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AN INVESTIGATION OF AIRCRAFT HEATERS

XVII - EXPERIMENTAL INQUIRY INTO STEADY STATE UNIDIRECTIONAL HEAT-METER CORRECTIONS

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SUMMARY

Section I of this report discusses a correction which must be applied to the heat meter when it is being used at other temperatures than that at which it was calibrated, as the thermoelectric power of a thermocouple and the properties of the heat-meter material are a function of temperature. Predicted and experimental results for this temperature correction are presented.

Section II of this report contains the results of the application of the two methods of correcting the heat-transfer rates for contact and heat-meter resistance to experimental data taken in the laboratory. From the resulting computations certain limitations on the use of the two methods were obtained.

INTRODUCTION

The theory and use of heat meters for the measurement of rates of heat transfer which are independent of time have been treated in reference 1. Two methods of correcting for contact and heat-meter resistance have been derived in reference 1.

The present report utilizes experimental data to investigate the application of the two methods of correction for contact and heat-meter resistance.

Because some of the properties of the heat meter vary with temperature, a correction must be applied to the heat-meter readings when used at temperatures other than that at which it was calibrated. Predictions of this correction are compared with experimental results obtained at low temperatures.

An analysis of the use of the heat meter under transient conditions of heat transfer is important. This analysis will appear in a forthcoming report.

This investigation, conducted at the University of California, was sponsored by, and conducted with financial assistance from, the National Advisory Committee for Aeronautics.

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I. TEMPERATURE CORRECTIONS TO HEAT METER

The electromotive force generated by the thermopile element of the heat meter is subject to corrections under conditions of use in which the temperature of the heat meter differs from the calibration temperature; this difference is due to a variation of heat-meter properties (thermal conductivity, thermoelectric power, and dimensions) with temperature. Steady state unidirectional heat flow conditions will be considered in this report.

SYMBOLS

E electromotive force generated by thermopile, millivolts

emf thermocouple electromotive force, millivolts

$e = \frac{d\,(\text{emf})}{dt}$ thermoelectric power of thermocouple, millivolts/$^{\circ}$F

f_c unit thermal convective conductance, Btu/hr ft^2 $^{\circ}$F

k thermal conductivity of material of which heat meter is constructed, Btu/hr ft$^2\left(\frac{^{\circ}F}{ft}\right)$

n number of pairs of junctions in thermopile

$\frac{q_M}{A}$ rate of heat transfer per unit area through meter in the direction hot to cold junction, Btu/hr ft^2

t temperature, $^{\circ}$F

t_M temperature of heat meter indicated by heat-meter thermocouple which is located between laminations of heat meter as shown in figure 2, $^{\circ}$F (also see reference 1, fig. 1).

α temperature coefficient of thermal conductivity defined by equation (4) $k = k_o \left[1 + \alpha \left(t_M - t_{M_o}\right)\right]$, $\frac{1}{^{\circ}F}$

β thermal coefficient of linear expansion of heat-meter material, $\frac{1}{^{\circ}F}$ defined by equation (5) $\Delta x = \Delta x_o \left[1 + \beta \left(t_M - t_{M_o}\right)\right]$

Δx distance between hot and cold junctions of thermopile element, ft

Δt temperature of hot junction minus temperature of cold junction, $^{\circ}$F

$\Delta t'$ temperature difference between heat-meter surface and ambient air, $^{\circ}$F

τ_a ambient air temperature, $^{\circ}$F

Subscripts:

o refers to datum or calibration temperature for heat meter

M refers to heat meter

1. Predicted Performance

Provided the thermoelectric power e is not a function of the temperature, or provided the temperature difference Δt is small, the electromotive force generated by the thermopile element (reference 2) may be expressed as follows:

$$E = ne\Delta t \tag{1}$$

where

E voltage generated by thermopile

n number of pairs of junctions in thermopile

e thermoelectric power of a thermocouple

Δt temperature of hot junctions minus temperature of cold junctions

The temperature difference Δt is caused by the unit heat flow $\frac{q_M}{A}$ through the heat meter and may be calculated by means of the conduction equation

$$\frac{q_M}{A} = k\,\frac{\Delta t}{\Delta x} \tag{2}$$

where

k thermal conductivity

Δx distance between cold and hot junctions

From equations (1) and (2)

$$E = ne\,\frac{\Delta x}{k}\,\frac{q_M}{A} \tag{3}$$

The quantity $\left(\dfrac{1}{ne\,\dfrac{\Delta x}{k}}\right)$ determines the calibration of a heat meter; because the terms in this expression cannot be predicted accurately, it is necessary to calibrate the heat meter.

If the thermal conductivity k and the dimension Δx are expressed as a function of temperature,

$$k = k_o \left[1 + \alpha(t_M - t_{M_o})\right] \tag{4}$$

$$\Delta x = \Delta x_o \left[1 + \beta(t_M - t_{M_o})\right] \tag{5}$$

where

t_M and t_{M_o} heat-meter temperatures taken to be uniform between hot and cold junctions because Δt is small

α thermal conductivity coefficient defined by equation (4)

β thermal expansion coefficient defined by equation (5)

t_M temperature of heat meter

The subscript o refers to some given temperature of the heat meter (consider this to be the datum or calibration temperature of the heat meter).

The electromotive force in millivolts of a silver-constantan thermocouple is:

$$\text{emf} = 0.02186\ t + 0.0000153\ t^2 - 0.715 \tag{6}$$

(the reference junction is at 32° F)

The thermoelectric power of a thermocouple $\left(e = \frac{d(\text{emf})}{dt}\right)$ obtained by differentiation of equation (6) is

$$e = 0.02186 + 0.0000306\ t_M \tag{7}$$

Substituting (4), (5), and (7) into equation (3), the general relation for the thermopile voltage is:

$$E = n(0.02186 + 0.0000306\ t_M)\ \frac{\Delta x_o \left[1 + \beta(t_M - t_{M_o})\right]}{k_o \left[1 + \alpha(t_M - t_{M_o})\right]}\ \frac{q_M}{A} \qquad (8)$$

If, as has been previously stated, the calibration temperature of the meter is considered to be the datum, then at this datum equation (8) reduces to: (for $t_M = t_{M_o}$)

$$E_o = n(0.02186 + 0.0000306\ t_{M_o})\ \frac{\Delta x_o}{k_o}\ \frac{q_M}{A} \qquad (9)$$

An inspection of equations (8) and (9) reveals that for a given value of $\frac{q_M}{A}$ the voltage generated by the thermopil will be different if the heat meter is at a temperature othe than that at which it was calibrated. Thus equations (8) an (9) indicate the manner in which the heat-meter electromotiv force varies with heat-meter temperature. An expression for this variation in terms of the datum conditions may be obtained by dividing equation (9) by equation (8) resulting in:

$$E_o = E \left[\frac{0.02186 + 0.0000306\ t_{M_o}}{0.02186 + 0.0000306\ t_M}\right] \left[\frac{1 + \alpha(t_M - t_{M_o})}{1 + \beta(t_M - t_{M_o})}\right] \qquad (10)$$

Suppose that data are taken when the meter temperature t_M is at -60° F and the calibration is known for $t_{M_o} = 100^\circ$ F. The thermal coefficient of expansion β in the above-mentioned expression is $0.0000167\ \frac{1}{^\circ F}$; for the above-mentioned temperature difference, the expression $\left[1 + \beta(t_M - t_{M_o})\right]$ would change only 0.3 percent, indicating that Δx varies inappreciably. A survey of the literature revealed no substantial data on the thermal conductivity of bakelite. An inspection of tables of thermal conductivity for other nonmetals indicates that the thermal conductivity coefficient α is usually very small. So for the first approximation α is considered to be zero, so that the thermal conductivity k may be taken to be a constant. Equation (10 will now be numerically evaluated. For a given rate of heat flow $\frac{q_M}{A}$ and the above-stated temperature conditions, the generated voltage at $t_{M_o} = 100^\circ$ F is 1.24 times the voltage at $t_M = -60^\circ$ F. Therefore, the multiplying coefficient of 1.24 must be applied to the voltage measured at $t_M = -60^\circ$ F before the data may be evaluated in terms of the calibration established at $t_M = 100^\circ$ F. For any heat-meter temperature equation (10) reduces to:

$$E_o = E\left[\frac{0.02186 + 0.0000306\ t_{M_o}}{0.02186 + 0.0000306\ t_M}\right] \tag{11}$$

The term $\left(\frac{0.02186 + 0.0000306\ t_M}{0.02186 + 0.0000306\ t_M}\right)$ in equation (11) is defined as the multiplying coefficient - that is, the quantity by which the heat-meter voltage must be multiplied in order to obtain the correct heat rate through the heat meter at the new temperature.

Figure 1 presents curves of the variation in the multiplying coefficient over a range of temperatures. The curve to be used in any particular case is the one which is marked with the temperature at which the particular meter calibration was accomplished. When the heat meter is used at the calibration temperature t_{M_o} the multiplying coefficient is equal to unity.

2. Experimental Verification

In order to determine the accuracy of the prediction of the change in the calibration of the heat meter as a function of temperature when the calibration at one temperature is known, it was necessary to calibrate over a range of heat-meter temperatures. Data on heat-meter calibrations over a range of meter temperatures from -1° to 129° F were obtained as the result of the experiments described below.

Initial attempts to perform low-temperature calibrations on the heat meters were unsuccessful; principally due to the fact that the first cold chamber used was too small resulting in large free convection currents. This flow condition created a vertical temperature gradient along the heat meter making it impossible to obtain a calibration.

The use of large constant-temperature cold rooms became necessary. A typical low-temperature room is shown in figure 3. To prevent sudden large drops in temperature in the inner room upon entering from the aisle which is at room temperature, an anteroom is situated between the aisle and main room. The temperature of the anteroom is somewhere between that of the main room and that of the aisle. The temperature of the rooms is thermostatically controlled, and the refrigeration is accomplished by the circulation of brine. The control was generally within $\pm 1^\circ$ F.

Calibration data were taken in three cold rooms the temperatures of which were maintained at -30°, 0°, and $+20^\circ$ F. The calibration heater with the two heat meters mounted upon it as schematically shown in figure 2 was placed upon the concrete floor of the cold room. The control panel including rheostats, meters, and potentiometer was located in the aisle. Power leads, thermocouple leads, and voltmeter leads from the calibration heater to the control panel were brought out in a cable. This arrangement made it possible to operate the equipment and take data in the aisle; it was only necessary to enter the cold rooms when assembling or dismantling the equipment. The center of the room probably would have been a more desirable location for the calibration heater; however, the presence of other material and equipment in the room made this impossible.

The two heat meters, UC-21 and UC-22, used in the check calibration possessed the same datum calibration of 19.5 Btu/hr ft^2 mv at $t_{M_0} = 104^\circ$ F. These heat meters were calibrated under the three different given temperature conditions. The experimental multiplying coefficient for the new temperature was obtained by dividing the thermopile voltage at its datum temperature by the thermopile voltage at the new temperature for a given rate of heat transfer. Table I exhibits the calibration results in the low-temperature rooms.

TABLE I

EXPERIMENTAL AND PREDICTED MULTIPLYING COEFFICIENTS

AS A FUNCTION OF HEAT-METER TEMPERATURE t_M

Heat-meter temperature, t_M (°F)	Experimental multiplying coefficient	Predicted multiplying coefficient[1]
Heat meter UC-21		
-1	1.107	1.142
12	1.077	1.122
43	1.100	1.076
47.5	1.090	1.070
63.5	1.090	1.050
Heat meter UC-22		
1	1.107	1.140
16	1.077	1.117
48	1.000	1.070
50.5	.986	1.066
69.5	.986	1.040

[1]From equation (11)

The predicted multiplying coefficient given in equation (11), $\left[\dfrac{0.02186 + 0.0000306\ t_{M_o}}{0.02186 + 0.0000306\ t_M}\right]$, is plotted together with the experimental multiplying coefficients in figure 4. Since both heat meters (UC-21 and UC-22) were calibrated at $t_{M_o} = 104^\circ$ F with a resulting calibration constant of 19.5 Btu/hr ft^2 mv, only one predicted curve for the multiplying coefficient resulted. The experimental points scatter on both sides of the predicted curve with a maximum deviation of about 7 percent. The spread of the points which exhibited the greatest deviation from the predicted curve can be attributed to the fact that experimental data were taken in rooms subject to varying temperature conditions; at times it was necessary for the personnel of the laboratory to enter these low-temperature rooms, and thus sudden temperature transients resulted.

When the two heat meters and the whole calibration unit had reached the steady state of heat flow, the proper data for calibration were taken. If, during the calibration, the air temperature suddenly varied due to air currents, a transient state of heat flow resulted. If readings were made during these transients, errors resulted. The variation in temperature distribution under these conditions will be considered in a forthcoming report. The maximum variation observed in the thermopile voltage reading was ±2.5 percent. The maximum variation in the reading of the thermocouple located under the first lamination of the heat meter was ±0.5 percent. In the calibration of the heat meters one postulate made is that the sum of the air-heat meter interface resistance plus the first heat-meter lamination resistance is the same for both heat meters. (See fig. 2.) The calibration constants of the two heat meters were obtained by apportioning the rates of heat flow in terms of the temperature potential across the resistance which includes the air-heat meter interface and the first heat-meter lamination. These thermal resistances were considered equal for both heat meters. However, when one of the two heat meters being calibrated has a greater surface temperature, the air-heat meter interface resistance is less for that heat meter since the unit thermal conductance for free convection and the unit thermal conductance due to radiation are proportional to the difference in temperature between the surface and ambient air temperatures. The variation in the unit thermal conductance for free convection and radiation which resulted during the calibration runs was ±2 percent. The variation in the value of the unit thermal conductances along the heat meters during the calibration test causes a slight error in the magnitude of the heat-meter calibration constants.

The composite effect of these experimental variations can be shown to be as great as ±7 percent.

II. CONTACT AND HEAT-METER RESISTANCE CORRECTIONS

When a heat meter is placed in a thermal circuit, a correction must be applied to the measurement of the rate of heat transfer through the heat meter to yield the rate of heat transfer which occurs without the heat meter in the circuit.

SYMBOLS

f_{c_1} unit thermal convective conductance from heat meter to fluid at temperature T_c, Btu/hr ft² °F

f_{c_o} unit thermal convective conductance from wall to fluid at temperature T_c, Btu/hr ft² °F

f_{r_1} equivalent unit thermal conductance for radiation from the heat meter to surroundings, Btu/hr ft² °F

$$f_{r_1} = \frac{0.173\ F_{AE}\left[\left(\frac{T_M'}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]}{(t_M' - T_c)}$$

f_{r_o} equivalent unit thermal conductance for radiation from wall to surroundings, Btu/hr ft² °F

$$f_{r_o} = \frac{0.173\ F_{AE}\left[\left(\frac{T_w'}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]}{(t_w' - T_c)}$$

$\frac{q_M}{A}$ rate of heat transfer per unit area through the heat meter, Btu/hr ft²

$\frac{q_o}{A}$ rate of heat transfer per unit area through wall when meter is removed, Btu/hr ft²

R_M thermal resistance of core and outer lamination of heat meter, °F/Btu hr

t_M temperature of heat meter given by the heat-meter thermocouple, $^{\circ}F$

t_W temperature of the portion of the wall covered by the heat meter, $^{\circ}F$

t_W' temperature of the wall adjacent to heat meter, but not covered by it, $^{\circ}F$

$$\Delta R = \frac{(f_{c_0} + f_{r_0}) - (f_{c_1} + f_{r_1})}{(f_{c_0} + f_{r_0})(f_{c_1} + f_{r_1})} \frac{1}{A}$$

τ_a temperature of fluid on far side of wall, $^{\circ}F$

τ_c temperature of fluid on near side of wall (side of wall on which heat meter is placed), $^{\circ}F$

F_{AE} modulus which includes effect of emissivities and geometrical configuration of radiating bodies in equation for f_r.

T_M' absolute temperature of outer surface of heat meter, $^{\circ}R$

T_s absolute temperature of surroundings, $^{\circ}R$

A area through which heat is being transferred, ft^2

$f_{c_1 (point)}$ local or point unit thermal convective conductance from heat meter to fluid at temperature τ_c, Btu/hr ft^2 $^{\circ}F$

u_1 free-stream velocity of fluid across heat meter, ft/sec

t_M' temperature of outer surface of heat meter, $^{\circ}F$

G weight rate of fluid per unit of cross-sectional area $= (u_1 \gamma 3600)$, lb/hr ft^2

Two methods of making the above-mentioned corrections are derived in reference 1. Correction method I may be expressed as follows:

$$\frac{q_o}{A} = \frac{q_M}{A}\left[\frac{\tau_a - t_w'}{\tau_a - t_w}\right] \tag{12}$$

Correction method II may be expressed as follows:

$$\frac{q_o}{A} = \frac{\dfrac{q_M}{A}}{1 - \dfrac{\dfrac{q_M}{A}}{\left|\tau_a - \tau_c\right|}\left[\dfrac{\left|t_w - t_M\right|}{\dfrac{q_M}{A}} + AR_M + A\Delta R\right]} \tag{13}$$

It is desirable to know some of the limitations on the use of the two correction equations (12) and (13). It is important to recognize which of the two correction methods is usable as a function of the location of the heat meter (on air-stream side or still-air side).

It is also necessary to know how large the heat-transfer correction for heat-meter and contact resistance is when the heat meter is fastened <u>tightly</u> against the cabin wall of an airplane in flight.

Because the equation for correction method I requires the measurement of three temperatures, it is important to locate the heat meter so that these temperature measurements can be made accurately. In using correction method II the evaluation of the term ΔR in equation (13) requires consideration. If the unit thermal conductance due to convection and the equivalent unit thermal conductance due to radiation of the <u>wall</u> are the same as the unit thermal conductance due to convection and the equivalent unit thermal conductance due to radiation of the <u>heat-meter</u> surface, the quantity ΔR is equal to zero. In some cases these conductances along the <u>wall surface</u> may be different from the corresponding conductances along the <u>heat-meter surface</u>, in which case the term ΔR may be estimated. Of course, if the unit thermal conductances (f_{c_o}, f_{r_o}) in the term ΔR are accurately known, it is not necessary to use a heat meter as a means of measuring the rate of heat transfer, as the heat transfer may be calculated from the known conductance and the temperature potential (wall temperature minus contiguous-fluid temperature). In most cases when the unit thermal conductances are not accurately known, approximate values can be used to evaluate the term ΔR to be used in

The correction methods I and II were checked for a typical system of heat loss from an uninsulated airplane cabin in flight. The unit thermal conductance for free convection and radiation is approximately 2 Btu/hr ft^2 $^\circ$F inside the cabin; whereas, the unit thermal conductance for forced convection and radiation on the outside may be from 6 to 20 Btu/hr ft^2 $^\circ$F. To simulate the above-mentioned conditions hot air was blown through a duct at such a velocity as to produce a unit thermal conductance for forced convection and radiation of about 6 to 10 Btu/hr ft^2 $^\circ$F. The outside of the duct was exposed to still air yielding a unit thermal conductance for free convection and radiation of about 2 Btu/hr ft^2 $^\circ$F. The heat meter was placed on either side of the duct wall exposing the instrument either to the air stream or still air. On the still-air side, spacers were placed between the heat meter and the wall in order to determine the effect of the method of heat-meter attachment or character of the surface upon which the meter may be placed. Figures 5, 6, 7, 8, 9, and 10 present photographs of various views of the duct and of the heat-meter mountings. Four thermocouples attached to the duct-wall surface and spaced around the heat meter were used to obtain an average temperature of the wall adjacent to the heat meter but not covered by it. It was necessary to average the four surface temperatures because of the existance of small temperature gradients upon the surface of the duct wall. The temperature of the duct-wall surface under the heat meter was measured with a thermocouple mounted upon the surface. Duct-wall surface temperatures were obtained accurately to $\pm 0.1^\circ$ F. The mixed mean temperatures of the hot air being blown through the duct were also measured to $\pm 2.0^\circ$ F.

RESULTS

When the heat meter was fastened to the still-air side of the hot-air duct wall without a spacer between the wall and meter, the heat-transfer correction due to contact and heat-meter resistance was a maximum of 7 percent using correction method I and 10 percent using correction method II. The emissivities, and thus the values of f_{r_o} and f_{r_1}, of the heat meter and adjacent duct-wall surfaces were known;[1]

[1]In an attempt to make the emissivities of the duct-wall and heat-meter surfaces the same, both were painted with one coat of flat-black paint. The emissivities of the two

(Continued on next page)

the unit thermal convective conductances f_{c_0} and f_{c_1} were believed to be equal and known approximately, thus the quantity ΔR in equation (13) was evaluated.

With the heat meter on the still-air side, bakelite spacers of 1/64, 3/64, and 5/64 inch in thickness were used to vary the contact or air gap resistance for a constant rate of heat loss from the duct wall. The rate of heat transfer through the heat meter required a correction of 33 percent when the air gap between the duct wall and the heat meter was 5/64 inch, evaluated according to correction method I. Correction method II was not used for this case because the values of the emissivities used to evaluate ΔR were not known.

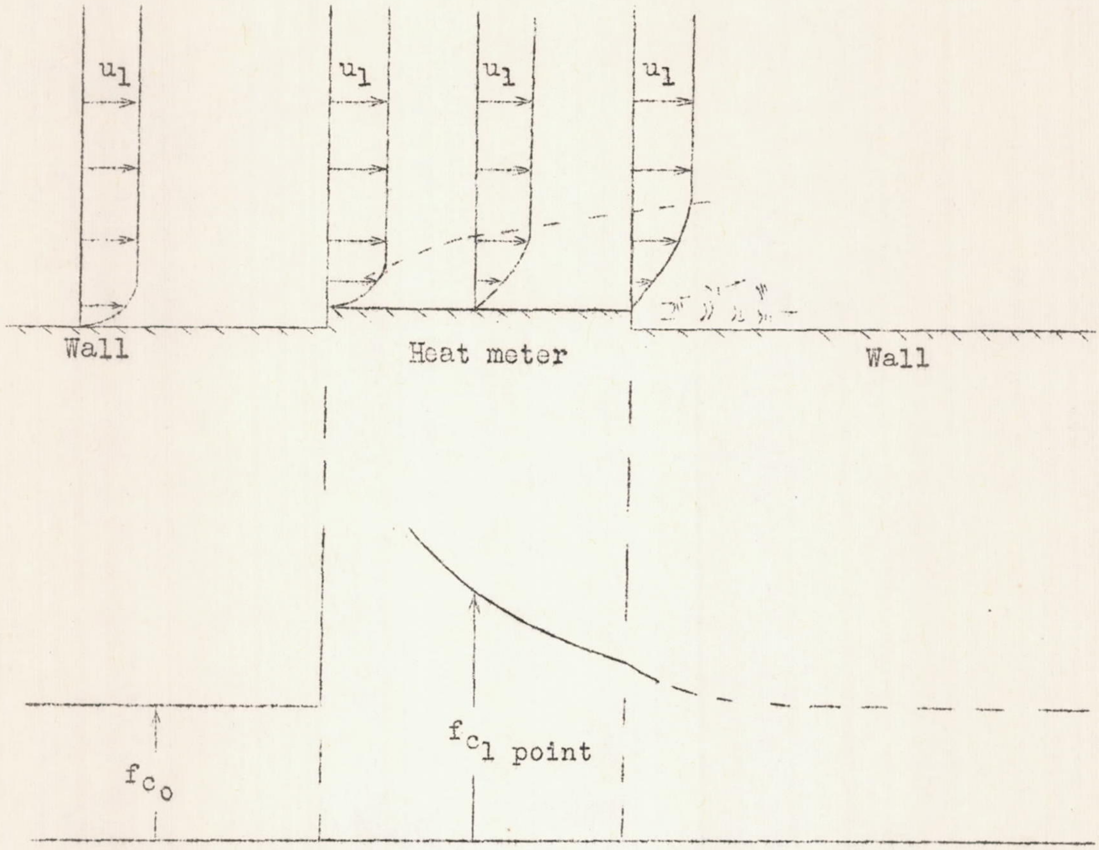
When the heat meter was placed on the hot-air side of the duct wall (without a spacer) a maximum correction due to contact and heat-meter resistance, to the rate of heat transfer through the heat meter, of 5 percent was needed, using correction method I. The corresponding correction using the correction method II was 7 percent. The unit thermal convective conductances (f_{c_1} and f_{c_0}) were estimated by means of equations (23) and (24) of reference 3. The equivalent unit thermal conductances due to radiation (f_{r_1} and f_{r_0}) were zero because the air duct was at a uniform temperature. Tabulated results are shown in tables II and III.

DISCUSSION

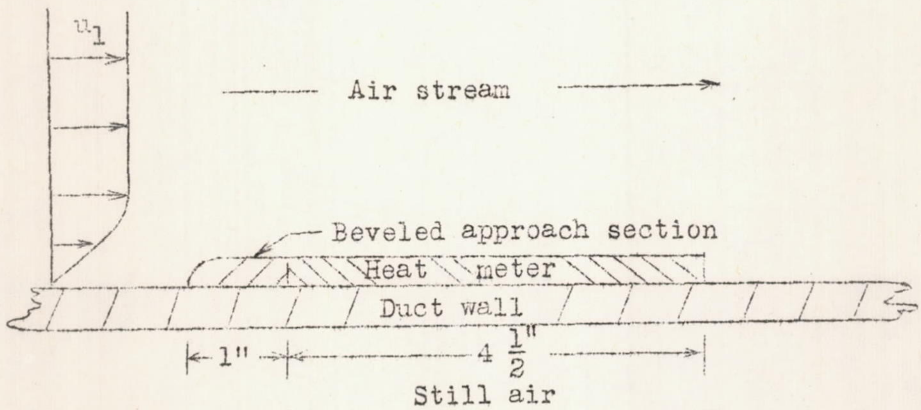
If the heat meter is attached to the airplane cabin wall on the air-stream side,[2] the unit thermal conductance f_c along the wall would be different from the f_c along the heat meter due to the fact that the air flowing over the heat meter would initiate a new retarded layer (reference 4).

(Continued from preceding page)
painted surfaces were then determined experimentally and were found to deviate from each other by 5 percent. Apparently the surface asperities of the metal wall and the bakelite were not completely covered by the paint.

[2]If the heat meter is placed on the still-air side, the f_c along the wall and along the meter also may differ. Even though this difference probably would be small, its effect may be large due to the fact that the f_c's of small value are the controlling resistances to heat transfer.



Data on heat-meter and contact resistance correction were taken when the heat meter was placed on the air-stream side of the duct wall. In an attempt to make the unit thermal conductances due to convection (f_{c_0} and f_{c_1}) equal, a beveled approach section 1 inch in length was joined to a $4\frac{1}{2}$- by $4\frac{1}{2}$-inch heat meter.



The value of $\dfrac{q_o/A}{q_M/A}$ was obtained by using correction method I, equation (12). The equivalent unit thermal conductances due to radiation (f_{r_1} and f_{r_o}) were approximately equal to zero because the inside duct surfaces were at a uniform temperature. Upon making these substitutions into equation (13) the percentage difference between the unit thermal conductances due to convection along the meter f_{c_1} and along the wall f_{c_o} was found to be about 70 percent (based on f_{c_o}). An attempt was made to predict this deviation by equations (23) and (24) of reference 3. The unit thermal convective conductance along the duct wall was evaluated from an equation for flow in a straight smooth duct. The unit thermal convective conductance along the heat meter was evaluated from an equation used for the flow along a flat smooth plate. The predicted percentage difference between the f_{c_o} and f_{c_1} obtained in this manner was 63 percent.

An inspection of the term ΔR in equation (13) reveals that this term may be either positive or negative depending upon the magnitudes of the thermal conductances (f_{c_o}, f_{c_1}, f_{r_o}, and f_{r_1}). If ΔR is negative, the added thermal resistance in the circuit is reduced.

During some of the tests when no spacers were placed between the heat meter and the duct wall, excessive pressures were applied to the heat meter. Under these conditions the correction to the rate of heat transfer due to heat-meter and contact resistance was about 1 percent.

CONCLUSIONS

1. When the contact and heat-meter resistances are small compared to the remainder of the thermal resistance in the circuit, the correction quantities $\left[\dfrac{T_a - t_w'}{T_a - t_w}\right]$ or

$$\frac{1}{\left[1 - \dfrac{q_M/A}{|T_a - T_c|}\left(\dfrac{|t_w - t_M|}{q_M/A} + AR_M + A\Delta R\right)\right]}$$

are very close to

unity. The maximum correction needed for the data taken in the laboratory without a spacer was 10 percent. Thus, if a heat meter is attached tightly to an airplane wall so as to yield a small contact resistance, and if one of the two unit thermal conductances is approximately 2 Btu/hr ft^2 $^\circ$F (still-air side), only a 10 percent error will occur if the correction to the heat rate indicated by the meter is not applied.

2. One condition necessary in using correction method I is that the temperatures present in equation (12) must be measured accurately. The accuracy necessary depends upon the magnitude of the heat-meter and contact resistance correction. When the quantities $(\tau_a - t_w)$ and $(\tau_a - t_w')$ in equation (12) are small and very nearly the same, a slight error in the measurement of t_w or t_w' will yield a large error in the heat-meter and contact resistance correction. The heat meter probably should be placed upon that side of the wall opposite to where the fluid temperature τ_a can be evaluated most accurately. The temperature differences $(\tau_a - t_w')$ and $(\tau_a - t_w)$ are the largest when the heat meter is on the side of the wall contiguous to the fluid having the highest unit thermal conductance. However, for this condition the flow of heat around the heat meter will be greater.[3]

3. If the term ΔR in equation (13) is equal to zero, it is a simple matter to use correction method II. If an airplane cabin wall is equipped with insulation, the best place to put a heat meter is between the cabin wall and the insulation, because in this case the term ΔR is equal to zero. Also, if a heat meter is mounted on the inside of an airplane cabin wall and the cabin is at a uniform temperature and no forced convection currents exist, the equivalent unit thermal conductances due to radiation along the heat meter and along the wall adjacent to the meter (f_{r_0} and f_{r_1}) will be nearly zero, and the corresponding unit thermal conductances due to convection (f_{c_0} and f_{c_1}) are nearly the

[3]Correction methods I and II have been derived on the basis of unidirectional heat flow. If the thermal resistance of the added heat-meter and contact resistance is large enough so that an appreciable amount of the heat flows around the heat meter rather than through it, equations (12) and (13) alone can no longer be used; additional corrections describing this phenomenon must be applied.

same; thus the term ΔR, of equation (13), is nearly zero. If the unit thermal conductances contained in the term ΔR are approximately known, the correction equation (13) can be utilized by using these approximations in the evaluation of ΔR. If the temperature differences $(\tau_a - t_w)$ and $(\tau_a - t_w')$ in the correction equation (12) are small, and if the accuracy in measuring the temperatures t_w and t_w' is not adequate, large errors in the ratio $\left(\frac{\tau_a - t_w'}{\tau_a - t_w}\right)$ may occur; under these conditions correction method II must be used even if ΔR is only very approximately known. An evaluation of this correction method by a trial and error technique is presented in the appendix. Also a sample calculation of the acquired data is presented.

4. If temperature gradients exist upon a surface through which the heat transfer is being measured by means of a heat meter, the temperature of the surface adjacent to the heat meter (t_w') must be determined by averaging the temperatures measured by several thermocouples spaced equally around the heat meter.

University of California,
Berkeley, Calif., November 1943.

APPENDIX

The following is a sample calculation illustrating how the rate of heat transfer is corrected for contact and heat-meter resistance. The data from Run d-5 of table III will be used.

$$t_M = 141.5^\circ \text{ F}$$

$$t_w = 133.7^\circ \text{ F}$$

$$t_w' = 136.4^\circ \text{ F}$$

$$\tau_a = 79.5^\circ \text{ F}$$

$$\tau_c = 148^\circ \text{ F}$$

$$\frac{q_M}{A} = 66.4 \text{ Btu/hr ft}^2$$

$$AR_M = 0.010 \frac{\text{ft}^2 \; {}^\circ\text{F}}{\text{Btu/hr}}$$ (obtained from calibration for this particular heat meter)

Using Method I:

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = \left[\frac{T_a - t_w'}{T_a - t_w}\right] \tag{12}$$

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = \left[\frac{79.5 - 136.4}{79.5 - 133.7}\right] = \frac{56.9}{54.2} = 1.05$$

If the temperature differences in correction equation (12) were small and if the accuracy in measuring the temperatures t_w and t_w' were not adequate, large errors in the ratio $\left(\frac{T_a - t_w'}{T_a - t_w}\right)$ might occur; under these circumstances the following trial and error solution can be used. The term $(f_{c_0} + f_{r_0})$ in the quantity ΔR is estimated. The term $(f_{c_1} + f_{r_1})$ is known because the heat transfer through the heat meter and the heat-meter surface temperature and ambient air temperature differences are known. From the approximated term ΔR thus obtained, the correction ratio $\frac{q_o/A}{q_M/A}$ can be evaluated. Since the rate of heat transfer through the wall and a corresponding difference in temperature between the wall surface and the ambient air are known, a calculated value of the term $(f_{c_0} + f_{r_0})$ can be obtained. Thus by trial and error the estimated value of $(f_{c_0} + f_{r_0})$ is adjusted until it is equal to the calculated one; hence the term ΔR can be evaluated.

By the use of the equation for the unit thermal convective conductance for straight smooth ducts (reference 3, equations (23) and (24)) the term f_{c_0} was estimated to be near 7 Btu/hr ft^2 $^\circ$F.

First Trial

try

$$(f_{c_0} + f_{r_0}) = 7 \text{ Btu/hr ft}^2 \ ^\circ\text{F}$$

where

$$f_{r_0} = 0$$

$$t_M' = (t_M' - t_M) + t_M = 0.7 + 141.5 = 142.2^\circ \text{ F}$$

where

$$t_M' - t_M = AR_M \left(\frac{q_M}{A}\right) = (0.010)(66.4) = 0.7^\circ \text{ F}$$

$$f_{c_1} = \frac{\frac{q_M}{A}}{T_c - t_M'} = \frac{66.4}{148 - 142} = 11.1 \text{ Btu/hr ft}^2 \ ^\circ\text{F}$$

or

$$(f_{c_1} + f_{r_1}) = 11.1 \text{ Btu/hr ft}^2 \ ^\circ\text{F}$$

since

$$f_{r_1} \cong 0$$

$$\therefore A\Delta R = \frac{(f_{c_0} + f_{r_0}) - (f_{c_1} + f_{r_1})}{(f_{c_0} + f_{r_0})(f_{c_1} + f_{r_1})} = \frac{7 - 11.1}{(7)(11.1)} = -0.053$$

From equation (13)

$$\frac{\frac{q_0}{A}}{\frac{q_M}{A}} = \frac{1}{\left[1 - \frac{\frac{q_M}{A}}{|T_a - T_c|}\left(\frac{|t_w - t_M|}{\frac{q_M}{A}} + AR_M + A\Delta R\right)\right]}$$

$$= \frac{1}{\left[1 - \frac{66.4}{|795 - 148|}\left(\frac{|133.7 - 141.5|}{66.4} + 0.010 - 0.053\right)\right]}$$

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = 1.08$$

$$\therefore \frac{q_o}{A} = \frac{q_M}{A} \; (1.08) = (66.4)\;(1.08) = 71.6 \text{ Btu/hr ft}^2$$

but

$$(f_{c_o} + f_{r_o}) = \frac{\frac{q_o}{A}}{T_c - t_w'} = \frac{71.6}{148 - 136} = 5.96 \text{ Btu/hr ft}^2 \; {}^oF$$

and the trial value was 7.00 Btu/hr ft^2 ^{o}F

Second Trial

try

$$(f_{c_o} + f_{r_o}) = 5.8 \text{ Btu/hr ft}^2 \; {}^oF$$

where

$$f_{r_o} \cong 0$$

$$\therefore A\Delta R = \frac{5.8 - 11.1}{(5.8)(11.1)} = -0.082$$

From equation (13)

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = \frac{1}{\left[1 - \frac{66.4}{|79.5 - 148|}\left(\frac{|133.7 - 141.5|}{66.4} + 0.010 - 0.082\right)\right]}$$

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = 1.05$$

$$\therefore \frac{q_o}{A} = \frac{q_M}{A}(1.05) = (66.4)(1.05) = 69.5 \text{ Btu/hr ft}^2$$

but

$$(f_{c_o} + f_{r_o}) = \frac{\frac{q_o}{A}}{T_c - t_w'} = \frac{69.5}{148 - 136} = 5.8 \text{ Btu/hr ft}^2 \text{ }^{\circ}\text{F}$$

The second trial value of $(f_{c_o} + f_{r_o})$ was 5.8 Btu/hr ft^2 $^{\circ}$F so that the value of

$$\frac{\frac{q_o}{A}}{\frac{q_M}{A}} = 1.05$$

is correct.

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2. Gier, J. T., Boelter, L. M. K.: The Silver-Constantan Plated Thermopile. Temperature, Its Measurement and Control in Science and Industry. Am. Inst. of Phys. Reinhold Pub. Co., New York, N. Y., 1941, pp. 1284-1292.

3. Boelter, L. M. K., Martinelli, R. C., Romie, F. E., and Morrin, E. H.: An Investigation of Aircraft Heaters. XVIII - A Design Manual for Exhaust-Gas and Air Heat Exchangers. NACA ARR No. 5A06, 1945.

4. Goldstein, S., Ed.: Modern Developments in Fluid Dynamics. Vol. II, ch. II. The Clarendon Press (Oxford), 1938.

TABLE II.- SUMMARY OF EXPERIMENTAL DATA

Run	τ_a (°F)	t_w (°F)	t_w' (°F)	$\frac{q_M}{A}$ (Btu/hr ft^2)	τ_c (°F)	t_M (°F)	$G=u_1\gamma(3600)$ (lb/hr ft^2)	Remarks
A. Heat meter on still-air side								
a-1	177	165.0	164.0	123	84	142.5	10,500	
2	178	165.0	164.4	140	84	150.0	10,500	
4	178	169.0	166.0	103	84	135.8	10,500	
5	180	168.0	167.0	121	84	145.0	10,500	
6	180	169.0	168.7	139	84	151.0	10,500	
b-1	179	161.0	160.0	133	83.5	139.0	11,580	A relatively large amount of pressure was put upon the heat meter.
2	181	160.8	159.5	133	83.5	139.6	11,580	
4	186.5	165.4	165.4	146	88.0	151.9	11,580	
5	189.5	168.5	168.2	142	88.5	152.1	11,580	
6	194	167.5	167.5	154	89.0	151.0	11,580	
8	187	168.1	168.0	156	89.2	150.4	11,580	
c-2	160.0	141.5	140.0	110	81.5	130.4	11,070	The surfaces of the heat meter and wall were painted with flat-black paint.
3	159.0	141.2	139.8	107	82	129.7	11,070	
4	159.0	140.1	139.0	121	82.5	131.5	11,070	
5	159.5	141.2	140.0	119	83	133.5	11,070	
B. Heat meter on air-stream side								
d-2	78.0	145.0	146.8	71.0	162	142.2	6,720	
3	79.0	143.5	145.5	72.0	161	151.5	6,720	
4	79.0	133.0	135.4	66.0	146.6	140.2	9,510	
5	79.5	133.7	136.4	66.4	148	141.5	9,510	

TABLE III.- SUMMARY OF CALCULATED RESULTS

Run	Correction method I	Correction method II	Spacer (in.)	Remarks
A. Heat meter on still-air side				
a-1	1.08		3/64	
2	1.05		1/64	
4	1.33		5/64	
5	1.08		3/64	
6	1.03		1/64	
b-1	1.06		3/64	A relatively large amount of pressure was put upon the heat meter.
2	1.07		3/64	
4	1.00		1/64	
5	1.01		1/64	
6	1.00		0	
8	1.00		0	
c-2	1.08	1.13	1/64	The surfaces of the heat meter and the wall were painted with flat-black paint.
3	1.08	1.14	1/64	
4	1.06	1.10	0	
5	1.07	1.09	0	
B. Heat meter on air-stream side				
d-2	1.03	1.03	0	The hot-air rate was varied.
3	1.03	1.04	0	
4	1.04	1.06	0	
5	1.05	1.07	0	

Correction method I:

$$\frac{\dfrac{q_o}{A}}{\dfrac{q_M}{A}} = \left[\frac{\tau_a - t_w'}{\tau_a - t_w}\right] \tag{12}$$

Correction method II:

$$\frac{\dfrac{q_o}{A}}{\dfrac{q_M}{A}} = \frac{1}{\left[1 - \dfrac{\dfrac{q_M}{A}}{\left|\tau_a - \tau_c\right|}\left(\dfrac{\left|t_w - t_M\right|}{\dfrac{q_M}{A}} + AR_M + A\Delta R\right)\right]} \tag{13}$$

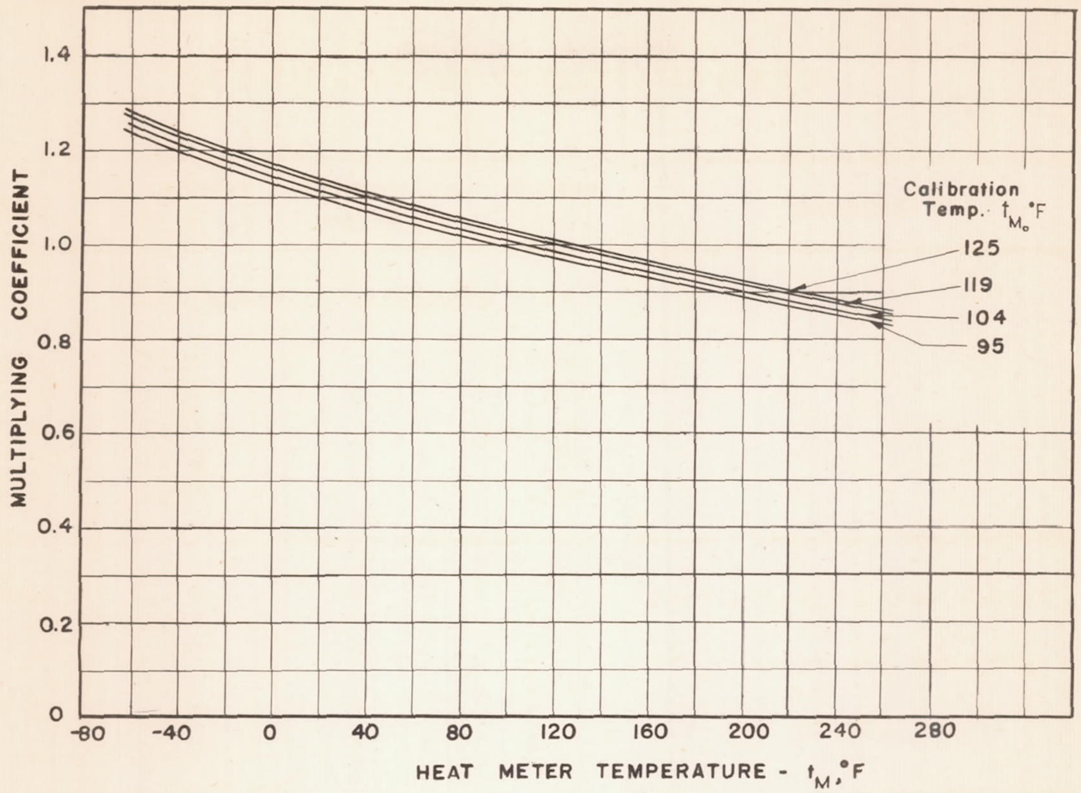

Fig. 1.- Multiplying Coefficient as a Function of Heat Meter Temperature (from eq.11) for any Bakelite Heat Meter Containing a Silver-Constantan Thermopile Element.

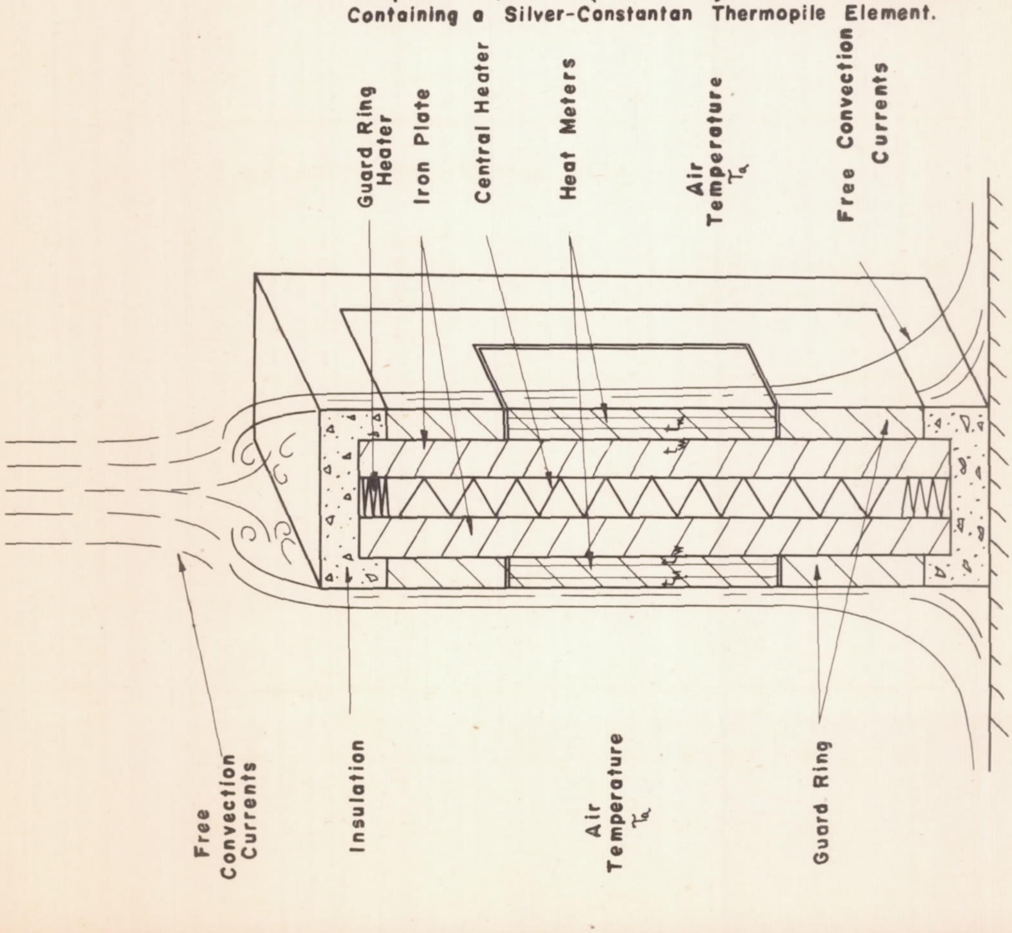

Fig. 2.- A Schematic Sketch of the Calibration System.

W-24

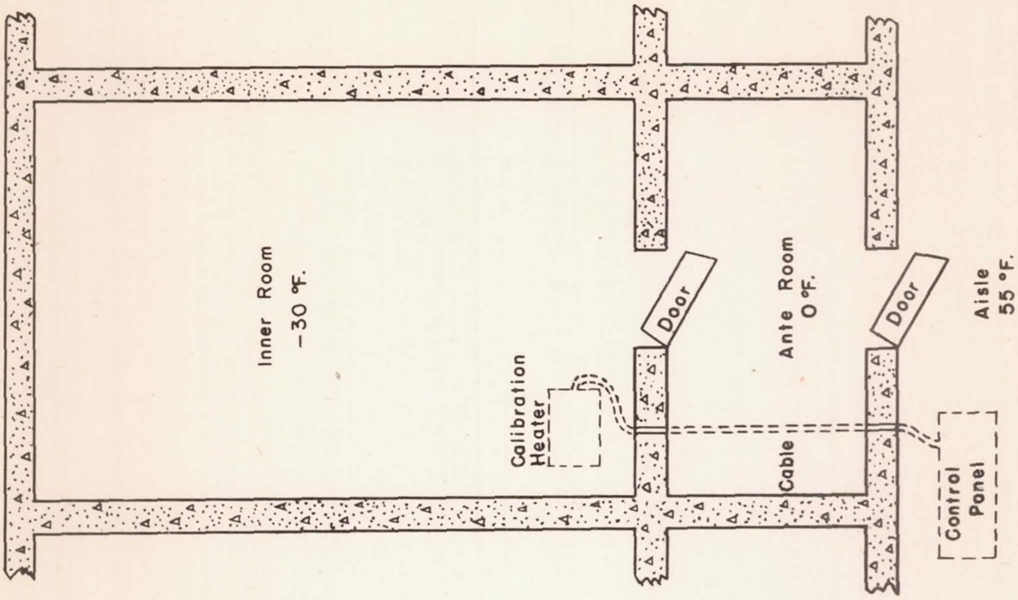

Fig.3.- A typical low temperature room in which heat meters were calibrated.

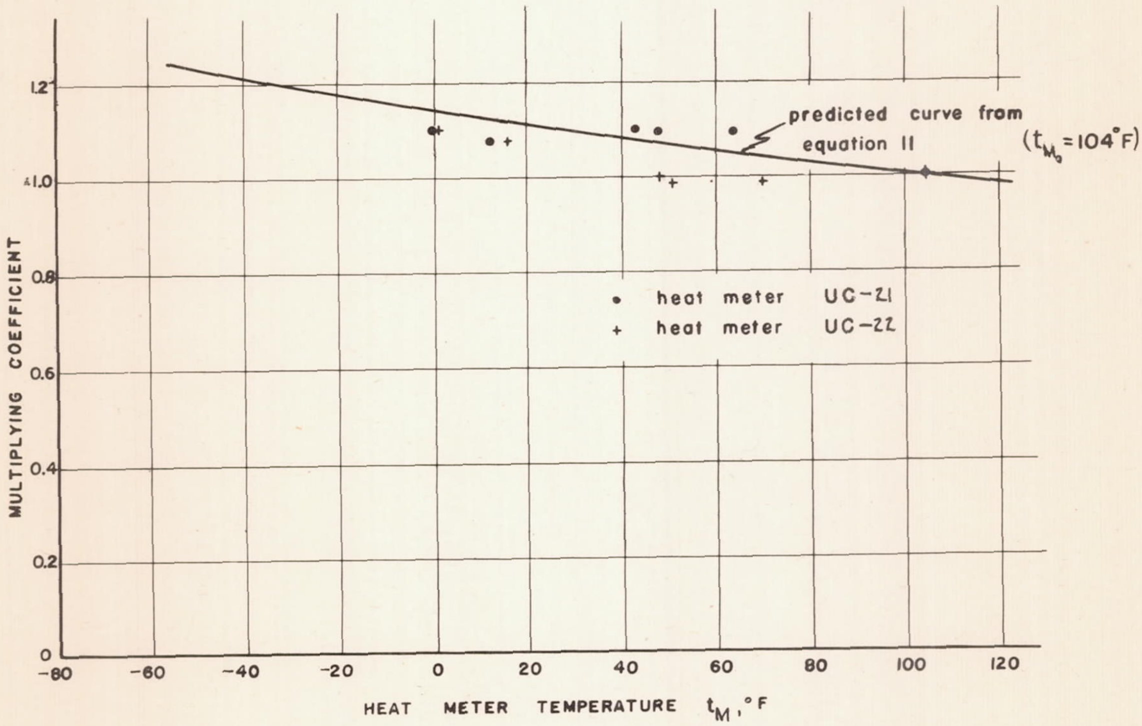

Fig. 4.- Experimental and Predicted Multiplying Coefficients as a Function of Heat Meter Temperature for Two Typical Bakelite Heat Meters.

W-24

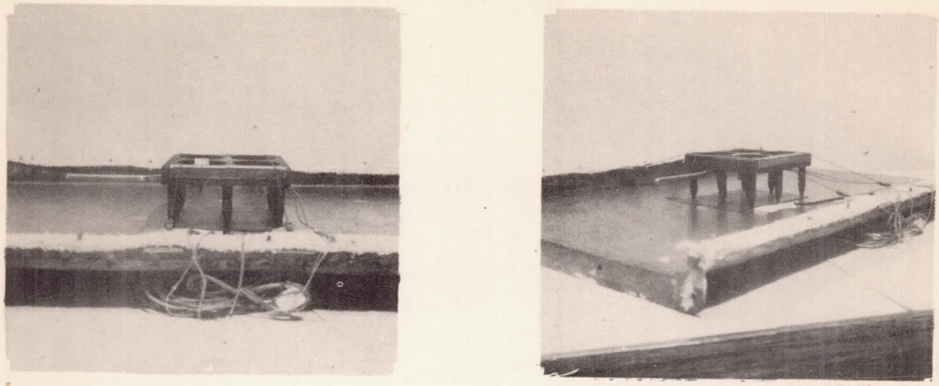

Figure 5,6.– The heat meter and its clamping device as viewed inside a section of the duct work.

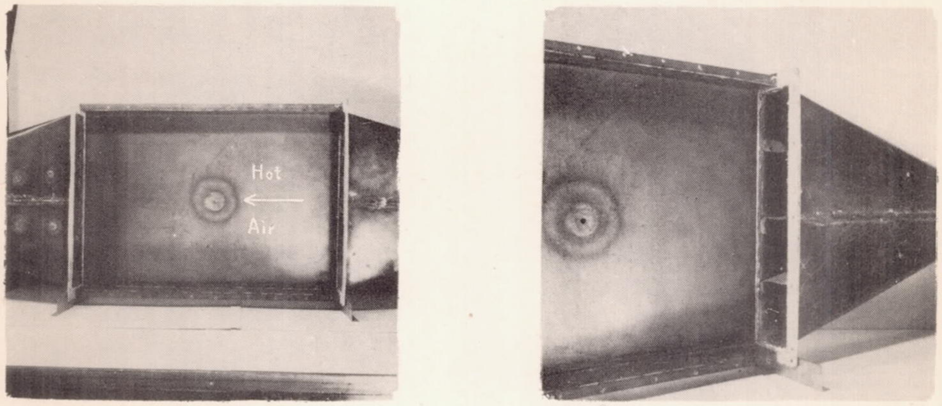

Figure 7,8.– The unassembled hot air duct.

Figure 9.– The traversing thermocouple used to obtain a temperature distribution of the hot air.

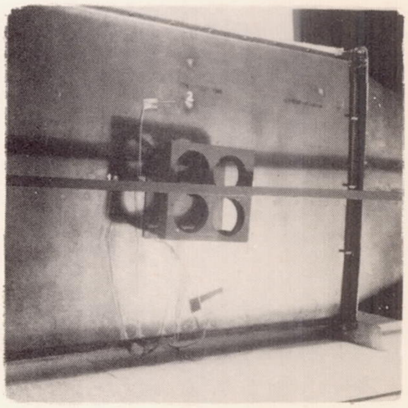

Figure 10.– The heat meter and clamping equipment as attached to the still-air side of the hot air duct.

W-24