/ft.² °R hr to the vapor which is three (3) times higher than the best available correlation from other fluids*. The higher value was used in our calculations for platinum wire because its use gives the smaller liquid to vapor voltage change. The governing heat transfer equation is given by equation (1) repeated below:

$$(1) \quad Q = hA_s (T_S - T_G) \left(1.8 \frac{^{\circ}\text{F}}{^{\circ}\text{K}} \right)$$

Ref. *: NASA TN D-2074, November, 1963. An Integrated Hot Wire - Stillwell Liquid Level Sensor System for Liquid Hydrogen and Other Cryogenic Fluids; William A. Olsen, Jr., Lewis Research Center, Cleveland, Ohio

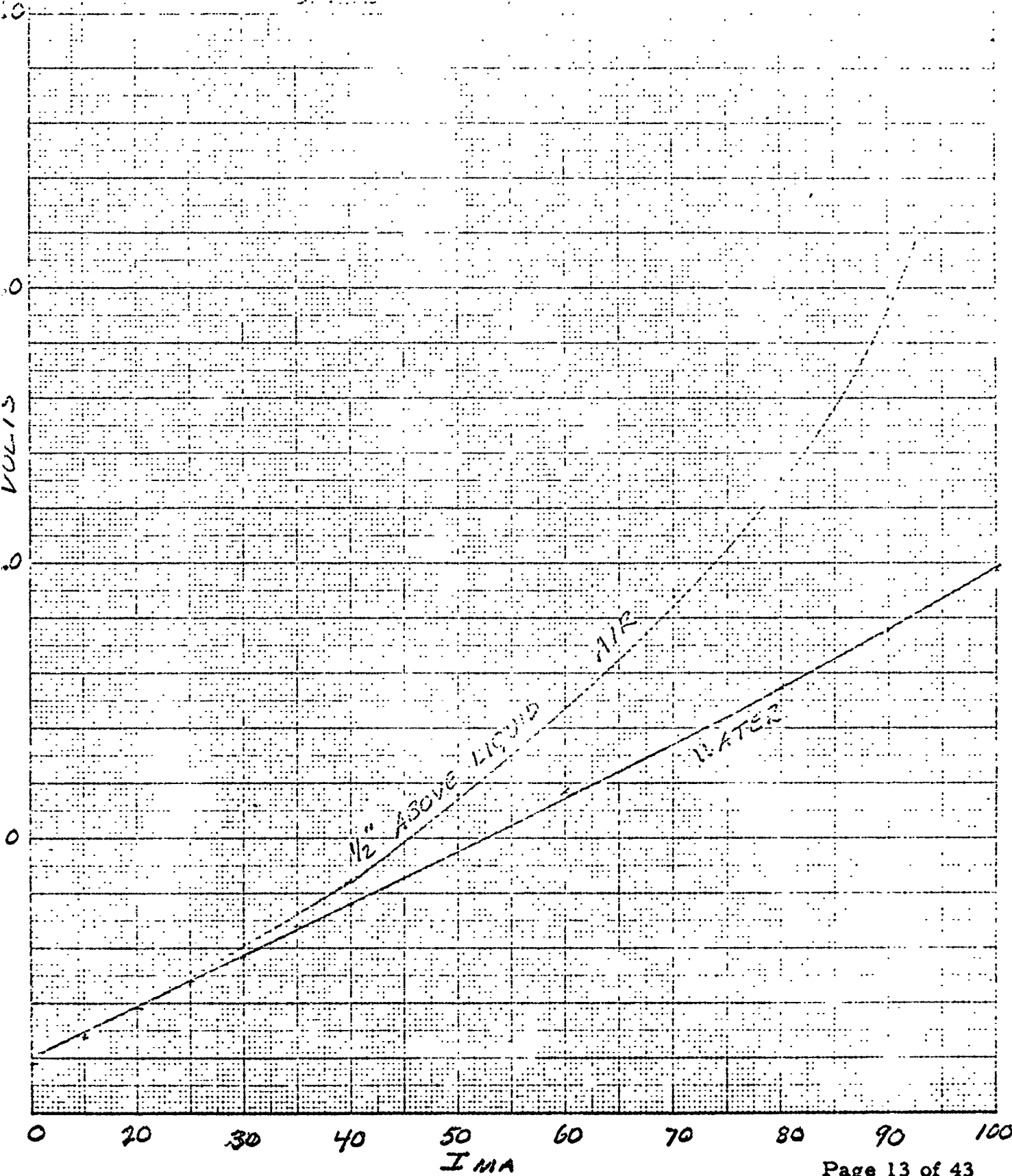
1107-10-10-10

WATER AND AIR

1/2" ABOVE LIQUID

POTENTIAL

10000



4.0

3.0

2.0

1.0

0

20

30

40

50

60

70

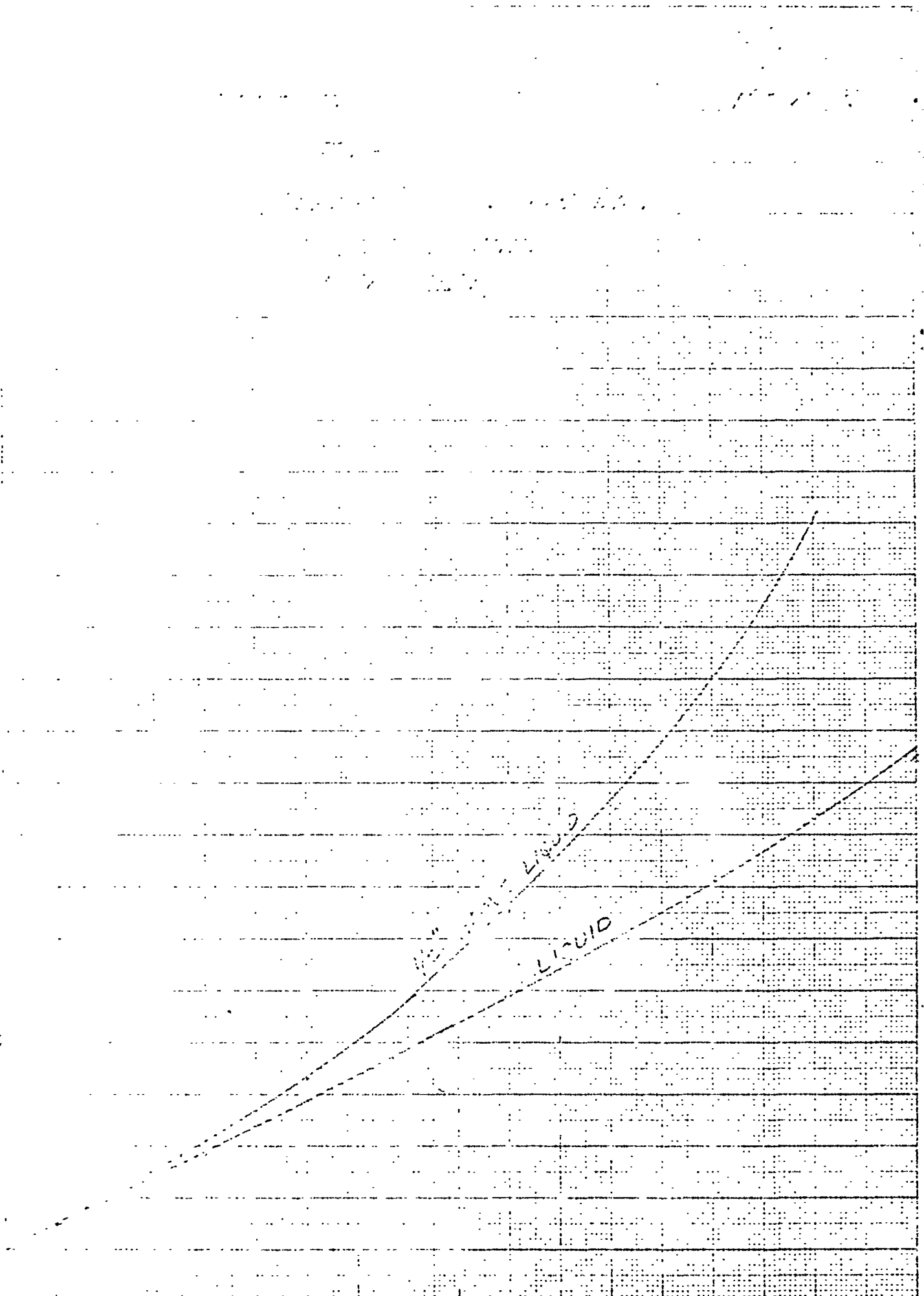
80

90

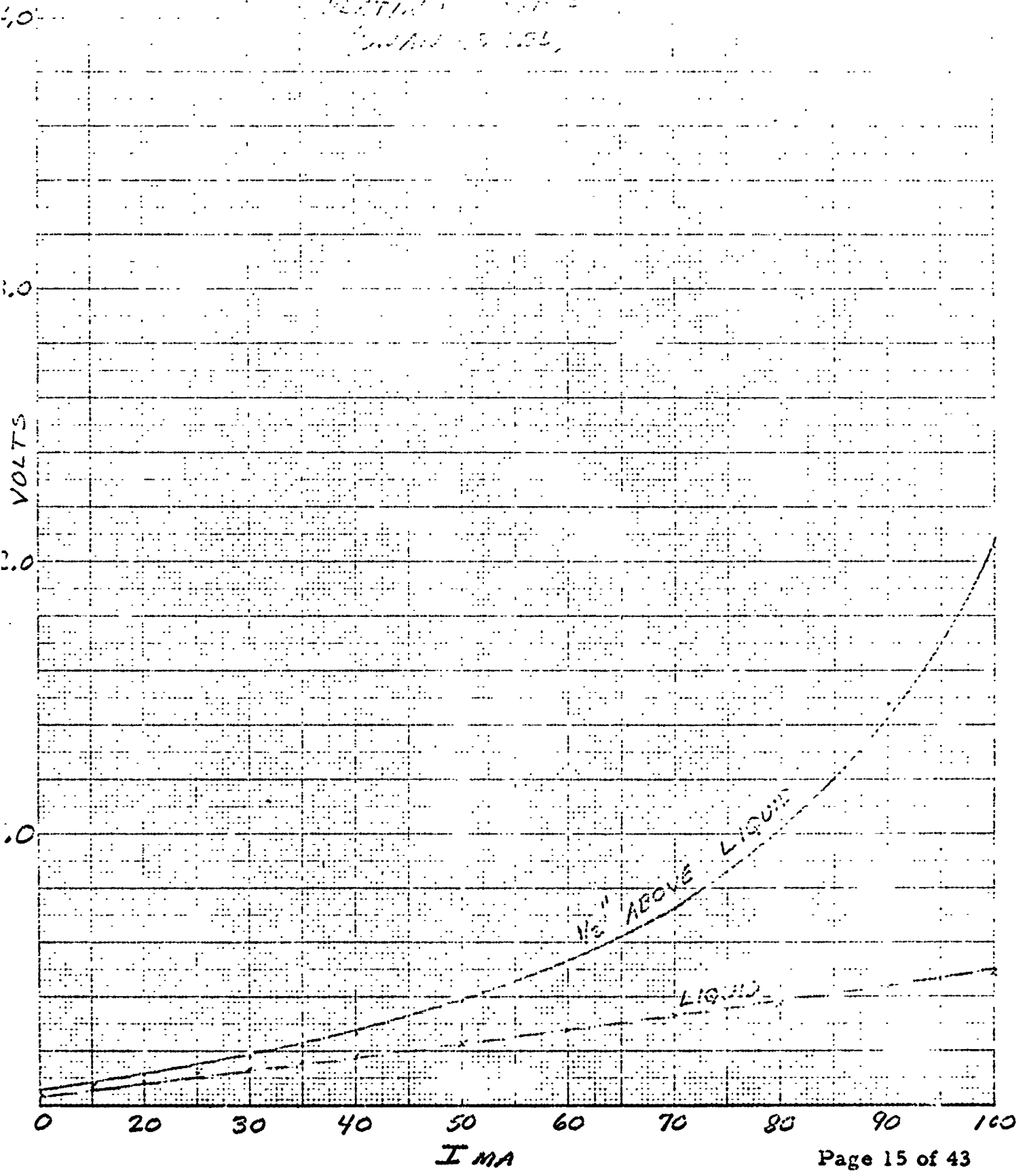
100

I MA

Page 14 of 43



PART 7
 TO THE
 1" 9.15 ...
 PARTIAL ...
 ...



where: $Q = \text{Power dissipated} = I^2 R \text{ watts/inch wire}$

if $I = \text{amps}$, $R = \text{resistance of wire, ohms}$.

$h = \text{heat transfer coefficient in BTU/hr ft}^2 \text{ }^\circ\text{F}$:

$A_s = \text{wire surface area/mil} = 1.57 \times 10^{-3} \text{ in}^2/\text{in}$

$T_S = \text{surface temperature of wire, }^\circ\text{K}$

$T_G = \text{gas temperature, }^\circ\text{K}$.

For hydrogen vapor, equation 1 becomes:

$$(2) \quad I^2 R \text{ watts/in} = \left(147 \frac{\text{watts}}{\text{ft}^2 \text{ }^\circ\text{R}} \right) \left(1.57 \times 10^{-3} \frac{\text{in}^2}{\text{in}} \right) \left(\frac{1.8}{144} \right) (T_S - T_G)$$

$$= (2.89 \times 10^{-3}) (T_S - T_G)$$

Where T 's are in $^\circ\text{K}$, this equation which must be satisfied can be rewritten:

$$(3) \quad T_S - T_G = 3.46 \times 10^2 I^2 R.$$

A sample calculation of an iterative method of determining wire temperature and thus its resistance in hydrogen vapor is given below using equation 3.

The first step is to pick a current, estimate the wire temperature and find the wire resistance at this temperature from Figure 1 for 1" length and solve equation 3 for T surface. If the assumed and calculated temperature are the same, then the resistance used is correct. The voltage change from liquid to vapor can then be calculated by equation 4, and the results plotted as in Figures 6-8.

$$(4) \quad \Delta V = V_{\text{vapor}} - V_{\text{liquid}} = I (R_{\text{vapor}} - R_{\text{liquid}})$$

where $R_{\text{vapor}} = \text{wire resistance corresponding to the correctly assumed wire temperature in vapor at the given current}$.

$R_{\text{liquid}} = \text{the resistance of 1" of wire in liquid. The wire temperature is only slightly above the liquid and can be assumed to be equal to the liquid without loss of accuracy; therefore, } R = 1 \text{ ohm at } 20.4^\circ\text{K}$.

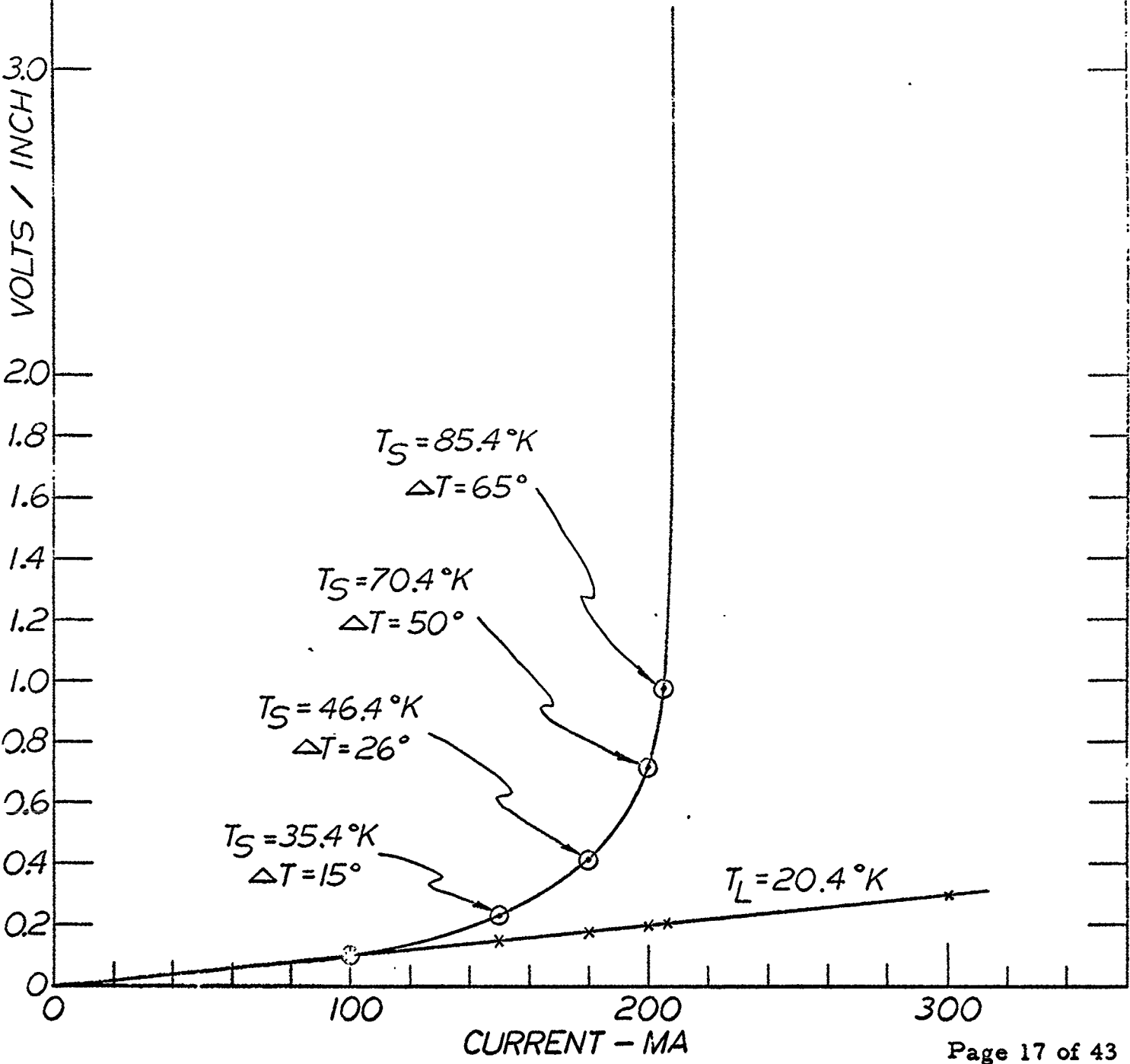
CALCULATED HEAT TRANSFER DATA

1/2 MIL PLATINUM SENSOR IN LIQUID
AND VAPOR HYDROGEN AT 20.4°K

$h_{\text{vapor}} = 500 \text{ BTU/hr. ft.}^2 \text{ }^\circ\text{R}$

HYDROGEN

⊙ VAPOR (CALCULATED)
× LIQUID (CALCULATED)



For I equal to 100 ma, for example, we assume $T_{\text{surface}} = 24.5^{\circ}\text{K}$ for a $T_S - T_G = 24.5 - 20.4 = 4.1^{\circ}\text{K}$. The R corresponding to 24.5°K is 1.2 ohms from Figure 1. Equation 3 becomes:

$$(5) \quad T_S - T_G = (3.46 \times 10^2) (0.1)^2 (1.2) \\ = 4.15^{\circ}\text{K}$$

which is the same as we correctly assumed. The voltage difference between a one (1) inch 1/2 mil platinum wire in liquid and vapor hydrogen at 20.4°K is calculated by equation 4.

$$(6) \quad \Delta V = (.100) (1.2 - 1.0) \\ = 20 \text{ millivolts.}$$

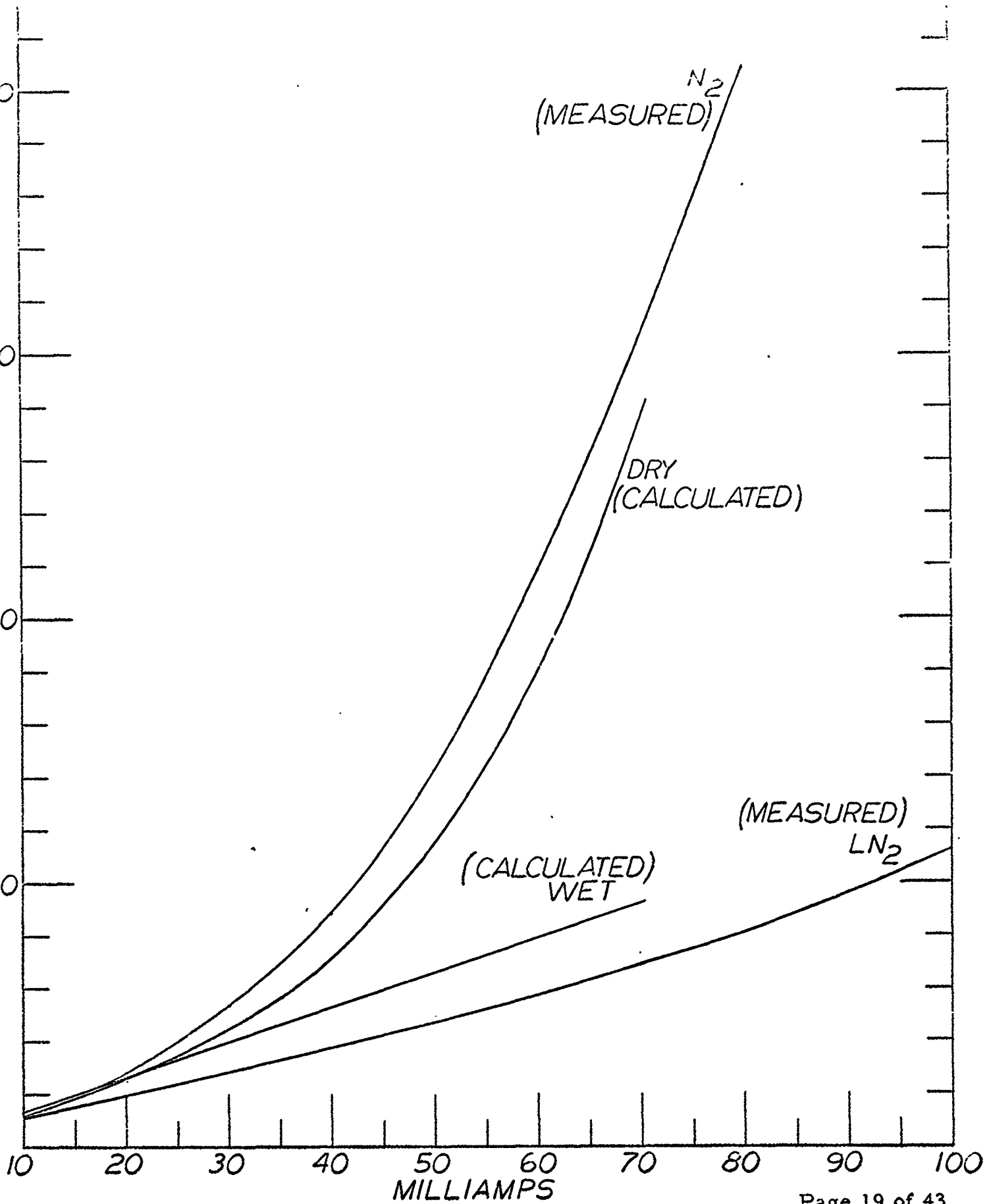
These results and others were then plotted in Figure 9 to give a calculated V vs I curve for hydrogen similar to Figures 2 - 5, which are measured values for other fluids. It should be noted that this signal is about three (3) times smaller than if we had used the lower value for "h" and is therefore conservative.

In the preceding paragraphs, we have developed all the test data for a single wire required to predict performance for an actual sensor. The final design for the sensor was based on approximately 20 loops around the supports shown in Cryonetics Corporation Drawing SK-592 with a 55 ohm nominal resistance at 70°F . The wire freely suspended from the posts which are on 0.030" centers is equal to $(20.5) (.030 \times 2)$ or 1.23" of "active" length. (This includes .030" of lead wire.) The "inactive" length or that length which is on the posts is equal to $\pi D \times 20$ turns = $(\pi) (.018) (20)$ or 1.13 inches. The total wire length is thus 2.36 inches.

In calculating the V-I curves for the wound sensor, the assumption was made that the "inactive" length would remain at the same temperature as the ambient fluid whereas the "active" length would heat up in vapor. These assumptions reduce to the following:

- 1) For a sensor that is uncapped and can be wetted, multiply the wet voltage for a one (1) inch piece by 2.36 to obtain sensor wet voltage.
- 2) For an uncapped sensor in vapor, the sensor voltage is the sum of the wet (voltage/inch) x (1.13) and the (dry voltage/inch) x (1.23).

HEAT TRANSFER TO NITROGEN
FROM A WOUND SENSOR



CONNECTIONS

INSULATING
TEFLON COAT
FOR B-SK 591

030 (REF)

0.0005 DIA. REF GRADE
PLATINUM WIRE
WINDING MUST NOT
TOUCH EACH OTHER

3.0000 DIA. MAX



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON:		
FRACTIONS	DECIMALS	ANGLES
UNDER 1"	2 PLACE	
± 1/64	± .010	± 1.0°
OVER 1"	3 PLACE	∇
± 1/32	± .005	
MATERIAL		
None noted		
FINISH		

NEXT ASSY. B-SK-593

1

As an illustration of the accurate results which can be achieved by scaling up on (1) inch data, Figure 10 is offered. The curve developed from one (1) inch data and from actual sensor data are seen to be very close, proving that the behavior of the support posts is correctly taken into account.

Figure 11 shows the experimental characteristic V-I curves for Water, JP-4, LN, and for LH_2 and a calculated LH curve. Data for helium was taken to determine behavior of the wire at very low temperature and for comparison with data calculated for hydrogen.

3.2 SENSOR TIME RESPONSE

The response time of a sensor using platinum wire is a function of the heat transfer coefficient in liquid and vapor, the enthalpy change and I^2R heating of the wire. Response time has both been measured (with nitrogen) and calculated (with hydrogen) with results of 100 milliseconds or better being typical for movement from or to a liquid or vapor of a free wire.

The calculation for hydrogen is given below. If we use a one (1) inch length of 1/2 mil platinum wire, the resulting resistance will be about 1.0 ohms at 20.4°K. These values are from Cryonetics Corporation's R vs T data which is given in Figure 1.

The response time can just be calculated as a simple step change of ambient temperature with negligible internal resistance, i. e. uniform internal temperature, and negligible I^2R loss. Equation 4.3 of Reference*, applies to our case.

$$\frac{T - T_a}{T_o - T_a} = \left(E \right) - \frac{h \bar{A}_s \theta}{pcv}$$

where

- T = temperature of wire = t (time)
- T_a = temperature of wire long after step change
- T_o = temperature of wire before step change occurs
- \bar{h} = average heat transfer coefficient
- \bar{A}_s = surface area of wire/inch
- = 1.09×10^{-5} ft² / inch
- pcv = an energy term equivalent to $\frac{\Delta H}{\Delta T}$
- θ = elapsed time.

* Ref: Principles of Heat Transfer, Frank Kreith, International Textbook Company, Scranton, Pennsylvania

Reference * gives the value of \bar{h} from a one (1) mil nickel-iron wire to hydrogen vapor to be $\frac{500 \text{ BTU}}{\text{ft}^2 \text{ }^\circ\text{R hr}}$.

To be conservative, we will use an "h" value of 100 BTU/ft² °R hr. We can now calculate the time required to sense 63% of the step change, i. e. the exponent of E is equal to 1. Solving for θ assuming 150°K to 20.4°K ΔT , gives

$$\begin{aligned} \theta &= \frac{\Delta H}{\Delta T} \frac{1}{\bar{h} A_s} = \\ &= \frac{2.0 \times 10^{-9}}{(100) (1.09 \times 10^{-5})} = 2 \times 10^{-6} \text{ hrs} \\ &= 2 \times 10^{-6} \text{ hrs or } 7.2 \text{ milliseconds.} \end{aligned}$$

Self-heating assists response time when moving from liquid to vapor and overcomes to some extent, the extra heat required to boil-off liquid clinging to the wire. When moving from vapor to liquid self-heating increases time response. High heat transfer rates in liquid, however, offsets this effect, somewhat.

3.3 VIBRATION

In the sensors, we achieve structural and vibrational integrity by designing wires, supports, etc. for a natural frequency higher than that of the highest forcing frequency, which is 10,000 cps 160 db sound pressure**. Deflections and thereby shock effects are reduced by rigidly holding the sensor wire at the supports by heating the teflon to sink the wire into it. Since the sensor has been designed above resonant frequency and the forces are small, no vibration or acceleration difficulties should be noted. The vibration and shock calculations for the platinum wire and its support posts are given as follows:

- - - - -

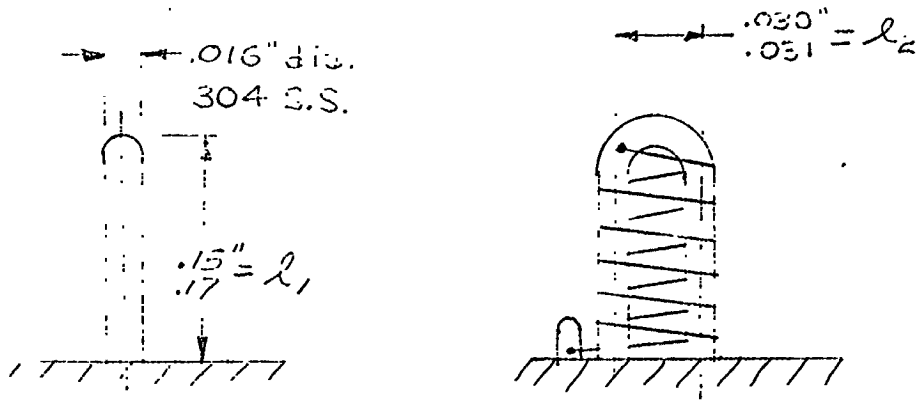
* Ref: NASA TN-D-2074 - An Integrated Hot Wire Stillwell Liquid Level Sensor System for Liquid Hydrogen and Other Cryogenic Fluids, Olsen, William A., Jr., Lewis Research Center

- - - - -

** Ref: Paragraph 4.0 of MSFC - Specification R-P + VE-PMS-SPEC-1-64 Revision A - September 14, 1964.

A structure equivalent to that of Cryonetics Corporation's Drawing SK-593 is shown in Figure 14 below:

FIGURE 14
Equivalent Structure



The natural frequency for circular cross section beams is given by:

$$(1) \quad f = A \frac{D}{\ell^2} \sqrt{\frac{E}{W_1}}$$

where

A = constant dependent upon the vibration mode and end support, equal to 2.7 for first mode of a cantilevered beam and 7.7 for the first mode of a simply supported beam.

D = diameter of rod in inches

ℓ = length in inches

E = Young's Modulus: at 300°K $28 \times 10^{+6}$ lbs/in² for stainless steel and $22 \times 10^{+6}$ lbs/in², for annealed platinum

W = density lbs/in³; 0.284 lbs/in³ for stainless steel, .775 lbs/in³ for platinum.

For the 304 stainless steel cantilevered support posts, e. g.

(1) becomes:

$$(2) \quad f_{ss} = (2.7) \frac{(.016)}{(.17^2)} \sqrt{\frac{28 \times 10^6}{0.284}}$$

$$= 14,900 \text{ cps}$$

For the 1/2 mil platinum wire .031" long and simply supported at the ends.

$$(3) \quad f_{Pt} = (7.7) \frac{(.0005)}{(.031^2)} \sqrt{\frac{22 \times 10^6}{0.775}}$$

$$= 21,300 \text{ cps.}$$

A span of $\approx .044$ " gives an $f_1 = 10,000$ cps. Thus, the sensor span is .013" below critical length. Both the wire and its support posts are therefore conservatively designed.

3.4 SHOCK

The shock requirement is given as 60 G's maximum (Paragraph 4.3 of Reference *). Stresses resulting from this shock were calculated and found acceptable. As an illustration, the calculation for the simply supported platinum wire is given below:

Equivalent Wire Loading

Uniform loading due to 60 G's acting on wire mass



* Ref: Paragraph 4.3 of MSFC - Specification R-P + VE-PMS-SPEC-1-64
Revision A - September 14, 1964.

The bending stress equation is:

$$\sigma_B = \frac{Mc}{I}$$

where

$$M = \text{Bending moment in beam, } M_{\max} = \frac{w \ell^2}{8} ;$$

$$w = \text{load/inch}$$

$$c = \frac{\text{wire dia}}{2}$$

$$I = \text{Inertia of wire about its axis}$$

$$= \frac{\pi D^4}{64} = 3.05 \times 10^{-5} \text{ in}^4 \text{ for } 1/2 \text{ mil wire.}$$

$$\text{For 1 G loading, } w = (1) (0.78 \text{ lbs/in}^3) (19.6 \times 10^{-8} \text{ in}^2)$$

$$\text{or } 15.3 \times 10^{-8} \text{ lbs/in. For 60 G: } w = 9.18 \times 10^{-6} \text{ lbs/in}$$

$$M_{\max} = \frac{w \ell^2}{8} = (9.2 \times 10^{-6} \text{ lbs/in}) \left(\frac{.031}{8}\right)^2$$

$$M_{\max} = 1.1 \times 10^{-9} \text{ lbs in}$$

and

$$\sigma_{\max} = \frac{(1.1 \times 10^{-9} \text{ lbs in})}{3.05 \times 10^{-15} \text{ in}^4} \left(\frac{5 \times 10^{-4} \text{ in}}{2}\right)$$

$$= 90 \text{ lbs/in}^2 \text{ Tension.}$$

Since the tensile strength of annealed platinum is 20,000 psi, we will have no difficulty in withstanding the 90 psi tensile load due to 60 G shock.

* Ref: Marks Mechanical Engineers' Handbook - 6th Edition - page 5 -31, McGraw-Hill

3.5 SERVICE MEDIA

The sensors were designed to be compatible with the required service media, i.e. water, RP-1 fuel, LOX, LN2 and LH2. This was accomplished by using corrosion resistance materials such as 347 stainless steel for the eyelet and cap and 304 stainless steel for the posts. In addition, all materials used are listed as acceptable with LOX in References * and **.

3.6 PROOF PRESSURE

The sensing probe was designed such that minimum collapsing pressure would well exceed 135 psig. This pressure is much higher than the required proof and operating pressures and is therefore the most difficult to meet. The only possible danger from these pressures is that of collapse of the sensor cap. Referring to Cryonetics Corporation's Drawing SK-590, we see that the cap is a closed cylinder (when assembled) with fixed ends 0.250" long, .010" thick and 0.17" in diameter with helium-4 enclosed.

From Figure 334 of Reference ***, we find that the cylinder buckles in the form of four (4) lobes, and that the values of K is 7. The elastic buckling pressure (critical) is given by:

$$P_{cr} = KE \left(\frac{t}{d} \right)^3$$

where $K = \text{coefficient} = f \left(\frac{l}{r}, \frac{d}{t} \right)$

$E = \text{Modulus of elasticity of material, } 28 \times 10^6 \text{ psi for stainless steel}$

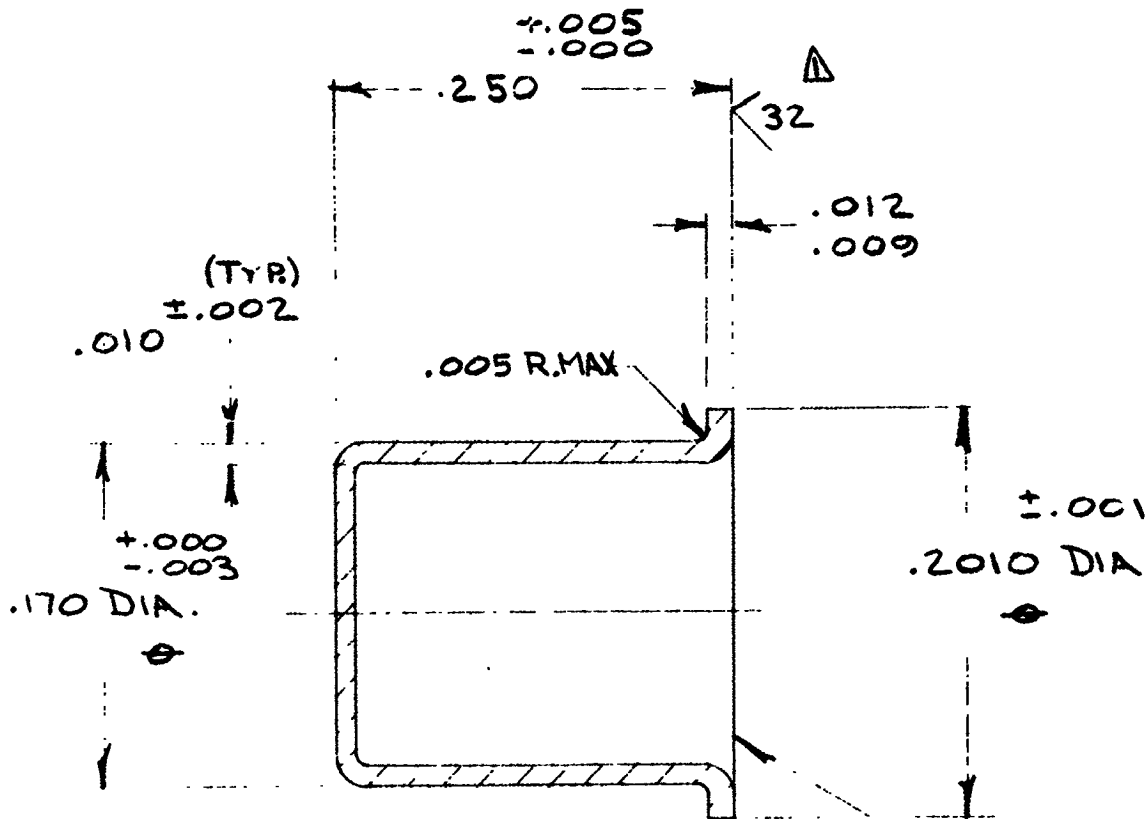
$t = \text{thickness of shell} = .010''$

$d = \text{outside diameter of cylinder} = 0.17 \text{ .}$

* Ref : Compatibility of Materials with Liquid Oxygen, C. F. Key and W. A. Riehl, George C. Marshall Space Flight Center, MTP - P + VE-M-63-14

** Ref : Compatibility of Materials with Liquid Oxygen, C. F. Key and George C. Marshall Space Flight Center, NASA TMX-53052, 5-26-64

***Ref : Advanced Mechanics of Materials, 2nd Edition, Seely, Fred B. and Smith, James D., John Wiley + Sons, Inc. New York



SURFACE TO BE THICKNESS TO B

NOTES:

- 1.) DO NOT USE SULPHUR OIL
- 2.) DO NOT TUMBLE IN ALUM. OXIDE
- 3.) MUST BE FREE OF BURRS, SPLITS, INCLUSIONS & DEEP TOOL MARKS
- 4.) DIA'S. MARKED \varnothing MUST BE CONCENTRIC WITHIN .002

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER \varnothing $\pm 1/64$	2 PLACE $\pm .005$	$\pm 1/2^\circ$
OVER \varnothing $\pm 1/32$	3 PLACE $\pm .002$	✓

MATERIAL

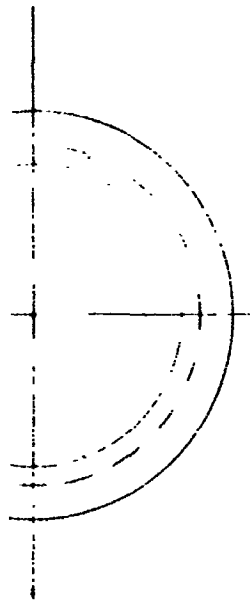
#347 ST STL.

FINISH

NEXT ASSY. B-SK-594

#1

REVISIONS			
SYM	DESCRIPTION	DATE	APPD



-AT WITHIN .001
EVEN WITHIN .0005

DR H. STOWE	DATE: 12-7-64
CHK DES	12-7-64
ENGR. APPD <i>J. O. Hill</i>	12-10-64
PROD. APPD <i>W. J. Steer</i>	12-10-64

 **CRYONETICS CORPORATION**
BURLINGTON, MASSACHUSETTS

TITLE
CAP

CODE IDENT NO.	SIZE B	DRAWING NO. SK-590
SCALE ~	WT	SHEET 1 OF 1

#2

Thus

$$P_{cr} = (7) (28 \times 10^6) \left(\frac{.010}{.17} \right)^3$$

$$= 39,800 \text{ psi.}$$

This stress would cause a circumferential stress:

$$\sigma_{cr} = \frac{P}{2} \left(\frac{d}{t} \right) = \frac{39,800}{2} \left(\frac{.17}{.010} \right) = 340,000 \text{ psi.}$$

Since the value of σ_{cr} is greater than the yield point of the material, the tube will fail by circumferential stress quicker than by buckling. With a 75,000 psi compressive yield strength,

$$P_{critical} = (\sigma_{cr}) (2) \left(\frac{t}{d} \right) = \left(\frac{75,000}{17} \right) (2) = 8,800 \text{ psi.}$$

Since $P_{cr} = 8,800$ psi, the caps should be able to withstand the 135 psi peak pressure with no difficulty.

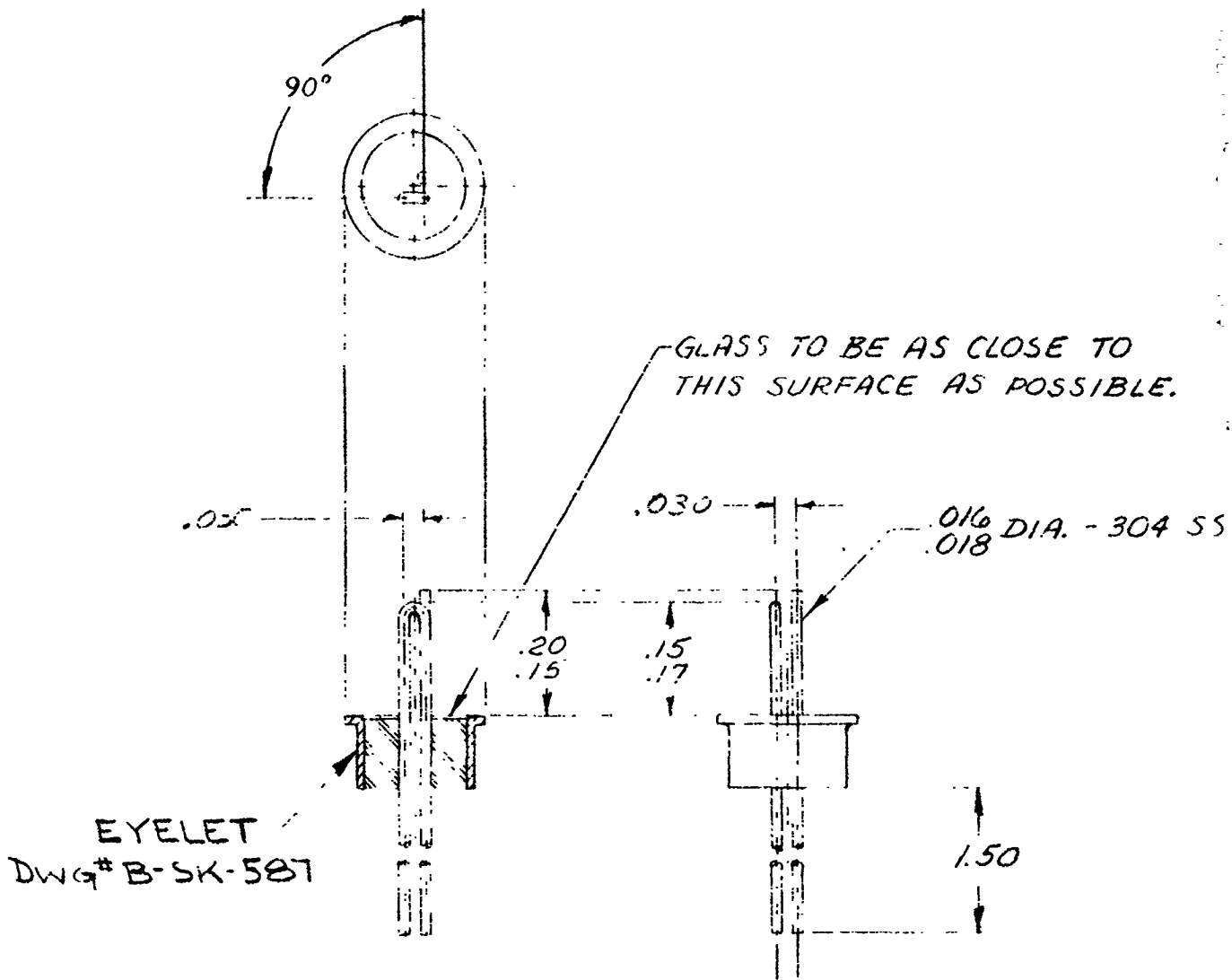
3.7 FABRICATION

The sensors were wound on a header assembly as shown in Cryonetics Corporation's Drawing SK-554. The eyelet detail is shown in Cryonetics Corporation's Drawing SK-587.

Prior to winding, the header assembly is insulated with teflon coatings applied as per Cryonetics Corporation's Drawing SK-591.

The actual winding was performed on a very unique device, similar to a jeweler's lathe, which was developed specifically for this job. The winder is shown in Cryonetics Corporation's Drawing SK-721. With the gearing and lead screw shown, the winding pitch is approximately .0042 inches. Other combinations of gearing and lead screw could be chosen if it is desired to vary the winding pitch. The wire tension is maintained by an automatic tension device as shown on the drawing.

The winder speed is reduced by feeding the drive motor through a gear reduction box. The motor speed is regulated by a variable motor speed control.



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER 6"	2 PLACE	± 1/2°
± 1/64	± .010	
OVER 6"	3 PLACE	∇
± 1/32	± .005	

MATERIAL

NOTED

FINISH


NEXT ASSY. B-SK-591

#1

REVISIONS

SYM	DESCRIPTION	DATE	APPD
Δ	SEE ECO # 126	12-7-64	R. J. C.

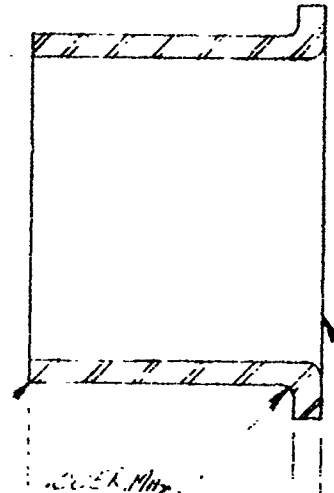
WIRE

R. R. CLOUTIER	DATE: 11-2-64	 <p>CRYONETICS CORPORATION BURLINGTON, MASSACHUSETTS</p>
HK 100	12-1-64	
ENGR. APPD [Signature]	11-2-64	
PROD. APPD [Signature]	12-10-64	
TITLE		HEADER
CODE IDENT NO.	SIZE	DRAWING NO.
	B	SK-554
SCALE 4/1	WT	SHEET

2

DES Note #5 .050 \pm .003 .017

.010 \pm .001
 +.006
 -.003
 .170



2.0 MAX T.A.M.
ALLOWABLE RAD. .005 MAX.

NOTES:

1. DO NOT USE SULPHUR OILS
2. DO NOT TUMBLE IN ALUM. OXIDE.
3. MUST BE FREE OF BURRS, SPLITS
INCLUSIONS & DEEP TOOL MARKS.
4. DIA'S MARNED & MUST BE CONCENTRIC
WITHIN .001
5. NO DEFORMATION OF THE EYLET IS
ALLOWED IN THIS AREA, THE SIDES
MUST BE STRAIGHT & PARALLEL WITHIN .0005
NEXT ASSY. B-SK-554

UNLESS OTHERWISE SPECIFIED
 DIMENSIONS ARE IN INCHES
 TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER 6"	2 PLACE	± 1/2°
± 1/64	± .005	
OVER 6"	3 PLACE	✓
± 1/32	± .008	

MATERIAL

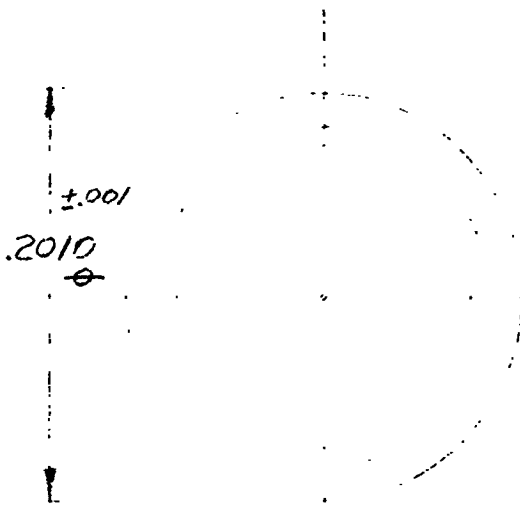
#347 ST. STL.

FINISH

#1

REVISIONS


SYM	DESCRIPTION	DATE	APPD
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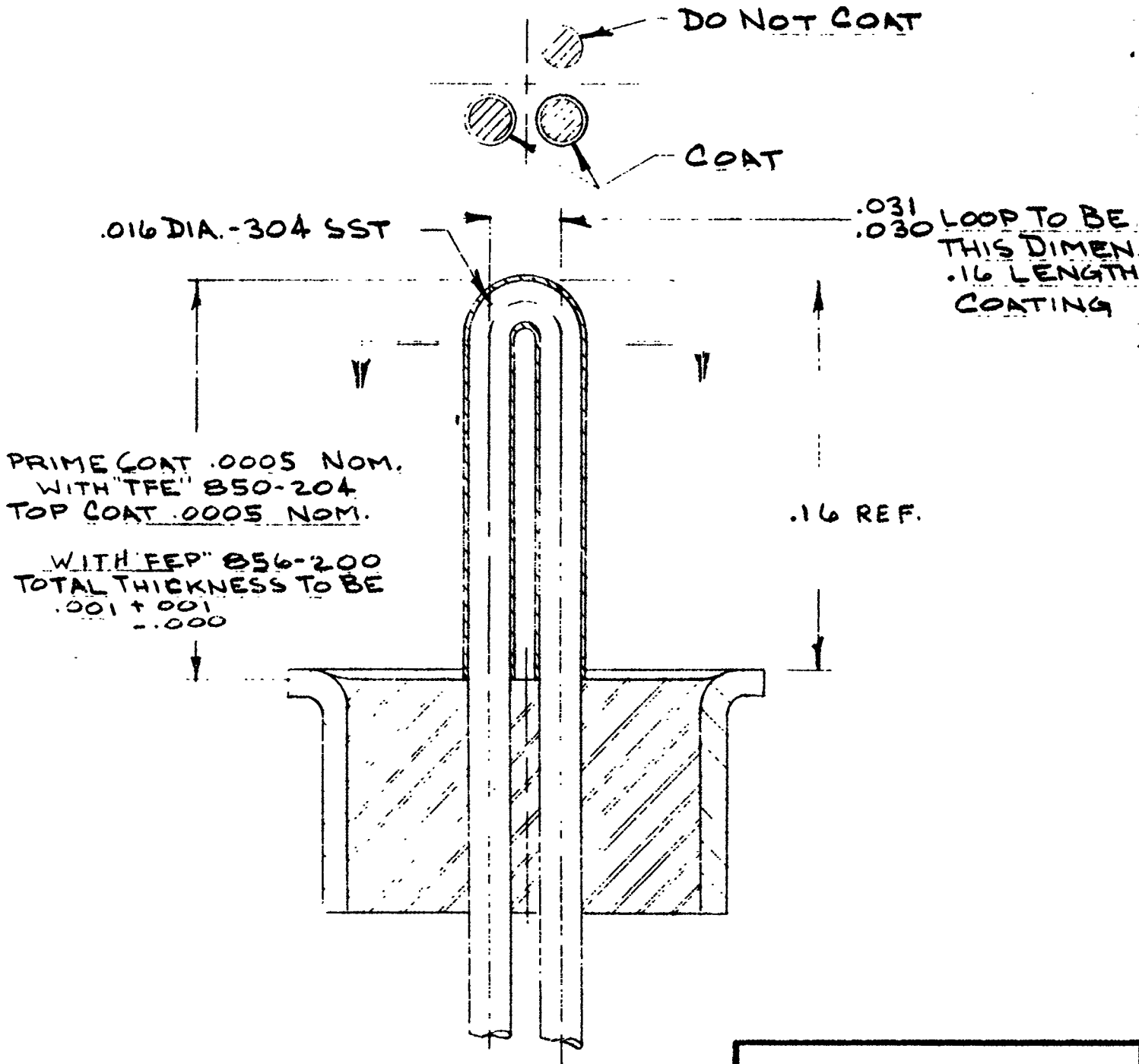
SURFACE TO BE FLAT WITHIN .001
THICKNESS TO BE EVEN WITHIN .0005

REF DWG.

A-205-2
 ISSUE:K

R NH	DATE: 11-30-64	 <p>CRYONETICS CORPORATION BURLINGTON, MASSACHUSETTS</p>
CHK	11-30-64	
ENGR. APPD <i>J. O'Neil</i>	11-30-64	
PROD. APPD <i>Wester</i>	12-10-64	
TITLE		<p style="text-align: center;">EYELET</p>
CODE IDENT NO.	SIZE	
SCALE	WT	SHEET

2



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON		
FRACTIONS	DECIMALS	ANGLES
UNDER 6" ± 1/64	2 PLACE ± .005	± 1/2°
OVER 6" ± 1/32	3 PLACE ± .003	✓
MATERIAL		
NOTED		
FINISH		

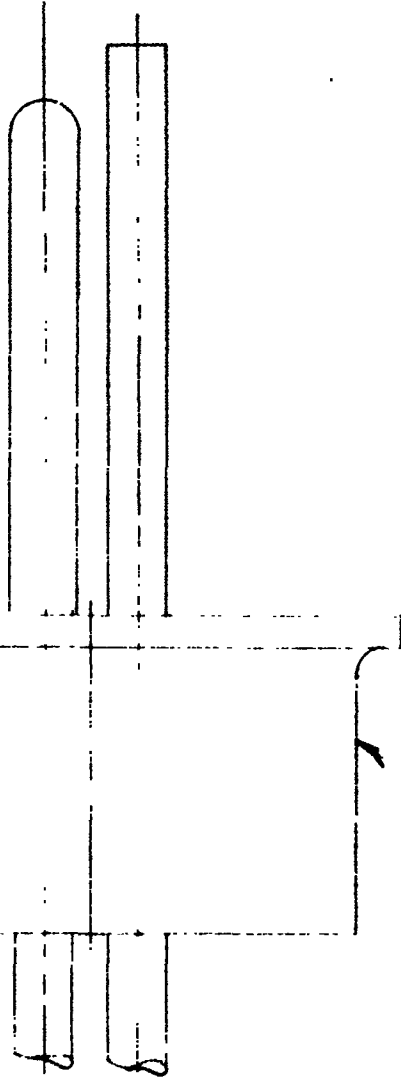
NEXT ASSY. B-SK-592

#1


REVISIONS

SYM	DESCRIPTION	DATE	APPD
△	SEE E.C.O # 150	3-17-63	111

SPACED TO
ON FOR
EFORE



HERMETITE HEADER
DWG B-SK-554

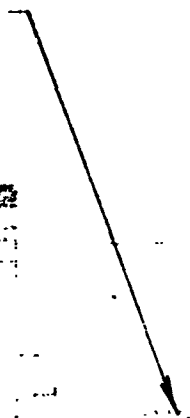
H. STOWE	DATE: 12-9-64	 <p>CRYONETICS CORPORATION BURLINGTON, MASSACHUSETTS</p>
SK (initials)	12-11-64	
ENGR. APPD J. O. M. I.	12-10-64	
PROD. APPD Ruston	12-10-64	
		TITLE
		SENSOR-INSULATING TEFLON COAT
CODE IDENT NO.	SIZE	DRAWING NO.
	B	SK-591
SCALE 1/16	WT	SHEET 1 OF 1

2

TOP
LEFT

1

24 THREADS PER INCH



2

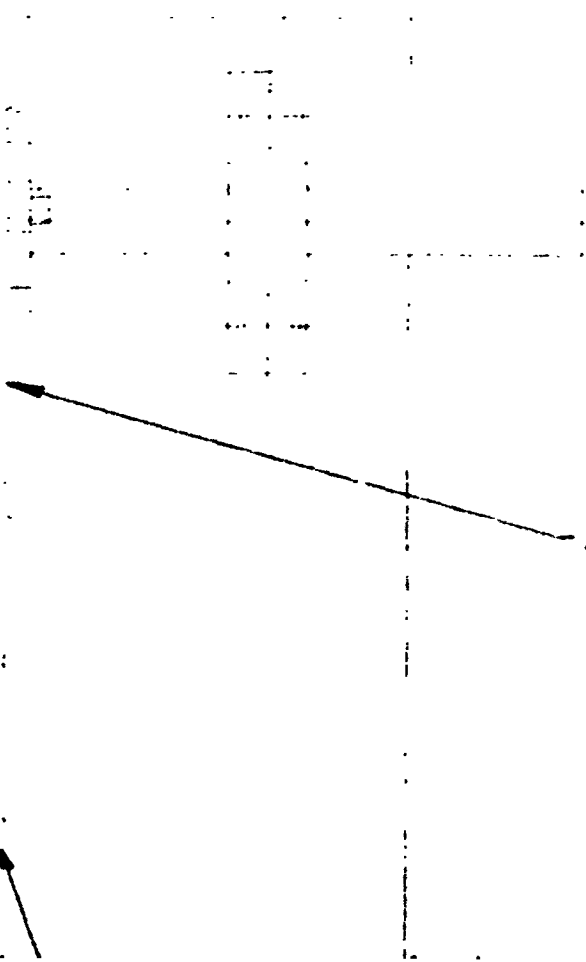
SYM



PLATINUM WIRE SPOOL

A schematic diagram of a platinum wire spool. It consists of a vertical rectangular frame with a horizontal line across the top. Inside the frame, there are several horizontal lines representing the wire. An arrow points from the text 'PLATINUM WIRE SPOOL' to the right side of the frame.

2



AUTOMATIC TEMPERATURE CONTROLLER

A schematic diagram of an automatic temperature controller. It features a vertical rectangular frame with a horizontal line across the top. Inside the frame, there are several horizontal lines representing the controller's components. An arrow points from the text 'AUTOMATIC TEMPERATURE CONTROLLER' to the right side of the frame.

317-1000

REVISIONS

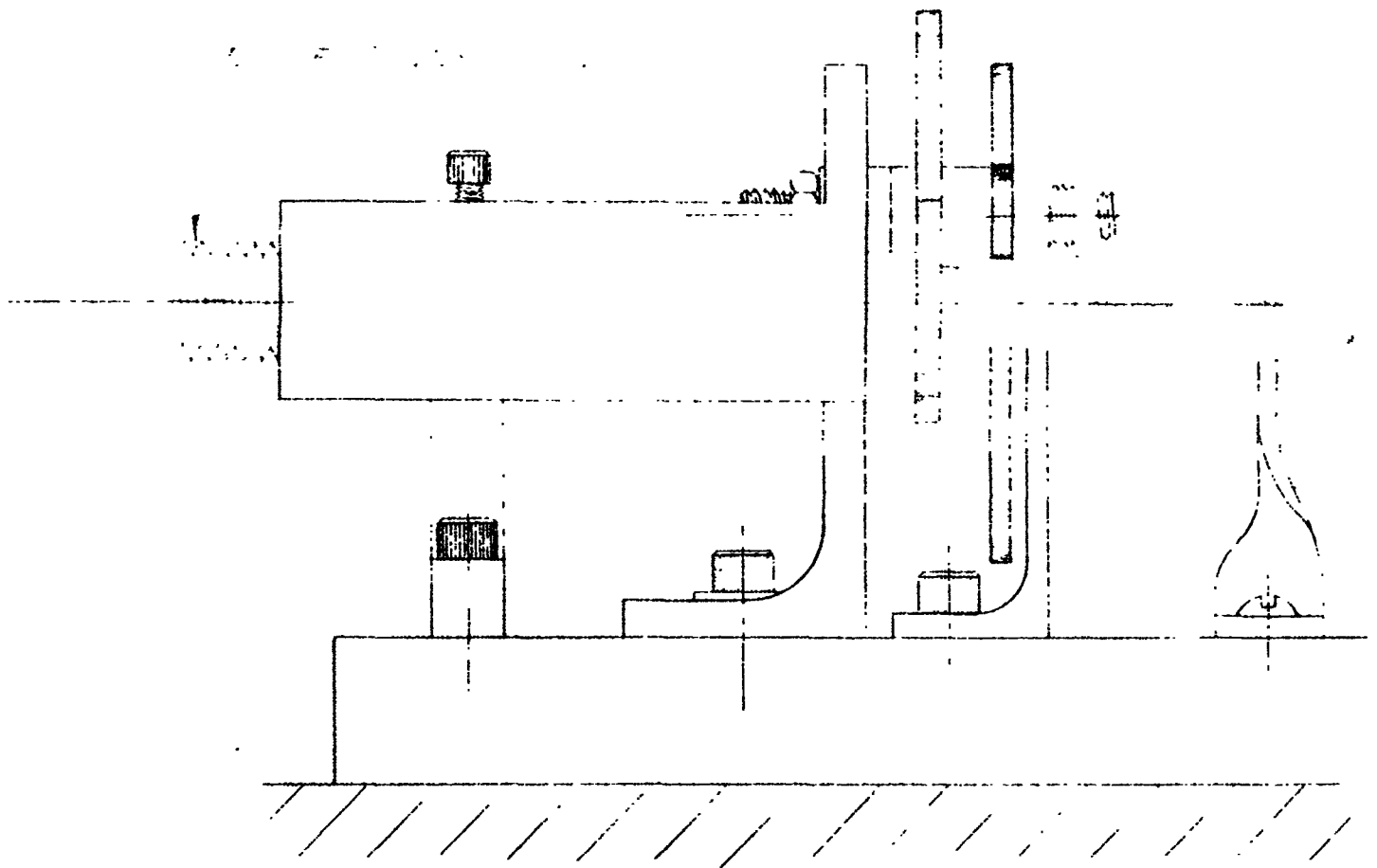
DESCRIPTION	DATE	APPD
-------------	------	------

#3

TOP
RIGHT

1. 11 - 2. 1987

1. 20 - 1. 500 PITCH - 1. 4 1987

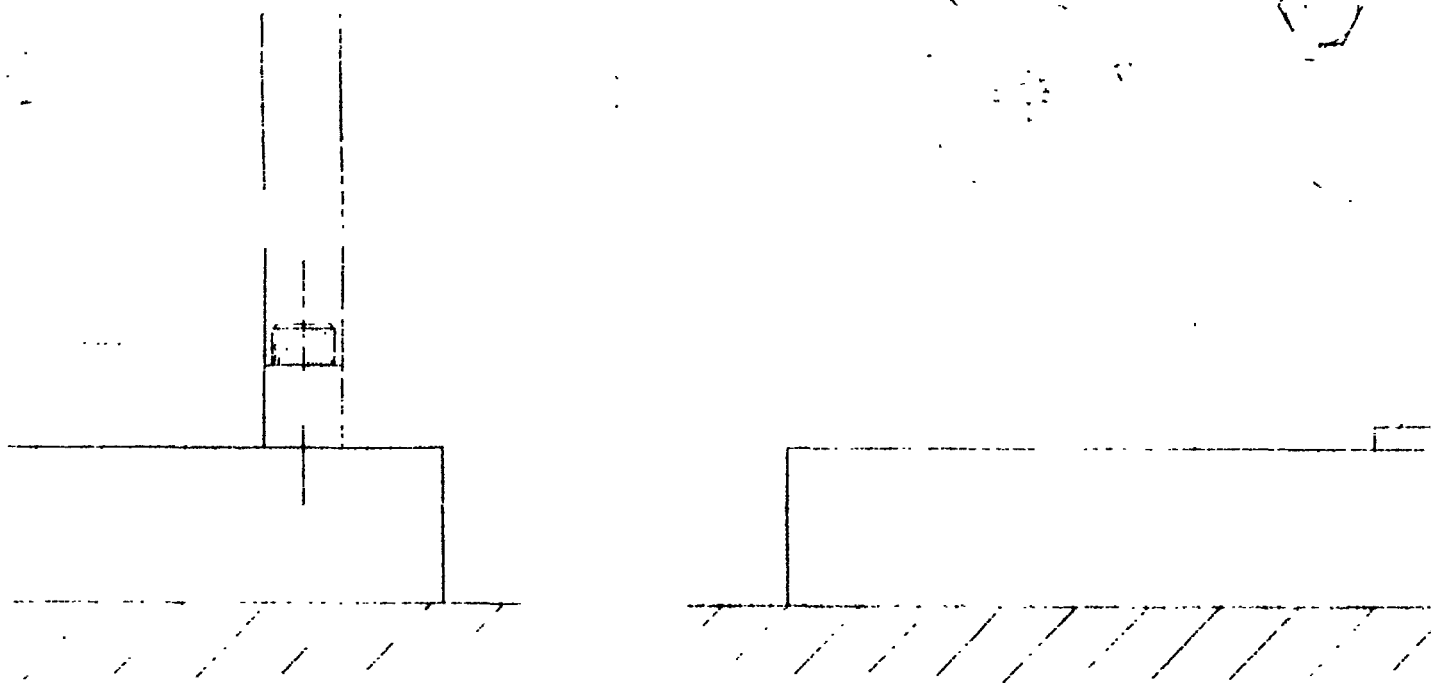


LOWER
LEFT

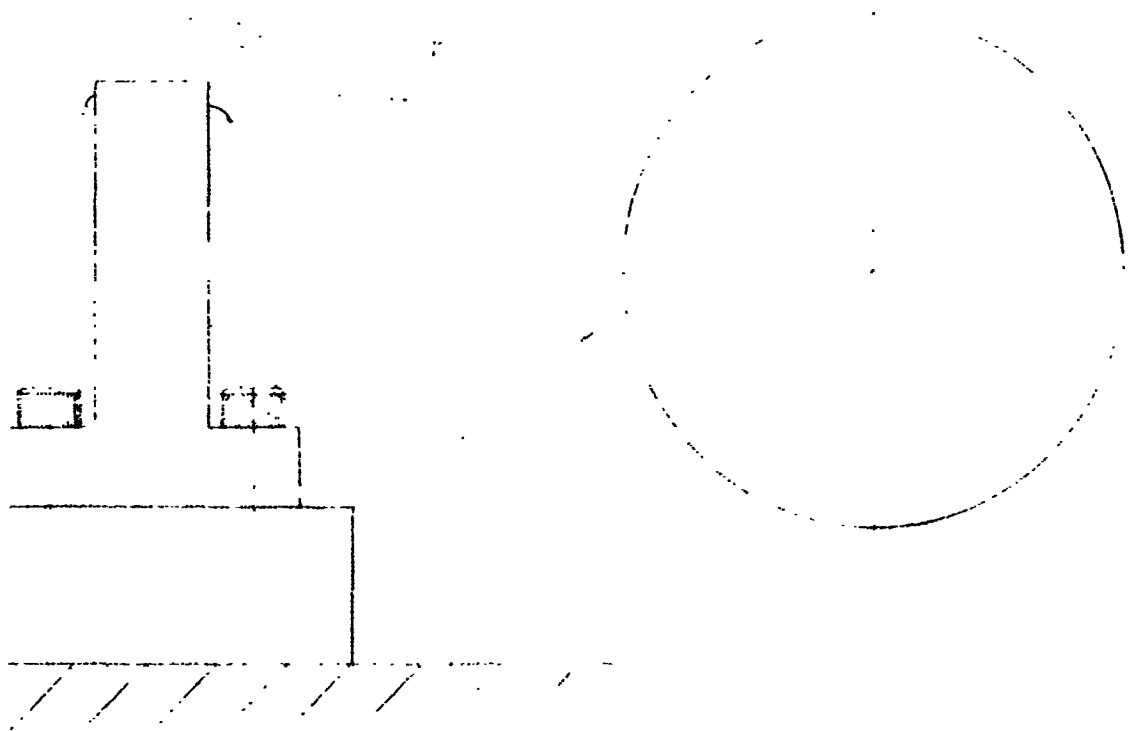
4

SENSOR

2 40 210 4.0 4.0 4.0



<p>UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON</p> <table border="1"> <thead> <tr> <th>FRACTIONS</th> <th>DECIMALS</th> <th>ANGLES</th> </tr> </thead> <tbody> <tr> <td>UNDER 6" ± 1/64</td> <td>2 PLACE ± .010</td> <td>± 1/2°</td> </tr> <tr> <td>OVER 6" ± 1/32</td> <td>3 PLACE ± .005</td> <td>∇</td> </tr> </tbody> </table>			FRACTIONS	DECIMALS	ANGLES	UNDER 6" ± 1/64	2 PLACE ± .010	± 1/2°	OVER 6" ± 1/32	3 PLACE ± .005	∇	DR <i>R. CLOUTIER</i>	
			FRACTIONS	DECIMALS	ANGLES								
			UNDER 6" ± 1/64	2 PLACE ± .010	± 1/2°								
			OVER 6" ± 1/32	3 PLACE ± .005	∇								
CHK													
ENGR. APPD <i>[Signature]</i>													
PROD. APPD													
MATERIAL	APPROVALS												
FINISH													



DATE:
4-12-65



CRYONETICS CORPORATION
BURLINGTON, MASSACHUSETTS

TITLE
4-12-65

TITLE *SENSOR WINDER*

CODE IDENT NO.

CODE IDENT NO.

SIZE

C

DRAWING NO.

SK-721

SCALE

SCALE *FULL*

WT

~

SHEET

#1

Lower Right

Before the header is secured in the chuck for winding a lock wrap of the .0005" platinum wire is made around the bottom of a straight pin on the header as shown in Cryonetics Corporation's Drawings SK-592 and SK-593. This locking wrap is resistance welded to the straight pin. The minimum electrode pressure of approximately 50-inch pounds was applied to the joint and the welder was set to deliver 1.5 watt - seconds which results in a good weld. After completion of the winding, a locking wrap is made at the top of the wind and welded as before. This is also shown in Cryonetics Corporation's Drawings SK-592 and SK-593.

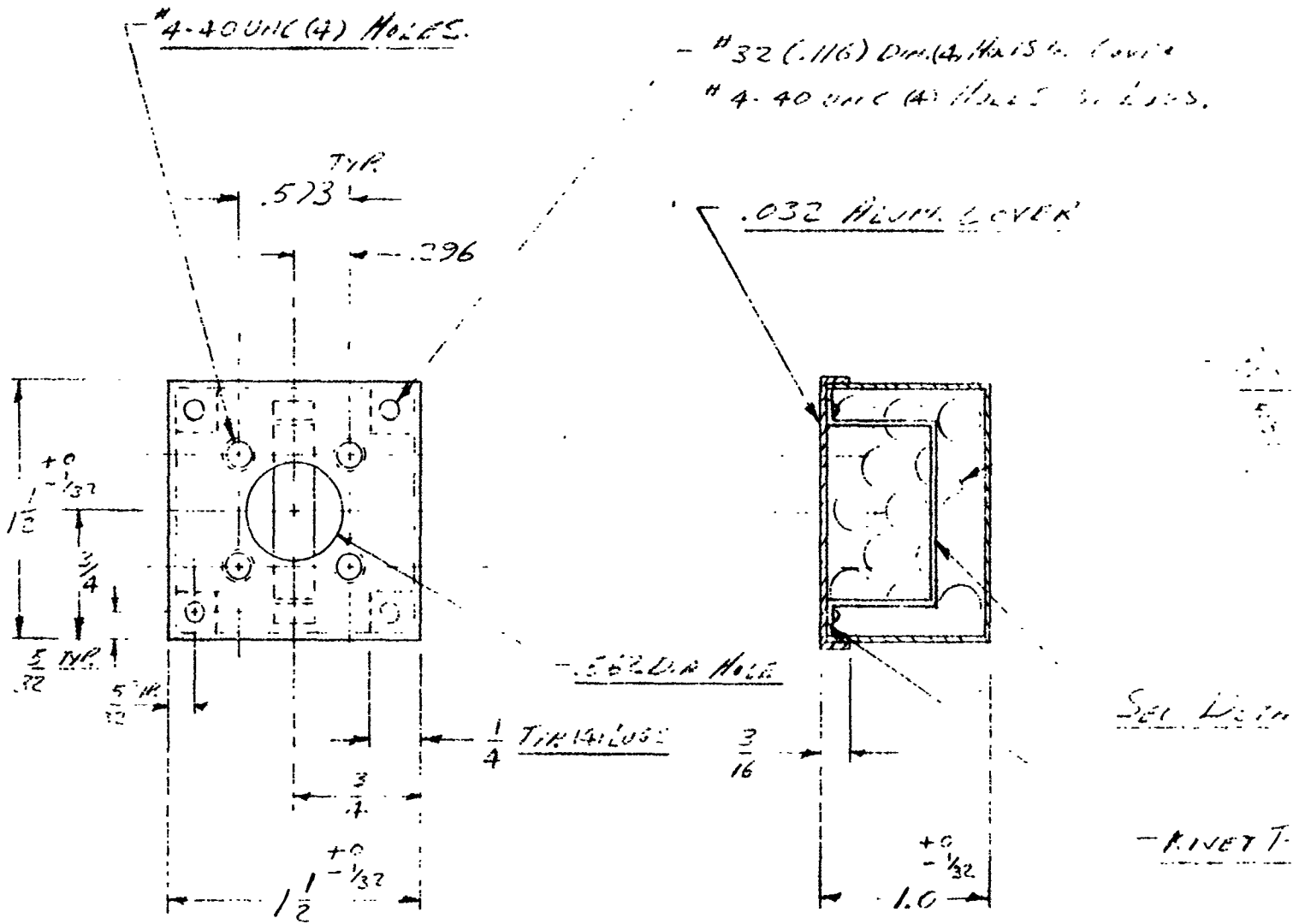
Once the sensors are wound, they are placed in an oven and raised to a temperature of 500°F for one (1) hours. This softens the outer teflon insulating coating sufficiently so that the platinum wire imbeds itself and holds the individual windings securely after cool-down.

The reference sensors are encapsulated after winding. The drawing of the cap is shown in Cryonetics Corporation's Drawing SK-590, and the reference sensor assembly capped is shown in Cryonetics Corporation's Drawing SK-594.

The sensors are capped in a helium atmosphere. When the capping is complete, they are leak checked with a mass spectrometer at a leak rate of 1×10^{-7} cc/second.

For actual use with the sensing system, the sensors are mounted on a support bracket in a protective envelope as shown in Cryonetics Corporation's Drawing SK-652.

The sensors are held firmly by crimping the base to the support bracket. As the sensor leads are stainless steel, they are soldered to the connectors. The connections are then washed with warm water and alcohol.



NOTES:

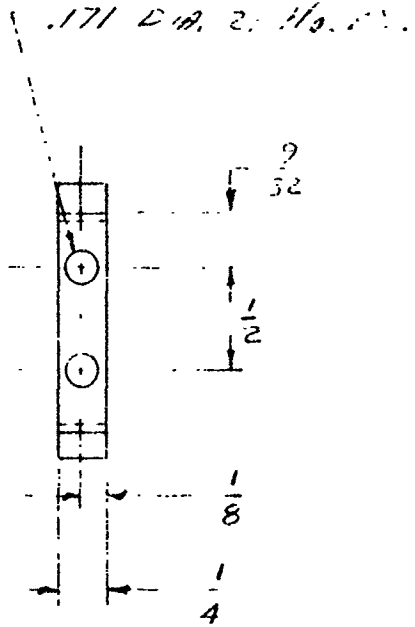
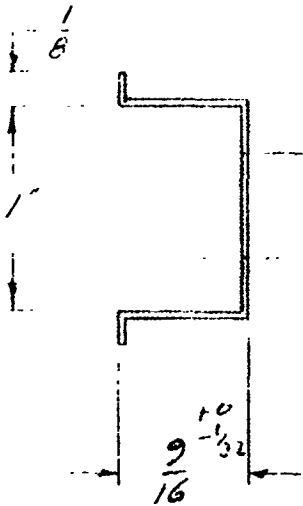
1. REMOVE ALL BURRS & SHARP EDGES.
2. ALL EXTERNAL WELDS TO BE GROUND SMOOTH.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON		
FRACTIONS	DECIMALS	ANGLES
UNDER 6" ± 1/64	2 PLACE ± .010	± 1/2°
OVER 6" ± 1/32	3 PLACE ± .005	✓
MATERIAL		
AS NOTED		
FINISH		
ANODIZE-MIL-A-8625		


REVISIONS

SYM	DESCRIPTION	DATE	APPD
-----	-------------	------	------

Handwritten: *SENSOR SUPPORT # 5052-432*



Handwritten: *SENSOR SUPPORT BRACKET; PART SET ALONG*

DR	NH	DATE:	2-2-65
CHK	NH	DATE:	2-11-65
ENGR. APPD	NH	DATE:	2-11-65
PROD. APPD	NH	DATE:	2-11-65
 CRYONETICS CORPORATION BURLINGTON, MASSACHUSETTS			
TITLE <i>SENSOR SUPPORT BRKT. & PROTECTIVE ENVELOPE - NAS8-11734</i>			
CODE IDENT NO.		SIZE	DRAWING NO.
SCALE		WT	SHEET
FULL			51-652

4.0 ELECTRONICS

In order to effectively utilize the ΔV that appears across the bridge (discussed in Section 2.2) when the active sensor passes from vapor to liquid, the circuitry which follows the bridge should respond only to liquid level changes, not transients or false signals. To insure this, the threshold of the output switch should be high enough to preclude triggering by transients or other false signals. For this reason the circuitry which follows the bridge has a narrow dynamic range.

The electronics package contains the following circuitry which will be described in order; the 6.8 VDC level set, the 20 VDC level set, the bridge circuit, the differential amplifier, the double-to-single ended stage. Reference is made to Cryonetics Corporation Drawing SK-676.

4.1 LEVEL SET 6.8 VDC

The 6.8 VDC level set circuit consists of a zener diode, which obtains its voltage from the 24-32 VDC input. This constant 6.8 VDC is used to supply power to the bridge circuitry.

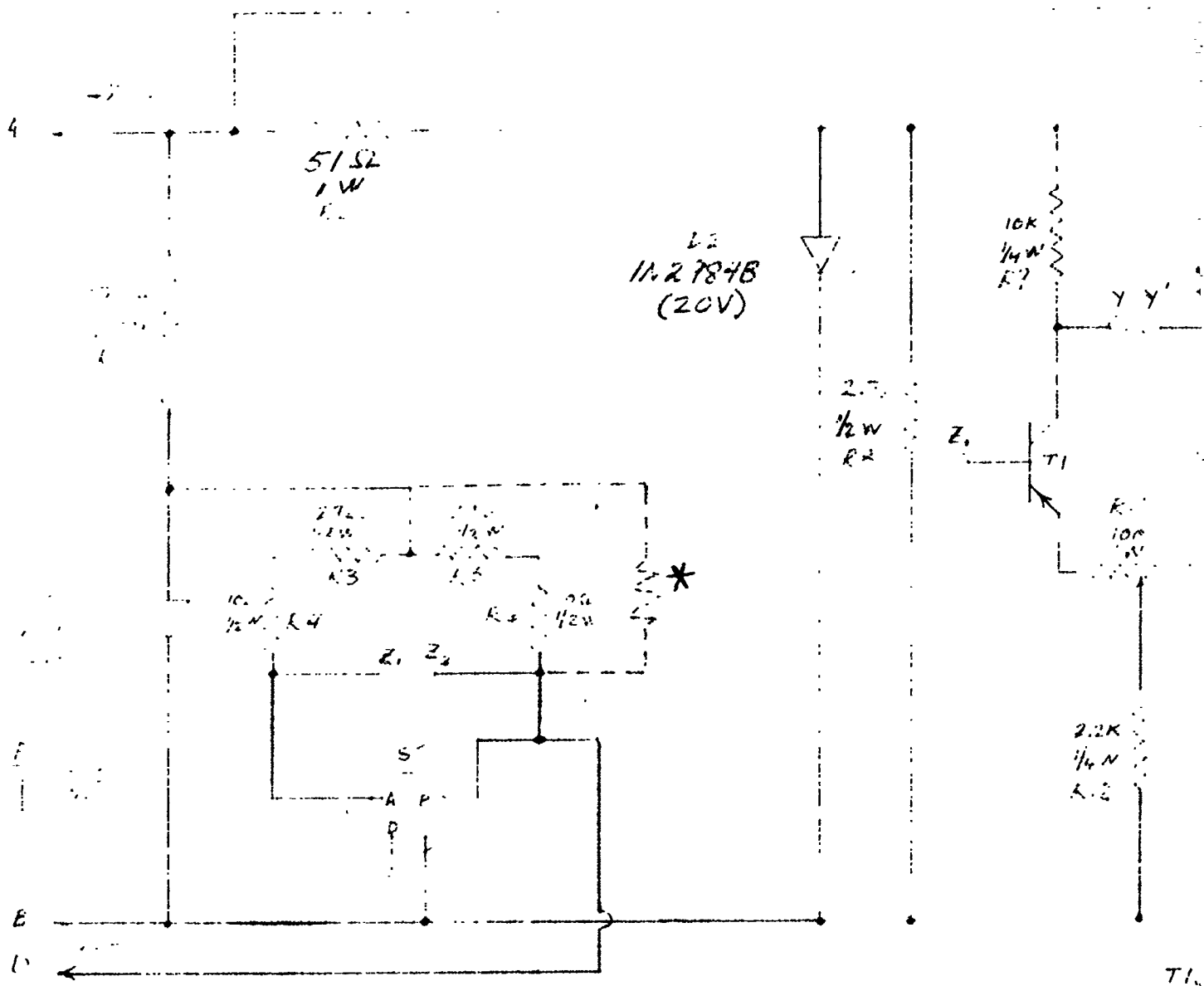
4.2 BRIDGE

The bridge consists of two (2) fixed resistance arms of 37 ohms each and the sensor arms. It is to be noted, that in two (2) instances, it was necessary to parallel one (1) fixed arm of the bridge with an additional resistor to obtain initial bridge balance, because of a slight difference in the sensor resistance at room temperature. When the "wet" sensor is immersed in the cryogenic liquid, the bridge becomes unbalanced and a difference signal appears across the terminals Z_1 , Z_2 , which are tied to the base of T1 and T2 respectively.

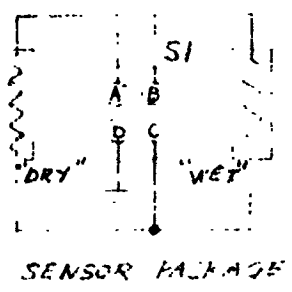
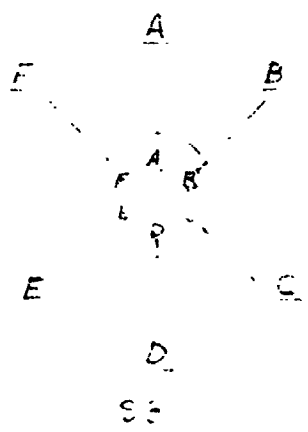
4.3 DIFFERENTIAL AMPLIFIER

The differential amplifier requires a minimum input voltage, or ΔV , of about 100 MV to turn the switch completely on. ΔV 's greater than 300 MV saturate the amplifier.

T1 and T2 comprise the differential amplifier. The gain of this amplifier is approximately 60 for small signals (130 MV) across Z_1 and Z_2 , and decreases to approximately 8 for large signals (1V) across Z_1 and Z_2 .



* PADDING RESISTOR TO BAL.



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ON

FRACTIONS	DECIMALS	ANGLES
UNDER 6" ± 1/64	2 PLACE ± .005	± 1/8°
OVER 6" ± 1/32	3 PLACE ± .002	✓

MATERIAL

FINISH

4.4 DOUBLE-TO-SINGLE ENDED STAGE

The output of the differential amplifier is fed to Y, Y^1 , which is the input to the double-to-single ended stage, T3 and T4. The gain of this stage is approximately 0.5. The output is taken at point X and fed to the base of the emitter follower driver.

4.5 EMITTER FOLLOWER DRIVER

The emitter follower driver, T5, is in a conducting state at all times. Its emitter is held constant at 16V by D3, a zener diode. The output of T5 is taken across the 200 ohm resistor R21, which is connected to the cathode end of D3. As the bridge goes from a balanced to an unbalanced condition, the base to emitter voltage of T5 changes. This change appears across the series combination of D3 and R21. D3 tends to hold the voltage across its terminal constant. It does this by passing more or less current as conditions demand. Therefore, as the base-to-emitter voltage of T5 increases an increase in current through D3 and R21 raises the voltage across R21. This is applied to the base of T6.

4.6 SWITCHING STAGE

The switching stage, T6, is near cut-off when the bridge is balanced. In this condition less than 0.5V appears across the external 550 ohm load resistor. When the bridge becomes unbalanced by as little as 100 MV, T6 is driven into saturation and minimum of 23 volts, with an input of 24 volts, appears across the 550 ohm load resistor.

4.7 SIMULATED OPERATION

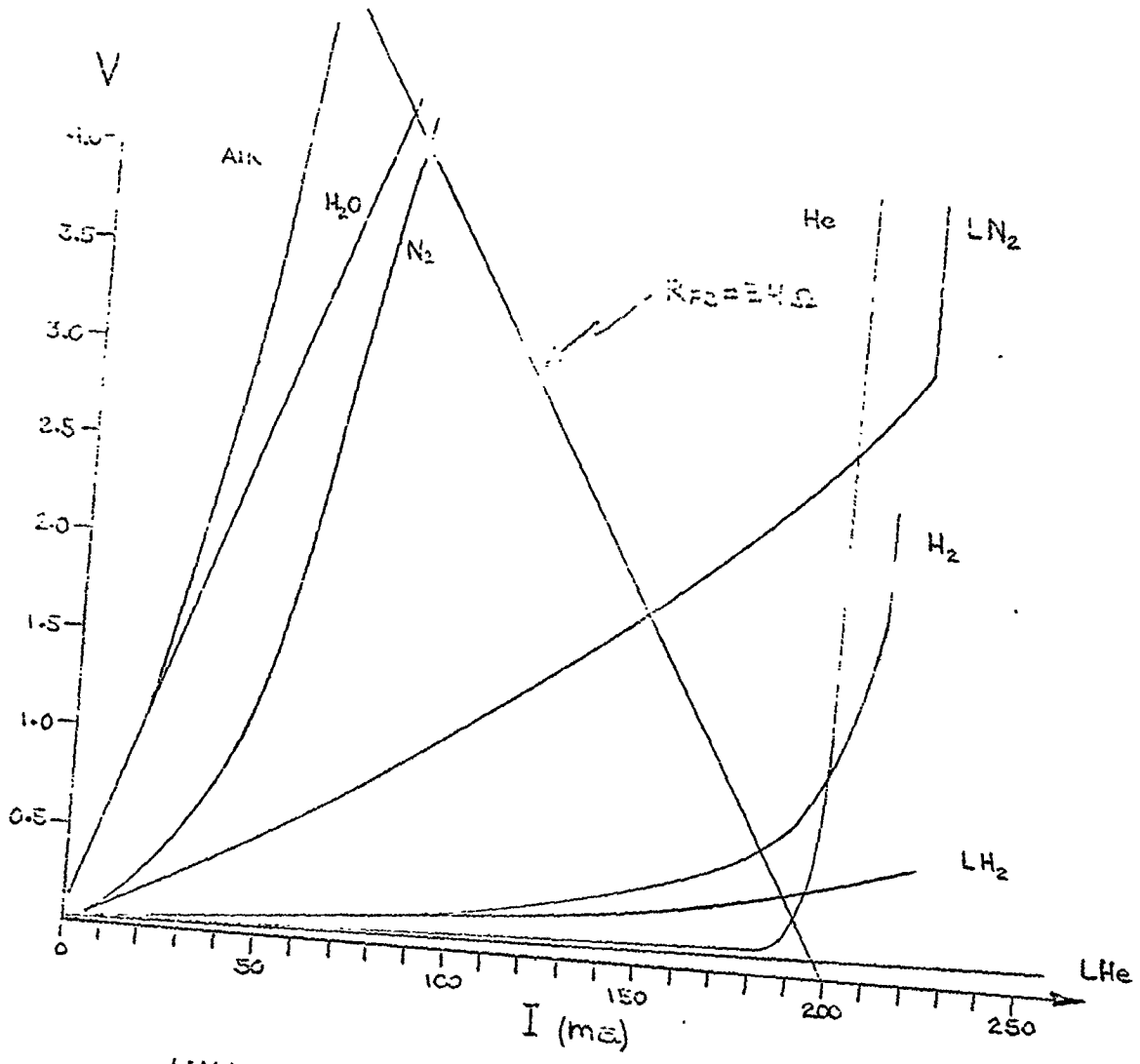
In order to simulate the presence of liquid when the sensing probe is dry, it is merely necessary to unbalance the bridge. With reference to the circuit schematic, Cryonetics Corporation's Drawing SK-676, it can be seen that by applying 24 to 32 V to pin D of connector S3, one effectively shorts the "wet" sensor, unbalancing the bridge.

5.0 OPERATION

The sensors have been designed to operate in the following media: water, liquid nitrogen, RP-1 (JP-4), liquid oxygen, liquid hydrogen and liquid helium. Tests have been conducted in water, JP-4, liquid nitrogen and liquid helium. The results of these tests are summarized in the curves of Figure 11. These VI curves were generated by placing a 55 ohm room temperature platinum sensor in the vapor of a particular media and then varying the current through the sensor in discrete steps. The voltage across the sensor was monitored after each current change. These steps were repeated for the various liquids. Data was not obtained for hydrogen and oxygen. The hydrogen curve shown was calculated and the response in oxygen is similar to that of nitrogen. These facts were mentioned previously.

By plotting the curves of Figure 11 compositively, the universality of the sensor becomes apparent. If one now places a load line on the curves of Figure 11, employing the method used in Section 2.1, it is possible to predict the amplitude of the signals (ΔV) that can be obtained as the "wet" sensor passes from the vapor to the liquid. The value of the load line shown in Figure 11 was chosen for $R_{f2} = 34$ ohms. However, many possible load lines can be used. The first criteria for choosing a particular load line should be based on the minimum signal required for positive switching. This means that one should choose a load line that will produce a minimum ΔV of 100 millivolts when passing from the vapor to the liquid of a particular media. It may not be possible for one load line to meet this criteria for all media simultaneously. If this is the case, single load lines can be used to optimize operation for particular media.

The reason for using the 34 ohm load line on the curves of Figure 11 is apparent when one refers to Figure 11. It can be seen that in order to realize a useable signal as the "wet" sensor passes from the vapor to the liquid in helium or hydrogen, the sensor current required is approximately 150 to 180 milliamps. With the sensor current this high, the load line becomes universally useful for all media.



UNIVERSAL VI CURVES FOR A
55 OHM (AT 300°K) SENSOR

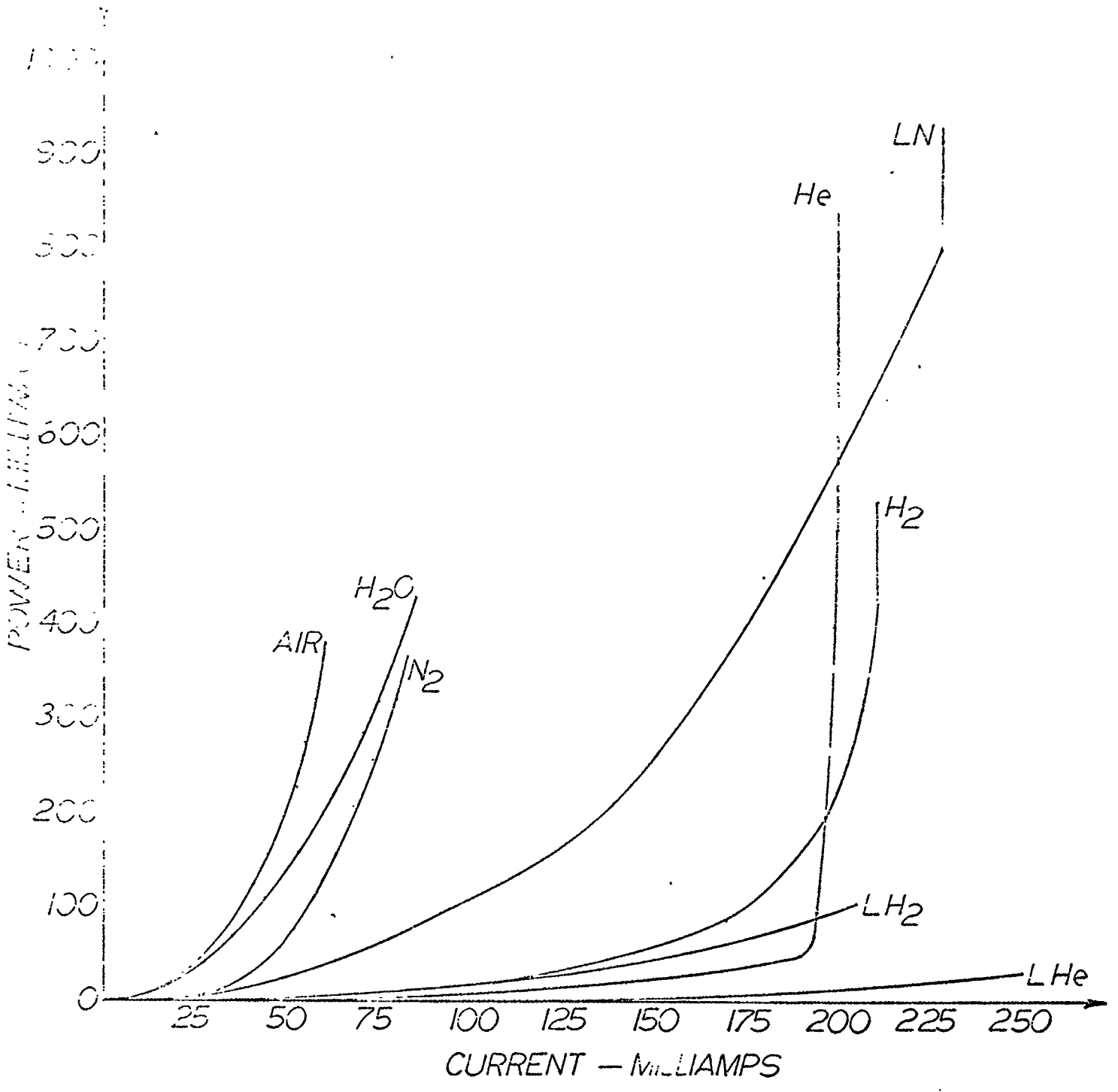
FIG. 11

5.1 PERFORMANCE

The sensing probe has level accuracy related to the thickness of the pc sts; $\approx 0.016''$ diameter. Even including the effects of a meniscus, the accuracy is well within $\pm 0.100''$ as called for in the specifications. The time response of the electronic circuitry is 10 microseconds or better for simulated operation.

It is of interest to know the amount of power that was applied to the sensors when the characteristic VI curves of Figure 11 were generated. This is especially important when placing a load on the curves of Figure 11 when sensor power dissipation must be kept to a minimum. For this reason, Figure 12, the sensor power vs. sensor current curves were generated from the characteristic V-I curves of Figure 11.

Fig. 1

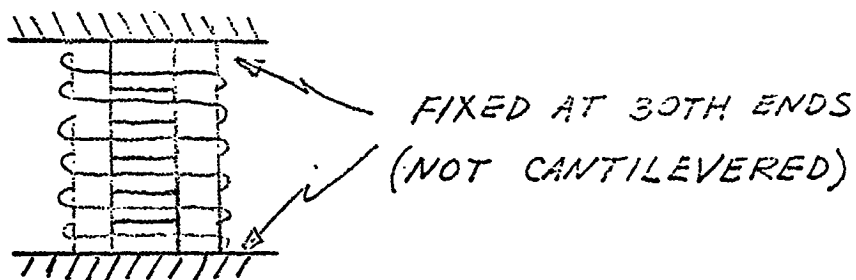


SENSOR POWER vs. SENSOR CURRENT FOR VARIOUS SERVICE MEDIA

6.0 PROJECTION

In order to "redesign" the Liquid Level System, in retrospect, let us commence at the transducer end and work through to the switch, pointing out problem areas and possible solutions.

The physical dimensions of the sensors limit the amount of platinum wire that can be wound on them. This fact dictates that the sensors must be low impedance devices and therefore to get reasonable static voltages across them large static currents are necessary. As we are operating with power source voltages of from 24 to 32 volts DC it is necessary to drop this voltage to 6.8 volts to supply the bridge power. Clamping at 6.8 volts with a zener diode requires a series dropping resistor. Because of the high bridge currents the series dropping resistor is fairly high wattage and a great deal of heat is generated and transferred throughout the electronics package. This is undesirable. An obvious solution is to reduce the bridge power. From Fig. 11 we see that if we reduce the static sensor current our signal is decreased when the active sensor goes from "Dry" to "Wet". To reduce bridge current and still maintain sufficient signal the sensor windings could be increased if the sensors were made larger. We believe that a larger sensor, constructed and supported as shown in Fig. 13 could be designed to meet all mechanical specifications. Increasing the impedance of the bridge would allow us to operate at lower currents reducing the dissipation in the dropping resistor.



Sensor

FIG. 13

Another possible solution would be to drive a high impedance bridge with reasonably high voltage pulses of low duty cycle. These pulses would provide high currents but the average bridge power could be lower. The amplification of the bridge ΔV due to bridge unbalance could be performed by AC amplifiers. This would eliminate the inherent problems of DC amplifiers. The amplifier output would be integrated to provide a DC level shift to trigger a switch.