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Thermoelectric Circuits and the Performance of Several Aircraft Engine Thermocouples

RATIONALE

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ABSTRACT

The NET EMF of a thermoelectric circuit can be thought of as originating entirely in the regions of temperature gradient. Any extraneous materials, such as switch or connector terminals, in a temperature gradient may cause an error in the temperature measurement.

In addition to circuitry errors, jet engine thermocouple indications require correction for the effects of conduction, radiation, response rate, and gas velocity. The magnitudes of the corrections depend on the thermocouple design and the environmental conditions. Performance curves for several typical jet engine thermocouples are presented, with the methods of making the various corrections.

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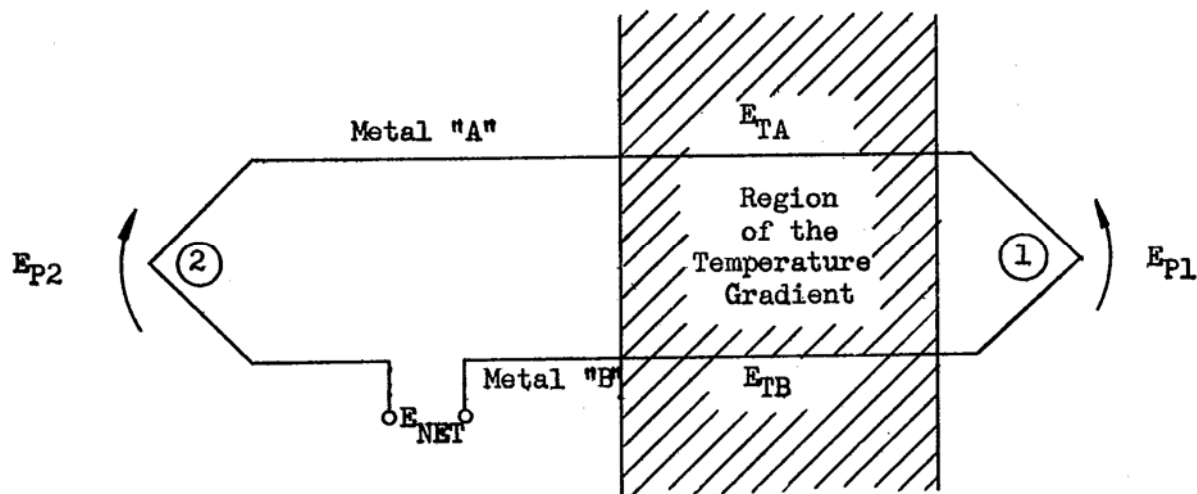


SECTION I

Thermoelectric Circuits

The basic thermoelectric circuit consists of two wires of different materials, joined at their ends to form a loop. When the two junctions of this loop are at different temperatures, an EMF will be developed. The magnitude and direction of the EMF will depend on the materials involved and on the difference in temperature between the two junctions. This EMF is the resultant of four distinct EMF's generated in the circuit: A Peltier EMF generated at each of the two junctions and a Thomson EMF generated in each of the two component wires. The Peltier EMF's are related to the temperatures at the junctions of wires, while the Thomson EMF's are developed in the individual wires in the regions of the temperature gradients.

The following figure shows the location of the four component EMF's in a thermoelectric loop of materials A and B.



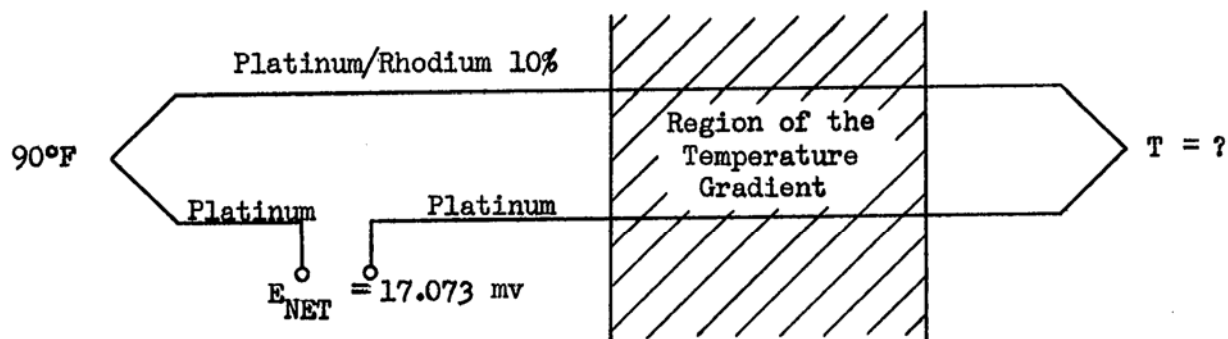
The EMF tending to cause the current to flow is the algebraic sum of the four EMF's shown:

$$E_{NET} = E_{P1} + E_{P2} + E_{TA} + E_{TB}$$

The separate values of the Peltier and Thomson EMF's are chiefly of interest to physicists and are known for only a few materials, and over a limited temperature range. The commonly used tabulations of EMF versus Temperature are in terms of the NET EMF for a circuit of the given pair of materials (such as Copper-Constantan, Chromel-Alumel, or Platinum-Platinum/Rhodium).

In using tabulated values of EMF versus Temperature, it should be born in mind that the EMF values given are those which would be generated in a thermoelectric loop of the materials under consideration with one junction at a stated reference temperature and the other junction at the tabulated temperature. The reference temperature is usually taken as 0° F or 32° F and each table will state the temperature for which it was derived.

In a simple loop circuit with one of the junctions at a standard reference temperature (0° F or 32° F), the temperature of the hot junction can be found directly from the measured NET EMF by reference to a table of a temperature versus EMF for the materials used. If the reference junction is not at a standard reference temperature, the hot junction temperature cannot be found directly. The measured NET EMF must be corrected for the extra reference junction EMF, and the CORRECTED NET EMF used to go back into the table. For example, in the circuit below, the reference junction is at 90° F and the NET EMF is 17.073 millivolts:



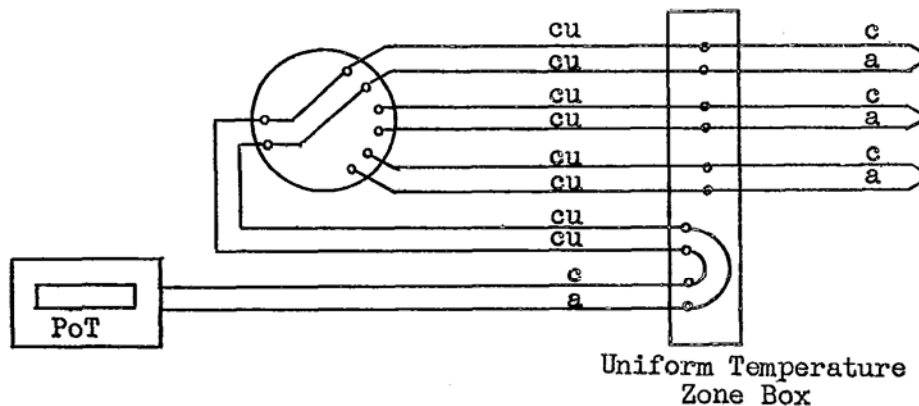
Since there are no reference tables based on a 90° F reference junction temperature, it is necessary to determine what the NET EMF would be if the reference junction were at 32° F (or 0° F).

To accomplish this it is necessary to find the amount of extra "back EMF" generated due to the 90° F junction. From the tables of temperature versus EMF for Platinum/Rhodium - Platinum, it is found that the 90° F temperature results in an EMF of .187 mv with respect to a 32° F reference. Thus, if the cold junction had been 32° F, the NET EMF would have been .187 mv higher or 17.260 mv (17.073 + .187). From the same table (32° F reference) this EMF is found to correspond to a temperature of 2995° F. The same final temperature would have been attained using the 0° F reference table.

Due to the non-linearity of the temperature-EMF curves, it is not correct to obtain a temperature reading corresponding to the measured NET-EMF (17.073 mv) in, say, a 32° table and then correct for the difference in degrees F between the actual cold junction and 32° F. This would result in an error, as can be easily seen. The EMF of 17.073 mv corresponds to 2966.6° F in the 32° F table. The 90° actual reference junction is 58° hotter than the reference temperature for the table. (90 - 32 = 58° F). Making the correction in this manner would yield an apparent hot junction temperature of 3024.6° F which is not correct.

The thermoelectric loop was defined as two wires of different materials joined at their ends to form a loop. It was also stated that when the two junctions of this loop are at different temperatures, an electric current will tend to flow, driven by the NET EMF. If, however, the two junctions of the loop are at the same temperature, there will be no NET EMF and no current will flow. This principle can be extended to the consideration of any segment of homogeneous wire in the loop: if both ends of the segment are at the same temperature, then there will be no NET EMF generated within that segment. Thus, any material which is not in a temperature gradient does not contribute to the NET EMF.

This principle can be used to the advantage of the test engineer, where a large number of thermocouples are being used, and long leads are required. The following figures shows a typical "zone-box" installation.



The "zone-box" consists of a terminal box designed so that the interior of the box is always uniform in temperature. It is not necessary that the temperature inside the box be known, or constant, so long as it is uniform. The leads from each test thermocouple are brought into the box as Chromel-Alumel (or whatever material is used) and a connection is made, inside the "zone box" to copper extension wires. It is the copper wires, then, which run from the test cell to the observers location.

In general, the copper leads are connected to the stations of a selector switch. The commons from the selector switch then return to the "zone box" and are connected to a Chromel-Alumel pair. This one Chromel-Alumel pair is then returned to the potentiometer or other measuring devices. The circuit through the selector switch is entirely homogeneous, copper in both legs of the circuit, and since the copper begins

and ends at the same temperature (zone box temperature) the copper branch does not contribute to the circuit EMF. The advantage of the "zone-box" circuit lies in the saving of material--only one length of thermocouple material need be run between the test equipment and the observer, and a copper selector switch may be used instead of one made of thermocouple materials.

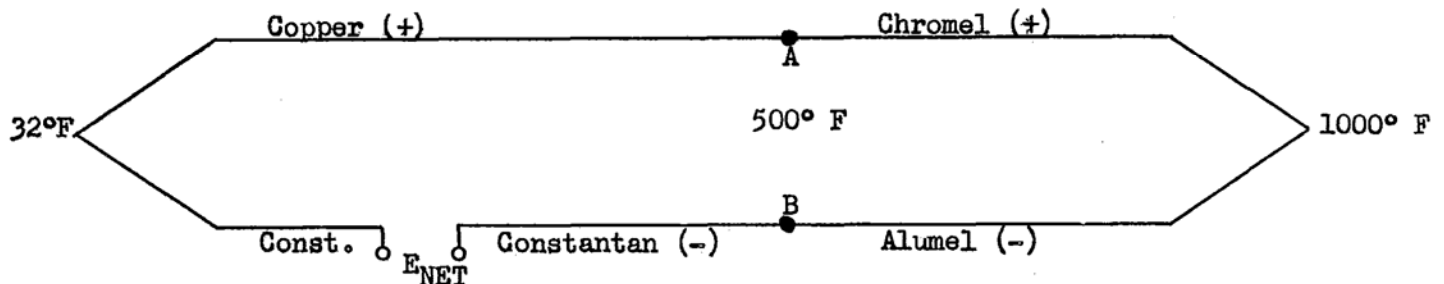
The "zone-box" circuit is an example of the proper use of a third material in a thermoelectric circuit. In general, however, extraneous materials should be regarded with suspicion. Any material which begins and ends at two different temperatures will contribute to the NET EMF of the circuit. This contribution will depend on the difference in temperature from end to end, but not on the temperature profile within the material. This is especially important in the case of switches and connectors used in a thermocouple circuit. As long as there is no temperature gradient across the switch or connector, it will not introduce an error. If, for instance, Chromel and Alumel enter a connector at 100° F and leave at 75° F, there will be an error in the NET EMF unless the materials in the connector have the same thermoelectric properties as Chromel and Alumel. Since the temperature-EMF characteristics of Chromel and Alumel are influenced by cold working, it is possible that the connector might not have the same thermoelectric properties as the wire even though made of nominally the same material. In such a case there will be an error if there is a temperature gradient. The difference in properties may be small, and also the error, but for accurate work the possibility should be borne in mind. Figure 1 shows the errors induced by four different firewall connectors when they were subjected to temperature gradients. Three of the connectors were of nominal Chromel-Alumel construction. The fourth used Iron and a compensating alloy yielding a net temperature-EMF characteristic for the pair which was similar to that for Chromel-Alumel. As can be seen, errors of 40° F are possible even with Chromel-Alumel construction. For this reason, connectors should be placed in regions of little or no temperature gradient if at all possible.

The NET EMF is often considered to be the result of EMF's generated at the junctions in the thermoelectric loop. This approach is suitable for the analysis of simple circuits, but does not lend itself to the more complex cases. In general, a thermocouple circuit will include one or more connectors, lead, wire, and instrument connections in addition to the thermocouple probe itself. Thus, there may be as many as six or eight intermediate junctions to consider in predicting the performance of the circuit if attention is focused on the junctions.

The analysis of such a circuit can be simplified by considering the EMF's to be generated in the regions of temperature gradient rather than at the junctions. This approach focuses attention on the fact that any material which is in a temperature gradient will contribute to the NET EMF, while material which is not in a temperature gradient is merely acting as a conductor to complete the circuit.

The NET EMF of a circuit containing more than one pair of thermocouple materials may be broken down in either of two ways: the contribution of each pair (when both elements of the pair are in the same temperature gradient) or the contribution of each individual element (when the elements of the pairs are not in the same temperature gradient).

This can be illustrated using a circuit containing two pairs of thermocouple materials. Assume a circuit consisting of a Chromel-Alumel thermocouple and Copper-Constantan leads. Such a circuit will serve to illustrate the possible effects of using lead wires of different calibration than the thermocouple wire, or of having extraneous materials in the circuit.



From the 32° point to AB, there will be an EMF generated due to a Copper-Constantan couple in a gradient from 32 to 500° F. From the table we find the NET EMF generated in this part of the circuit to be 12.57 mv (12.57 - 0 from the 32° table or 13.24 - .67 from the 0° table). Continuing through the Chromel-Alumel side of the circuit from AB to 1000° F, there will be an EMF due to Chromel-Alumel between 500 and 1000° F. From the Chromel-Alumel table, this EMF would be 11.69 mv (22.25 - 10.56 from the 32° F table or 22.93 - 11.24 from the 0° F table). The circuit is connected with the Copper (positive) connected to the Chromel (positive), hence the EMF's are additive and the resultant EMF of the circuit is 11.69 + 12.57 or 24.26 mv. The significance of the polarity of the EMF in a thermocouple wire cannot be directly compared to that of a battery. A material is "positive" if the cold end is positive with respect to the hot end when a temperature difference exists. Similarly, a material is "negative" if the cold end is negative with respect to the hot end.

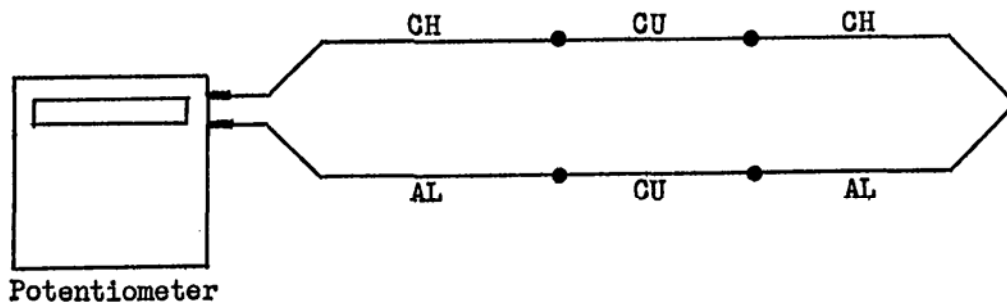
This can best be illustrated graphically. Figure 2 shows the temperature-EMF characteristics of some of the common thermocouple materials, using Platinum as a reference. The EMF's are those existing at the cold ends. Thus, the cold end of Chromel is positive with respect to the cold end of Platinum. The information in Figure 2 may be used to find the EMF of a compound circuit by graphical analysis. The preceding circuit (Chromel-Alumel and Copper-Constantan) is solved graphically in Figure 3 by considering the contribution of each individual wire. Starting at point 1 and moving in Copper through a region of increasing temperature to point 2, line 1-2 is drawn parallel to the temperature-EMF line for Copper (given at the top of Figure 3) with its origin at zero circuit-EMF and 32° F. The line 2-3 is drawn to represent the EMF generated in the Chromel wire between 500 and 1000° F. From point 3, the line 3-4 is drawn parallel to the Alumel EMF line, coming back from 1000° to 500°. The circuit is completed by line 4-5 representing the EMF generated in the constantan wire from 500° F to 32° F. The magnitude and direction of the NET EMF are found from the ordinate of point 5. The sign of the ordinate is the sign of the difference (1) minus (5). Thus, since point 5 is positive, the sign of the difference 1 minus 5 is positive, and point 1 is the positive pole of the compound circuit.

It is not necessary for the temperature rise to be uniformly distributed along the wire for this analysis to be valid, if the wire is homogeneous. The graphical construction is always made using the NET temperature difference between the two ends of each wire, regardless of how the temperature change is effected. The temperature rise could be a step change, anywhere along the wire, without affecting the validity of the graphical method. The steeper the temperature gradient, however, the more important it is that the wire be homogeneous. A steep gradient might happen to fall on the inhomogeneous region and cause an error, if the inhomogeneity had a temperature-EMF characteristic which was different from that of the wire.

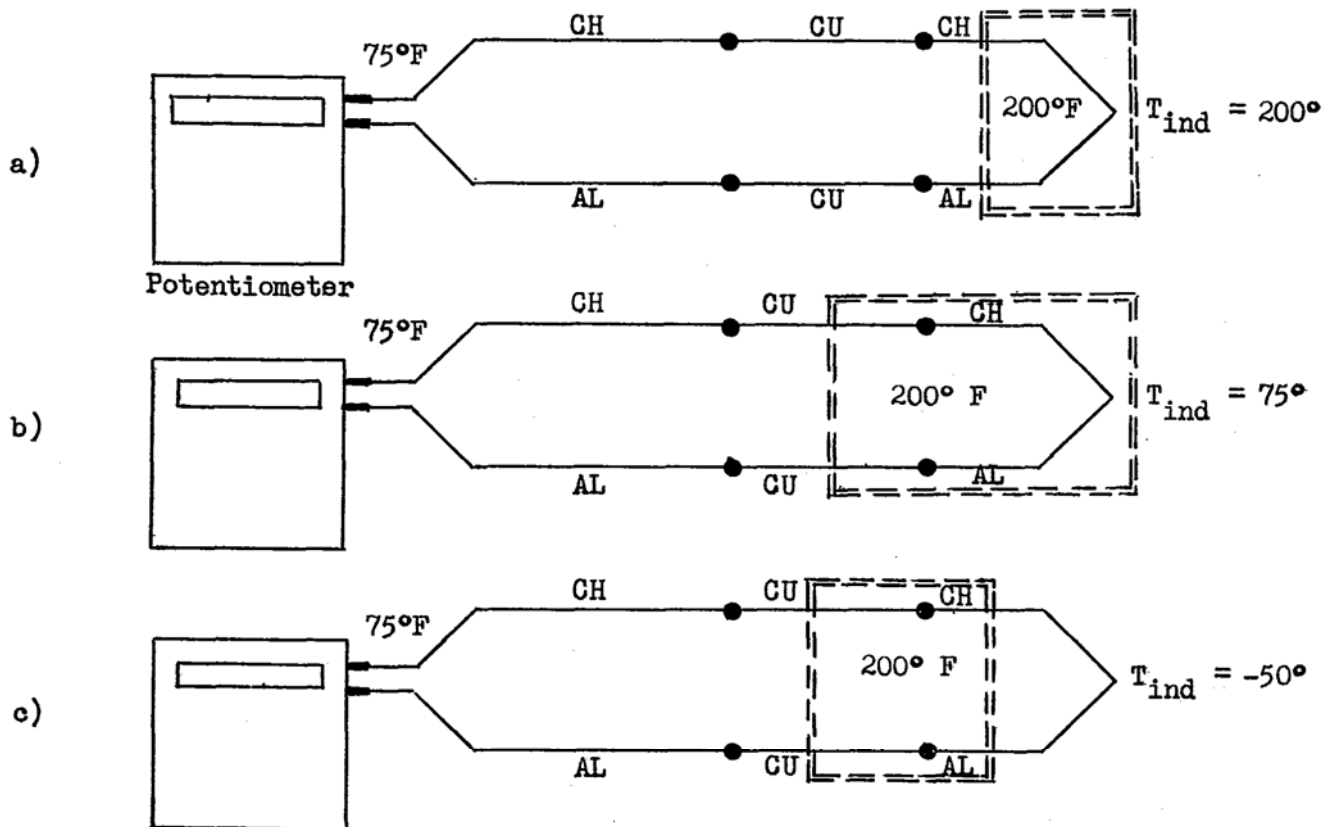
The graphical treatment is chiefly valuable in providing a visualization of what is happening in a thermocouple circuit, especially in circuits which contain extraneous materials such as switch and connector terminals. The temperature of a "hot-junction" can be found graphically even if the intermediate junctions (2 and 4) are not at the same temperature. The reference junction temperature, the intermediate temperatures and the NET EMF must be known, and graphical construction starts with the known NET EMF and proceeds along the lines of known slope (for the materials involved) through the intermediate temperatures.

In many cases where thermocouples have been suspected of large "errors", it has been shown that the trouble was caused by having the temperature gradient in the wrong place in the circuit. This caused part of the EMF to be generated in the wrong material.

As an example, the following circuit, simulating a thermocouple circuit through a slip ring assembly, was statically calibrated using an electric furnace.



As this circuit was immersed farther and farther into the furnace, the temperature measured with the potentiometer changed considerably. The sketches below show the successive positions of the circuit, and its resulting signal.



In all cases the temperature gradient is from 75° F (the ambient temperature) to 200° F (inside the furnace). The potentiometer is constructed such that if the external thermocouple circuit yields no NET EMF (meaning no net temperature gradients in the external circuit) the potentiometer will indicate ambient temperature (75° F).

In case (a) the temperature gradient was positive (external junction hotter than the potentiometer), and was in CH-AL. Thus, an EMF was generated in that section of wire. The rest of the circuit was acting merely as a conductor of electricity since it was not in a temperature gradient.

In case (b) the gradient was entirely in Copper wire, positive in one wire, negative in the other, yielding no NET EMF. The potentiometer then indicated ambient temperature.

In case (c) the positive gradient was entirely in the Copper-Copper part of the circuit, while there was a negative gradient in the CH-AL. Since this gradient was from 200 to 75° , it produced an EMF approximately equal to a net -125° signal. The potentiometer then read 125° F below room temperature or -50° F ($75-125$).

SECTION II

Thermocouple Corrections

Thermocouples are widely used for gas temperature measurement, the thermocouple temperature being taken as true gas temperature. In general this is not correct. A thermocouple can only indicate its own temperature, which may be considerably different from gas temperature. Radiation or conduction may cause the thermocouple to be 200° F or more above or below gas temperature. A thermocouple in a high velocity gas stream may be as much as 50° F below gas total temperature. During rapid changes of gas temperature the thermocouple may lag by 500 to 1000° F.

The temperature of the thermocouple, under steady state conditions, is determined by the balance between three heat transfer rates: convection from the gas, radiation from the surroundings, and conduction to the probe support. During transients, another factor must be considered: the heat stored in the thermocouple. This can be expressed in a simple heat balance:

$$Q_{\text{stored}} = Q_{\text{convection}} + Q_{\text{radiation}} + Q_{\text{conduction}}$$

In the following section, the effects of these modes of heat transfer are discussed, and methods presented for making correction for their effect on thermocouple temperature.

Radiation Effect

Any two objects which can "see" each other will exchange heat by radiation. The rate of radiant heat exchange is a function of the fourth power of the temperatures of the objects involved. For a thermocouple and its surroundings this can be expressed by the following relationship:

$$q_r = \sigma E A_r (T_p^4 - T_w^4) \quad (1)$$

where

q_r = Heat exchanged by radiation, BTU/Hr.

σ = Stephan-Boltzmann constant $.174 \times 10^{-8}$ BTU/Hr. Ft.² °R⁴

E = Emissivity, related to blackbody performance

A_r = Area available for radiation, Ft.², of the thermocouple

T_p = Temperature of the probe, °R

T_w = Temperature of the surrounding walls, °R

Under steady state conditions a thermocouple will come to equilibrium at some temperature between that of the gas and the surrounding walls. The heat lost by radiation to the walls will be gained from the gas by convection. This heat transfer by convection can be expressed as follows:

$$q_c = h_c A_c (T_{\text{eff}} - T_p) \quad (2)$$

with the terms defined as follows:

q_c = Heat transferred by convection, BTU/Hr.

h_c = Coefficient of convective heat transfer BTU/Ft.² Hr. °R

A_c = Area available for convective heat transfer, Ft.²

T_{eff} = Effective temperature of the gas °R; the steady state temperature attained by the probe in the absence of radiation and conduction errors (includes the effect of velocity error)

T_p = Temperature of the probe °R

The effect of radiation on the thermocouple equilibrium temperature can be found by equating the rate of heat transfer by radiation to the rate of heat transfer by convection. The equation can then be solved for the difference between thermocouple and gas temperature as shown below (assuming no conduction):

$$q_c = q_r \quad (3)$$

$$h_c A_c (T_{\text{eff}} - T_p) = \sigma E A_r (T_p^4 - T_w^4) \quad (4)$$

$$T_{\text{eff}} - T_p = \frac{\sigma E A_r}{h_c A_c} (T_p^4 - T_w^4) \quad (5)$$

The radiation error ($T_{\text{eff}} - T_p$) is therefore determined by the emissivity of the thermocouple, the convective heat transfer coefficient, the areas available for radiation and convection, and the difference in the fourth powers of the temperatures of the objects involved.

The radiation error due to a given wall temperature depression can be reduced by using a low emissivity covering on the thermocouple, by increasing the value of h_c , by providing more area for convection than for radiation, or by surrounding the thermocouple with shields which prevent it from "seeing" the walls.

The convective heat transfer coefficient (h_c) increases with mass velocity (pounds gas flow per square foot per second). Radiation errors can often be reduced appreciably (50° F or more) by moving the thermocouples into a region of higher mass velocity.

Determinations of Radiation Correction

For approximating radiation errors, a simpler form of equation (5) may be defined, based on the first power difference between gas and wall temperature.

$$(T_{\text{eff}} - T_p) = \frac{\theta_r}{\theta_w} (T_{\text{eff}} - T_w) \quad (6)$$