TEMPERATURE MEASUREMENTS IN LOW VELOCITY HIGH TEMPERATURE GAS STREAMS

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Abstract

Many investigations have been conducted for the development of suitable devices for the measurement of gas temperature in the field of gas turbines and jet propulsion. Each of the methods developed is suitable for a certain range of temperature and some of the methods need further development to establish their accuracy.

In the present investigations some of the conventional devices such as the shielded thermocouple probes have been tested in the temperature range of 1600° F. and 2200° F., in a low velocity gas stream, where radiation error is predominant. Besides, the thermodynamic method as developed by Clark and Rohsenow has been applied to the above range of temperatures with a suitable probe developed for that purpose. The results presented give an indication of the behaviour of the probes in the temperature range of 1600 to 2200° F.

In low velocity high temperature gas streams such as those obtained in rig-testing of gas turbine combustion chambers, errors due to impact and compression are negligible. The main sources of error arise from the heat transfer by radiation between the thermocouple junction and the surroundings and conduction of heat along the probe itself. The temperature indicated in such circumstances will be only an equilibrium temperature after the heat transfer processes are fully established.

The main problem in the development of temperature probes for low velocity high temperature gas streams is the reduction of radiation error with minimum complications in probe construction. Much work has been done in this field especially by King,[1] Rohsenow and Hunsaker,[2,3] Dahl and Fiock,[4] Moffat[10] among others, to evolve a suitable shielded probe for high temperature work. It can be seen from a review of the existing literature that data is lacking especially in the temperature range of 1800 to 2200° F. on the behaviour of shielded probes. Hence, in the present investigations, the temperature range of 1600 to 2200° F. is considered and the extent of radiation errors of various probes has been investigated. A modified version of the thermodynamic system of Clark and Rohsenow,[16] the most promising of the pressure sensitive systems has been designed with a view to testing its applicability and accuracy in the above temperature range.

The experimental set-up, Fig. 1, consists of a blower, a combustion chamber with auxiliaries, test section and finally the exhaust. The combustion chamber

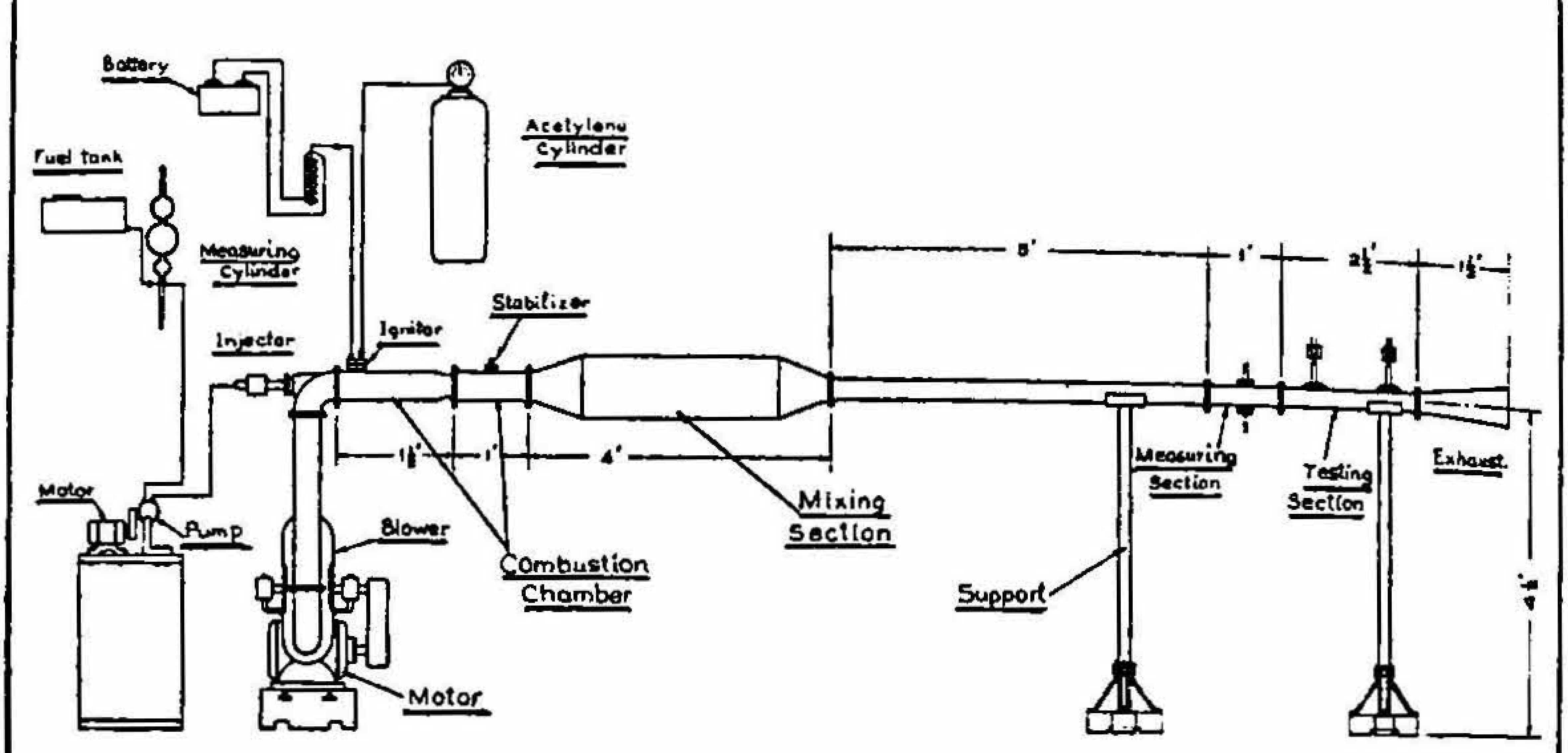


FIG. 1. TEST SET UP

TEMPERATURE MEASUREMENTS IN HOT GAS STREAMS

FIG. 1

Fig. 2 is of the elbow type, fitted with a primary air tube, two flame tubes and a flame holder, all of high grade stainless steel. The injector is of the simple type and is situated in the centre of the primary air tube. Ignition is effected by a special acetylene ignitor and spark plug. A flame stabilizer has been added on to the combustor exit, to extend the operating limits of the combustor and to ensure smooth combustion. A supply of hot gases in the temperature range 1600 to 2300° F. could be obtained in the test section. The test section Fig. 3 consists of a 3" standard steel pipe 2½' long provided with two slots with covers for insertion of probes. Pipe wall temperatures at each station could be measured by three peened thermocouples. The gas flow was measured at a measuring section by means of pilot tubes. The thermocouple leads are connected to a junction box and thence to a Leeds and Northrup Potentiometer.

The heat balance equation for a bare thermo-junction in a hot gas stream flowing in a duct is given by

$$q_t + q_{or} + h_c A_p (T_t - T_p) = F \cdot A_p \cdot \epsilon (0\cdot173) \left[\left(\frac{T_p}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4 \right] + q_k \quad (1)$$

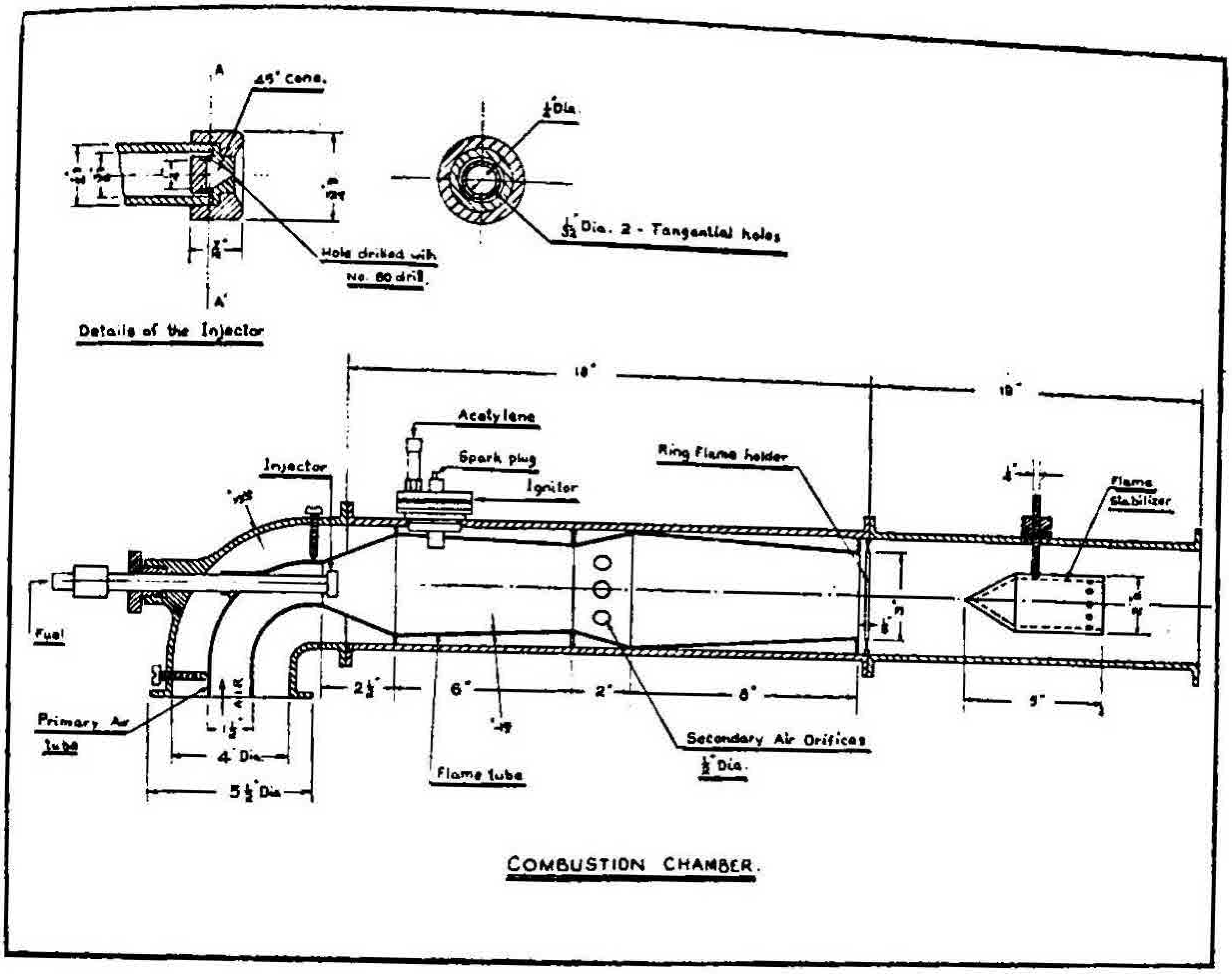


FIG. 2

Considering each term separately, the extent to which the probe reading is affected by each can be estimated.

1. *Flame Radiation.*—The exact magnitude of this term is difficult to estimate because it depends on the soot-concentration which varies with the fuel composition and operating conditions and also to the extent to which the flame is visible to the thermo-junction. Equation (2) gives an approximate value,

$$q_f = 0{\cdot}173\ A_p \cdot X\,\epsilon \cdot \epsilon_f \left[\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_p}{100}\right)^4\right] \qquad (2)$$

where X = fraction of the total so'id angle over which the junction sees the flame. The errors due to this are not taken into consideration in the present tests, because the test section was so arranged that the flame was not visible to the junction located in the test section.

2. *Gas Radiation.*—Usually the presence of CO_2, CO, water vapour SO_2, etc., give rise to gas-radiation by absorbing and emitting radiation in certain wave-length regions, different for each gas.[19] Exhaust gases from combustion chambers contain CO_2 and water vapour, the amount of each depending on the

fuel air ratio. An approximate calculation was made taking the values from a representative test and this was found to be negligible.

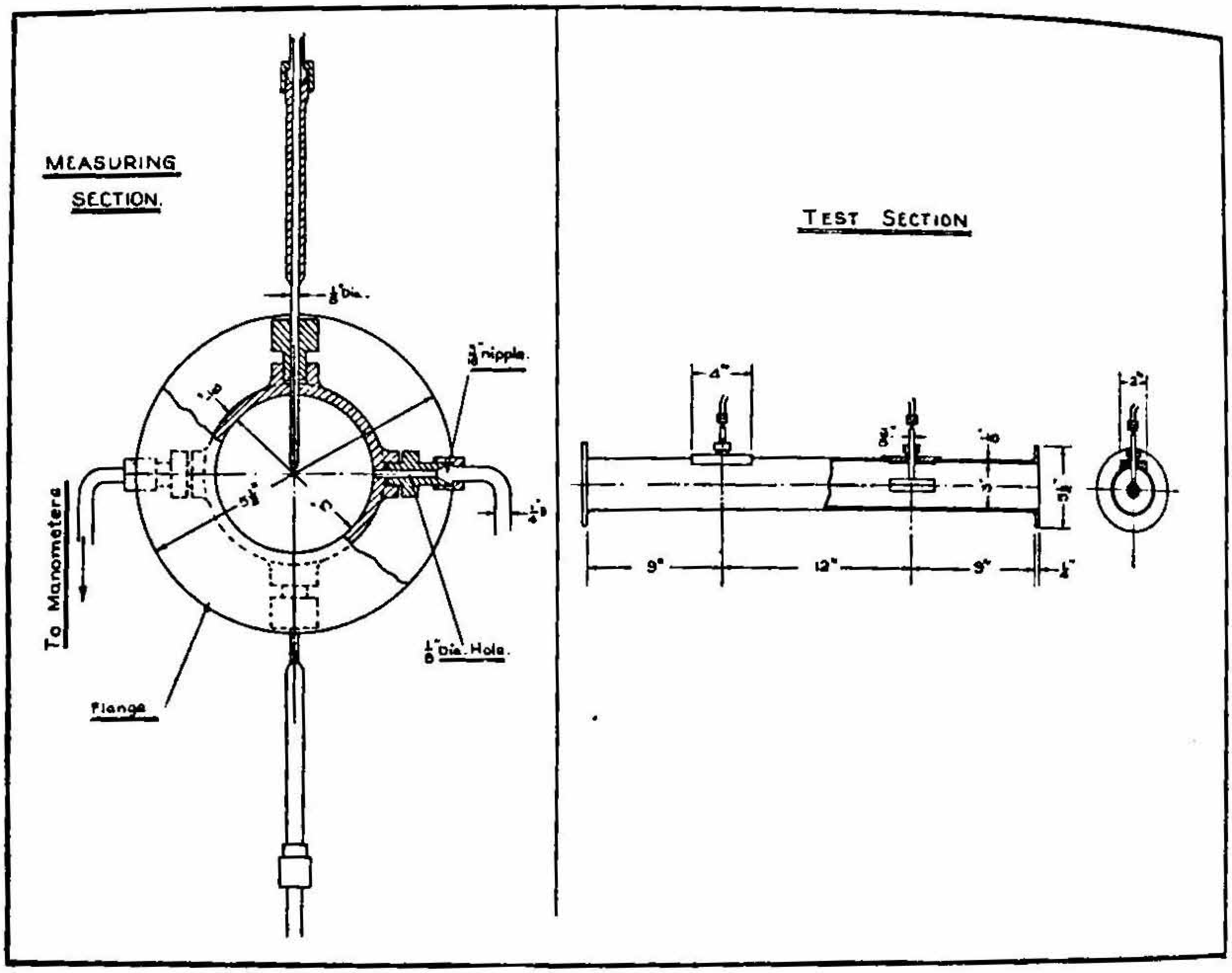


FIG. 3

3. *Conduction.*—There will be heat flow by conduction from the probe tip to the upper parts. A general equation for a simple case without taking into consideration any temperature gradient is given by

$$\frac{d^2T_x}{dX^2} - m^2T_x = - m^2T_t \tag{3}$$

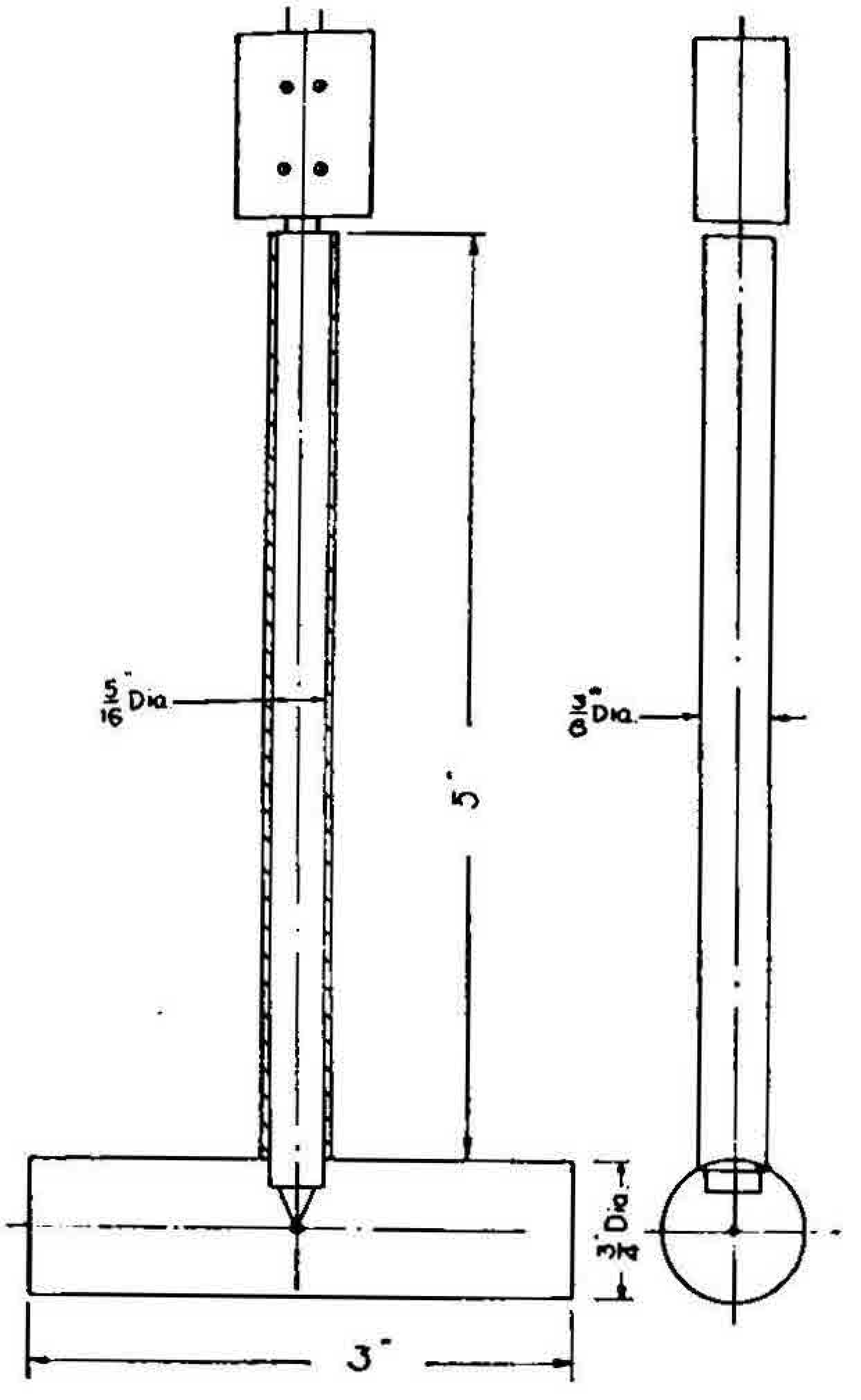
T_x = temperature at a distance x from the duct wall and

$$m = \left[\frac{h_c \cdot \text{perimeter of wire}}{k \cdot \text{sectional area of wire}}\right]^{\frac{1}{2}} = \sqrt{\frac{4\,h_c}{kd}}$$

When $x = L$ the depth of immersion of the thermocouple

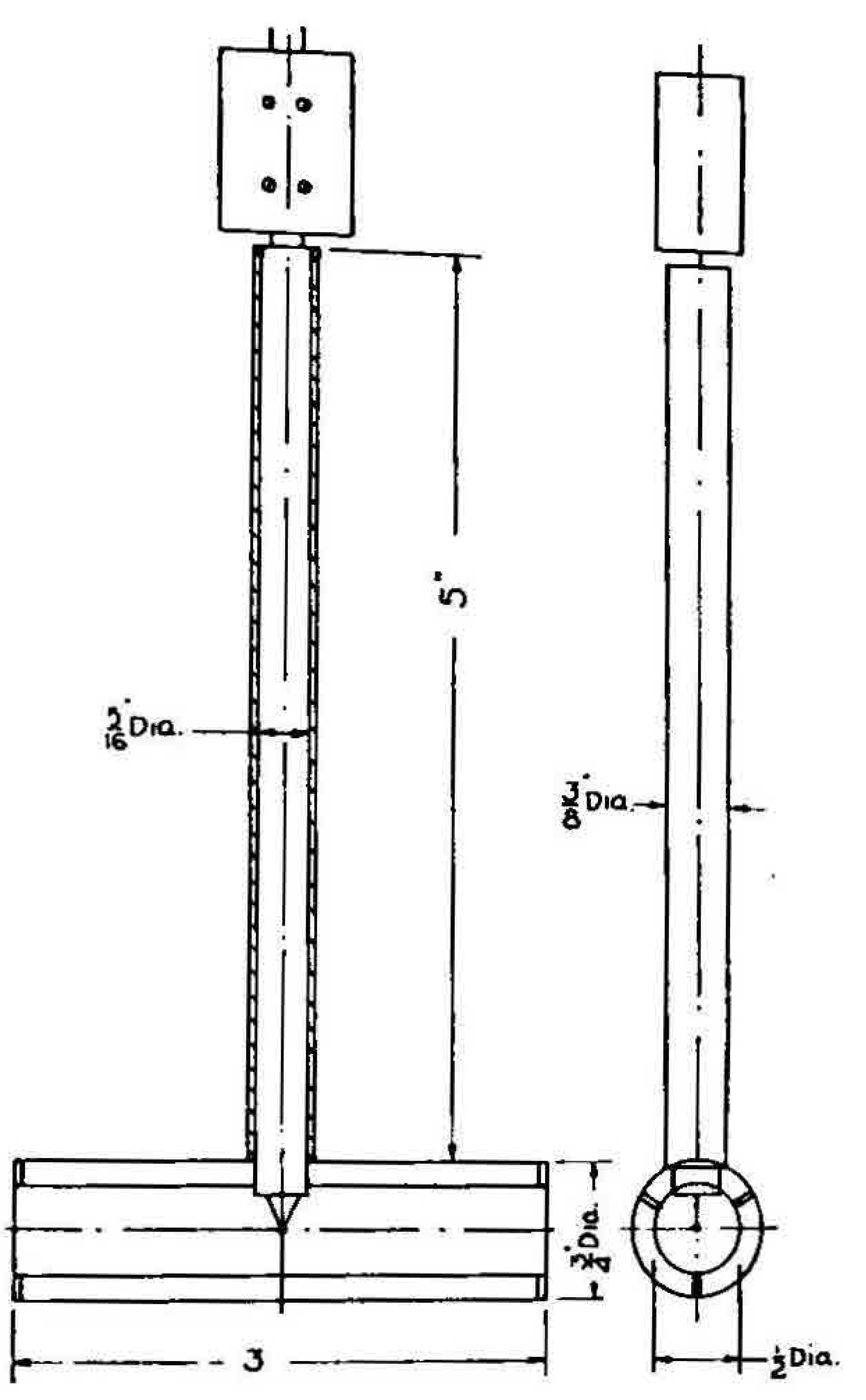
$$\frac{T_t - T_p}{T_p - T_w} = \frac{1}{\text{Cosh } L \cdot \sqrt{\frac{4h_c}{kd}} - 1} \tag{4}$$

From this equation the approximate conduction error for any particular set of readings may be calculated. By having adequate depth of immersion and using thin wires this was minimised to a negligible value.



SINGLE SHIELD PROBE

FIG. 4



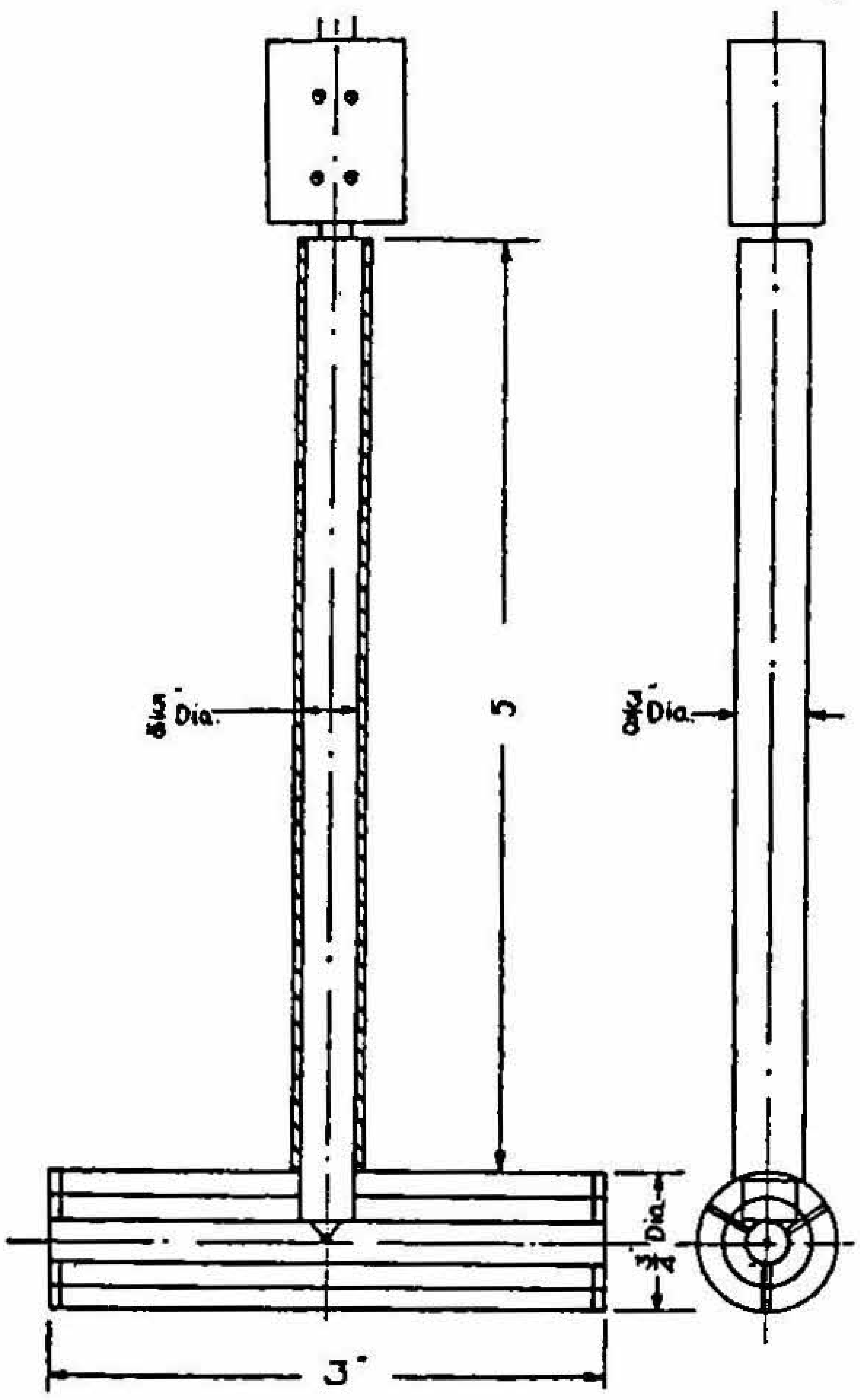
DOUBLE SHIELD PROBE

FIG. 5

From the above considerations it is obvious that the main source of error in the thermocouple probe reading is due to radiation from the junction to the surroundings, which increases enormously at higher temperatures.

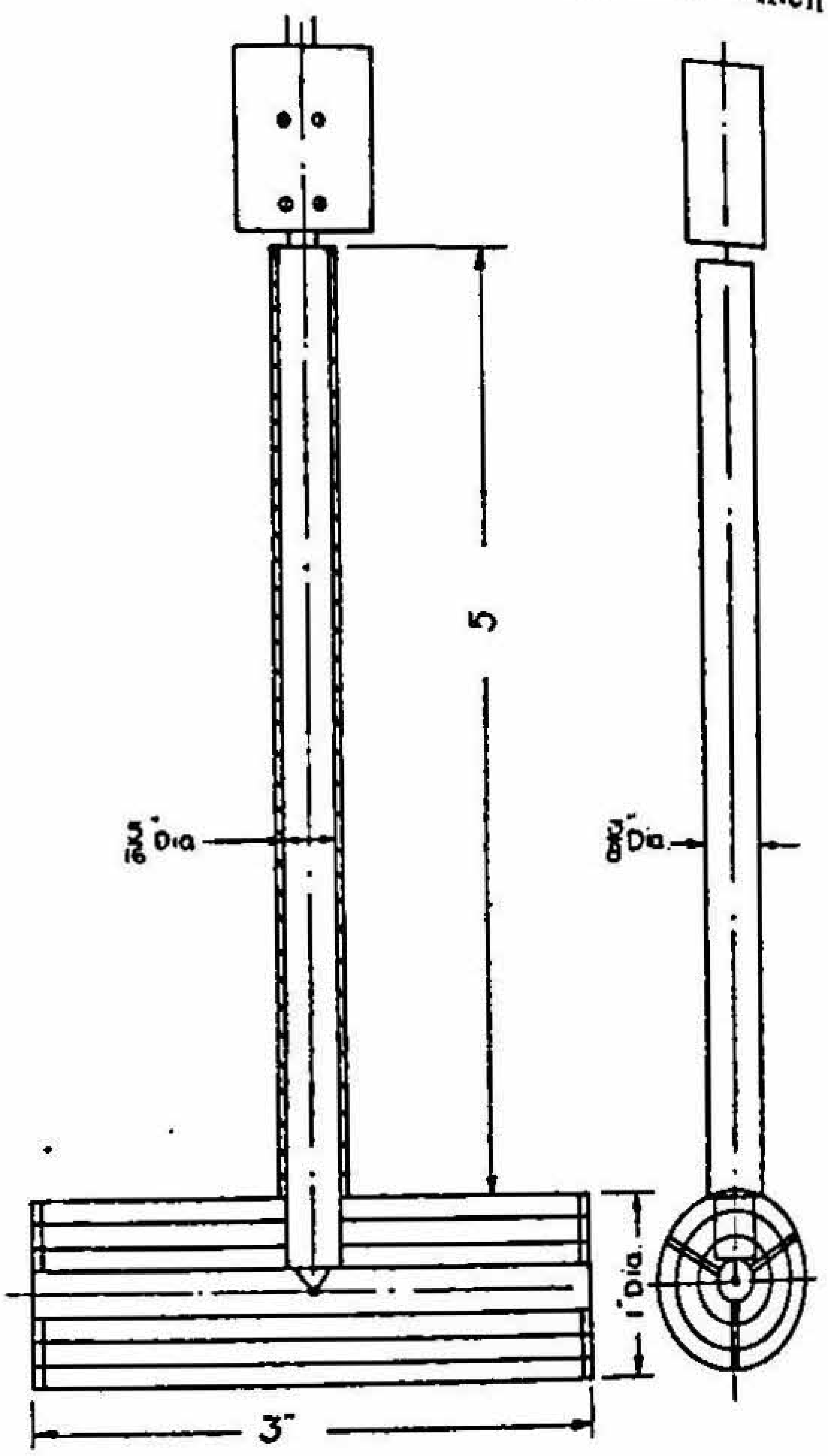
Several shielded probes were constructed and tested to find out the magnitudes of error at the different temperatures. Single, double, triple and quadruple shielded probes, Figs. 4, 5, 6 and 7 were tested. The shields were constructed out of 1/32" thick stainless steel tubes of $\frac{1}{4}$", $\frac{1}{2}$", $\frac{3}{4}$" and 1" diameter. In all cases 3" length was used. In each, the thermocouple was introduced into the middle of the shield through a central $\frac{3}{8}$" dia. stainless steel tube welded to the outer tube of the shield assembly. The thermocouple was of 22 gauge crhomel-alumel wire housed in double hole porcelain tubes. Another shielded probe was constructed in which the thermo-junction was located in the throat of a nozzle which was centrally fixed inside a double shield assembly, Fig. 9. This was to test the effect of increase in local velocity over the junction.

A heated shield probe, Fig. 8 and a suction of probe, Fig. 10, were constructed with a view to testing their accuracy in the higher temperature range. The heated shield probe was made of a stainless steel tube ½" dia. 3" long, over which



TRIPLE SHIELD PROBE

FIG. 6



QUADRUPLE SHIELD PROBE

FIG. 7

heater wire was wound using magnesia cement as insulator. The temperature of the tube wall was measured by two peened thermocouples. During operation, the temperature of the tube wall was made equal to that of the main thermocouple by suitably adjusting the current input to the heater winding so that the net heat transfer by radiation between the thermocouple junction and the tube wall is zero. The reading of the probe was taken when this balance was attained.

The suction probe in which the gas is drawn over the junction at a high velocity by means of a suction pump is shown in Fig. 10. It is also provided with a double radiation shield to prevent losses due to radiation. In this probe 32 g. platinum-platinum rodium thermocouple was used for greater accuracy.

All these shields were tested in the set-up one by one and in each case a bare junction thermocouple probe was located at one of the stations so that the results of the various shielded probes could be compared with the bare junction readings. The results are shown in Fig. 13. Fig. 14 shows the deviations of the readings of different probes from the calculated temperature values.

The Thermodynamic Method.—An expression can be developed for the static temperature at any point in a gas stream flowing in a duct in terms of the

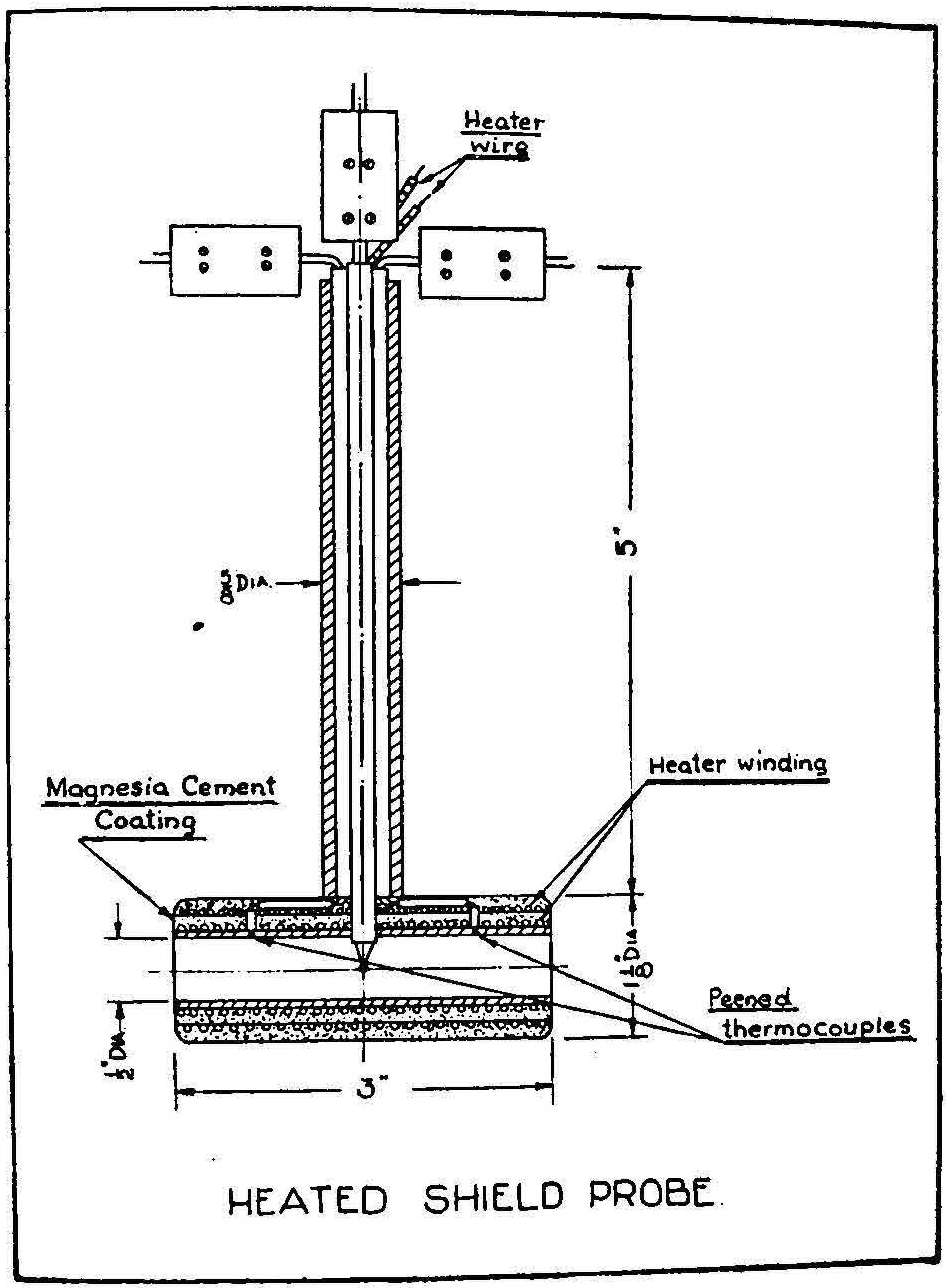
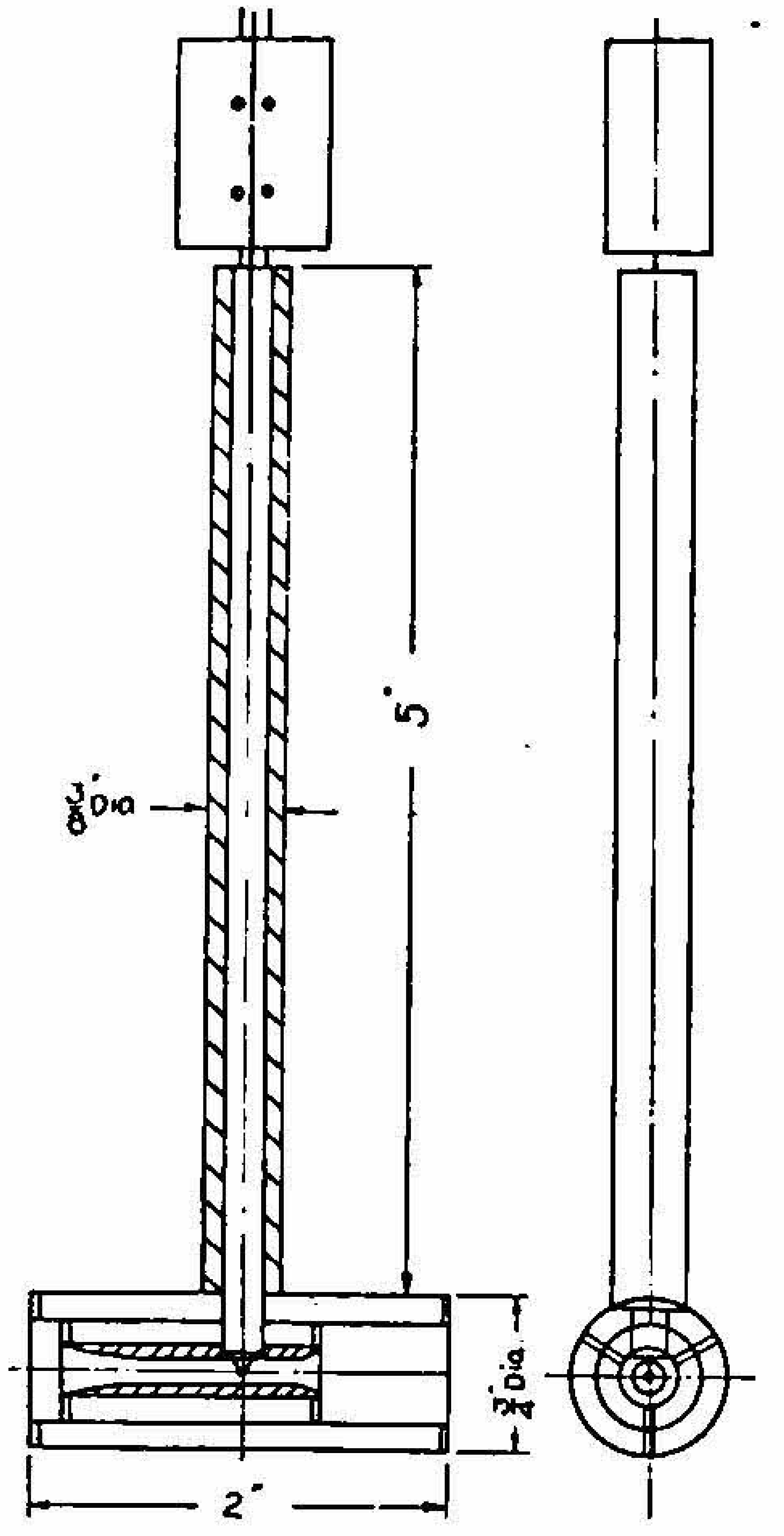


FIG. 8

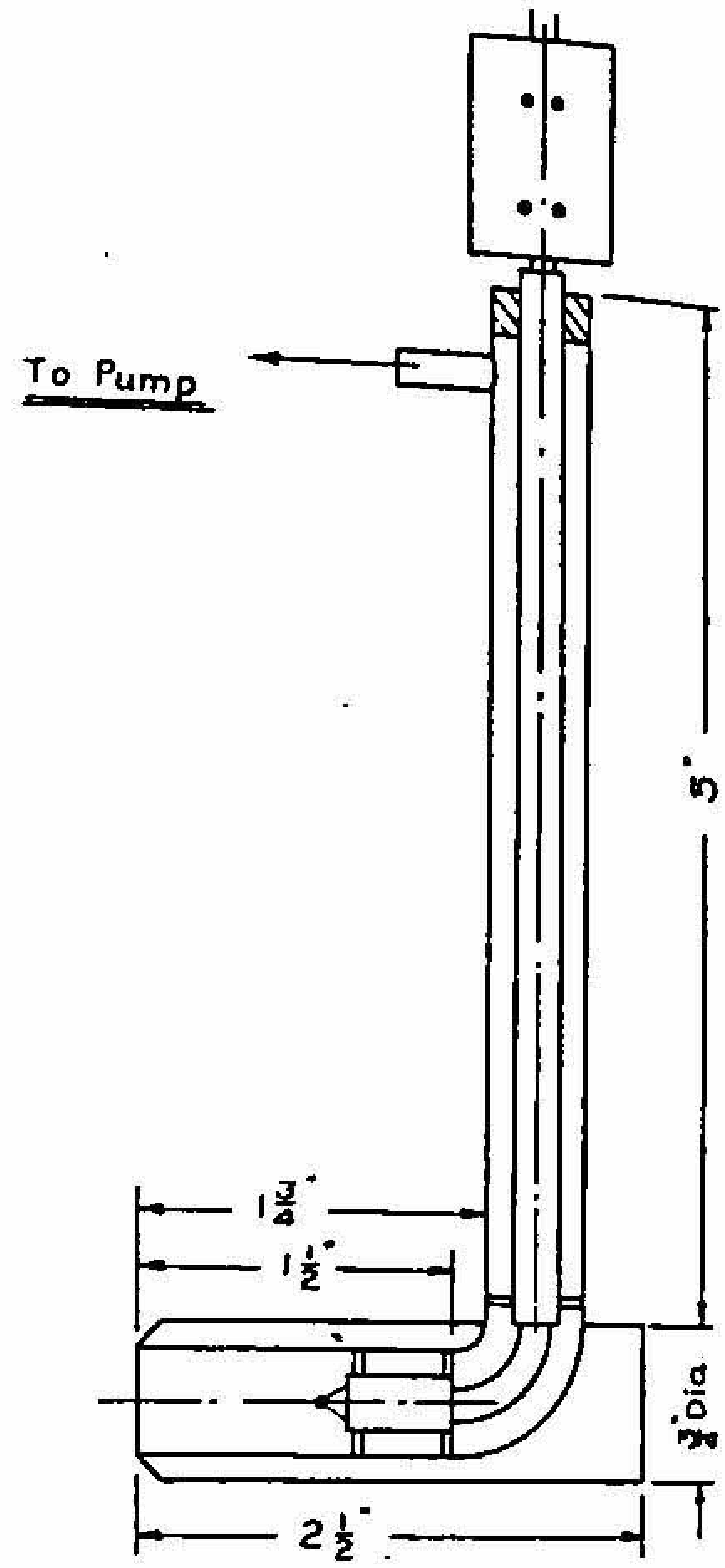
other properties of the gas which are either known or can be easily measured with a minimum of error, starting from the fundamental equations of thermodynamics and one dimensional compressible gas flow.[15]

If p, ρ, T and V represent the properties at any point in the gas stream the equation of state can be written as $p = \rho RT$. Assuming isentropic flow



DOUBLE SHIELD WITH NOZZLE

FIG. 9



SUCTION PROBE

FIG. 10

$p =$ constant times $(\rho)^{\gamma}$, the energy equation for frictionless compressible flow of a perfect gas is

$$\frac{V^2}{2gJ} + C_p T_s = C_p T_t \tag{5}$$

The above equation holds good for flow with friction also because the heat added due to friction cancels the work done against friction by the fluid.[21] Making use of the well-known equations of compressible flow and combining the above equations, the following equation for the static temperature of a gas at any point can be derived:—

$$T_s = \frac{2g\gamma}{R(\gamma - 1)} \left(\frac{P_s}{G}\right)^2 \left[\left(\frac{P_t}{P_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{6}$$

In the course of the present investigation a suitable probe assembly has been designed to measure the values of p_t and p_s at the point considered and also to measure the weight flow at a suitable point where the gas has been cooled to a conveniently lower temperature.

The scheme of the apparatus is shown in Fig. 12. The probe itself, Fig. 11, consists of an inner ¼" stainless steel tube, through which the gas is sucked, and which also acts as an impact tube when gas flow to the suction pump is shut off. This is surrounded by another tube with an annular passage between

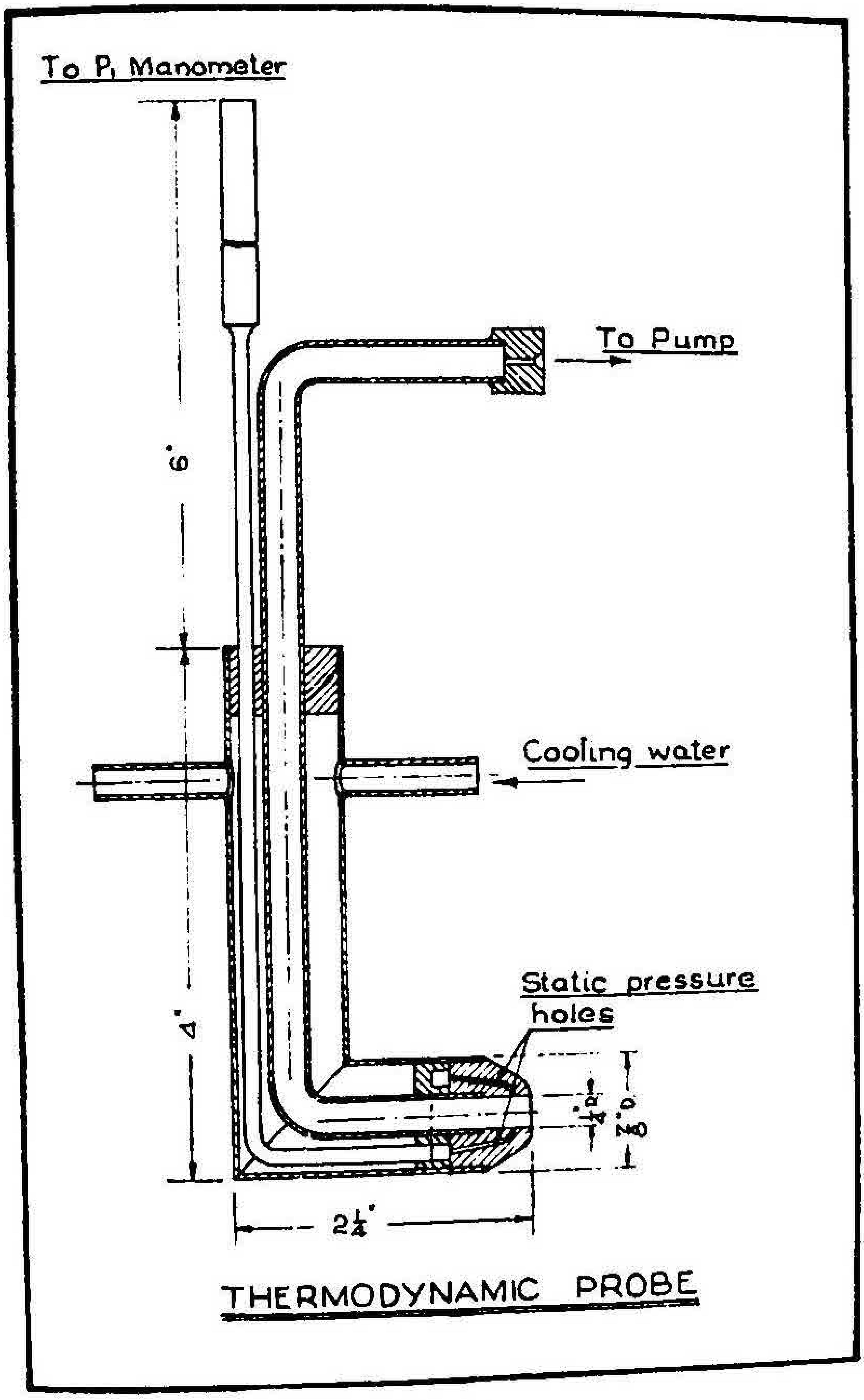


Fig. 11

the two so that cooling water passes around the inner tube. The probe-tip is constructed separately. Two tiny holes are drilled at an angle at its end, which measure the static pressure at the entry of the probe. These two holes are connected to a ring-groove, and thence to a 2·4 mm. stainless steel tube which communicates with a manometer. The gas sample sucked through the probe is led by means of a stainless steel pipe to a heat exchanger which consists of a coiled pipe in a water-bath, where the flow of water can be adjusted to control the temperature of the gas. The cooled gas then passes to a calibrated orifice where the mass rate of flow is measured. The gas then passes to the suction pump through a valve. By maintaining the pressure difference $(p_{s_1} - p_w) = 0$, always, the value of G at the probe entrance can be made equal to its original local value in the hot gas stream in the absence of the probe.

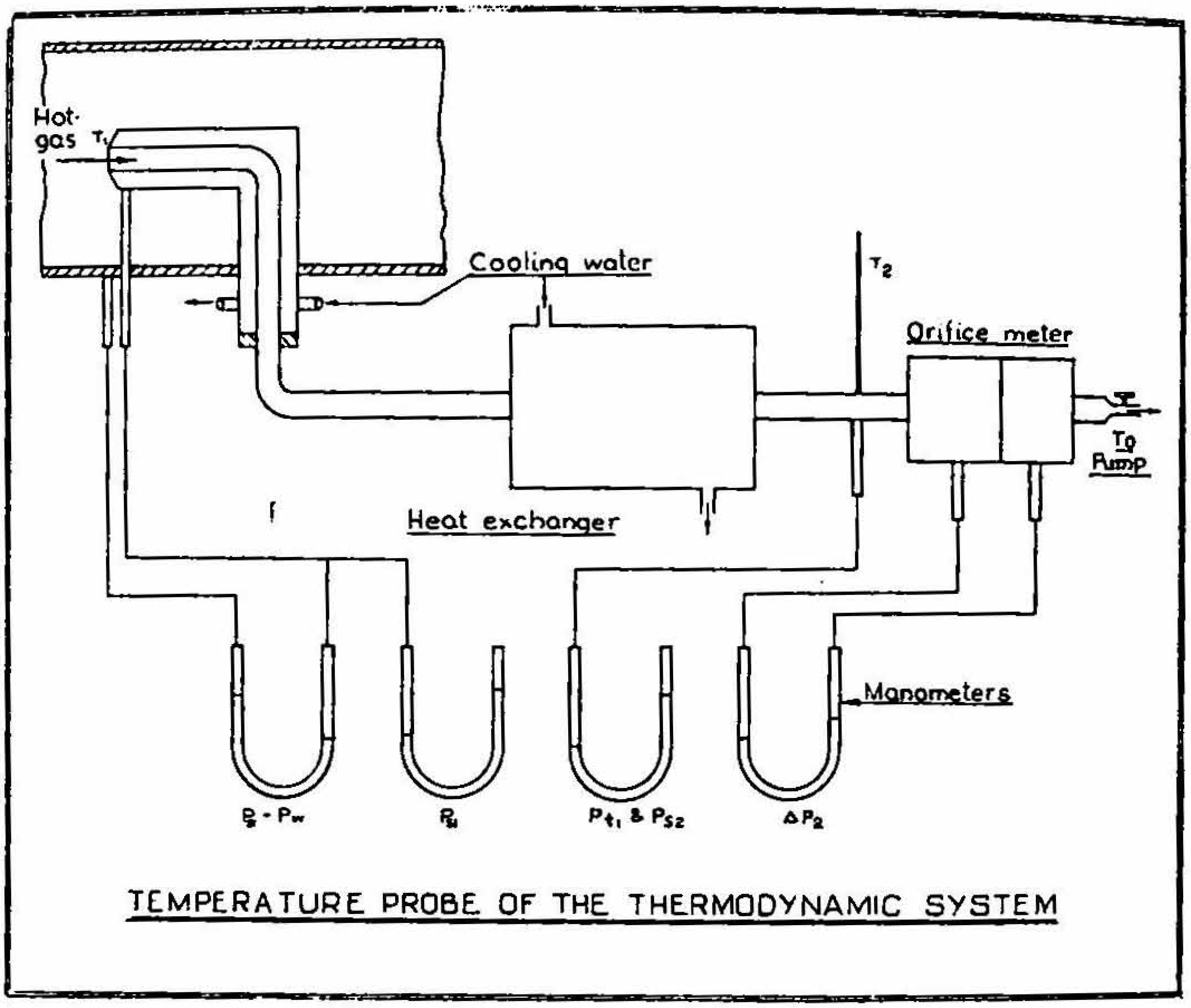


FIG. 12

The orifice of the probe was originally calibrated with reference to a wet testmeter. The probe was assembled and put in the test section. The combustor was started and after steady conditions were attained at the test section, the suction pump was started. Cooling water was started on, both at the probe and at the heat exchanger; the flow at the latter being adjusted such that the gas temperature did not go below about 300° F. The readings of p_{s1}, p_{s2}, T_2 and Δp_2 the orifice pressure differential were taken. Then, after shutting off the flow to the pump, p_{s2} manometer read the value of p_{t_1}. A similar set of readings were taken at each temperature.

Calculation

The weight flow rate at the orifice is given by

$$w = A_2 K C \sqrt{2g \frac{p_{s2}}{R_2 T_2} \Delta p_2} \tag{7}$$

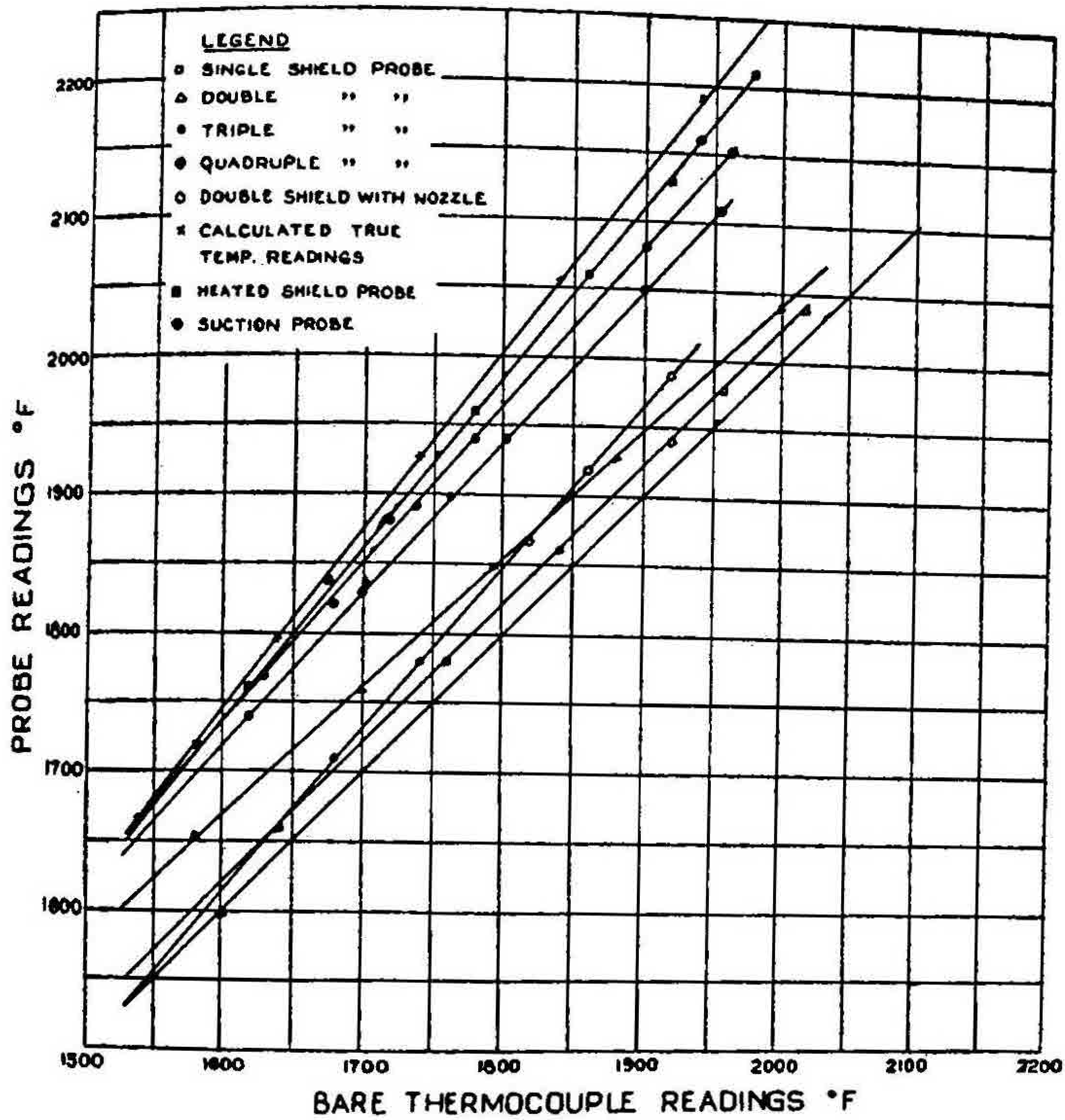


FIG. 13

The value of G corresponding to T_1 is given by

$$G = \frac{A_2}{A_1} KC \sqrt{2g \frac{p_{s2}}{R_2 T_2} \Delta p_2} \tag{8}$$

Combining equations (6) and (8)

$$T_1 = C_1 \frac{p_{s1}^{\,2}}{p_{s2} \Delta p_2} \left[\left(\frac{p_{t1}}{p_{s1}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \cdot T_2 \tag{9}$$

Here,

$$C_1 = \frac{\gamma}{\gamma - 1} \left(\frac{A_1}{A_2} \right)^2 \cdot \left(\frac{1}{C^2 K^2} \right) \cdot \frac{R_2}{R_1} ;$$

can be calculated for each set of readings. But, if R, γ and the orifice coefficient K are assumed to be fairly constant over the temperature range considered, which will be the case usually, C_1 can be determined for all sets of readings by taking

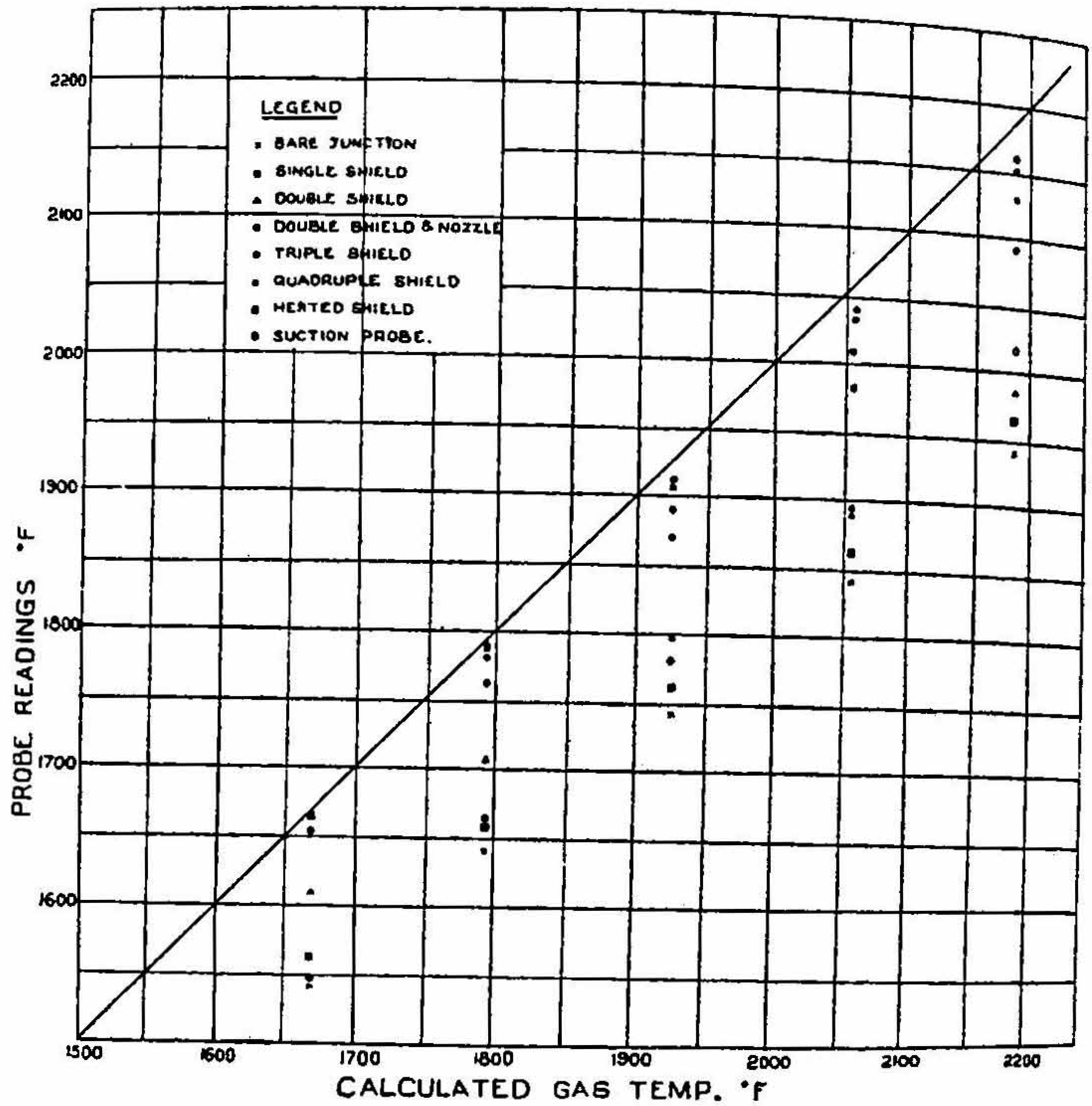


FIG. 14

average values for all the constants involved. The effect of gas composition on R is negligible, because, even at very rich fuel-air ratios the weight of the fuel forms only a very small percentage of that of air. Hence it can be assumed that $R_1 = R_2$ for calculation. The variations in gas composition may have some effect on γ, but since the change in gas composition for the range of fuel-air ratios considered in the present investigations is very little, the effect on γ has been neglected. An average value of $\gamma = 1 \cdot 35$ has been assumed for calculation. The value of C_1 can be calculated, as an instrument constant. Figure 17 shows the results obtained with the thermodynamic system, as compared to the calculated values of gas temperature.

DISCUSSION OF RESULTS

Figure 15 shows that the errors of all the probes, except the thermodynamic probe, increase with increasing temperature. The heated shield and suction probes give fairly accurate results upto about 2000° F. after which the error of these

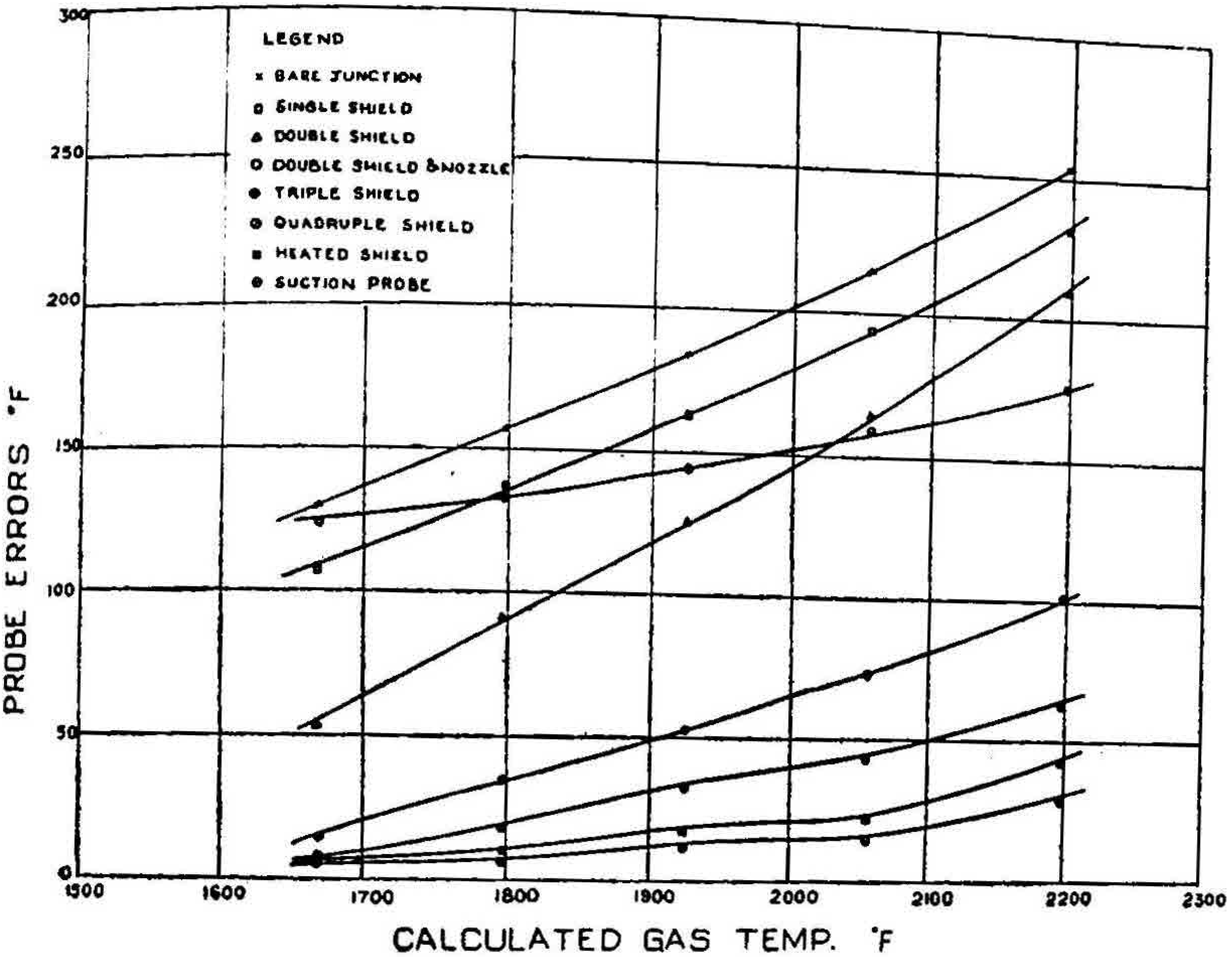


Fig. 15

probes assume larger proportions. In the case of the suction probe, this may be due to the inadequacy of the two radiation shields provided over the junction, at temperatures higher than 2000° F. With the heated shield probe it was very difficult to obtain a balance between the shield and gas temperatures, giving rise to an increase in errors. Among the other shielded probes, the quadruple shielded probe gave comparatively the best results as expected. But as Fig. 15 indicates, the quadruple shield can be used with best results upto 1,800° F. Above 1800° F. the error increases. Single, double and triple shielded probes can be used, only when the corrections to be applied on their readings are known. In the case of double shield with nozzle, the error at 1600° F. is very high and almost equal to that of a bare probe. At temperatures higher than 2000° F. its performance is better than that of single and double shield probes.

The thermodynamic system has given very good results in the temperature range of 1600 to 2300° F. The readings obtained with this probe agree very well with calculated values of gas temperature. During the operation of the thermodynamic system the pressure differential $(p_{s_1} - p_w)$ was about 1·5" of water throughout the tests. This could not be reduced further due to suction pump limitations.

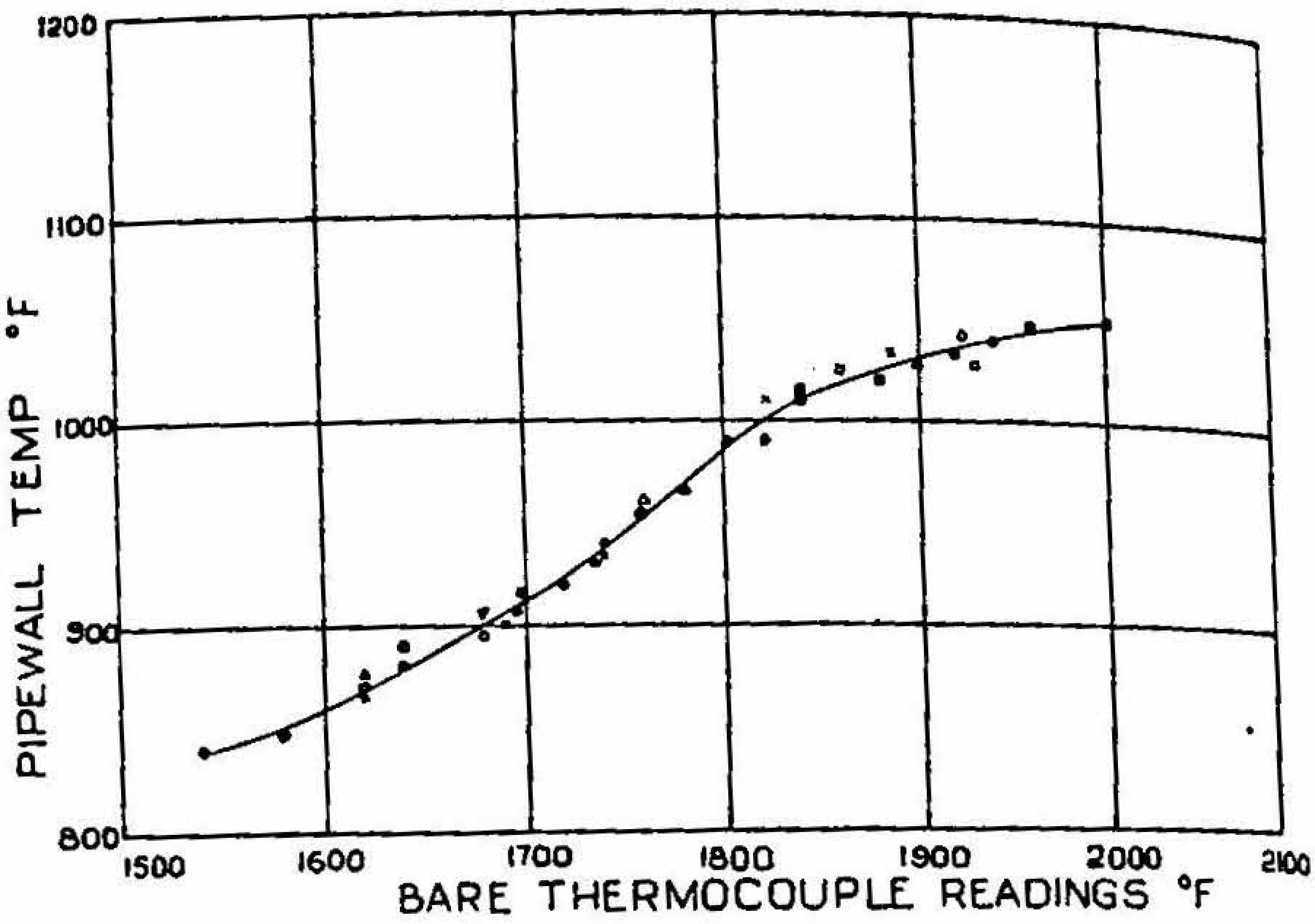

1200
1100
1000
900
800
PIPEWALL TEMP °F
1500
1600
1700
1800
1900
2000
2100
BARE THERMOCOUPLE READINGS °F

FIG. 16

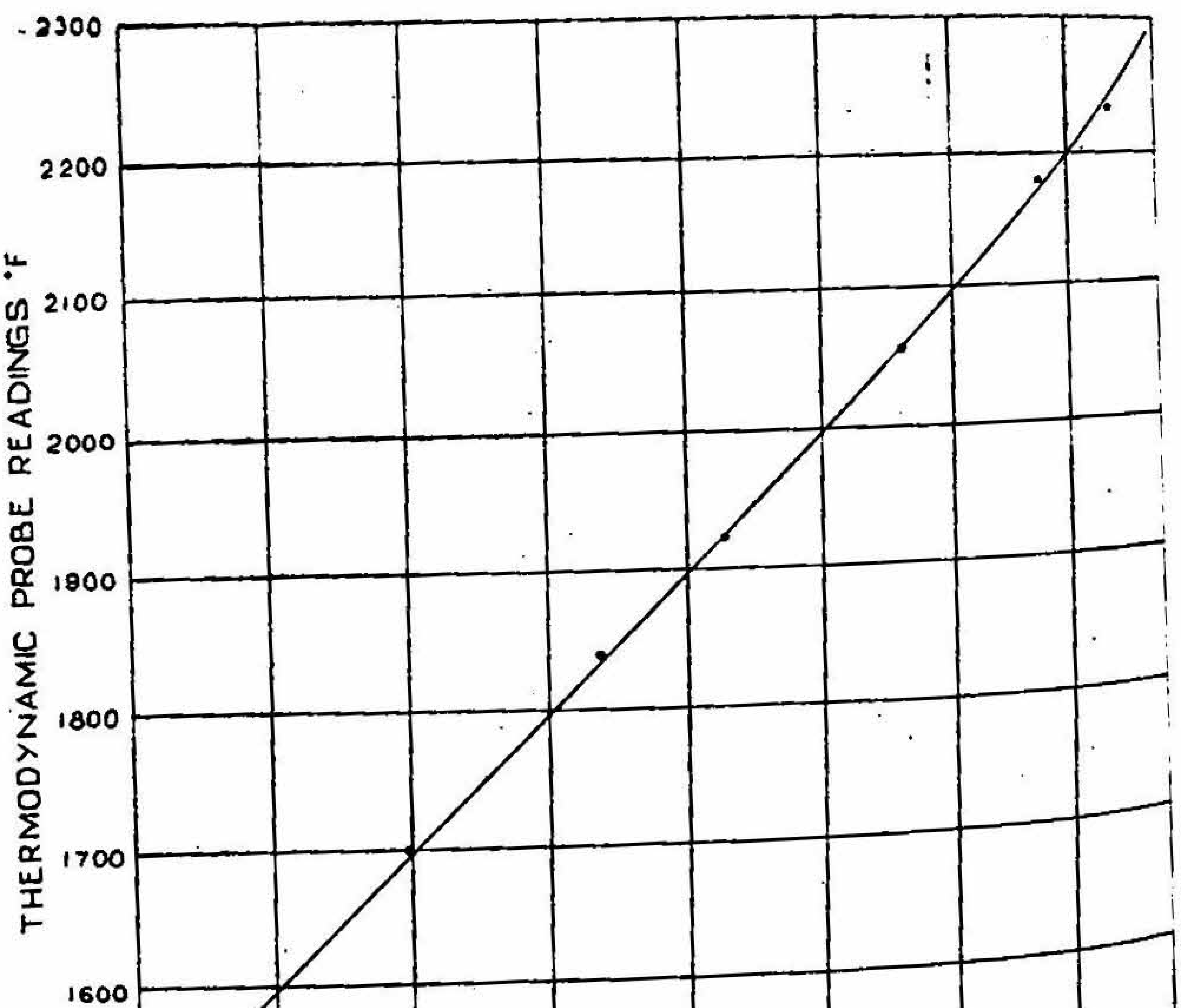

2300
2200
2100
2000
1900
1800
1700
1600
THERMODYNAMIC PROBE READINGS °F
1500
1600
1700
1800
1900
2000
2100
2200
CALCULATED GAS TEMP. °F

FIG. 17

CONCLUSIONS

The following conclusions can be drawn from the results of these investigations.—

(1) Thermocouple probes with one, two or three concentric radiation shields are subject to large errors and can be used only when the nature of corrections to be applied on their readings are known.

(2) The quadruple shielded probe can be used for measuring gas temperature upto 1800° F. with an error of about 1·5% at 1800° F. It can be used upto 2000° F. with proper corrections on its readings or when a reading within 3% error is permissible.

(3) The heated shield probe gives good results upto a temperature of 2000° F. beyond which it is difficult to operate and its readings are not reliable. Upto 2000° F. it can be used as a standard for comparison with other probes. At 2200° F. the error of the heated shield probe is of the order of 2·05%.

(4) All these probes, especially the multiple shielded and heated shield probes become unserviceable after continued use for about 30 to 40 hours, especially in the temperature range of 1800 to 2200° F. because of mechanical failure and in some cases failure of the thermo-junction in addition to mechanical failure.

(5) The suction probe gives fairly accurate results upto 2000° F. With adequate radiation shielding it may give better results upto about 2200° F. in a low velocity gas stream. It is simpler in construction than the heated shield probe.

(6) The thermodynamic method gives the best results throughout the temperature range of 1600 to 2300° F. The probe constructed for this system is simple and rugged, and water-cooling of the probe permits it to be used at still higher temperatures. As may be seen from Fig. 17, this is quite accurate and applicable to the low velocity high temperature range.

NOMENCLATURE

T_p Temperature indicated by the Probe, ° F. (abs.)

T_s Static temperature of the gas, ° F. (abs.)

T_t Total temperature of the gas, ° F. (abs.)

q_f Quantity of Heat Transfer by Flame Radiation, BTU/hr.

q_{gr} Quantity of Heat Transfer by Gas Radiation, BTU/hr.

q_k Quantity of Heat Transfer by Conduction along the thermocouple wires, BTU/hr.

F Geometrical factor for Radiation.

A_p Area of thermocouple junction, sq. ft.

L Depth of immersion of the thermocouple probe, ft.

d Diameter of thermocouple wire, ft.

V	Velocity of the gas stream at the centre of the duct, ft./sec.
p_t	Total pressure of the gas stream at the point considered.
p_s	Static pressure of the gas stream at the point considered.
p_w	Static pressure of the gas at the duct wall at the point considered.
Δp	Differential pressure across the measuring orifice.
A_1	Area of the thermodynamic probe entrance, sq. ft.
A_2	Area of the measuring orifice, sq. ft.
C	Constant of the measuring orifice.
C_1	Constant of the thermodynamic system.
K	Coefficient of the measuring orifice.
G	Mass velocity of the gas, lb./sec. ft.^{2}
w	Weight flow as measured by the orifice, lb./sec.
N_{nu}	Nusselt Number.
N_{Re}	Reynolds Number.
h_c	Convection Coefficient of heat transfer, BTU/hr. ft.^{2}, °F.
N_{pr}	Prandtl Number.
r	Recovery factor.
k	Thermal Conductivity of the thermocouple wires, BTU/hr. ft.^{2}, °F. per ft.
C_p	Specific heat of gas, BTU/lb., ° F.
k_g	Thermal conductivity of gas, BTU/hr. ft.^{2}, ° F. per ft.
R	Gas Constant ft. lb./lb., ° R.
J	Mechanical Equivalent of heat, ft. lb./BTU.
ϵ	Emissivity of Probe tip.
ϵ_f	Emissivity of primary flame.
σ	Stefan-Boltsmann constant.
γ	Ratio of Specific Heats.
ρ	Density of the gas, lb./ft.^{3}
μ	Viscosity of gas, lb./sec. ft.
g	Acceleration due to gravity, ft./sec.^{2}

Subscripts 1, 2 refer to different stations in the gas flow where the measurements are taken.

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