



AEROSPACE INFORMATION REPORT

AIR46™

REV. C

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Superseding AIR46B

The Preparation and Use of Thermocouples for Aircraft Gas Turbine Engines

RATIONALE

AIR46C has been revised to incorporate the contents of AIR46B with three other documents to create a single comprehensive report covering thermocouples. The details of the other three documents are as follows:

- AIR65: Thermoelectric Circuits and the Performance of Several Aircraft
- ARP690: Standard Exposed Junction Thermocouple for Controlled Conduction Errors in Measurement of Air or Exhaust Gas Temperature
- ARP691: Recommended Ice Bath for Reference Junctions

Due to the availability of similar and more up-to-date information in the public domain, together with the extensive effort required, the original material has not been brought up to date.

Upon publication of AIR46C, the three superseded documents—AIR65, ARP690, and ARP691—will be cancelled. This strategy was agreed by the SAE E-32 committee in accordance with the Committee Master Plan.

FOREWORD

This document, originally prepared in 1956, was reviewed by industry and committee members between 1983 and 1988. Those who reviewed it generally agreed that the document, with minor changes, would continue to be a useful industry reference. Changes were limited to updating the list of references, as well as to exhibit temperatures in both °F and °C.

Changes made in 1996 were format/editorial only.

Changes made in 2021 to incorporate the content of AIR65, ARP690, and ARP691, thus rendering these three documents obsolete. These changes combine the detail relating to the use of thermocouples for aircraft gas turbine engines with the detail on the thermo-electric circuits of the thermocouple systems used in gas turbines and the associated errors of such circuits.

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Documents

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1. SCOPE

This SAE Aerospace Information Report (AIR) reviews the precautions that must be taken and the corrections which must be evaluated and applied if the experimental error in measuring the temperature of a hot gas stream with a thermocouple is to be kept to a practicable minimum. Discussions will focus on Type K thermocouples, as defined in National Institute of Standards and Technology (NIST) Monograph 175 as Type K, nickel-chromium (Kp) alloy versus nickel-aluminium (Kn) alloy (or nickel-silicon alloy) thermocouples. However, the majority of the content is relevant to any thermocouple type used in gas turbine applications.

1.1 Purpose

The purpose of this document is to assist those concerned with measuring gas temperatures in turbines and those who wish to utilize gas temperature for actuating engine controls. In these applications, the problem of temperature measurement may be considered to consist of two distinct parts: namely, a determination of the actual temperature of the measuring junction or junctions and a reliable estimation of the difference in temperature between this junction/s and the gas. The former requires that numerous precautions be observed in the construction, installation, and use of the thermocouple or thermocouples in a circuit; the latter requires proper application of appropriate corrections for such effects as impact and heat exchange by conduction, convection, and radiation.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

International Practical Temperature Scale of 1968

AF Technical Report No. 5738 National Bureau of Standards Reports on Test of Chromel-Alumel Thermocouples Supplied by General Electric Company

AF Technical Report No. 5739 National Bureau of Standards Report on Tst of Thermocouples, Type K.L.G. 64/I675

AF Technical Report No. 6455 Test of Commercial Chromel-Alumel Thermocouples for Jet Engines

NIST Monograph 175 Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90

WADC TR 53-251 Tests of Four Total Temperature Probes

WADC TR 53-341 Performance Tests of Firewall Thermocouple-Connector Assemblies

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM 470B Special Technical Publication 470B: Manual on the Use of Thermocouples in Temperature Measurement

2.1.3 ANSI Accredited Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ANSI C96.1 Standard for Temperature Measurement Thermocouples

2.1.4 ASME Publications

Available from ASME, P.O. Box 2900, 22 Law Drive, Fairfield, NJ 07007-2900, Tel: 800-843-2763 (U.S./Canada), 001-800-843-2763 (Mexico), 973-882-1170 (outside North America), www.asme.org.

ASME Preprint No. 57-GTP-8 Designing Thermocouples for Response Rate

2.1.5 Other Publications

"Temperature, Its Measurement and Control in Science and Industry" ISA, Vol. 3 (1962) and Vol. 4 (1972).

Carbon, M.W., Kutsch, H.J., and Hawkins, G.A., "The Response of Thermocouples to Rapid Gas-Temperature Changes," Trans. Am. Soc. Mech. Engrs. 72, 655 (1950).

Dahl, I. and Fiock, E.F., "Circuitry Errors of Ladder-Type Thermocouple-Harness Assemblies," WADC Tech. Report 53-4 (December 1952).

Dahl, I. and Fiock, E.F., "Response Characteristics of Temperature-Sensing Elements for Use in the Control of Jet Engines," J. Research Nat. Bur. Standards 45, 292 (1950).

Dahl, I. and Fiock, E.F., "Use of Parallel Thermocouples in Turbojet Engines," USAF Technical Report No. 6546 (July 1951).

Dahl, I., "Stability of Base-Metal Thermocouples in Air from 800 to 2200 °F," J. Research Nat. Bur. Standards 24, 205 (1940).

Fiock, E.F. and Dahl, A.I., "Temperature Measurements in High-Velocity Streams of Hot Gas," Proc. Iowa Thermodynamics Symposium, p. 190. State Univ. Iowa, Iowa City (April 1953). Also NBS Report 3164 (April 1953).

ISA Bulletin No. RP-1.2, page 4.

ISA Bulletin No. RP-1.3, page 9.

Jacob, M., "Heat Transfer," John Wiley & Sons, Inc. (1949), pages 560-561.

McAdams, W.H., "Heat Transmission," 3rd ed. McGraw-Hill, New York (1954).

Roeser, W.F. and Wensel, H.T., "Methods of Testing Thermocouples and Thermocouple Materials," J. Research Nat. Bur. Standards 14, 247 (1935).

Unpublished Data, General Motors Research Staff (1953).

Unpublished Data, General Motors Research Staff (1954).

Unpublished Data, General Motors Research Staff (1956).

2.2 Abbreviations

α	$\sqrt{4h/Dk}$
τ	characteristic time, in seconds
γ	ratio of heat capacities at constant pressure and at constant volume
σ	Stefan-Boltzmann constant = $5.68 \times 10^{-12} \text{ W/cm}^2 (\text{deg K})^4$ = $1.716 \times 10^{-9} \text{ Btu/ft}^2 (\text{deg R})^4$
ε_t	emissivity for total radiation = W_{jt}/W_{bt} for a measuring junction
$^{\circ}\text{C}$	degrees Celsius
$^{\circ}\text{F}$	degrees Fahrenheit
$^{\circ}\text{K}$	degrees Kelvin = $273.16 + ^{\circ}\text{C}$
$^{\circ}\text{R}$	degrees Rankine = $459.7 + ^{\circ}\text{F}$
a	a distance; depth of immersion
A	surface area; subscripts j, c, and r indicate the total area of a junction and the areas effective in convection and radiation, respectively
A, B, a, b, c	constants in empirical equations
C_p	heat capacity at constant pressure
D	diameter of a thermocouple wire
e	base of Napierian logarithms; EMF from one of a group of parallel thermocouples
E	electromotive force (EMF), in millivolts of a standard thermocouple or of a group of thermocouples in parallel
EMF	electromotive force
E_{NET}	the NET EMF of a circuit
E_P	a Peltier EMF, generated at the junction of two dissimilar metals, in millivolt
E_T	a Thomson EMF, generated in the region of temperature gradient in a homogeneous conductor
g	gravitational constant (32.2 ft/s^2)
h	coefficient of heat transfer by convection
J	mechanical equivalent of heat (778 ft-lb/Btu)
k	thermal conductivity
K_n	negative thermo element for Type K thermocouples
K_p	positive thermo element for Type K thermocouples
M	Mach number

MgO	magnesium oxide
mV	millivolts
Q	rate of heat transfer, with subscripts c and r meaning by convection and radiation, respectively
r	recovery factor; resistance
R ₀ , R _t	resistances of Pt resistance thermometer at 0 and t °C
R _{t_m} , R _{a_m}	resistances of the m th thermocouple in a ladder-type network and of the adjacent harness section, respectively
T	absolute temperature, with subscripts t, s, g, j, and w meaning total, static, gas, junction, and wall, respectively
t	temperature in °C; time
v	velocity
W _t	radiant flux density for total radiation, with additional subscripts b and j to indicate black body and junction, respectively

3. THERMO-ELECTRIC CIRCUITS

A simple thermoelectric circuit consists of two wires of dissimilar conductive materials (usually metals), joined at their ends to form an electric loop. A net electromotive force (EMF) is produced in the loop when it experiences a temperature gradient between the two material junctions. This phenomenon is called the “Seebeck effect.” The magnitude of the resulting EMF is proportional to the temperature difference between the two material junctions (points 1 and 2 in Figure 1) and by the difference in the Seebeck (α) coefficients of the two materials. Note that the sign and magnitude of the Seebeck coefficient of a material depends on what material is used. The Seebeck effect as described is found to be a product of two other thermoelectric properties, the Thomson effect and the Peltier effect.

$$(\alpha_A - \alpha_B) (T_1 - T_2) = \alpha_{AB} (T_1 - T_2) = E_{net} \quad (\text{Eq. 1})$$

The first thermoelectric property contributing to the Seebeck effect is called the Thomson effect. This is the phenomenon by which electric charge moves along a wire of a single material when subjected to a temperature gradient. In traditional conductors (i.e., copper) electrons will diffuse from areas of high temperature to areas of low temperature in the material, having the net effect of producing an electric current in that single material wire. However, a hot-to-cold current flow is not always the case. The directionality of the current flow depends on whether the conductor is a p type or n type. This notation also used in the semiconductor industry referring to materials that have excess free electrons (n type), and thus are negatively charged or materials that have excess electron paths, or holes (p type) and thus are positively charged. This is directly applicable when discussing Kp - Kn (K type) thermocouples as the two materials used are classified in just this way. Like the Seebeck effect, the Thomson effect also has a unique coefficient for a given material, called the Thomson coefficient (τ). In a thermoelectric circuit it is related to the Seebeck coefficient and temperature via the Equation 2, where T is temperature at the material junction.

$$\tau_{AB} = \tau_A - \tau_B = T \frac{d\alpha_{AB}}{dT} \quad (\text{Eq. 2})$$

The second thermoelectric property leveraged in a thermocouple circuit is the Peltier effect. However, this is traditionally exploited in an “active” way for heating/cooling applications (Peltier refrigeration) where a source voltage is applied to the circuit. In the traditional, or active, thermoelectric circuit such as that shown in Figure 1, it would be assumed that there is a source voltage connected at the “E_{net}” point of the circuit with the thermal gradient remaining as depicted in Figure 1. Under that set of conditions, the Peltier effect would describe the heat transfer between the two materials at the junctions (points 1 and 2). A Peltier coefficient (π_{AB}) of the junction relates the heat transfer rate (q) through the junction as a function of applied current (I).

$$\pi_{AB} I = q$$

In the passive case of a thermocouple, the Peltier effect still holds significance as an EMF generation point. The root of the EMF generation is a result of the individual materials' bulk electrical properties, specifically the difference in the energy bands at which electrons move through each individual material. Once heat energy is applied to the material junction, electrons absorb a portion of that heat energy in the form of moving to a more energetic state. This excited state allows free electrons from the n type material to transfer across that energy band gap that exists between the two materials resulting in a net current flow, or EMF, where only a charge difference existed in the absence of the heat energy. The effect in a thermoelectric circuit is that the electrons that absorb the heat energy transfer it across the junction to elsewhere in the material and results in heating or cooling of a particular junction depending on the electron direction of flow (materials dependent). The Peltier coefficient of a junction can also be directly related to the Seebeck coefficient via the temperature of the junction (T) by the Equation 4.

$$\pi_{AB} = \alpha_{AB} T \quad (\text{Eq. 4})$$

An analogy of a capacitor can be made to a Peltier junction where there exists a positive charge (p type material) and negative charge (n type material) in close proximity to one another without any charge exchange. When a critical charge density is reached in the capacitor via a current input (heat energy input for the thermoelectric circuit) the electrons can flow across the dielectric of the capacitor (across the energy band gap for the thermoelectric circuit). This results in a current flow where there existed only a charge difference before. This explanation of the Peltier effect is a simplified version relative to the actual solid-state physics that occurs in real material junctions but can be thought of in this way for the purposes of this document.

Figure 1 shows the location of the four component EMFs in a thermoelectric loop of materials A and B.

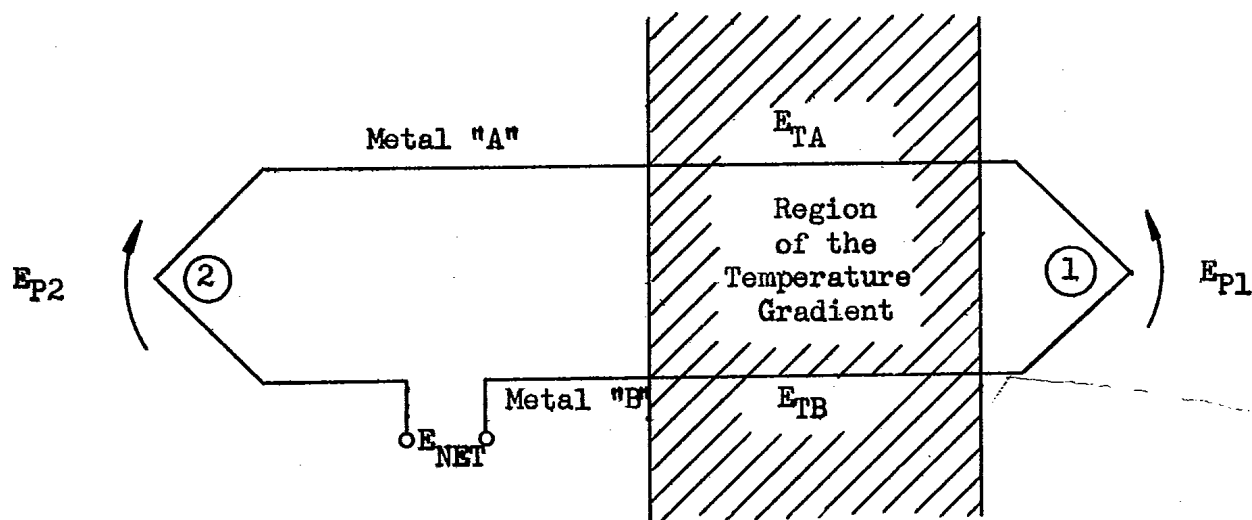


Figure 1 - EMF in a thermoelectric loop

3.1 Using EMF Tables

The EMF tending to cause the current to flow is the algebraic sum of the four EMFs as shown in Equation 5:

$$E_{NET} = E_{P1} + E_{P2} + E_{TA} + E_{TB} \quad (\text{Eq. 5})$$

The separate values of the Peltier and Thomson EMFs 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, Kp-Kn, or Platinum-Platinum/Rhodium).

When using tabulated values of EMF versus temperature, 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 (-17.78 °C) or 0 °C (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, the temperature of the hot junction can be found directly from the measured net EMF by reference to a table of 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 in Figure 2, the reference junction is at 32.22 °C (90 °F) and the net EMF is 17.073 mV.

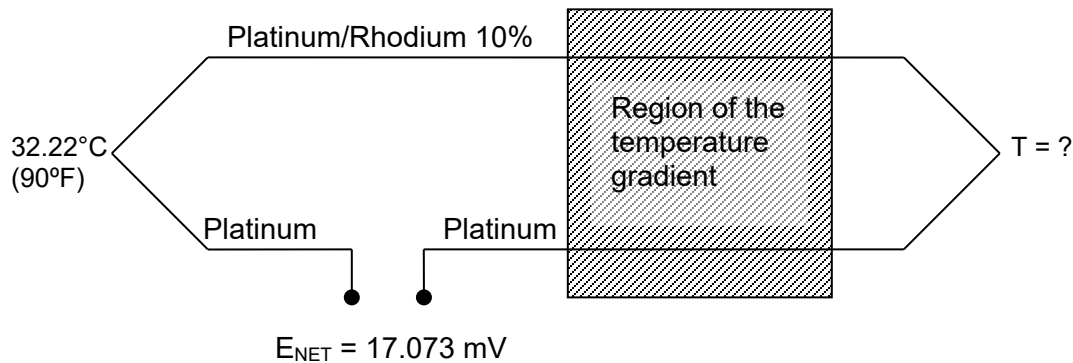


Figure 2 - Thermoelectric loop without standard reference temperature

Since there are no reference tables based on a 32.22 °C (90 °F) reference junction temperature, the net EMF if the reference junction were at 0 °C (32 °F) needs to be determined.

To accomplish this, the amount of extra “back EMF” generated due to the 32.22 °C junction must first be found. From the tables in NIST Monograph 175 of temperature versus EMF for Platinum/Rhodium-Platinum, an EMF of 0.187 mV is found for the 32.22 °C temperature with respect to a 0 °C reference. Thus, if the cold junction had been 0 °C, the NET EMF would have been 0.187 mV higher or 17.260 mV (17.073 + 0.187). From the same table (0 °C reference) this EMF is found to correspond to a temperature of 1640.9 °C. The same final temperature would have been attained using the 0 °F (-17.78 °C) reference table.

Conversely, erroneous results are obtained if a temperature reading corresponding to the measured net EMF (17.073 mV) in a 0 °C table, for example, and then correcting for the difference in degrees Celcius between the actual cold junction and 0 °C. The EMF of 17.073 mV corresponds to 1630 °C in the 0 °C table. The 32.22 °C actual reference junction is 32 °C hotter than the reference temperature for the table. (32.22 - 0 = 32.22 °C). Making the correction in this manner would yield an apparent hot junction temperature of 1662.6 °C.

3.2 Basic Thermoelectric Loop

The thermoelectric loop was defined as two wires of different materials joined at their ends to form a loop. Further, when the two junctions of this loop are at different temperatures the NET EMF results in an electric current. 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. 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. Figure 3 shows a typical “zone-box” installation.

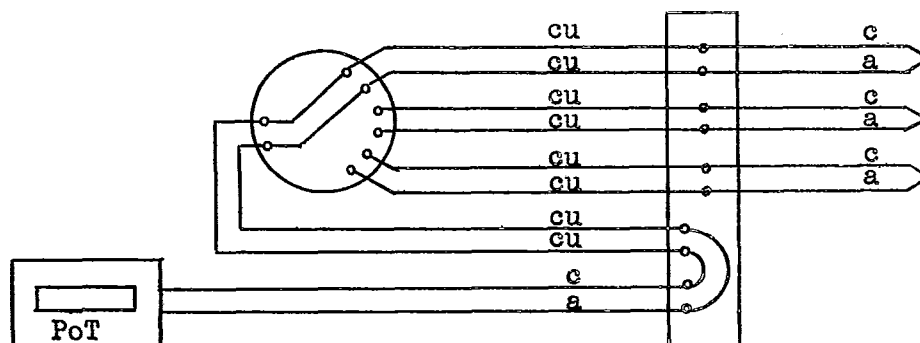


Figure 3 - Uniform temperature zone box

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 Kp-Kn (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 observer’s 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 Kp-Kn pair. This one Kp-Kn 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, Kp and Kn enter a connector at 38 °C and leave at 24 °C, there will be an error in the NET EMF unless the materials in the connector have the same thermo-electric properties as Kp and Kn. Since the temperature-EMF characteristics of Kp and Kn 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 4 shows the errors induced by four different firewall connectors when they are subjected to temperature gradients. Three of the connectors are of nominal Kp-Kn construction. The fourth used iron and a compensating alloy yielding a net temperature-EMF characteristic for the pair which was similar to that for Kp-Kn. As can be seen, errors of 40 °F are possible even with a Kp-Kn construction. For this reason, connectors should be placed in regions of little or no temperature gradient if at all possible.

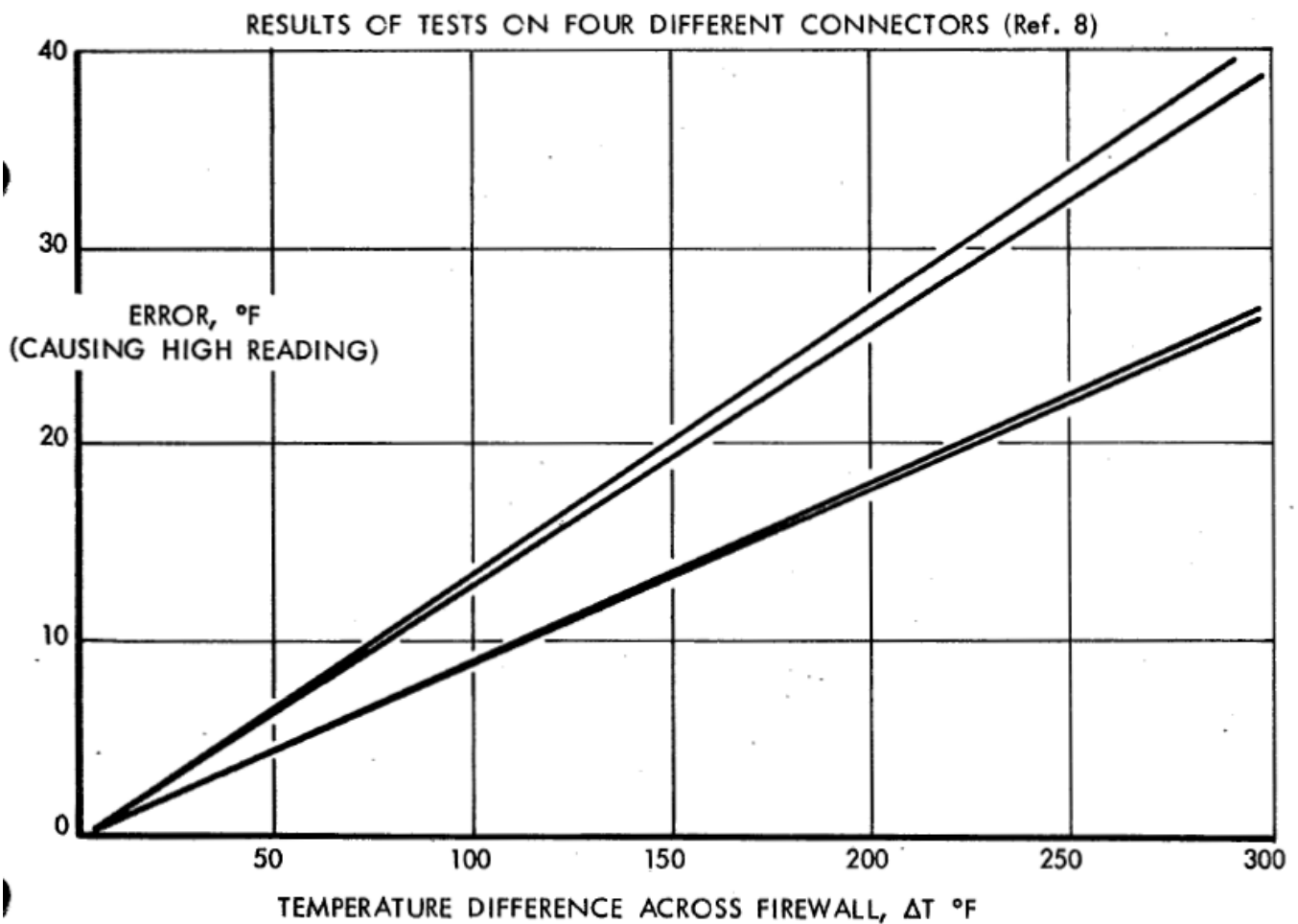
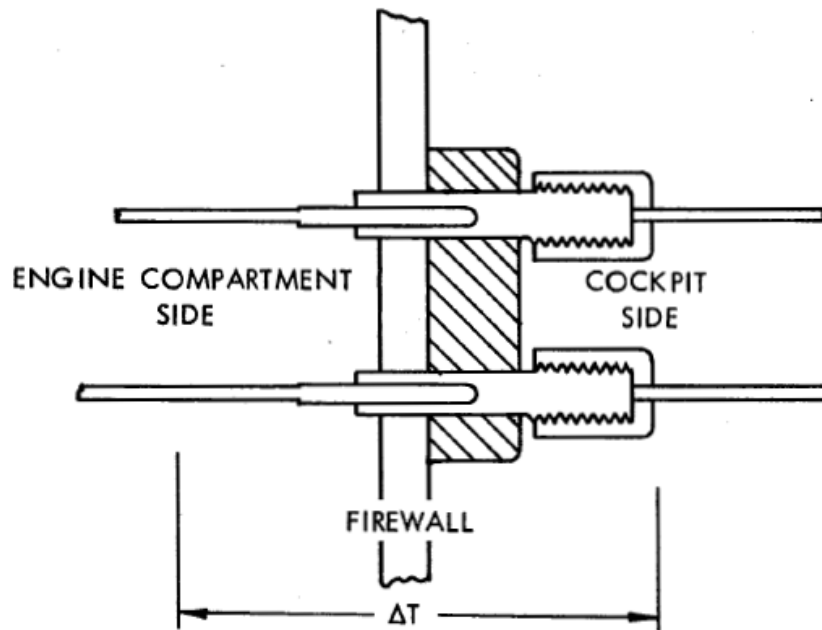


Figure 4 - Connector induced thermocouple error

3.3 Net EMF of Material in Temperature Gradient

The NET EMF is often considered to be the result of EMFs 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 EMFs 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). Figure 5 shows the temperature-EMF characteristics of some of the common thermocouple materials.

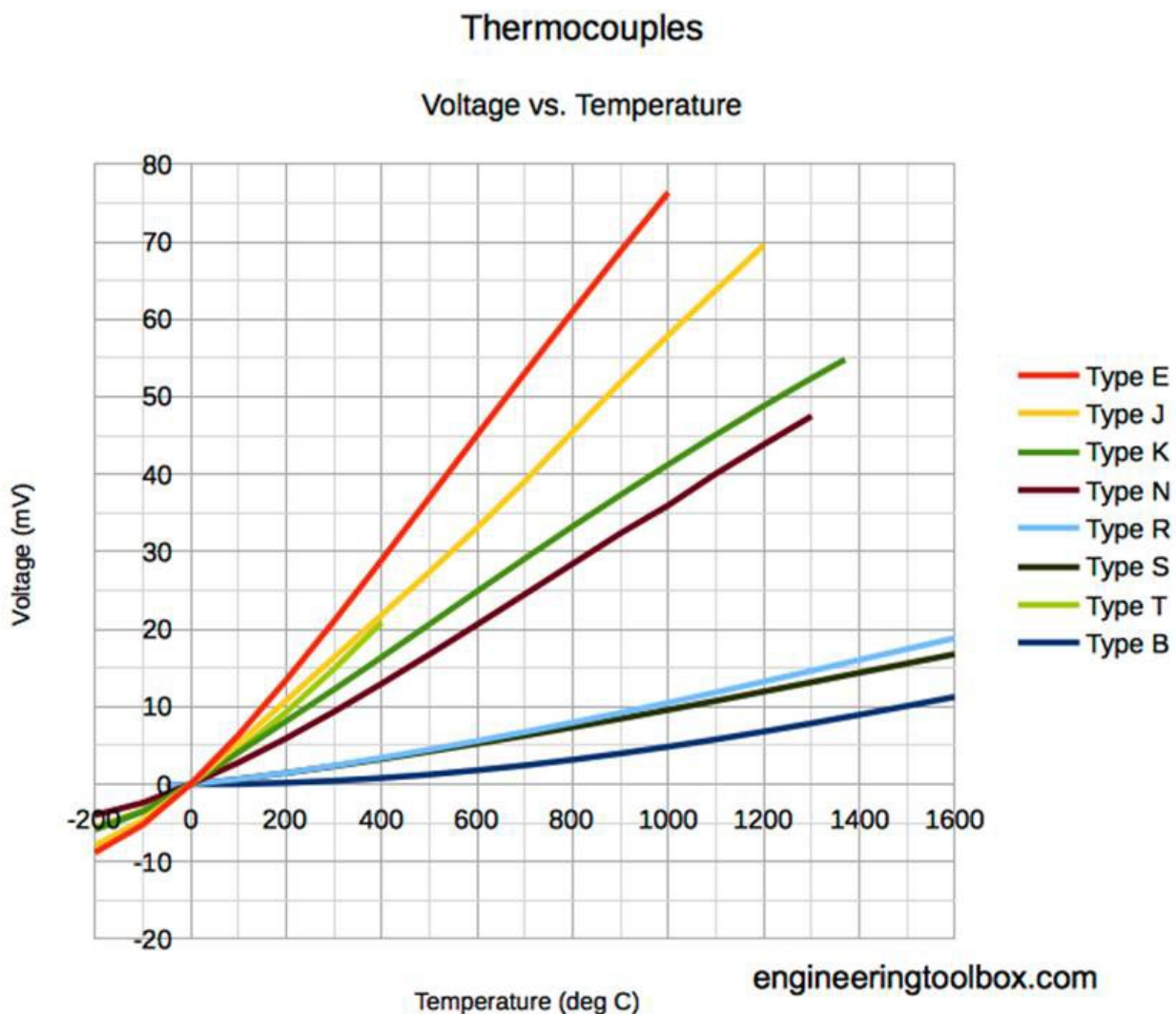


Figure 5 - EMF-temperature relationship of various materials

Consider a circuit consisting of a Kp-Kn thermocouple and copper-constantan leads. Such a circuit, depicted in Figure 6, serves to illustrate the possible effects of using lead wires of different calibration than the thermocouple wire, or of having extraneous materials in the circuit.

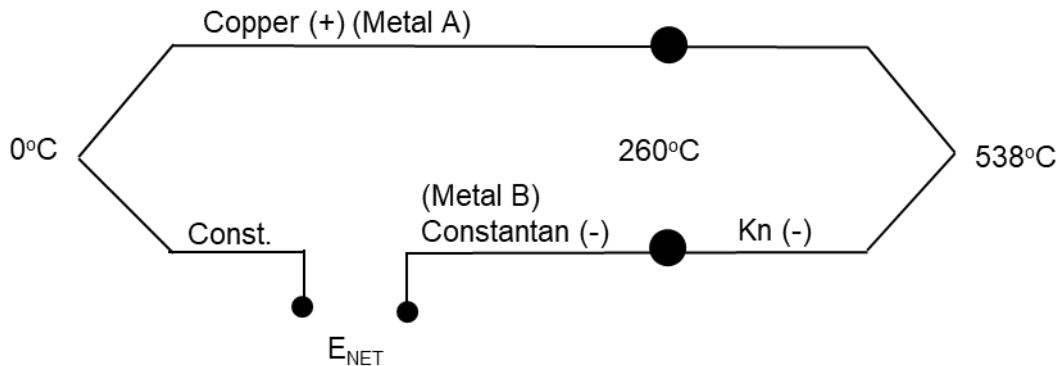


Figure 6 - Dissimilar thermocouple and leads circuit

There will be an EMF generated across AB due to the Copper-Constantan couple in a gradient from the 0 °C point to 260 °C. From the table in NIST Monograph 175, the NET EMF generated in this part of the circuit is found to be 12.57 mV (12.57 - 0 from the 0 °C table). Continuing through the Kp-Kn side of the circuit from AB to 538 °C, there will be an EMF due to Kp-Kn between 260 °C and 538 °C. From the Kp-Kn table, the EMF would be 11.69 mV (22.25 - 10.56 from the 0 °C table). The circuit is connected with the copper (positive) connected to the Kp (positive), hence the EMFs 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 polarity definition can best be illustrated graphically. The EMFs are those existing at the cold ends. Thus, the cold end of Kp is positive with respect to the cold end of platinum. The information in Figure 7 may be used to find the EMF of a compound circuit by graphical analysis.

3.4 Net EMF Determined via Graphical Method

The preceding circuit (Kp-Kn and Copper-Constantan) is solved graphically in Figure 7 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 7) with its origin at zero circuit-EMF and 0 °C. The line 2-3 is drawn to represent the EMF generated in the Kp wire between 260 °C and 538 °C. From point 3, the line 3-4 is drawn parallel to the Kn EMF line, coming back from 538 to 250 °C. The circuit is completed by line 4-5 representing the EMF generated in the constantan wire from 260 to 0 °C. 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.

GRAPHICAL SOLUTION FOR THE
NET EMF OF A COMPOUND CIRCUIT

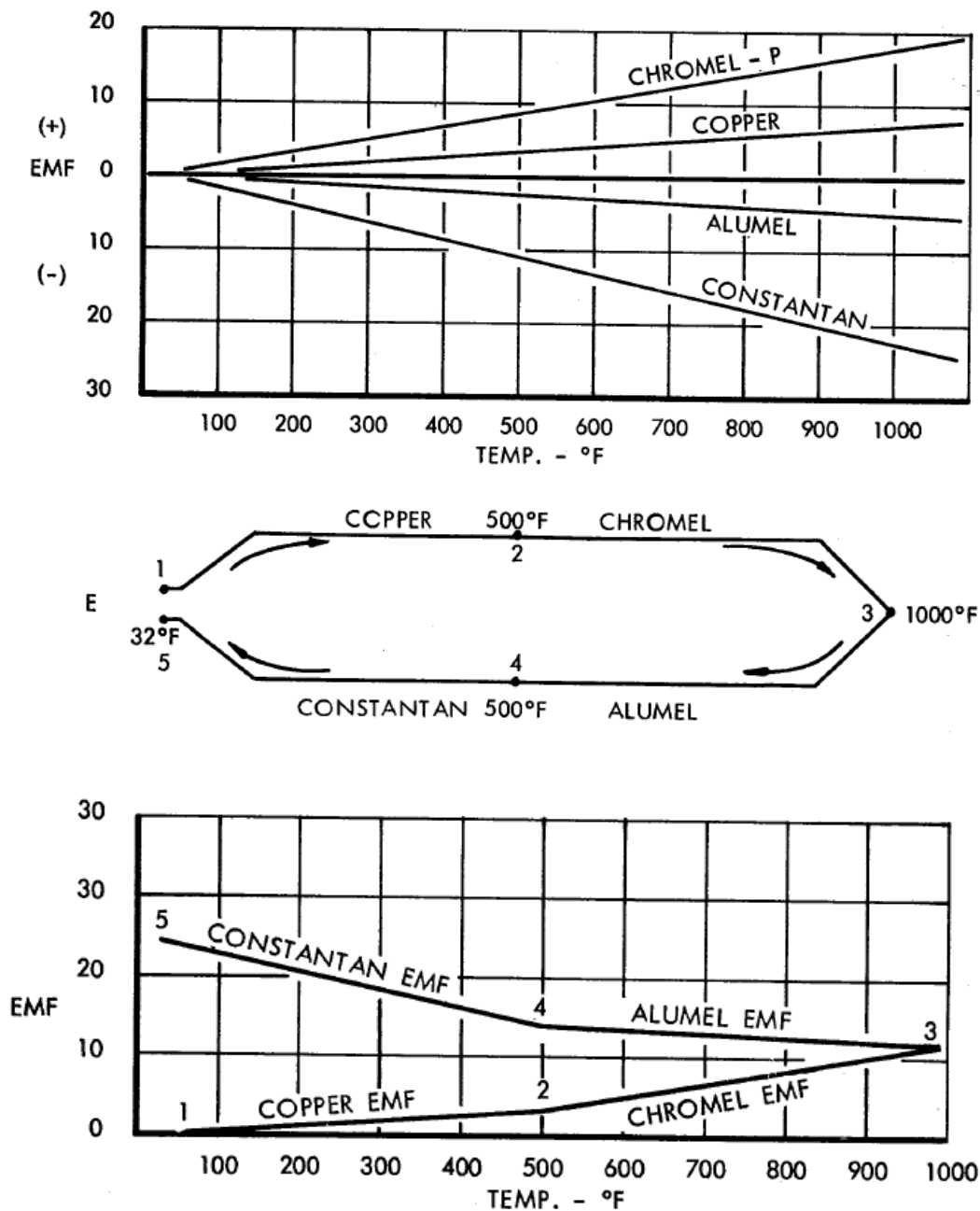


Figure 7 - Graphical solution for the NET EMF of a compound circuit

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 in homogeneity 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.

3.5 Error from Misplacement of Circuit in Temperature Gradient

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 circuit depicted in Figure 8, simulating a thermocouple circuit through a slip ring assembly, was statically calibrated using an electric furnace.

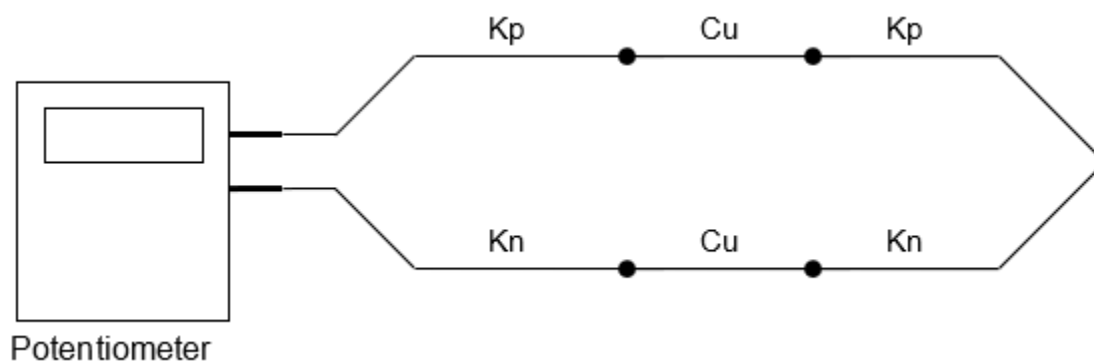


Figure 8 - Slip ring thermocouple installation

As this circuit is immersed further and further into the furnace, the temperature measured with the potentiometer changes considerably. Figure 9 shows the successive positions of the circuit and its resulting signal.