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AN INVESTIGATION OF AIRCRAFT HEATERS

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AN INVESTIGATION OF AIRCRAFT HEATERS

V - THEORY AND USE OF HEAT METERS FOR THE MEASUREMENT OF RATES OF HEAT TRANSFER WHICH ARE INDEPENDENT OF TIME

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SUMMARY

A meter which will measure the heat flowing through surfaces is described. Its operation is based on the measurement of the temperature decrease through a fixed thermal resistance. Several methods of application of the meter are noted and the corresponding necessary corrections are presented. In this report only the case of heat flow independent of time has been discussed. The meter is calibrated and a typical unit will generate approximately 1 millivolt for each 18 Btu/hr ft^2 flowing. Special applications of the meter which are pertinent to the airplane are the heat flow through the wings, cabin walls, and clothing of personnel.

INTRODUCTION

An instrument, based on the work of Nichols (references 1, 2, and 3), has been developed* which allows a rapid measurement of the rates of heat flow through walls, clothing, into the ground, from engine surfaces, and so forth. A typical unit is 0.050 inch thick and $4\frac{1}{2}$ inches square, (See fig. 1.) The operation of the instrument is based on the fact that a definite relation exists between the temperature drop across and the rate of heat flow through a fixed thermal resistance. The instrument (fig. 1) consists of a central core containing two "elements" around which are wound a large number (160 per element) of electroplated thermocouple junctions connected in series (reference 4). Half of the junctions are in contact with one side of the element strip, the remainder with the other side. The two elements are connected in series, so that

*Developed by the staff of the Spectro-Radiometric Laboratory, Dept. of Mech. Engg., Univ. of Calif., Berkeley, Calif.

between the terminal strips labeled "thermopile" there are 320 thermocouple junctions. The electromotive force generated by these thermocouples is proportional to the temperature drop across the elements resulting from heat flow through the meter, and thus, after proper calibration, the unit may be utilized to measure rates of heat transfer.

The central core, which is 0.016 inch thick, is cemented between two laminations, each of which is 0.016 inch thick. In addition to the meter elements, the instrument is equipped with a single copper-constantan thermocouple located near the center of the meter between the central core and one of the laminations. All normal meter readings may be made with a thermocouple potentiometer of about 40 millivolt range. This voltage corresponds to a rate of heat transfer through the meter of about 700 Btu/hr ft².

SYMBOLS

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

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

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

$$f_{r_1} = \frac{0.173\ F_A\ F_E \left[\left(\frac{T_M'}{100}\right)^4 - \left(\frac{T_S}{100}\right)^4\right]}{(t_M' - \tau_c)}$$

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

$$f_{r_o} = \frac{0.173\ F_A\ F_E \left[\left(\frac{T_W'}{100}\right)^4 - \left(\frac{T_S}{100}\right)^4\right]}{(t_W' - \tau_c)}$$

$_a$ total unit conductance from wall to fluid at temperature τ_a, Btu/hr ft² °F

$_A$ shape modulus, the factor in the radiation equation which allows for the geometrical position of the radiating surfaces (reference 7)

F_E emissivity modulus, the factor in the radiation equation which allows for the non-Planckian character of the radiating surfaces (reference 7)

q_M rate of heat transfer as measured by heat meter, Btu/hr

q_o rate of heat transfer through wall when meter is removed, Btu/hr

R_G thermal resistance of air gap between meter and wall (including inner lamination of meter), $\frac{^{\circ}F}{Btu/hr}$

R_i thermal resistance of insulation, $\frac{^{\circ}F}{Btu/hr}$

R_M thermal resistance of meter (core and outer lamination only), $\frac{^{\circ}F}{Btu/hr}$

R_{TM} thermal resistance of meter (core and both laminations), $\frac{^{\circ}F}{Btu/hr}$

R_w thermal resistance of wall, $\frac{^{\circ}F}{Btu/hr}$

ΔR resistance defined by equations (13) and (14)

τ_a temperature of fluid on far side of wall (side of wall which does not contain meter), $^{\circ}F$

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

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

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

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

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

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

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

T_w' absolute temperature of the wall adjacent to heat meter, but not covered by it, OR

$\Delta t_w = \left| t_w' - t_w \right|$

$\Delta t_a = \left| t_w - T_a \right|$

$\cong$ denotes "approximately"

DISCUSSION

Use of the Meter

The meter is utilized by placing it in direct contact with the surface through which the rate of heat transfer is being determined. Nine mounting holes are provided for this purpose.

The presence of the meter reduces the rate of heat transfer through the surface by virtue of the increased thermal resistance with the meter in place. It is important to determine whether the thermocouple junctions are influenced by the heat transfer from the edges of the meter. An approximate flux plot (reference 5) indicates that end effects are negligible. Another effect of the meter is to change the temperature of the surface on which it is placed. This change in temperature will cause some heat to flow _along_ the wall and _around_ the meter. Flux plots are now being drawn to evaluate this error. Certain corrections must be applied to the observed meter readings in order to evaluate the rates of heat transfer which exist when the meter is removed. The system is analogous to an ammeter in an electrical circuit, except for the leakage around the meter referred to above.

In the thermal circuit (reference 5) the resistances are functions of many variables and also depend upon the method of application of the heat meter. Several methods of meter correction for the steady state condition have been studied; two of the most applicable are presented.

If the heat flow to be measured depends upon time, a correction for the thermal impedance (capacitance and resistance) must be made. The following discussion applies only to the case for which the heat flow does not depend upon time.

Corrections to Heat Meter for Steady Unidirectional Heat Flow

<u>First Method of Correction (I).</u>– Figure 2 represents the meter applied directly to a wall. The total resistance to heat flow will be the sum of the resistance between the air and the wall $\frac{1}{f_a A}$, of the wall R_w, of the gap R_G, of the meter R_M, and on the outside of the meter $\frac{1}{(f_{c_1} + f_{r_1})A}$. The resistance on the outside of the meter is treated as two resistances in parallel, since heat flows to or from the meter by both convection and radiation. For these thermal circuits, the rate of heat transfer when the meter is installed is:

$$q_M = \frac{(\tau_a - \tau_c)}{\left[\frac{1}{f_a A} + R_w + R_G + R_M + \frac{1}{(f_{r_1} + f_{c_1})A}\right]} \tag{1}$$

where $(\tau_a - \tau_c)$ is the temperature difference of the air on either side of the wall. When the meter is removed, R_M and R_G are eliminated so that the true rate of heat transfer is

$$q_o = \frac{(\tau_a - \tau_c)}{\left[\frac{1}{f_a A} + R_w + \frac{1}{(f_{r_o} + f_{c_o})}A\right]} \tag{2}$$

where f_a and R_w are postulated as unchanged, but f_{r_o} and f_{c_o}, the unit conductances between the air and the wall, may differ from f_{r_1} and f_{c_1}, the unit conductances between the air and the meter.

Dividing equation 2 by equation 1 gives

$$\frac{q_o}{q_M} = \frac{\frac{1}{f_a A} + R_w + R_G + R_M + \frac{1}{(f_{c_1} + f_{r_1})A}}{\frac{1}{f_a A} + R_w + \frac{1}{(f_{c_o} + f_{r_o})A}} \tag{3}$$

The thermal resistance is defined as the temperature difference divided by the rate of heat transfer. The various thermal resistances in equation 3 may, as a consequence, be expressed as follows:

$$\left(\frac{1}{f_a A} + R_w\right) = \frac{\tau_a - t_w'}{q_o} \qquad (4)$$

$$\left(R_G + R_M + \frac{1}{(f_{c_1} + f_{r_1})A}\right) = \frac{t_w - \tau_c}{q_M} \qquad (5)$$

and

$$\left(\frac{1}{f_a A} + R_w + \frac{1}{(f_{c_o} + f_{r_o})A}\right) = \frac{\tau_a - \tau_c}{q_o} \qquad (6)$$

Thus, substituting equations 4, 5, and 6 into equation 3 gives

$$\frac{q_o}{q_M} = \frac{\dfrac{\tau_a - t_w'}{q_o} + \dfrac{t_w - \tau_c}{q_M}}{\dfrac{\tau_a - \tau_c}{q_o}} \qquad (7)$$

or, solving for q_o and dividing both sides by the meter area A,

$$\frac{q_o}{A} = \frac{q_M}{A}\,\frac{\tau_a - t_w'}{\tau_a - t_w} \qquad (8)$$

Thus, to correct the observed magnitudes q_M/A to the value q_o/A, three temperatures must be determined:

1. The temperature of the fluid on the far side of the wall (the side opposite that on which the heat meter is installed) (τ_a)

2. The temperature of the portion of the wall covered by the meter (t_w)

3. The temperature of the wall adjacent to the meter, but not covered by it (t_w')

The accuracy of the correction is limited only by the accuracy of measurement of the three temperatures and the leakage of heat around the meter. (See comment on p. 2.)

Notes on Method I.– (a) A rough calculation reveals that for a meter installed on the wall of an airplane cabin the ratio $\left(\frac{\tau_a - t_w'}{\tau_a - t_w}\right)$ may be as large as 1.20, while for a meter measuring the rate of heat transfer through a 6-inch brick wall the ratio is about 1.05.

(b) In the case of measurement of the rate of heat flow through metal aircraft walls, the meter may be placed either on the inside of the wall or on the outside of the airplane. The unit conductance on the inside of the cabin wall is of the order of magnitude of 1.0 Btu/hr ft^2 $^{\circ}$F, while on the outside of the airplane the unit conductance is of the order of magnitude of 20 Btu/hr ft^2 $^{\circ}$F (reference 7). Thus, if the meter is placed on the inside of the cabin wall, the magnitude of $(\tau_a - t_w')$ will be very small, about 3° to 4° F. The magnitude of $(t_w' - t_w)$ will be a fraction of a degree. The correction expressed by equation (8), therefore, will be difficult to determine accurately. On the other hand, the error due to heat flowing around the meter will be small.

If the meter is placed on the outside of the airplane, the magnitudes of $(\tau_a - t_w)$ and $(t_w' - t_w)$ become appreciable,* thus increasing the accuracy of measurement. This method of application would be ideal, except for the fact that if the temperature difference $(t_w' - t_w)$ is of the order of magnitude of 10° to 20° F, the error due to the heat flow around the meter becomes serious. A guard ring of the material of which the meter is constructed is placed around the meter to reduce this leakage.

If the correction expressed by equation (8) is to be utilized for the meter mounted on the walls of the cabin of an airplane, the meter should be mounted on the outside of the cabin and surrounded by a guard ring. If this method is not feasible, the correction technique discussed under Method II will be found satisfactory.

(c) In some applications the meter may be mounted in a composite wall. Figure 3 illustrates a meter application for this case. The resistances R_{G1}, R_{G2}, and R_{G3} are the gap resistances between the various elements as shown in

*τ_a is defined as the temperature of the fluid on the far side of the wall (the side which does not contain the heat meter).

figure 3. A consideration of the appropriate thermal circuits reveals that equation (8) may be applied directly to this system.

(d) The meter may be placed on clothing in order to determine the rate of heat transfer from the human body under various conditions. The temperature T_a becomes the body temperature (about 98.6° F). The meter may be attached securely, either between garments or on the outside of the clothing and the temperatures t_w and t_w' obtained by means of appropriate thermocouples. The correction ratio $\left(\frac{T_a - t_w'}{T_a - t_w}\right)$ may be as large as 1.10 for this application.

(e) In some cases it may be convenient to measure temperature differentials between t_w', t_w, and t_w', T_a, obtaining Δt_w and Δt_a, respectively.

Then:

$$\frac{q_o}{A} = \frac{q_M}{A}\left(\frac{1}{1 - \frac{|\Delta t_w|}{|\Delta t_a|}}\right) \tag{9}$$

The "differential" technique cannot be used when the wall is an electrical conductor.

<u>Second Method of Correction (II)</u>. - Although the method of correction discussed above is by far the most simple and the most direct, it may yield inaccurate results, in some cases, as has been discussed in note (b). A more complex, but under certain conditions more accurate, method of correction is discussed below:

For the system shown in figure 2, equation (3) states that:

$$\frac{q_o}{q_M} = \frac{\frac{1}{f_a A} + R_w + R_G + R_M + \frac{1}{(f_{c_1} + f_{r_1})A}}{\frac{1}{f_a A} + R_w + \frac{1}{(f_{c_o} + f_{r_o})A}} \tag{10}$$

Let

$$R_o = \frac{1}{f_a A} + R_w + \frac{1}{(f_{c_o} + f_{r_o})A} \tag{11}$$

Then, by adding $\frac{1}{(f_{c_1} + f_{r_1})A}$ to both sides and transposing $\frac{1}{(f_{c_o} + f_{r_o})A}$, there follows:

$$\frac{1}{f_a A} + R_w + \frac{1}{(f_{c_1} + f_{r_1})A} = R_o + \left[\frac{1}{(f_{c_1} + f_{r_1})A} - \frac{1}{(f_{c_o} + f_{r_o})A}\right] \tag{12}$$

or, by clearing fractions in the term inside the square brackets:

$$\frac{1}{f_a A} + R_w + \frac{1}{(f_{c_1} + f_{r_1})A} = R_o + \left[\frac{(f_{c_o} + f_{r_o}) - (f_{c_1} + f_{r_1})}{(f_{c_o} + f_{r_o})(f_{c_1} + f_{r_1})}\frac{1}{A}\right] \tag{13}$$

$$= R_o + \Delta R \tag{14}$$

Substituting, equation (10) yields:

$$\frac{q_o}{q_M} = \frac{R_o + R_G + R_M + \Delta R}{R_o} \tag{15}$$

But

$$R_o = \frac{\tau_a - \tau_c}{q_o} \tag{16}$$

and

$$R_G = \frac{t_w - t_M}{q_M} \tag{17}$$

Thus, upon rearrangement of equation (15) and utilizing equations (16) and (17), there follows:

$$\frac{q_o}{A} = \frac{q_M/A}{\left[1 - \frac{q_M/A}{|\tau_a - \tau_s|}\left(\frac{|t_w - t_M|}{q_M/A} + AR_M + A\Delta R\right)\right]} \tag{18}$$

$$\text{where} \quad \Delta R = \frac{(f_{c_o} + f_{r_o}) - (f_{c_1} + f_{r_1})}{(f_{c_o} + f_{r_o})\,(f_{c_1} + f_{r_1})}\,\frac{1}{A} \qquad (19)$$

and $|\tau_a - \tau_c|$ and $|t_w - t_m|$ are the absolute magnitudes of the temperature differences indicated. The correction of q_M/A by means of equation (18) depends mainly upon the evaluation of the three terms, $\frac{t_w - t_M}{q_M/A}$, R_M, and ΔR. The latter term ΔR is the most difficult to determine, but in some cases, as is discussed below, this term may be eliminated by proper methods of installation.

Notes on Method II.- (a) When the meter is applied to the inner surface of the cabin of an airplane, $f_{c_1} \cong f_{c_o}$, as long as the cabin air is not forced over the meter at a high velocity. Further, if there are not many occupants in the cabin, the meter "sees" surfaces at the cabin wall temperature, and thus $f_{r_1} \cong f_{r_o} \cong 0$.

The total resistance, R_{TM}, (two laminations plus core) of a typical meter* as shown in figure 1, has been measured to be 0.35 $\frac{^oF}{Btu/hr}$. The corresponding value of $A\,R_M$ is 0.0324 $\frac{^oF\,ft^2}{Btu/hr}$. The correction equation for this meter then becomes:

$$\frac{q_o}{A} = \frac{q_M/A}{1 - \dfrac{q_M/A}{|\tau_a - \tau_c|}\left[\dfrac{|t_w - t_M|}{q_M/A} + 0.0324\right]} \qquad (20)$$

Four temperatures are necessary for the correction of a given meter as expressed by equation 20: that is, the air temperature on the far side of the wall τ_a; the air temperature on the near side of the wall τ_c, the temperature of the meter thermocouple t_M, and the temperature of the wall behind the meter t_w.

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*This particular meter was constructed of bakelite.

(b) If this meter is placed in a composite wall and covered by insulation (fig. 3), ΔR is necessarily zero, since $f_{r_1} = f_{r_0} = 0$, and $f_{c_0} = f_{c_1}$. Thus, equation (20) may be utilized directly for this application.

(c) For the determination of heat losses through clothing, equation (20) is directly applicable as long as this meter is placed between garments so that it does not "see" the surroundings.

(d) Equation (20) cannot be applied when this meter is placed on the surface of a body the temperature of which differs appreciably from that of the surroundings. In this case ΔR is not zero and must be evaluated in order to apply the complete correction expressed by equation (18). Fortunately, equation (8) is probably applcable to this system.

CONCLUSIONS

1. Methods of correction for the measurement of rates of heat transfer which are independent of time have been included in order to extend the range of utility of the meters. The corrections to be applied to heat meters are small, usually, if the meter is properly chosen and is correctly attached. A "properly chosen" meter implies, among other items, that the meter resistance and the contact resistance are both small compared to the thermal circuit resistance.

2. Exclusive of the thermal flow around the meter, the methods of correction are those applied to the reading of an ammeter which is placed in a circuit, the correction being necessary by virtue of the resistance of the ammeter which may be large compared with the load resistance.

3. The experimental evaluation of the rate of heat transfer through pertinent airplane surfaces in flight will eliminate the hazards of "estimating" these quantities.

Grateful appreciation is extended to Messrs. R. V. Dunkle, F. Lory, F. White, D. Turner, H. Poppendiek, and J. T. Gier for their excellent work on the construction of the heat meter and help in preparing this report.

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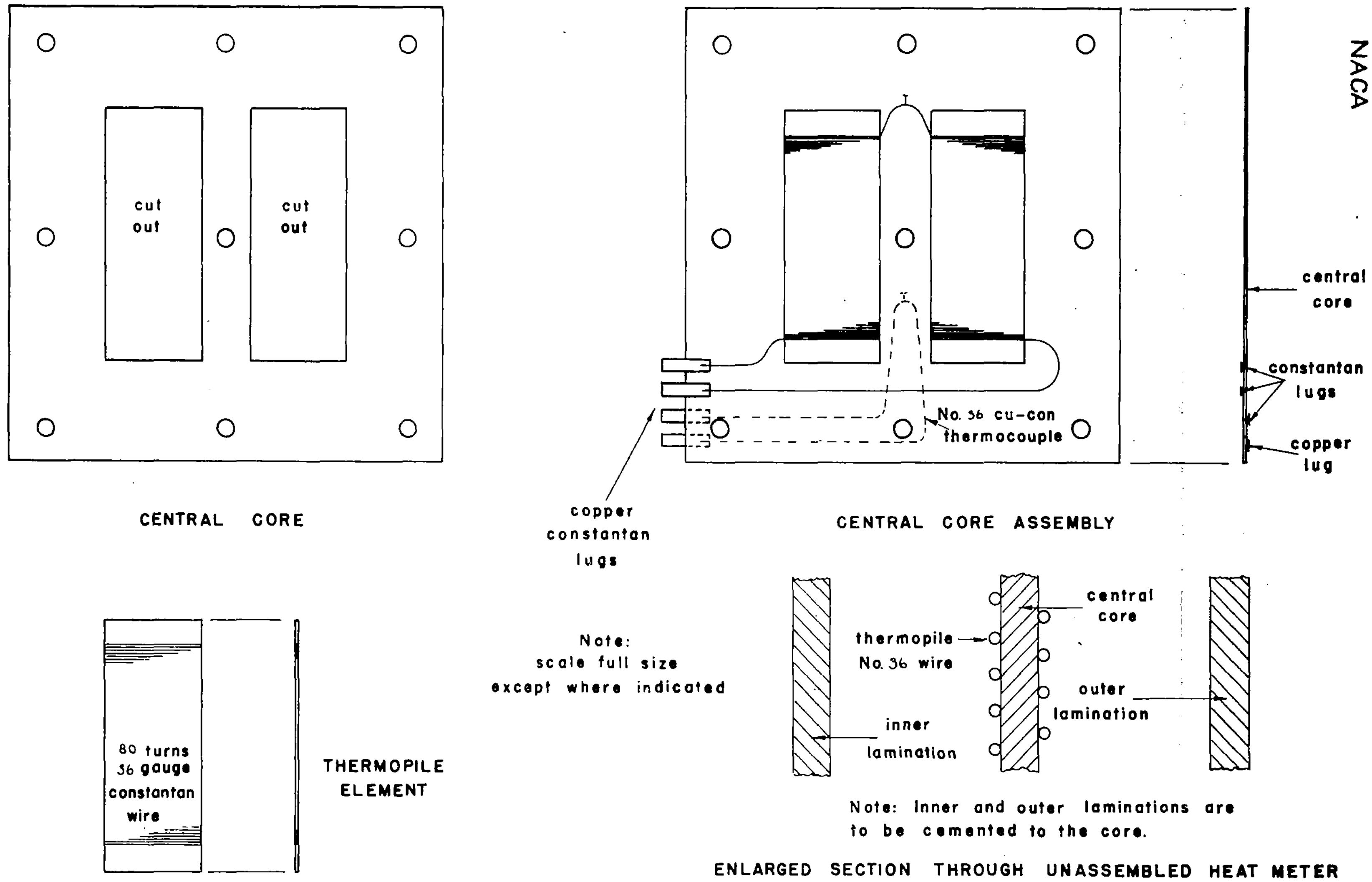
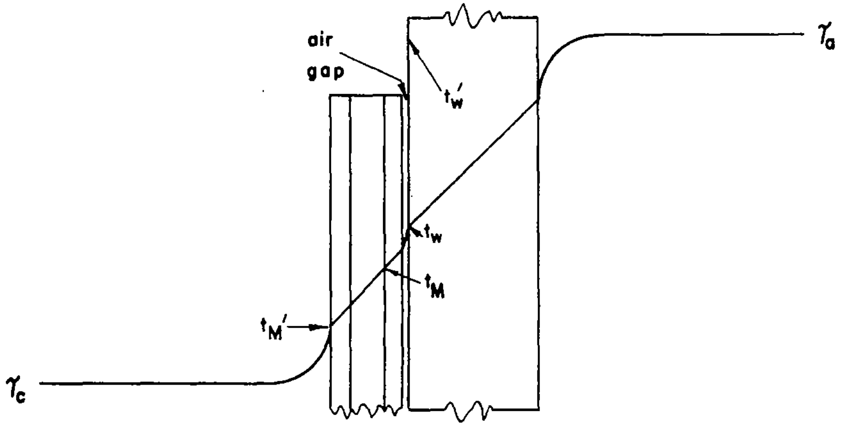
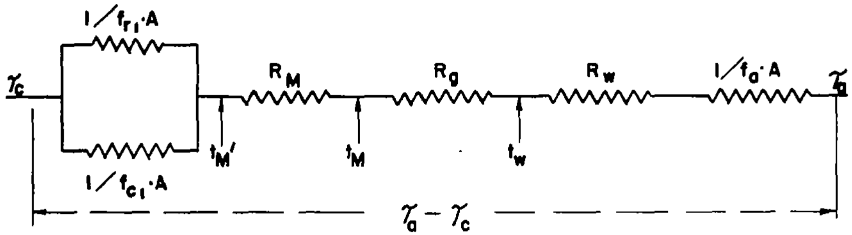


FIGURE I. THE COMPONENTS OF A TYPICAL HEAT METER



The thermal circuit for the system shown above is:



When the meter is removed:

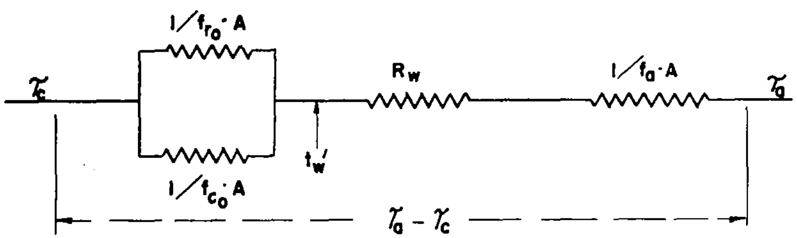
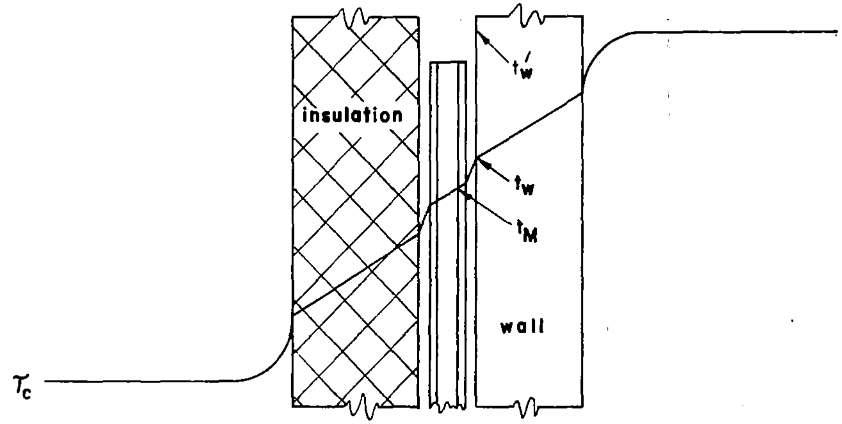
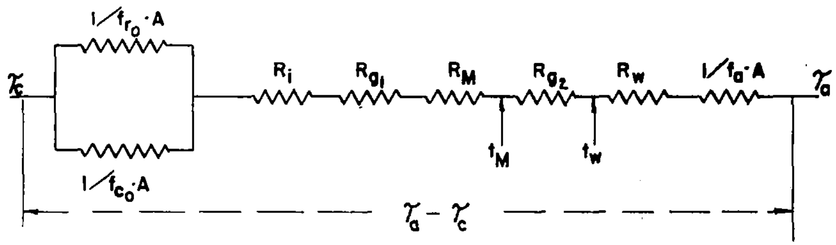


Figure 2. Thermal circuit for heat meter placed on wall



The thermal circuit for the system shown above is:



When the meter is removed:

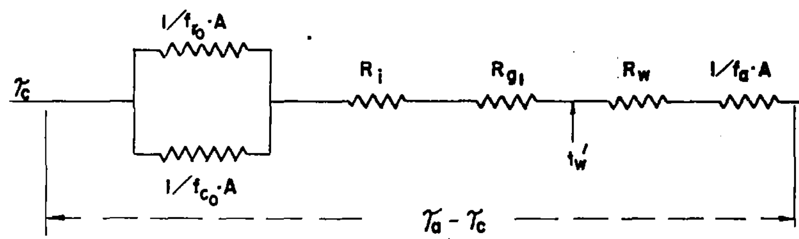


Figure 3. Thermal circuit for heat meter placed in composite wall