LOW LEVEL GAS PURGED RADIOMETER

MODEL NO. R8100A

FINAL REPORT, PHASE II

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Prepared for:

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TABLE OF CONTENTS

I. INTRODUCTION

Considerable interest has developed during the past several years in the field of low level thermal radiation. The importance of this area is seen when one considers the fact that, although current and past instrumentation techniques have defined the high heating rate regions encountered during launch, staging, re-entry and static firing, little work has been accomplished until now in low level radiant heat flux measurements. Yet sustained low-level radiation for prolonged periods can have equal or greater damaging effects compared to those from high heat flux for short duration.

Instruments have been fabricated and are commercially available which will operate under low input conditions. These instruments are however relatively low in output and have excessively long response times. They are therefore not adequate for measuring rapidly changing conditions. Furthermore, in order to obtain reasonable working output signals, the instruments have of necessity been quite large.

It became apparent that in order to overcome these shortcomings a new design concept was necessary which would provide the following improvements:

1. Smaller over-all size.
2. Faster response to changes in input.
3. Higher millivolt output signals compatible with available telemetry systems.

Additional features which were desirable are a wide view angle and an effective gas purge system.

The scope of work encompassed by this program covered the design, development, fabrication and testing of wide angle low heat flux level gas purged radiometers. The units were divided to cover three separate ranges: 0 - 1, 0 - 2, 0 - 5 Btu/ft^2-sec. Each instrument was to have a nominal output of 10 millivolts under full scale input.

Initial investigations were directed toward the Hy-Cal Engineering Asymptotic® rapid response type calorimeter. It was found that, although a multiple sensor unit could be used for the 0 - 2 and 0 - 5 Btu/ft^2-sec. ranges, the performance in the 0 - 1 Btu/ft^2-sec. range would be marginal.

In view of the extremely low energy levels involved in the lowest range instrument the applicability of the Hy-Cal Engineering Hy-Therm calorimeter concept was also investigated. With minor modifications to this design a sensor was evolved which was capable of providing the desired output for all three ranges. The final instruments were fabricated using this sensor, designated the "Hy-Therm H".

II. ASYMPTOTIC ® SENSOR

The Asymptotic® sensor is capable of giving fast response with small diameters and it has a high degree of reliability. It was therefore a logical first choice for consideration in this application. (See Theory and Principle for the Asymptotic® Rapid Response Calorimeter at the end of this section.)

In the design of an Asymptotic® rapid response radiometer, the limitations which are imposed by the inherent characteristics of such a sensor must be considered in order to obtain a high output. Two techniques may be used. First, the foil may be made large in diameter; and second, the foil may be made thin. Each of these parameters tend to produce a high output signal. The large diameter, as noted above, results in very slow response to changes in input, while the thickness of the foil is limited by the handling characteristics and fabrication techniques. The use of extremely thin foils will decrease the reliability of the instrument under flight environmental conditions. Since a single sensor, having the desired output, would have a response time of two to three seconds, it becomes necessary to consider several small diameter sensors connected in electrical series such that the outputs are additive. The small diameter sensors would individually and collectively have a short response time, while the desired output could be obtained through the use of a sufficient number of these sensors.

It was thus apparent that in the design of a multi-sensor instrument three parameters must be considered. These parameters are foil thickness, foil diameter, and number of sensors. The foil thickness is limited to approximately .0005 inches or greater, while the number of sensors is limited by the available space and, of course, the sensor diameter chosen.

An additional feature which had to be considered is the effective view angle of the resulting array of sensors. It is necessary that all sensors be identical and that the geometrical array is symmetrical about all axes. If these two conditions are not met, the view angle can be directionally dependent.

In order for the individual sensor outputs to be additive, all units must be electrically isolated from each other. This can be accomplished in several ways. One technique is to mount the units in an electrically insulating material such as phenolic refrasil. This technique has the drawback that, because of the low thermal conductivity of the phenolic type materials no common heat sink characteristics are offered the individual sensors which could cause them to operate at different temperature levels. Another technique, which appeared most practical, was the use of an anodized aluminum body. Holes just large enough to accept the outside diameter of the individual sensors are drilled in the aluminum body and the entire part anodized. The sensors can then be cemented in place and will be electrically isolated by the anodizing, while still offering good thermal contact and good common heat sink characteristics for all sensors.

An analysis of the optimum size and arrangement of the sensors was conducted and it was concluded that seven (7) sensors, approximately 1/4 inch in diameter, should be used. These sensors would be arranged with six (6) placed on a 3/4 inch diameter circle with one (1) unit in the center of the circle.

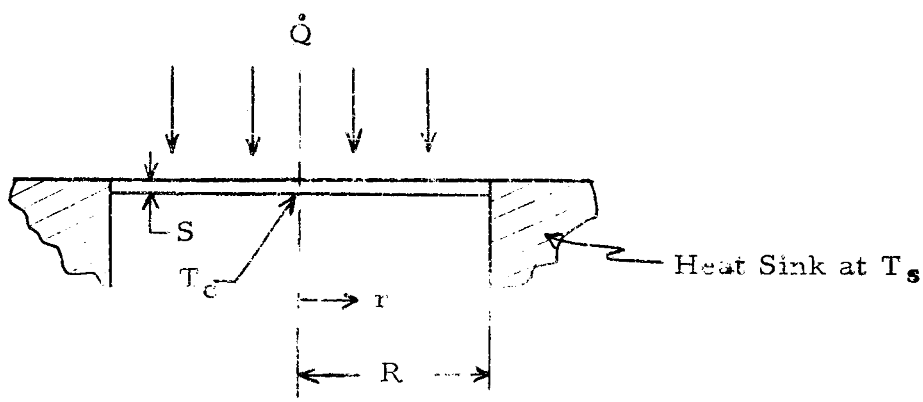
It can be shown that by using the minimum foil thickness and the maximum foil diameter, within the 1/4 inch over-all sensor diameter, the 10 millivolt output signal can be obtained for instruments operating over the ranges of 0 to 2 and 0 to 5 Btu/ft^2-sec. However it was concluded that the fast response, multi-sensor, concept was marginal in terms of output signal in the 0 to 1 Btu/ft^2-sec. range.

THEORY AND PRINCIPLE
for the
ASYMPTOTIC® RAPID RESPONSE CALORIMETER

All Hy-Cal Engineering Asymptotic® rapid response type heating rate transducers, whether used for total heat flux measurements, or as the sensor of a radiometer for radiant energy measurements only, will follow the theory and principle incorporated in the present line of Hy-Cal rapid response heating rate sensors. An instrument employing these principles provides a direct readout in millivolts which is proportional to heating rate. Therefore, no loss coefficient or correction for time interval is required, as in conventional slug or slope type heating rate sensors. This transduction method has been proven on such programs as Minuteman, Polaris, Titan, Thor, Centuar, Saturn, etc. to name a few.

The Asymptotic® calorimeter consists basically of a thin metallic foil suspended over a cavity in a heat sink, thermally and electrically attached to the heat sink at the periphery of the cavity using metallurgical bonding techniques. By making the foil from a thermoelement material such as Constantan, the heat sink from a second thermoelement material such as copper, and metallurgically bonding a fine wire of the same material as the heat sink to the center of the foil, a differential thermocouple is formed with the hot and cold junctions at the foil center and periphery respectively. The temperature difference between center and periphery of the foil is directly proportional to the heat flux over the surface of the foil.

The governing equations can be developed from the theoretical model shown below.



A heat balance on an elemental annulus of the foil will result in the standard heat conduction equation, in polar coordinates, with a heat generation (absorption) term. That equation is as follows:

$$\frac{\rho C}{K} \frac{\partial T}{\partial t} = \frac{\dot{Q}}{SK} + \frac{1}{r} \frac{\partial T}{\partial t} + \frac{\partial^2 T}{\partial r^2} \cdot \qquad (1)$$

The boundary conditions for this equation are:

$$T = T_s \text{ at } t = 0, \qquad 0 < r < R \qquad (2)$$

$$T = T_s \text{ for } 0 < t < \infty \qquad r = R \qquad (3)$$

The steady state solution to the above equation is:

$$T = T_s + \dot{Q} \frac{R^2 - r^2}{4\ K\ S} \qquad (4)$$

or, rearranging and setting r = 0 (foil center)

$$\dot{Q} = (T_c - T_s) \frac{4KS}{R^2} = \frac{4KS}{R^2} \Delta T \qquad (5)$$

Analysis of the transient solution of equation (1) shows that the instrument response time to a step change in heating rate (i.e., time to rise to 63.2% of steady state output) is given by the close approximation,

$$\tau = \frac{\rho C R^2}{4K} \qquad (6)$$

It can be seen from equation (5) that the temperature difference between the center and edge of the foil is directly proportion to the heating rate, $\dot{Q}$. If the temperature difference is measured by employing the differential thermocouple concept, the output, E, is directly proportional to $\dot{Q}$.

In order to be rigorously correct, the effects of heat sink temperature should be included in equation (5). The resulting equation is, after substitution of $E = e_o (1 + \beta \bar{T}) \Delta T$;

$$E = \frac{\dot{Q} R^2 e_o (1 + \beta \bar{T})}{4SK_o (1 + \gamma \bar{T})} \cdot \qquad (7)$$

It should be noted in reviewing equation (7) that in order to obtain a linear output signal directly proportional to flux, it is necessary that all terms of this equation remain constant with foil temperature. All terms essentially fulfill this requirement except terms $(1 + \beta \bar{T})$ and $(1 + \delta \bar{T})$. If, however, these terms are equal they can be cancelled and one obtains the simple relationship:

$$E = \frac{\dot{Q} R^2 e_o}{4 S K_o} \qquad (8)$$

Thru the proper choice of materials this is possible at least over a limited, and fortunately the normal, temperature range of operation. In view of its importance, Hy-Cal Engineering has given this aspect of the problem considerable thought. After reviewing and working with a wide variety of materials, it was found that copper/Constantan is best able to meet these requirements, at least over a heat sink temperature range of from ambient to approximately 400°F.

NOMENCLATURE

E = output signal

$\dot{Q}$ = heat flux

R = radius of foil

r = radius (variable)

e = thermoelectric potential of thermoelement combination

K = thermal conductivity of foil

S = thickness of foil

C = specific heat of foil

ρ = density of foil

T = temperature

t = time

δ = constant which defines variation of thermal conductivity with average foil temperature

β = constant which defines variation of thermoelectric potential with average foil temperature

τ = time constant of calorimeter (time for calorimeter output to reach 63% of steady-state output when subjected to a step input of flux)

Subscript:

c = denotes center of foil

o = denotes value at ambient conditions assumed equal to 75°F

s = denotes heat sink

III. HY-THERM SENSOR

In view of the problem described in the previous section, it was felt that another sensor concept should be investigated. Recent developments in the Hy-Cal Engineering "Hy-Therm" calorimeter indicated that with minor modifications it would also be applicable to use in a low level radiometer. The "Hy-Therm" is a sensor concept developed by Hy-Cal Engineering based on the principle of a thermopile. The output characteristics are limited, as in the Asymptotic® rapid response type, by space available and the desired response time. It is, however, capable of providing higher output in less space than that required by the Asymptotic® rapid response sensor. The "Hy-Therm" was being used in the higher heat flux range between 10 and 25 Btu/ft^2-sec. It appeared, however, that minor modifications to the system would provide the desired output.

The "Hy-Therm" type sensor has several advantages over other more conventional types. First, by increasing the over-all sensor receiving area, the output can be increased without affecting the response time. Second, if the response time is of little or no concern, the attainable full scale output can be made very high, typical values being as high as 100 to 200 millivolts. Third, the "Hy-Therm" is a very rugged instrument since the sensor itself is bonded directly to the heat sink. There is, therefore, no problem of suspended masses which could cause resonance problems during vibration.

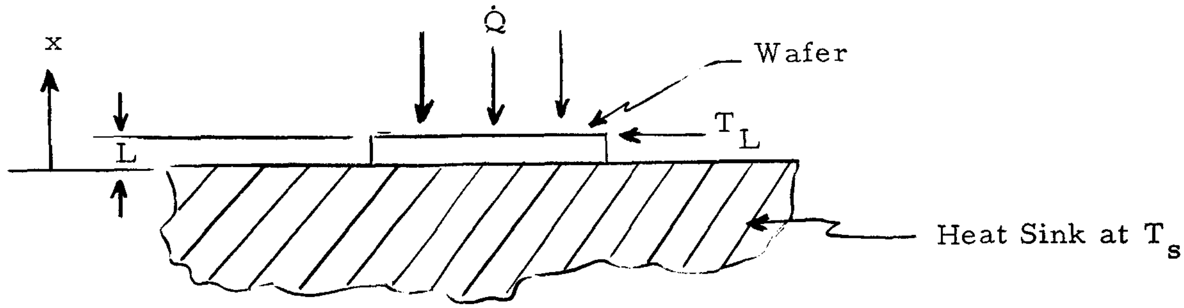
Following is an analysis of this type instrument entitled "Theory and Principle of the Hy-Therm Output Calorimeter". This analysis shows the modes of heat transfer within the instrument itself and shows the derivation of the governing equations indicating the major operational parameters.

THEORY AND PRINCIPLE
of the
HY-THERM^{tm} HIGH OUTPUT CALORIMETER

The Hy-Cal Engineering Hy-Therm^{tm} type heating rate transducers, regardless of range, size, or mode of application, functions according to the theory and principle of a simple thermopile. An instrument operating on these principles will provide a direct readout in millivolts proportional to heating rate. The output signal can be made very large by increasing the number of active thermoelectric junctions, limited only by the space available.

The Hy-Therm^{tm} calorimeter consists basically of an insulating wafer, with a series of thermocouples consisting of thermoelement combinations such that consecutive thermoelectric junctions fall on opposite sides of the wafer. This assembly is bonded to a heat sink to assure heat flow through the Hy-Therm^{tm} sensor. Heat is received on the exposed surface of the wafer and conducted through to the heat sink. A temperature drop across the wafer is thus developed and is measured directly by each junction combination embodied along the wafer. Since the differential thermocouples are connected electrically in series, the voltages produced by each set of junctions is additive, thereby amplifying the signal directly proportional to the number of junctions. The temperature drop across the wafer, and thus the output signal, is directly proportional to the heating rate.

The governing equations can be developed from the theoretical model shown below.



A heat balance on an elemental volume of the wafer results in the standard one dimensional heat conduction equation in Cartesian coordiantes as follows:

$$\frac{\rho C}{K} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

The boundary conditions for this equation are:

$$T = 0 \text{ at } x = 0 \tag{2}$$

$$-K \frac{\partial T}{\partial x} = \dot{Q} \text{ at } x = L \tag{3}$$

$$T = 0 \text{ at } t = 0 \tag{4}$$

The steady state solution to the above equations, which can be obtained by inspection, is,

$$T = T_L + \frac{\dot{Q}x}{K} \tag{5}$$

or, setting x = L and rearranging,

$$\dot{Q} = (T_L - T_s)\frac{K}{L} = \frac{K}{L}\,\Delta T \tag{6}$$

The transient solution to equation (1) is far more complex. It includes an infinite exponential series which describes the transient characteristics. It can be shown, however, that the first term of the series is a valid approximation of the sum within less than 1%. The response time to a step change in input (i. e., time to rise to 63% of steady state output), as given by the first term, is,

$$\tau = \frac{4 \quad CL^2}{K\pi^2} \tag{7}$$

From the equation (6) it is seen that the temperature difference between the two surfaces of the wafer is directly proportional to the heating rate, $\dot{Q}$. A differential thermocouple measuring this difference will, therefore, have an output, E, which is proportional to $\dot{Q}$.

In order to indicate the true characteristics of the transducer, equation (6) should be modified to include temperature dependent thermal properties and the temperature dependence of the thermoelectric properties of the differential thermocouples. Making these additions and rearranging terms, results in the following equation for the voltage output of a transducer, having N sets of thermocouple junctions:

$$E = \frac{N\dot{Q}L \quad _o(1 + \beta T)}{K_o\,(1 + \gamma T)} \tag{8}$$

It should be noted in reviewing equation (8) that in order to obtain a linear output signal directly proportional to heat flux, it is necessary that all terms in the above equation remain constant. Since the temperature of the heat sink cannot be expected to stay constant, the effects of coefficients β and γ are significant. If $\beta = \gamma$ the instrument will be linear, and will follow equation,

$$E = \frac{\dot{Q} L e_o}{K_o} \tag{9}$$

With the proper choice of materials, behavior of the sensor in accordance with equation (9) can be realized over a normal working temperature range. The standard Hy-Cal Engineering Hy-Therm[tm] embodies such materials.

NOMENCLATURE

E = output signal

$\dot{Q}$ = heat flux

L = thickness of wafer

x = space coordinate

e = thermoelectric potential of thermoelement combination

N = number of active differential thermocouples connected in series

K = thermal conductivity of wafer

C = specific heat of wafer

ρ = density of wafer

T = temperature

t = time

γ = constant which defines variation of thermal conductivity of wafer with temperature

β = constant which defines variation of thermoelectric potential with temperature

τ = time constant of sensor (time for output to reach 63% of steady state when subjected to a step input of flux

Subscripts

s = denotes heat sink

L = denotes heated surface of wafer

o = denotes value at ambient conditions

Model units fabricated according to a modified Hy-Therm design proved to be capable of fulfilling the requirements of all three instrument ranges, and the final units were made in this manner. The new design is identified as the "Hy-Therm H". A photograph and drawings of the final instrument are included at the end of the report.

IV. GAS PURGE

A critical factor in the design of the radiometer is the arrangement used to prevent sooting of the window during operation of the instrument. A deposit of any kind on the window would of course change the amount of radiation transmitted to the sensor and would effect the calibration. The typical solution to this problem is to keep gas flowing over the face of the window to sweep away all soot particles.

The use of a conventional conical purge system was investigated. This consisted of a nitrogen gas inlet at the back of the transducer which led to a plenum surrounding the spout. From this chamber the gas moves through a conical annular space surrounding the sensor. This ring is very accurately machined to force the gas to flow up over the window in a conical manner with the idea of sweeping particles up and away from the window.

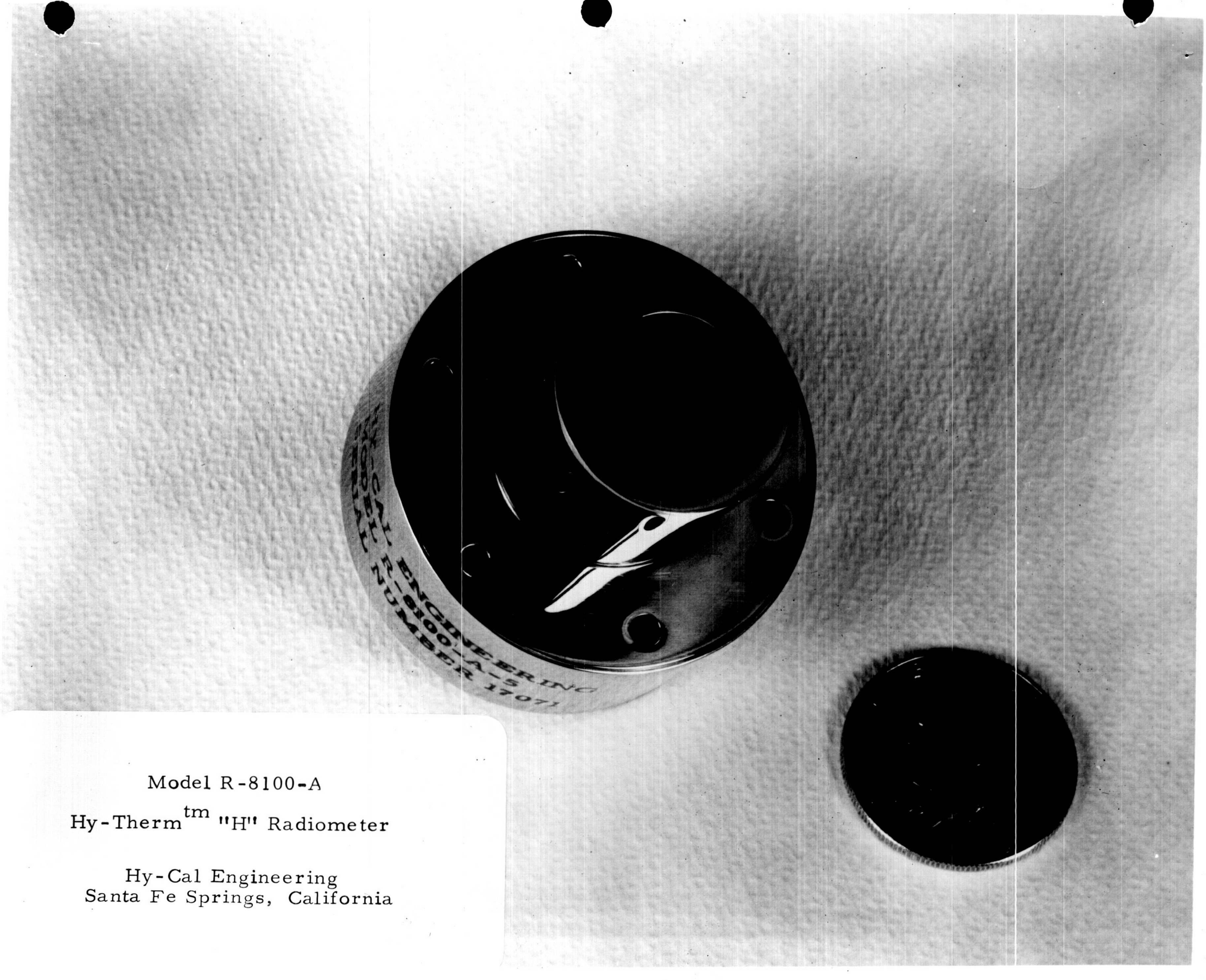
Tests of this system revealed that, while it was fairly efficient, some sooting of the window occurred. It appeared that some particles managed to get past the turbulence at the apex of the cone, and once in the relatively still region inside the cone they drifted down on the window.

A successful modification to this system was made by incorporating the Hy-Cal Engineering "Modified Cone" purging system which had previously proven excellent during flight qualification testing of radiometers for the Saturn program.

The units were tested in a pure acetylene flame with a No. 20 tip torch according to NASA specifications. The nitrogen purge flow was set at 3 CFM. The acetylene pressure was varied from 1 to 10 psi and the torch was moved to vary the angle of incidence from 0° to 60°. The distance between the torch and the transducer was set to produce the most severe sooting effect (see GA-2301). Results showed severe sooting of the surface surrounding the window, but the window itself remained free of contamination.

V. CONCLUSIONS

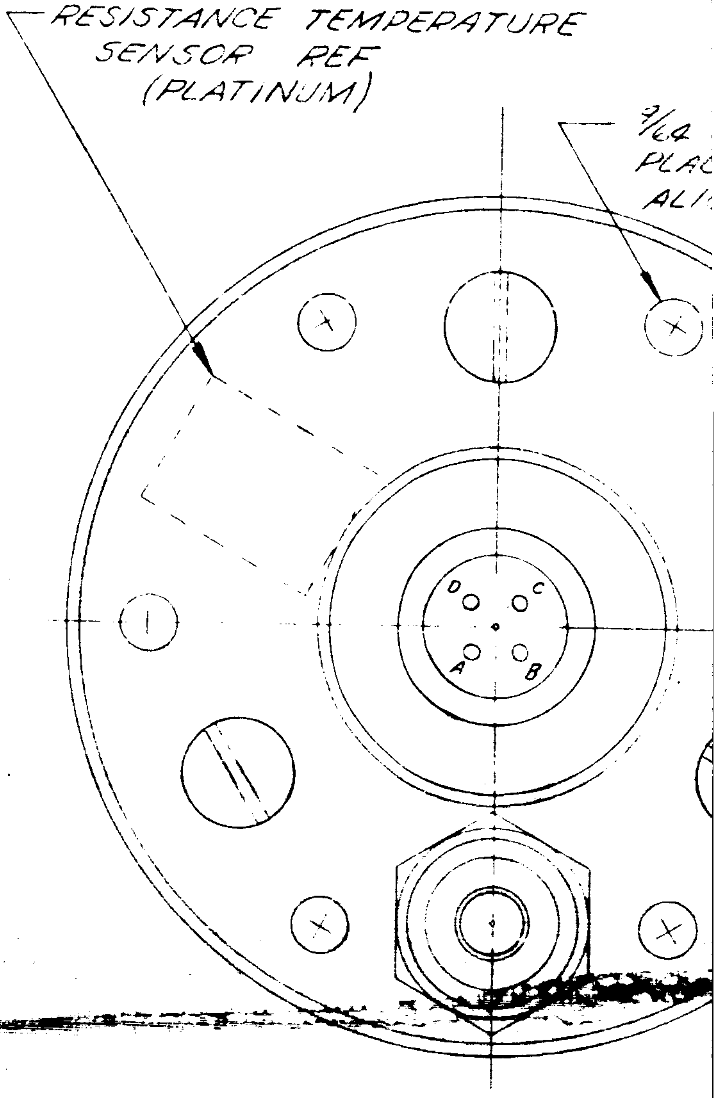
A modification of the Hy-Cal Engineering Hy-Therm sensor has been designed which is designated as the Hy-Therm-H. This unit has the high output and low response time characteristics which met the goal of the program. The design is a breakthrough in miniaturization of the sensor such that numerous sensors can be placed in a very small area. This permits fabrication of a multi-sensor instrument with a small overall configuration, high output and fast response time for the measurement of low level heat flux ranges.



Model R-8100-A

Hy-Therm^{tm} "H" Radiometer

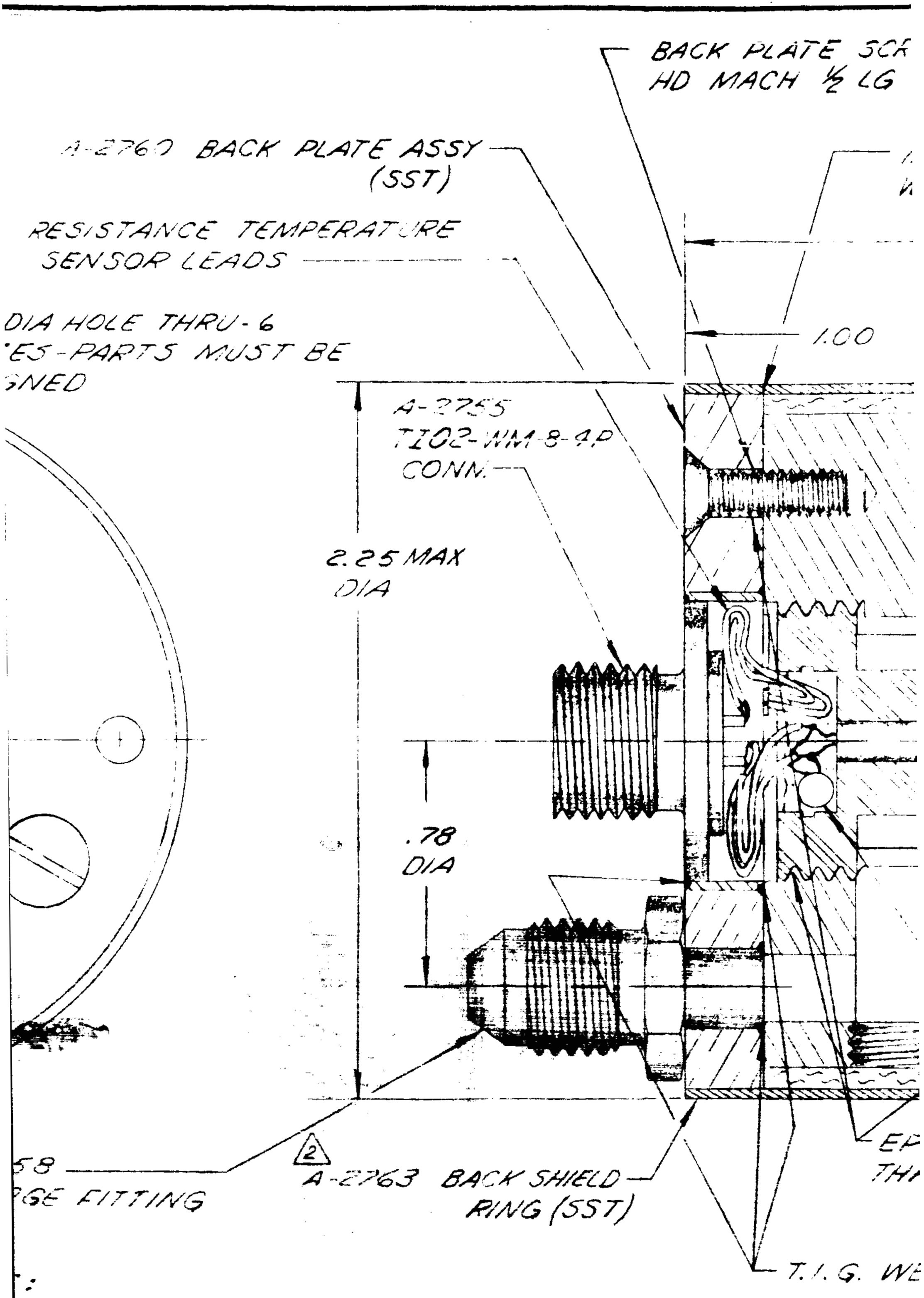
Hy-Cal Engineering
Santa Fe Springs, California



NOTES:

1. CONNECTOR PIN CONTACT ARRANGEMENT
   A-POSITIVE; B-NEGATIVE
   C & D-RESISTANCE TEMP. SENSOR

2 EPOXY IN PLACE AS SHOWN.



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ALL DIMENSIONS IN INCHES WITH FOLLOWING TOLERANCES UNLESS OTHERWISE NOTED:

DECIMALS	FRACTIONS	ANGLES
.X ± .030 .XX ± .010 .XXX ± .005	± 1/64	± ½°

Hy-Cal
SANTA FE SPRINGS

FINAL
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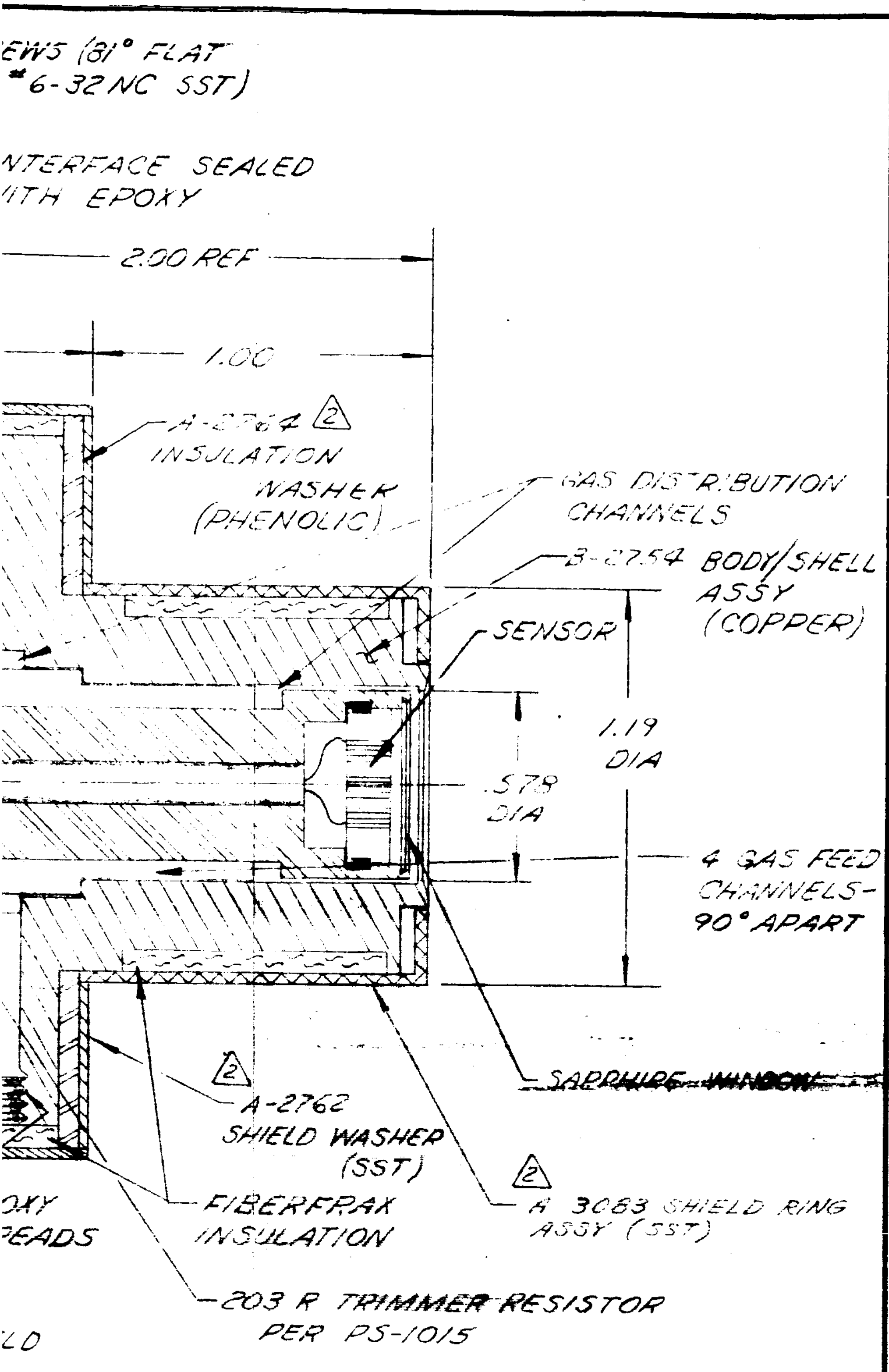

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Engineering CALIFORNIA	DATE 2-11-65	MATERIAL SEE ABOVE & DWGS
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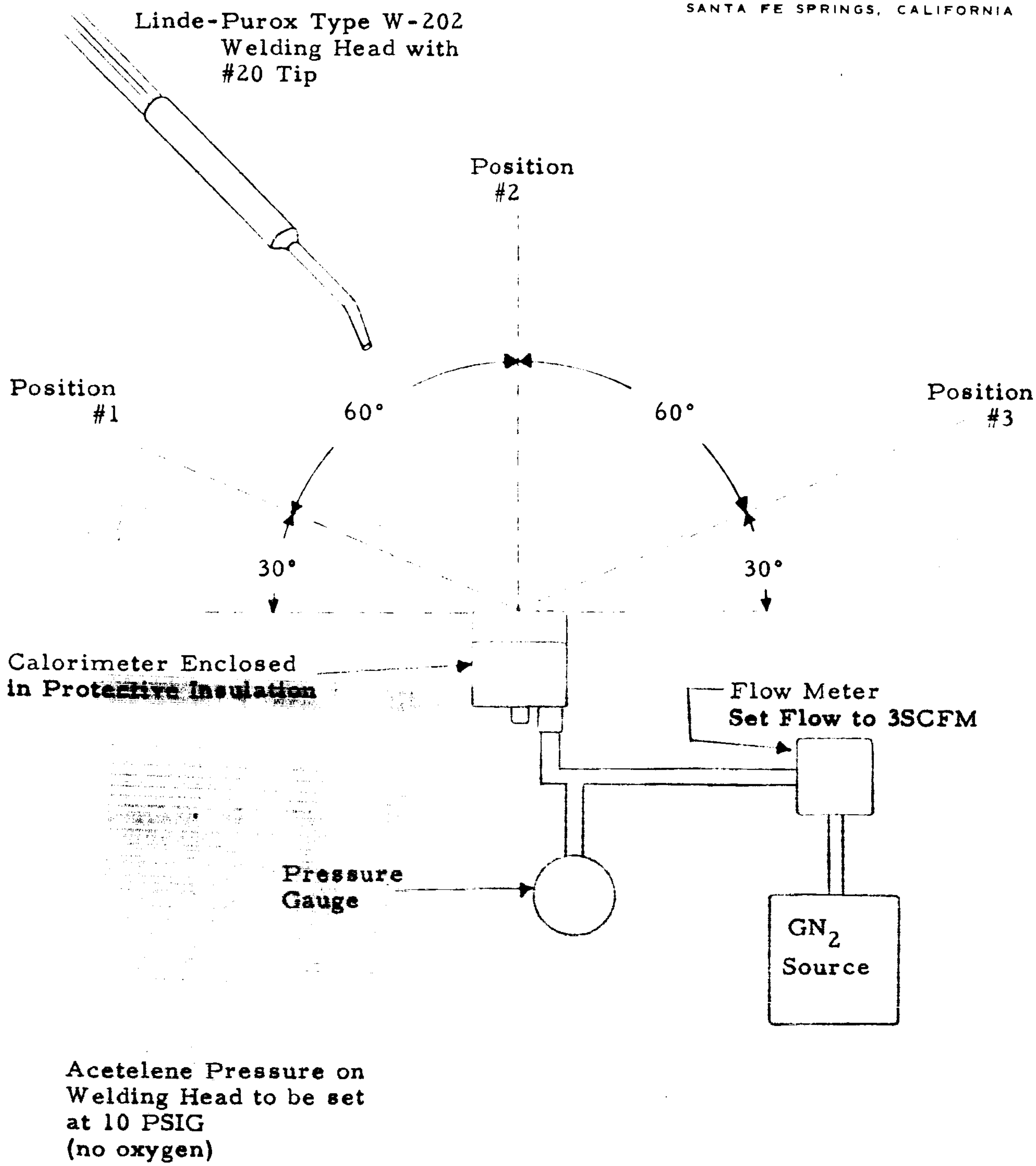
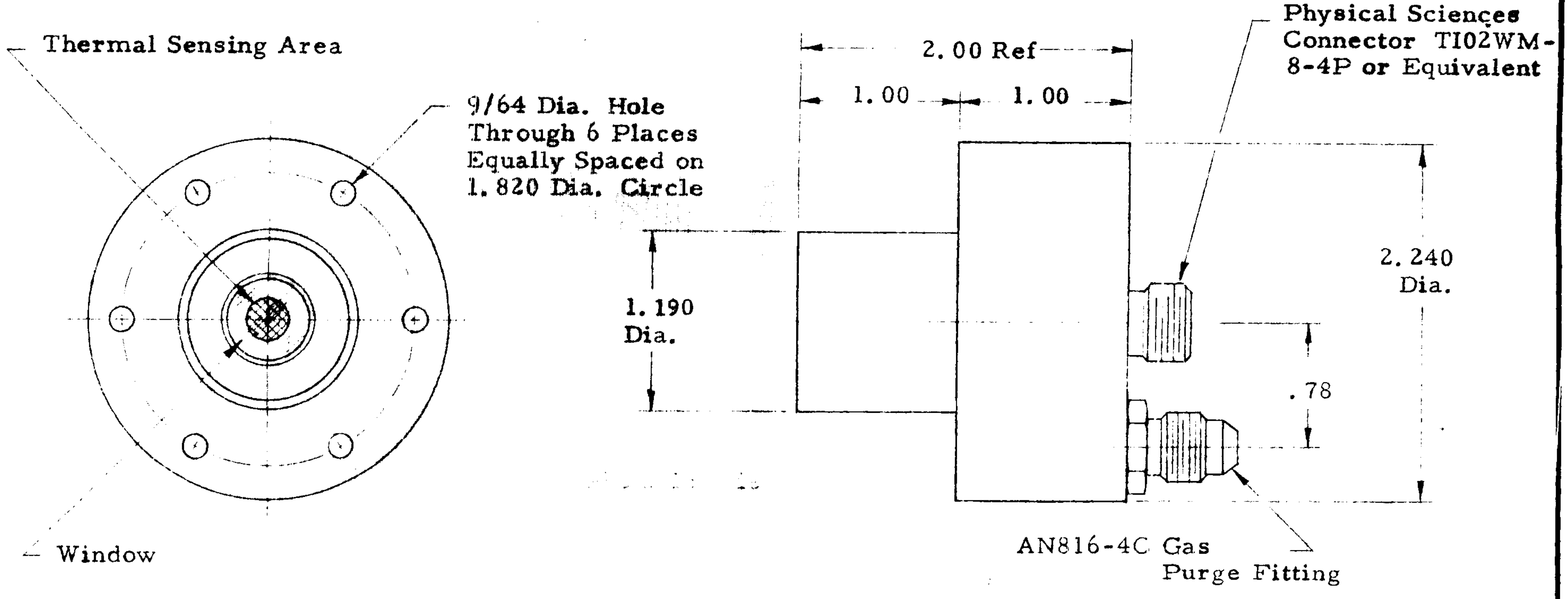
ASSEMBLY -8100-A	DRAWN WB	DRAWING NO. B-2635
	APP'D [illegible]	



NITROGEN PURGE TEST



NOTES:

1. Model dash number designated as follows:
   ZZ - Heating rate in Btu/ft^2-sec.
2. Standard Heating Rates: 1, 2, and 5 Btu/ft^2-sec.
3. Full scale output: 10 ± 1.5 m.v.
4. Maximum heat load capacity: 28.5 Btu or 1300 Btu/ft^2-when heated over 1.12 dia. (initial temperature assumed to be 75°F).
5. This instrument incorporates a platinum resistance body-temperature sensor with 233 or 500 ohms resistance at 32°F.
6. Gas purge system designed for operation with 3 CFM gas flow.
7. Radiant heat flux sensor incorporates optical grade sapphire window, grade UV.
8. Body material: Copper
9. All thermal and electrical junctions metallurgically bonded to assure non-variance from the normal EMF curve where applicable.
10. Maximum weight of instrument: 1.7 lbs
11. Connector contact arrangement:
    Pin A - positive; Pin B - negative
    Pins C and D - Resistance Body-Temperature Sensor

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ALL DIMENSIONS IN INCHES WITH FOLLOWING TOLERANCES UNLESS OTHERWISE NOTED:

DECIMALS	FRACTIONS	ANGLES
.x ± .15	± 1/32	± 1°
.xx ± .03		
.xxx ± .01		

Hy-Cal Engineering
SANTA FE SPRINGS CALIFORNIA

HY-THERM™ "H" RADIOMETER - GAS PURGED
Model: R-8100-A-ZZ

DATE	2-11-65
SCALE	Full
DRAWN	Aw
APP'D	[signature]
MATERIAL	Noted
DRAWING NO.	A-2632

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