AEROSPACE INFORMATION REPORT

AIR46™ REV. C

Issued 1956-03
Revised 2022-09

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 of 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Upon publication of AIR46C, the three superseded documents—AIR65, ARP690, and ARP691—will be cancelled.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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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 T*st of Thermocouples, Type K.L.G. 64/l675
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 $= 5.68 \times 10^{-12}$ W/cm^2 (deg K)^4
$= 1.716 \times 10^{-9}$ Btu/ft^2 (deg R)^4

ε_t emissivity for total radiation = W_{jt}/W_{bt} for a measuring junction

°C degrees Celsius

°F degrees Fahrenheit

°K degrees Kelvin = 273.16 + °C

°R degrees Rankine = 459.7 + °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 Naperian 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

Kn negative thermo element for Type K thermocouples

Kp 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_o,R_t resistances of Pt resistance thermometer at 0 and t °C

Rt_m,Ra_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).

$$\pi_{AB}\,I = q \quad \text{(Eq. 3)}$$

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.

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

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.

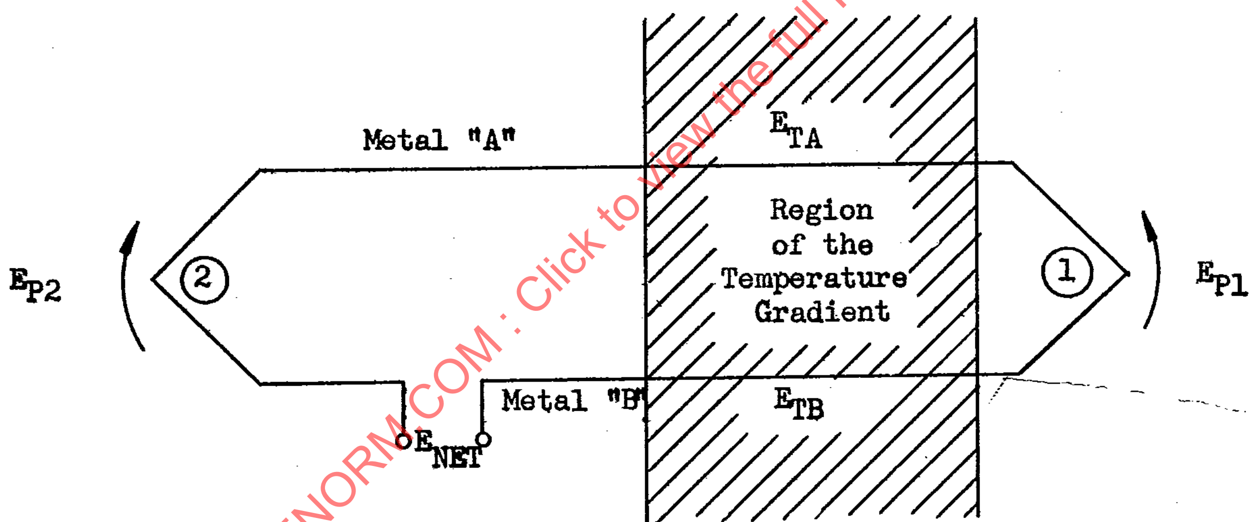

Figure 1 - EMF in a thermoelectric loop

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:

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

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.

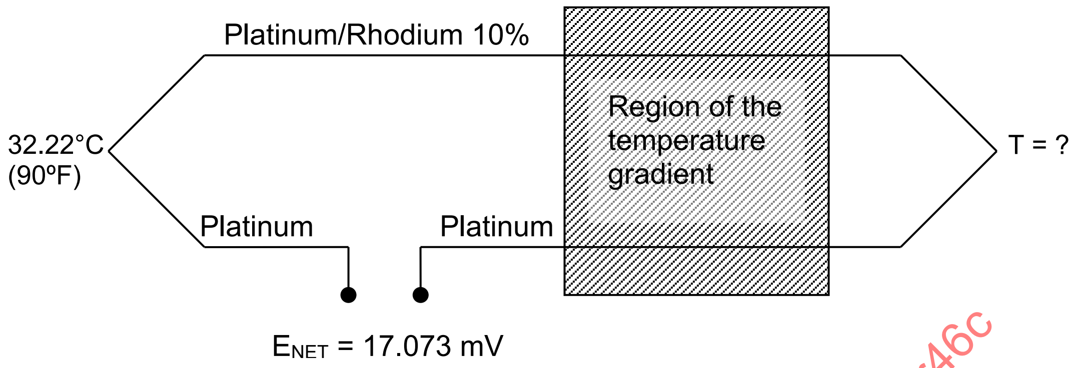

Figure 2 - Thermoelectric loop without standard reference temperature

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.

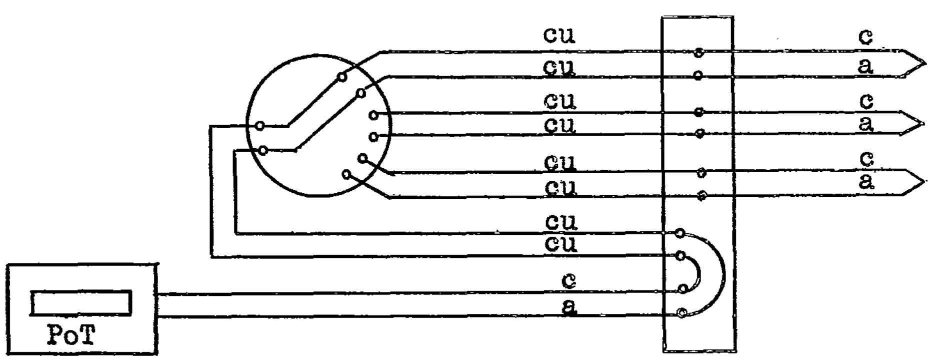

Figure 3 - Uniform temperature zone box

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.

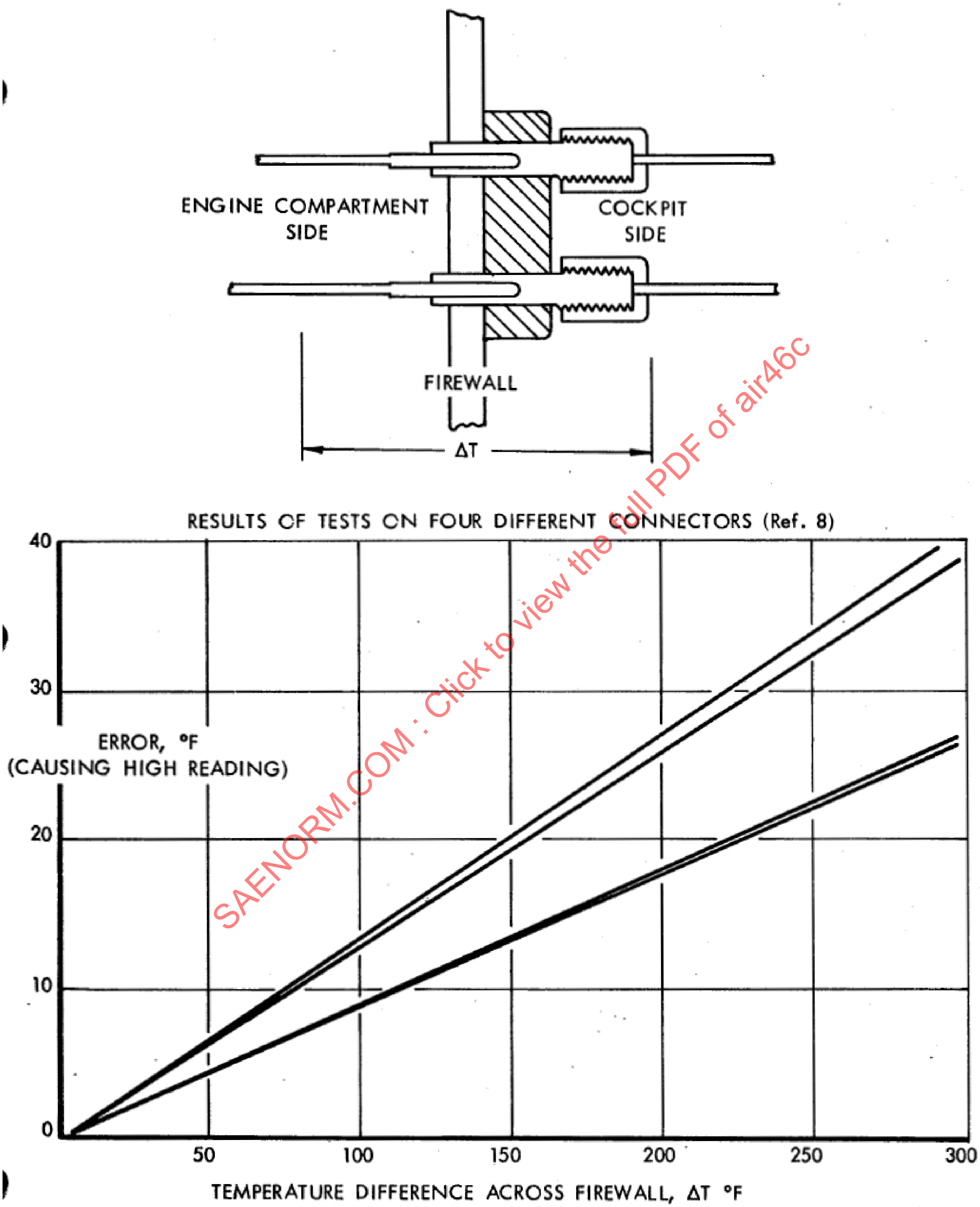

Figure 4 - Connector induced thermocouple error

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.

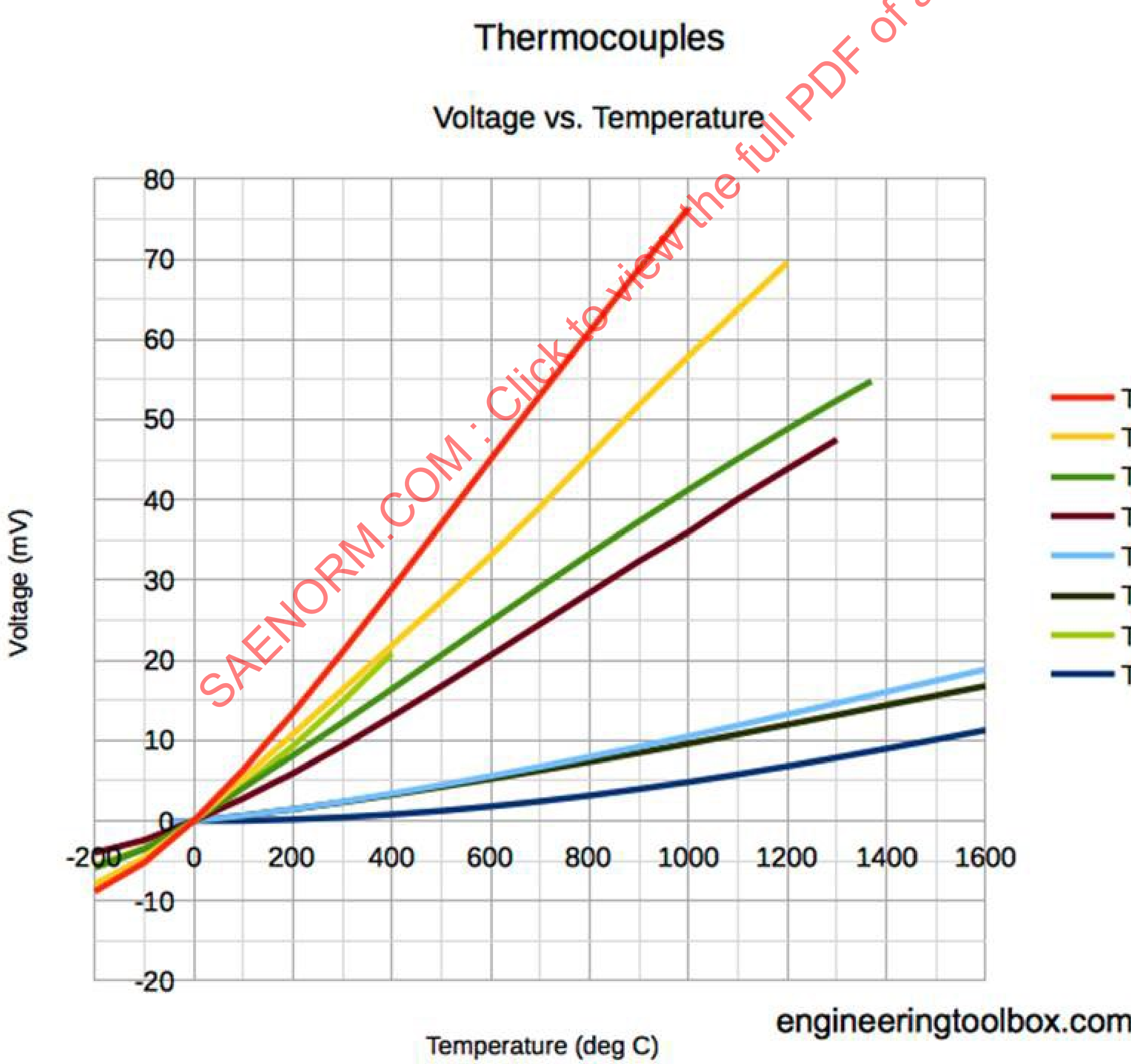

Figure 5 - EMF-temperature relationship of various materials

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.

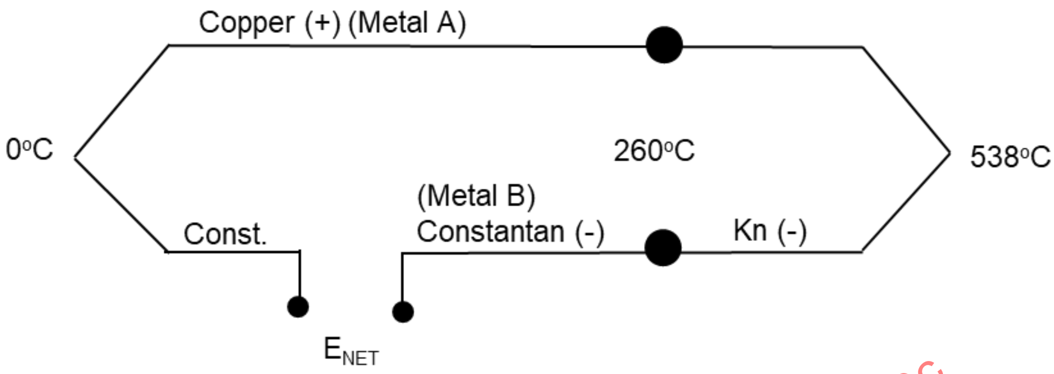

Figure 6 - Dissimilar thermocouple and leads circuit

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 (l) 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.

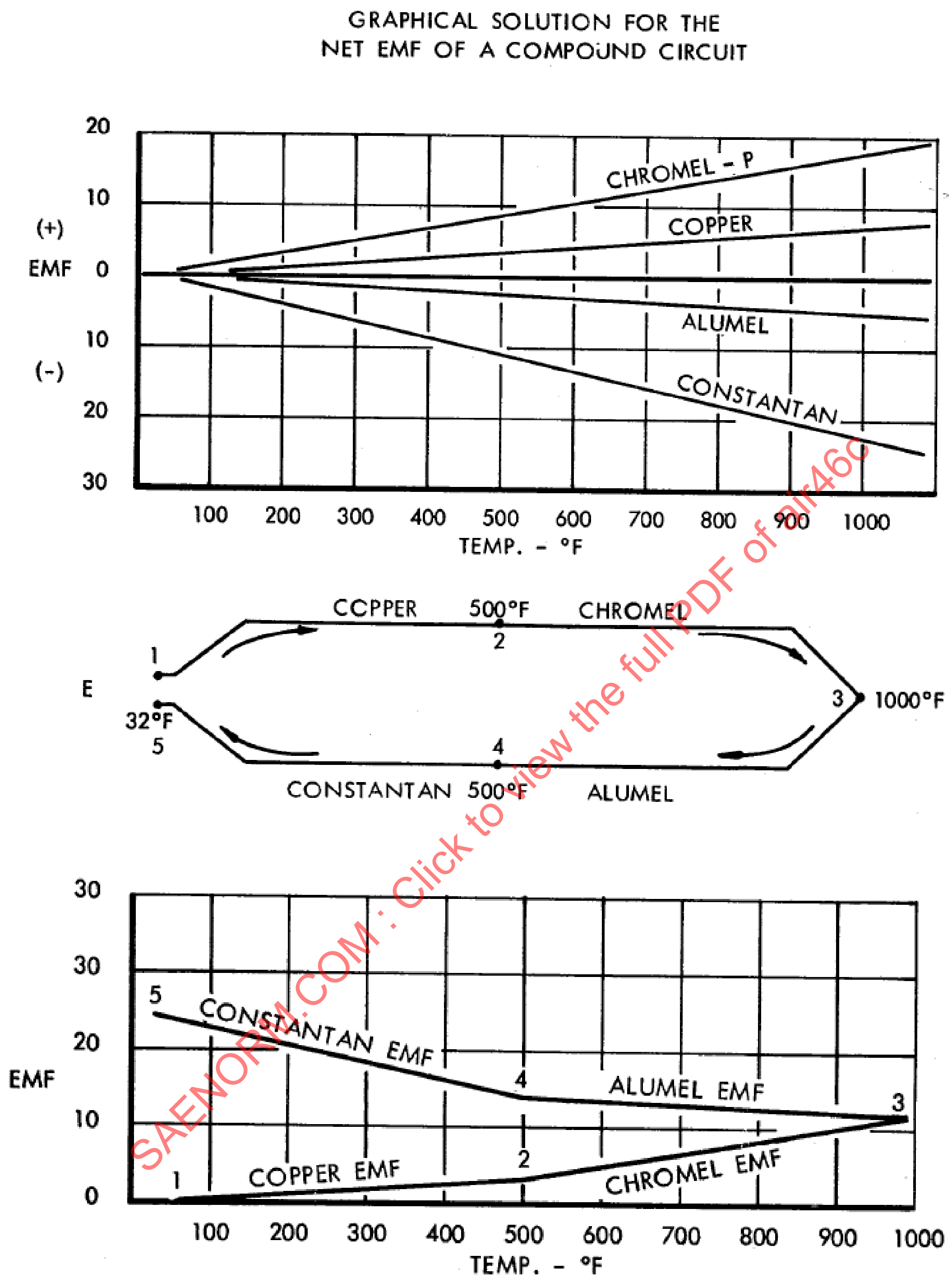

Figure 7 - Graphical solution for the NET EMF of a compound circuit

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.

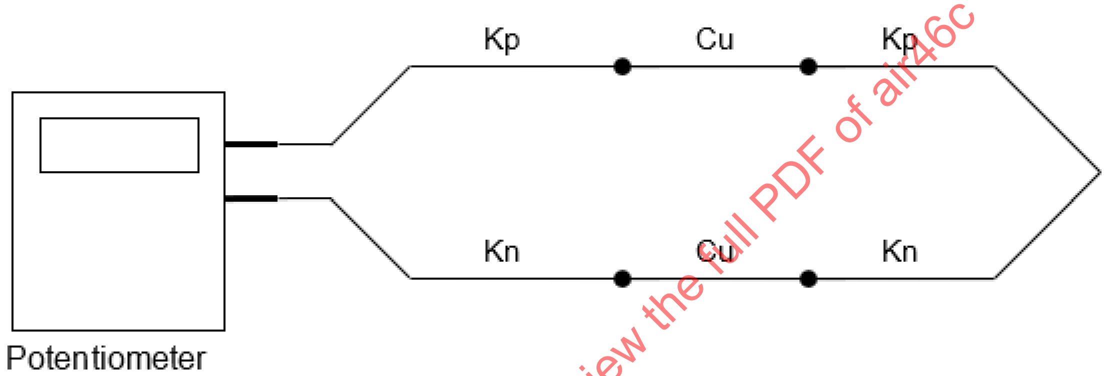

Figure 8 - Slip ring thermocouple installation

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.

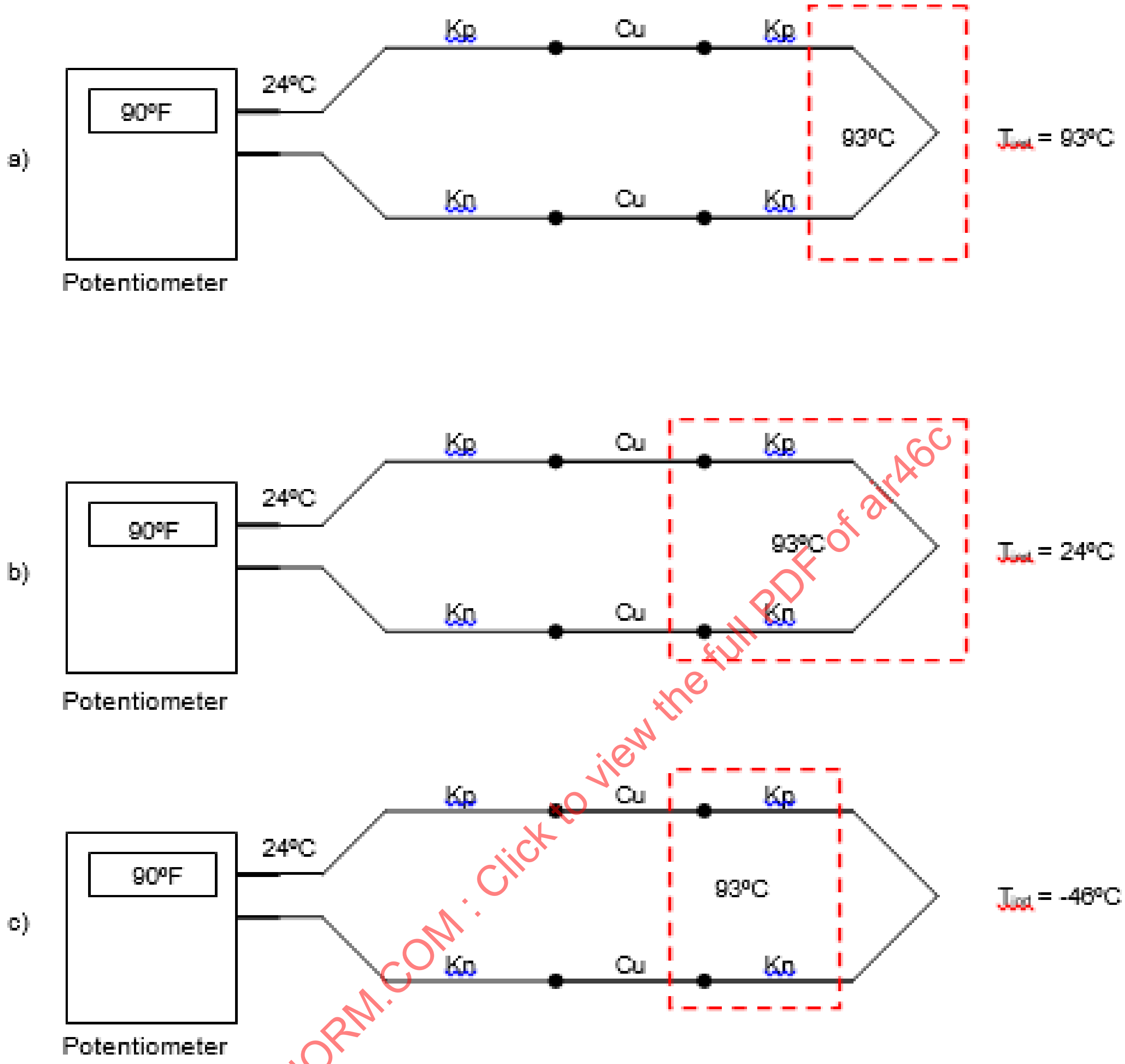

Figure 9 - Thermocouple travelling through a thermal furnace

In all cases, the temperature gradient is from 24 °C (the ambient temperature) to 93 °C (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 (24 °C).

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

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

In case (c), the positive gradient is entirely in the copper-copper part of the circuit, while there is a negative gradient in the Kp-Kn. Since this gradient is from 93 to 24 °C, it produces an EMF approximately equal to a net -69 °C signal. The potentiometer then read 70 °C below room temperature or -46 °C (24-70).

4. THERMOCOUPLE MATERIALS

Although Kp-Kn is the most commonly used thermocouple pair for jet engine temperature measurement, there are several other material combinations which can be used. The selection of a particular pair of materials is based upon consideration of the temperature range to be encountered and the nature of the surrounding atmosphere (reducing or oxidizing).

The temperature limits and atmosphere requirements are given in for several of the more commonly used pairs of materials in Table 1. A reducing atmosphere is defined as one containing less than 2% oxygen whereas more than 2% oxygen is considered oxidizing.

Table 1 - Maximum temperature for bare wire thermocouples

Type	Reducing Atmosphere	Oxidising Atmosphere	Alternating Atmosphere
T - Copper-Constantan	315 °C (600 °F)	315 °C (600 °F)	315 °C (600 °F)
J - Iron-Constantan	760 °C (1400 °F)	760 °C (1400 °F)	760 °C (1400 °F)
K - Nickel Chromium - Nickel Aluminium or Nickel Silicon (Kp-Kn)	760 °C (1400 °F)	1260 °C (2300 °F)	760 °C (1400 °F)
S - Platinum-Platinum/ 10% Rhodium	Not recommended	1482 °C (2700 °F)	Not recommended

The temperatures listed are maximums and will provide only short life. To obtain a reasonable service life, these bare wire temperatures should be lowered by 100 to 150 °C (200 to 300 °F) for the wire sizes usually used in jet engine instrumentation. Higher operating temperatures may be achieved by enclosing the thermo-elements inside a hermetically sealed protective sheath.

In addition to temperature and atmosphere requirements, consideration must be given to the variation of electromotive force (EMF) over a temperature range with respect to the standard calibration.

Table 2 presents the limits of temperature-EMF variation for the materials discussed in Table 1. Where the tolerance is expressed in percent, it refers to percent of the measured temperature.

Table 2 - Limits of temperature-EMF variation

Type	Temperature Range (°C)	Limits of Error [°C] (% Indicated with Respect to Measured Temperature - "t")	
		Standard	Special
T - Copper-Constantan	-200 to 0	±1.7 °C or ±1% of t, whichever is greater	-
	0 to 870	±1.7 °C or ±0.5% of t, whichever is greater	±1 °C or ±0.4% of t, whichever is greater
J - Iron-Constantan	0 to 875	±2.2 °C or ±0.75% of t, whichever is greater	±1.1 °C or ±0.4% of t, whichever is greater
K - Nickel Chromium - Nickel Aluminium or Nickel Silicon (Kp-Kn)	-200 to 0	±2.2 °C or ±2% of t, whichever is greater	-
	0 to 1260	±2.2 °C or ±0.75% of t, whichever is greater	±1.1 °C or ±0.4% of t, whichever is greater
S - Platinum-Platinum/10% Rhodium	-50 to 1540	±1.5 °C or ±0.25% of t, whichever is greater	±0.6 °C or ±0.1% of t, whichever is greater

The most widely used physical assembly of the thermocouple materials is the swaged or compacted form. In this assembly, the thermocouple pair is encased in a metal protecting tube filled with a refractory powder (typically magnesium oxide or aluminium oxide). The powder is highly compacted by swaging the tube or by ramming the powder, and serves to hold the wires firmly in place and electrically insulated. When properly made, the swaged or compacted stock will show a smooth hard surface when cut off on a lathe or with a saw. The powder should not crumble or fall out under vibration, and the wires should be well separated. Such stock is capable of being bent to a centreline radius of approximately three times the sheath diameter without failure, although it should not be subject to repeated bending, as this will likely cause work hardening. The material is available in a wide range of thermocouple pairs, or single wires, and with a variety of outside diameters and sheath materials. The calibration of a thermocouple made of such stock should be within the tolerance limits as given in Table 2.

A variety of refractory cements have been used in thermocouple manufacture chiefly on thermocouples made with loose wires inserted in a pre-formed ceramic tube, protected with metal tubing. Most ceramic cements tend to lose their electrical resistance as the temperature rises. Since low resistance to ground may interfere with the operation of the temperature measuring system, cements should not be used on the high temperature end of thermocouples. The temperature-EMF characteristics of thermocouples are affected by small changes in alloy composition. Over the years, changes have been made in the composition of iron and constantan wire used in making thermocouples. As a result, the accepted calibration curves have changed several times to conform to generally available material composition. At present, the 1938 calibration is used for Copper-Constantan and the “Modified 1913” (equivalent to SAMA “J”) calibration is used for Iron Constantan.

A more stable alternative to standard Kn (nickel aluminium) has been developed for the negative leg of the Type K thermocouple. This new alloy is now based on the Type N nickel silicon conductor. The alloy provides a temperature-EMF relationship that closely matches the standard Kn; therefore, a direct swap can be made without compromising the calibration curve.

5. CIRCUITRY FOR HIGHEST ACCURACY

5.1 Lead Wires and Terminals

Where highest accuracy is sought, it is preferred that the thermo elements extend without a break from the measuring junction to a reference junction. If this is impracticable, all parts of the thermocouple and lead circuit which contain alloys that differ in thermoelectric properties from the thermo elements proper should be kept at a uniform temperature. This is not possible in thermocouples which have a terminal lead in direct thermal contact with a hot part of an engine. The only alternative here is to match all parts of the thermocouple circuit in thermoelectric characteristics, inasmuch as large temperature gradients are bound to exist through the head. Joints should be made only by autogenous welding, never by use of any brazing or welding spelter.

5.2 The Reference or Cold Junction

A bath at 0 °C (32 °F) consisting of an intimate mixture of shaved ice and water provides the most convenient and easily reproducible bath for the reference junction. Keeping the reference junction at the ice point is recommended practice for all accurate thermoelectric thermometry, and most standard tables apply directly when the reference junction is at this temperature. As applied to the problem of engine thermocouples, an ice bath should be used in making all calibrations, in determinations of recovery factor, or when reproducibility better than ±1.1 °C (±2 °F) or 0.4% is required in the temperature of the reference junction.

A convenient form of ice bath is illustrated in Figure 10. A large-mouth Dewar (preferably 1 L capacity) is first filled with shaved or finely cracked ice, and enough water is added to fill all of the spaces between the pieces of ice, but not enough to float the ice. Any potable water and ice are sufficiently pure for this purpose. When first prepared, there should be ice down to the bottom of the Dewar. For each junction to be kept at the ice point, a small glass tube, closed at the bottom and flared at the top, is inserted through a hole in the cork for the Dewar. Enough mercury is placed within each tube to fill it for about 20 mm (0.75 inch). The cork and tubes are inserted so that the mercury is >30 mm (1.25 inches) below the top surface of the slush.

The actual reference junctions are made by inserting a thermo element and a copper wire, each polished with a file or sandpaper for about 12.5 mm (1/2 inch), but not as much as 20 mm (3/4 inch), and each insulated in some manner so that electrical contact between them is made only below the mercury. There must be no electrical contact between these wires above the mercury, because no other point is sure to be at the known reference temperature.

Excess water should be poured off, and more ice and water should be added, as indicated above, at regular intervals sufficiently short that the bottoms of the tubes containing mercury are never surrounded by water alone. The temperature of the water below floating ice may be several degrees above the ice point. Just how often such renewal is required will depend upon many factors, including the quality of the Dewar and the rate at which heat is conducted downward along the wires and glass tubes.

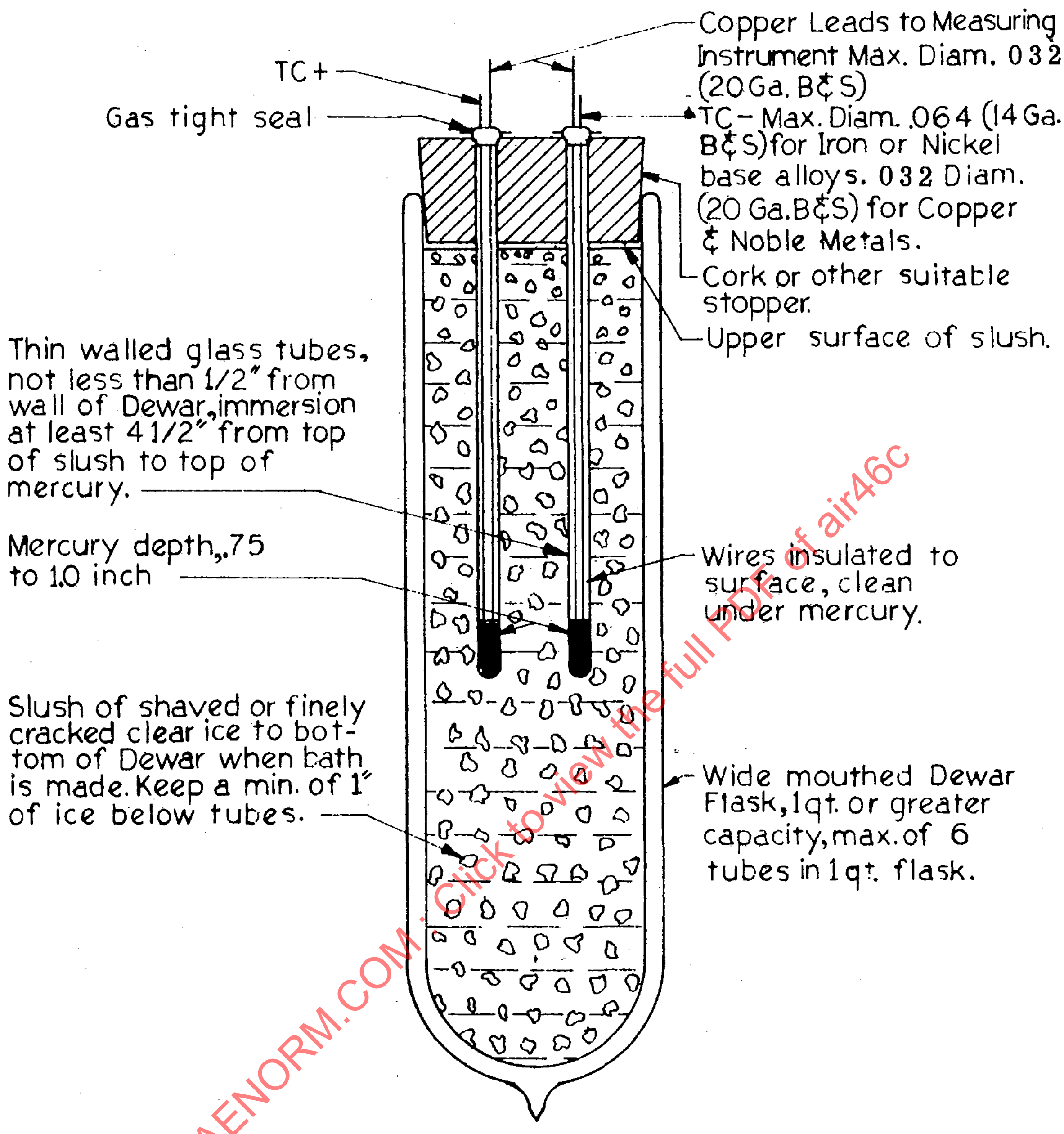

Figure 10 - Recommended reference junction at ice point

Cold junctions may be made by hard soldering the thermo elements to copper lead wires, but the excellent thermal and electrical contact provided by the mercury makes soldering unnecessary.

When an ice bath is used, the circuit from there on should be all copper. The use of other materials in switches, terminals, etc., will cause errors in the presence of temperature gradients.

When it is inconvenient to use an ice bath, a thermally insulated block of copper, aluminium, or silver, or a stirred liquid bath may be substituted to create an isothermal environment. In such case, the temperature of the reference junction must be measured with an auxiliary instrument and taken into proper account.

5.3 Automatic Cold-Junction Compensation

Some accuracy may be sacrificed for the convenience of eliminating the ice bath, and some indicating and recording instruments have built-in cold junction compensators. When a Type K thermocouple is used with a given instrument, its compensator must be for Type K, etc. In effect, the compensator adds to the indication of the measuring instrument a value equal to the EMF of a thermocouple with its measuring junction at the temperature of the compensator and its cold junction at the ice point. Rapid variations in temperature at the location of the compensator may lead to errors of several degrees. Controlled application of heat within a potentiometer in the vicinity of the compensator, as, for instance, by a thermostatically controlled light bulb, will improve the accuracy of compensation.

When a compensator is used, the thermo elements should ideally run without any kind of joint from the measuring junction to the instrument. Problems of installing parallel thermocouples in engines make this difficult and, in some cases, virtually impossible to achieve. Then the entire thermocouple circuit between the measuring junctions and the compensator should consist of material with the same thermoelectric properties as the elements constituting the measuring junction.

5.4 The Selector Switch

If a selector switch is used so that several thermocouples can be read on a single instrument, this should come between the reference junction and the instrument. It is thus usually in a copper circuit and should itself be of all copper for highest accuracy. When a selector switch having copper or brass contacts is used with a compensated instrument, the switch should be enclosed so that it is free from drafts and not subjected to large, sudden changes of temperature.

6. PROCURING AND CALIBRATING THERMOELEMENTS

This section concentrates on the procurement and calibration of Type K thermocouples but is largely relevant to all metal-to-metal thermo-element types, although some joining methods may not be suitable.

6.1 Specification of Thermocouple Wire

A reasonable thermoelectric specification for thermocouple wire to be used in making engine thermocouples is as follows: the NIST Monograph 175 and ASTM E230 define the limits of the temperature-EMF relation for thermocouples made from wire.

6.2 Methods of Making Thermocouple Junctions

The methods of forming the measuring junction include joining the thermo elements by means of a third material such as solder, brazing spelter or welding rod. Another means to form the junction is the use of a third element through which the thermocouple circuit is completed, as when the thermo elements are individually peened or welded to a solid conductor or dipped into a molten one. The addition of third materials is not recommended as it can limit the operating range of the thermocouple and or lead to measurement errors should there be any thermal gradients across its junctions with the thermocouple materials.

The preferred—and most widely used—method to form the junction is autogenous welding, in which the thermo elements are fused together by a torch or by electrical means without using any other metal to form the joint. The noble metals may be welded with a torch in the absence of flux. For base metals, it is advantageous to use a flux to minimize oxidation. Care should always be exercised to limit the heating to the very ends of the thermo elements and to avoid heating them too long or too hot. Oxy-acetylene, oxy-gas, or air-gas flames with small, sharply defined inner cones are suitable for making thermocouple junctions. Borax is often used as a flux, and after the weld has been made, all traces of flux should be removed. Immersion in boiling water for several minutes is effective for most fluxes.

Three methods of electric welding are in use. An arc between two carbon electrodes may be used to fuse the ends of the thermo elements together, or the thermo elements may be used as one of the electrodes with a carbon rod as the second. Another method utilizes mercury covered with oil as one electrode and the thermo elements as the other, so that the latter are arc welded together when brought into contact with the mercury. In all electrical methods, current and voltage must be adjusted to meet the specific needs. Resistance welding is well adapted to making butt-welded junctions. The ends of the thermo elements are held in firm contact and a surge of current is passed to effect fusion.

When measuring the surface temperature of a piece of metal, attaching the thermo elements separately to the article often produces the best results. Attachment may be done by spot welding or peening the wires to the metal whose temperature is to be measured. To avoid errors, the points of attachment should be close enough together that there is no significant difference in temperature between them.

Twisting the thermo elements at the measuring junction is not recommended, despite the fact that such a junction may have greater mechanical strength than its untwisted counterpart. Twisting leaves the exact location of the first electrical contact between the thermo elements in doubt as well as leaving strains in the wires which are particularly difficult if not impossible to remove from the negative (Kn) thermo element wire. A twisted junction responds less rapidly than its untwisted counterpart to sudden changes in temperature.

In any case, the junction length is to be kept as short as possible to achieve the most repeatable thermo-electric performance.

6.3 Calibration of Thermocouple Wire

All calibrations must be related directly or indirectly to the International Practical Temperature Scale (see 14.6). In general, the fixed points defined therein are used only for primary calibrations and the devices so calibrated are then used for calibrating others for practical application. More specifically, Type K thermocouples are normally calibrated by direct comparison with a standard platinum-platinum rhodium (Pt-PtRh) couple. As a result of experience and common practice over the years, reference values of EMF as a function of temperature have come into general usage. The reference tables for thermocouples in NIST Monograph 175 contain identical reference tables for several combinations of thermo elements, shown in Table 3.

Table 3 - Thermocouple materials and type designations

Type	
B	Platinum - 30% rhodium versus platinum - 6% rhodium
E	Nickel-chromium alloy versus copper-nickel alloy
J	Iron versus a copper-nickel alloy
K	Nickel-chromium alloy versus nickel-aluminium alloy or (nickel silicon alloy)
R	Platinum - 13% rhodium versus platinum
S	Platinum - 10% rhodium versus platinum
T	Copper versus copper-nickel alloy

For any given combination of thermo elements, the reference table serves as the goal toward which performance is directed, and from which unavoidable differences are determined and applied as corrections. Manufacturers and vendors of Type K thermo elements need to know the thermoelectric characteristics of each alloy individually, in order that batches of wire may be matched to perform as nearly in accordance with the reference table as the purchaser may specify. Calibration is typically done by determining the EMF of individual samples against pure platinum. One alloy being positive and the other negative to platinum (Pt), the sum of the EMF against Pt is identical with the EMF of the Type K couple.

Both the makers of Type K thermocouples and the users of these thermocouples are interested only in the EMF of the particular samples of Type K employed. In other words, the calibration which the users need is not of the individual thermo elements against Pt, but rather of the Type K directly.

A calibration of the latter type is made at NIST by welding the junction of a standard Pt-PtRh couple to that of the Type K couple being tested. This common junction is placed near the centre of a tube furnace which is heated by passing current through the furnace tube. Simultaneous readings are taken of the EMF of the two couples over the range of temperature which is of interest. Leads for this common junction are long enough that their reference junctions may be kept at the ice point. Immersion is sufficient to ensure against loss of heat by conduction from the junction. By using the comparison method, problems of heat transfer to and from the junction by radiation and convection do not arise.

The results of such a calibration are normally expressed in the form of a table or chart of differences from the reference curve. Samples of the thermo elements currently used in the manufacture of gas turbine thermocouples are originally calibrated in this or similar fashion with spot checks made at one or more stages in the manufacture of the couples. Deviations of the actual production thermocouples from the standard curve are not measured and hence no corrections can be applied for such differences as may exist from the reference curve for Type K. Assuming that the calibration of the Type K thermocouple is no farther from the reference curve than the thermo elements were originally, then the maximum errors that can arise from not applying corrections are therefore given by the tolerances in the specifications under which the thermo elements were purchased originally.

A paper by Roeser and Wensel (1935) provides details for the calibration of thermocouple wire by direct comparison with a standard Pt-PtRh thermocouple in a tube furnace, other methods for calibrating thermocouples and testing thermocouple materials, and the precautions which must be observed in order to attain various degrees of accuracy. Such calibrations are conducted at NIST for the public on a fee basis.

7. INDICATING AND MEASURING INSTRUMENTS

The EMF of a thermocouple depends upon the temperatures of its measuring and reference junctions, and after appropriate calibration, thermocouple EMFs may be translated quantitatively into temperature differences. If the temperature of the reference junction is known, and if the EMF is determined, the temperature of the measuring junction also becomes known. Thermocouple EMFs can be measured conventionally with appropriate millivoltmeters or potentiometers.

7.1 Analog Millivoltmeters

Analog millivoltmeters are galvanometer-type instruments with pointers and scales which may read in millivolts or directly in degrees. Since the deflection of a galvanometer is a function of the current flowing through it, the reading of a particular millivoltmeter-thermocouple system depends upon the total resistance of the circuit including the instrument. Thus, the instrument reads properly only when the total resistance is the same as it was during calibration. This requirement for proper adjustment of the resistances of instrument and circuit is a disadvantage per se, and such a system has the further disadvantages that its calibration may vary as a result of (a) unavoidable changes in resistance during use, as from changes in the temperature of the thermocouple, its leads, or the instrument; (b) physical or chemical changes in the various metals constituting the circuit; (c) contact resistances in connectors and switches; (d) changes in the strength of the permanent magnet and of the spring in the millivoltmeter; and (e) pivot friction in the instrument. Since the thermal EMF of Kp-Kn is approximately 0.04 mV per °C (0.02 mV per °F), and since the EMF of such a couple with reference junction at 0 °C (32 °F) and measuring junction at 1260 °C (2300 °F) is about 51 mV, it will be obvious that a millivoltmeter without suppressed zero would have to have a very large scale to be readable to better than 5 °C (10 °F).

Nevertheless, the millivoltmeter is in wide use in cockpits where small size and weight are desirable, and where the use of standard cells and batteries is inconvenient or impractical.

In some gas turbine installations, the same thermocouples are connected to a millivoltmeter in the cockpit and to a control system. Movement of the meter parts due to manoeuvres of the aircraft can generate EMFs within the instrument, which may feed back into and disturb the control system.

7.2 Digital Millivoltmeters

Many modern aircraft use high impedance digital millivoltmeters for engine monitoring and control systems to capture and convert the EMF into a temperature output. The high impedance eliminates the need for controlling input resistance.

7.3 Servo-Driven Indicators

This type of indicator is among the most accurate. In basic terms, a servo-motor drives the indicator. A servo-motor is often expensive relative to other types but is very robust.

7.4 Potentiometers

The potentiometer is an instrument which provides and measures a controllable EMF that can be made equal and opposite to that of the thermocouple. Being a null instrument, readings are made only when the two opposed EMFs are so nearly alike that no measurable current is flowing. In such a system, the balancing EMF is independent of the resistance of the circuit. However, the sensitivity with which the point of balance can be determined with a given detector decreases as the circuit resistance increases.

Conventional potentiometers contain a standard cell of known, constant EMF from which practically no current is ever drawn, and a dry cell which supplies the current that flows through the instrument. The so-called Mallory or mercury cells have been substituted successfully for both the standard cell and the dry cell in potentiometers designed for the battery voltages involved thereby. The mercury cells are more rugged and less sensitive to damage by freezing and by high temperatures than are the cells in common use.

Potentiometers are available commercially in types too numerous to mention, from portable, manual indicators to electronic, self-balancing indicators and recorders. Some read EMF directly, and others are calibrated in degrees. In the latter case, the instrument reads correctly only when used with thermo elements of a particular calibration and when the reference junction is at a particular temperature. Some potentiometers have the automatic cold junction compensation discussed in 6.3 of this report. In general, potentiometers are laboratory instruments, not well suited for installation in the crowded cockpit of an aircraft.

8. CORRECTIONS APPLICABLE TO GAS TURBINE THERMOCOUPLES

Even when all of the known precautions have been taken as to circuitry and instrumentation, and when the EMF is known as a function of temperature, errors are still possible. The only thing that a thermocouple can indicate is the temperature of its own measuring junction. Thus, when a thermocouple is used to determine the temperature of a medium to which its measuring junction is attached or in which it is immersed, the difference in temperature between the junction and the medium must be evaluated, or this difference must be reduced to a negligible amount.

When a thermocouple is used to indicate the temperature of the working medium of a gas turbine engine, major practical problems are involved in trying to determine how much the measuring junction differs in temperature from the gas. Actually, when such a measuring junction attains a steady state, its temperature is the resultant of several simultaneous rates of heat exchange between the junction and its surroundings, namely (a) the rate (Qk) at which heat is transferred to or from the junction by conduction along the thermo elements and other solid parts of the thermocouple, this being normally from the junction to the cooler walls; (b) the rate (Qc) at which heat is exchanged by convection between the gas and the junction, this being normally from the gas to the junction; and (c) the rate (Qr) at which heat is exchanged by radiation, this being normally from the junction to the cooler walls. If the gas velocity exceeds a few hundred m/s (ft/s), the junction also receives more or less heat as a result of the conversion of velocity head into heat wherever the measuring device slows down or stops gas which impinges upon it. This latter may be called the impact effect and may be considered to include effects of friction which are difficult if not impossible to determine separately. Under conditions of rapidly changing gas temperatures, immersed sensing devices always heat or cool at a slower rate than the gas itself, so that under changing conditions this lag may be thought of as still another correction which must be applied to convert indicated temperature into true gas temperature at any instant. The so-called rate of response or characteristic time of a thermocouple is also of importance in another way which may be discussed later.

8.1 Conduction Correction

Engine thermocouples are attached to walls which are cooler than either the measuring junction or the gas. Hence there is always a tendency for heat to flow from the junction toward the wall. As a matter of fact, this rate is normally too slow to be significant, as will now be shown.

For simplicity, consider that a wire of diameter D projects for a distance (a) into gas at temperature T_g from a wall at temperature T_w. Assume that the innermost end of the wire is located where a measuring junction might be, and that the temperature of the wire is T at a distance (x) from its free end.

Let h be the coefficient of heat transfer by convection from the gas to the wire, and let k be the thermal conductivity of the wire. For further simplicity, let the constant α represent a group of other constants already defined, to obtain Equation 6:

$$\alpha^2 = 4h / Dk \quad \text{(Eq. 6)}$$

By equating the rates of heat flow into and out of element δx of the wire, Equation 7 represents the steady state can be shown to be

$$d^2T / dx^2 = \alpha^2(T - T_g) \quad \text{(Eq. 7)}$$

Solving for this expression results in Equation 8:

$$T - T_g = Ae^{\alpha x} + Be^{-\alpha x} \quad \text{(Eq. 8)}$$

Here, the constants A and B may be evaluated from the boundary conditions of dT/dx = 0 at x = 0; and $T = T_w$ at x = a, and in which e is the base of Naperian logarithms. The final result is show in Equation 9.

$$\frac{Tg - T}{Tg - Tw} = \frac{\cosh 2x\sqrt{h / Dk}}{\cosh 2a\sqrt{h / Dk}} \quad \text{(Eq. 9)}$$

or, if T_j is the temperature of the measuring junction located at x = 0, Equation 10 results.

$$\frac{T_g - T_j}{T_g - T_w} = \frac{1}{\cosh 2a\sqrt{h / Dk}} \quad \text{(Eq. 10)}$$

Only the coefficient h of heat transfer by convection is not subject to direct measurement in an apparatus designed primarily for observing temperature. However, if the mass velocity, specific heat, absolute viscosity, and thermal conductivity of the fluid flowing around the wire are known, the value of h can be calculated from empirical equations given by McAdams.

Using the methods and equations listed above, numerical values of the conduction correction can be estimated under assumed engine operating conditions. Figure 11 shows such corrections for bare No. 22 and 14 gage Type K thermocouple wires and for a stainless steel tube 6.35 mm (0.25 inch) OD x 4.32 mm (0.17 inch) ID at an assumed T_g - T_w of 55 °C (100 °F) for mass flows of 0.40 kg/m^2-s (2 lb/ft^2-s), 0.80 kg/m^2-s (4 lb/ft^2-s), and 1.20 kg/m^2-s (6 lb/ft^2-s) gas turbine thermocouples normally consist of thermo element wires within packed magnesia and outer supporting tubes, and the thermal conductivity of the assembly is somewhat greater than the sum of the conductivities of the wires plus the tubes. Nevertheless, the conduction correction is insignificant at immersion of 50 mm (2 inches) and more, even at the low flow rates which correspond to gas turbine idling at sea level and to full speed at the flight ceiling. For mass velocities as high as those experienced in turboprop engines in normal operation, immersion of 25 mm (1 inch) or more seems ample to ensure against significant conduction error.

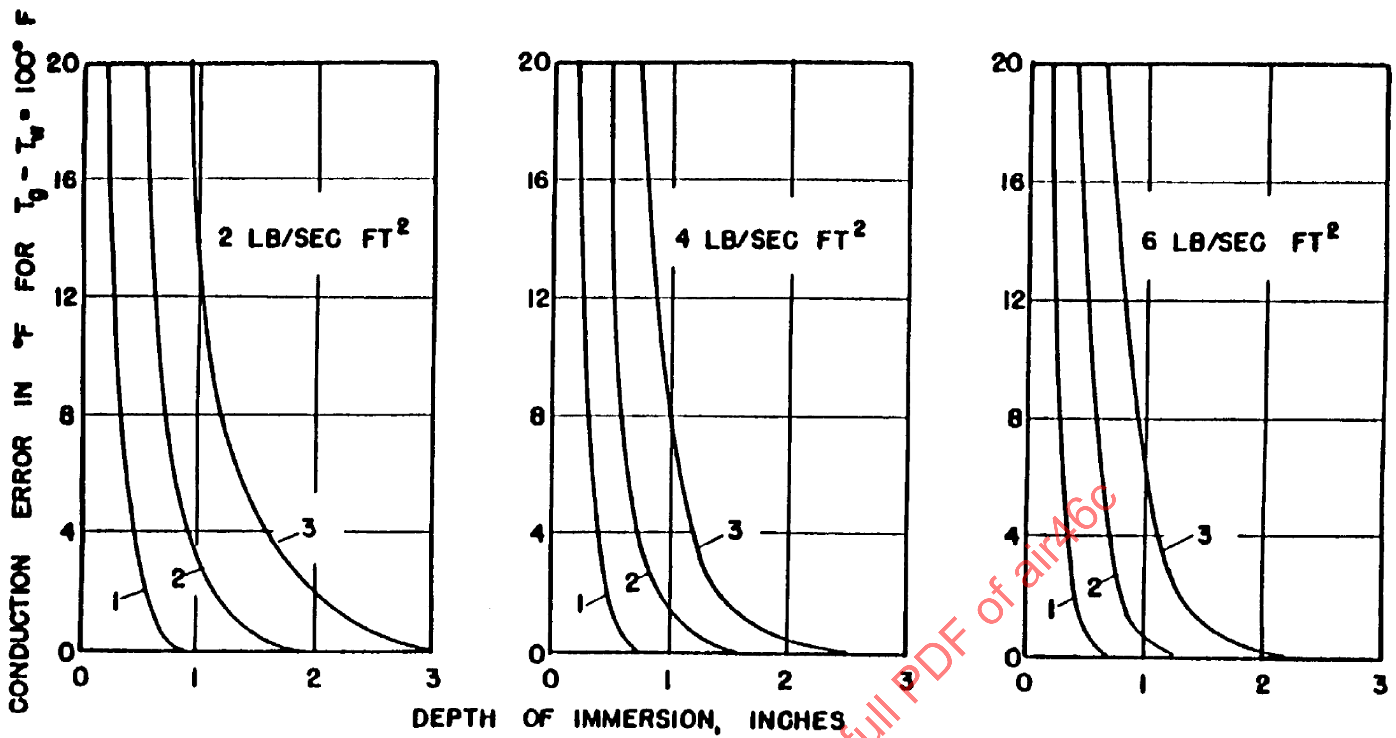

Figure 11 - Effect of immersion on conductor error

Curves 1 and 2 apply for vare No. 22 and No. 14 KP-KN thermocouples, respectively. Curve 3 is for a 0.25 inch OD X 0.17 inch ID stainless steel tube.

8.2 Heat Gain by Convection

The rate (Q_c) at which heat is gained from the gas by convection is given by Equation 11:

$$Q_c = hA_c(T_g - T_j) \quad \text{(Eq. 11)}$$

The area, A_c, is that of the junction through which heat is added by convection, and the other quantities have been defined previously. As pointed out in the previous section, h is strongly dependent upon the mass velocity.

8.3 Radiation Correction

If the conduction correction is negligible, a steady state is attained by the measuring junction when the Rate (Q_c) of heat gain by convection equals the rate (Q_r) of heat loss by radiation, Equation 12.

$$Q_c = Q_r \quad \text{(Eq. 12)}$$

The area of the measuring junction of a thermocouple is small compared to that of all the surroundings which it can “see.” Hence, little, if any, of the energy radiated by the junction is ever reflected back to it regardless of the ability of the surroundings to reflect. This means that the surroundings act as a black body, without regard to their surface emissivity.

By integrating Planck’s radiation law over all wavelengths from zero to infinity, the rate (W_{bt}) at which energy is radiated over all wavelengths per unit area of a black body surface is defined by Equation 13.

$$W_{bt} = \sigma T^4 \quad \text{(Eq. 13)}$$

in which α is the Stefan-Boltzmann constant and T is the absolute temperature, expressed in Kelvins or degrees Rankine. The ratio of the radiant flux density from an actual junction (W_{jt}) to that of a black body (W_{bt}) at the same temperature is called the emissivity (ε_t) of the actual body. This results in Equation 14.

$$Wjt = \sigma\varepsilon t\, T_j^4 \qquad \text{(Eq. 14)}$$

The factor $\sigma\varepsilon_t A_j T_j^4$ is the rate at which a junction having an area A_j and temperature T_j loses heat. It simultaneously gains heat from surroundings at temperature T_w at the rate of $\sigma\varepsilon_t A_j T_w^4$, and the net rate of heat loss by radiation is defined by Equation 15.

$$Q_r = \sigma\varepsilon_t A_j(T_j^4 - T_w^4) \qquad \text{(Eq. 15)}$$

Since $Q_c = Q_r$ at a steady state, Equations 16 and 17 hold true.

$$hA_c (T_g - T_j) = \sigma\varepsilon_t A_j (T_j^4 - T_w^4), \text{or} \qquad \text{(Eq. 16)}$$

$$T_g - T_j = \frac{\sigma\varepsilon_t}{h}\frac{A_j}{A_c}(T_j^4 - T_w^4) \qquad \text{(Eq. 17)}$$

The difference T_g - T_j is obviously the correction which must be applied for heat loss by radiation. Its value for a junction of given configuration is seen to depend upon the emissivity of the junction, the coefficient of heat transfer by convection (which is dependent upon the mass velocity), and upon the difference in the fourth powers of its own absolute temperature and that of the surrounding walls. Thus, the correction for radiation can be decreased by decreasing the emissivity of the junction, as by pressing a small shield of silver, gold or platinum around it, by locating it in a region of high mass velocity, or by surrounding it with radiation shields which attain higher temperatures than the walls.

8.4 Impact Effect

In a gas at rest, temperature is a measure of the mean kinetic energy of random motion of the gas molecules. However, in many gas streams which find current application, the directed velocity is appreciable as compared with the mean velocity of random motion. In such cases, the two temperatures of interest are the static temperature, T_s, which would be indicated by an error free instrument moving with the gas, and the total temperature, T_t, which would be indicated by an instrument immersed in the gas after it is brought to rest adiabatically. These two temperatures are related through Equation 18.

$$T_t - T_s = v^2/2gJC_p, \text{ and } T_t/T_s = 1 + M^2 (\gamma-1)/2 \qquad \text{(Eq. 18)}$$

in which v is directed velocity, g is the gravitational constant, J is the mechanical equivalent of heat, C_p is the heat capacity at constant pressure, M is the Mach number, and γ is the ratio of the specific heat at constant pressure to that at constant volume.

Typical values of the difference T_t - T_s for air with C_p = 0.24 Btu/lb/°F (310.148 J/kg/°C), as a function of velocity, are as follows in Table 4.

Table 4 - Total temp minus static temp as a function of velocity

Velocity m/s	Velocity ft/s	$T_t - T_s$ °F	$T_t - T_s$ °C
0	0	0.0	0.0
32.8	100	0.8	0.4
65.6	200	3.3	1.8
98.4	300	7.5	4.2
131.2	400	13	7.2
164.0	500	21	11.7
198.9	600	30	16.7
229.7	700	41	22.8
262.5	800	53	29.4
295.3	900	67	37.2
328.1	1000	83	46.1

A stationary instrument attains neither T_t nor T_s when immersed in flowing gas, but rather some intermediate value, T_j, which depends upon how completely the directed kinetic energy is converted into thermal energy upon impact. The capacity of an instrument for effecting this conversion is its recovery factor, r, defined in Equation 19.

$$r = (T_j - T_s)/(T_t - T_s) \quad \text{(Eq. 19)}$$

8.5 Response Time or Time Constant

The response time of sensing elements to sudden changes in temperature are of practical concern to those who are interested in observing transient conditions (as during engine acceleration), and to those dealing with control systems actuated by devices sensitive to gas temperature. To the former group, the amount by which the measuring junction lags behind the gas temperature at any instant can be regarded as a correction which might be applied to obtain the temperature at the same instant. To those interested in controls, the absolute value of the indicated temperature may be of less importance than the time between a sudden change in gas temperature and the development of a usable signal from the measuring junction as a result thereof. The more modern practice uses software to compensate for the time constant of the response to estimate the gas-path temperature from the sensed temperature.

When the temperature of a gas is increased instantaneously from T_1 to T_2, the increase (ΔT) in the temperature of an immersed object with time (t) thereafter by forced convection is given by Equation 20.

$$\Delta T = (T_2 - T_1)(1 - e^{-t/\tau}) \quad \text{(Eq. 20)}$$

In Equation 16, e is the base of Naperian logarithms and τ is a constant. It is apparent that τ must have the dimension of time, and that at time $t = \tau$, $\Delta T/(T_2 - T_1) = 1 - 1/e = 0.632$. Thus τ is the time required for the immersed object to undergo 63.2% of any temperature change to which it is subjected instantaneously and thus defined is referred to as the characteristic time (time constant) of the object.

Actually, τ is not characteristic of the object alone, but of the object and the rate at which heat is transferred to it. The latter varies with the coefficient of heat transfer to the object, so that a numerical value of τ is significant only when the flow rate is specified. The coefficient also varies somewhat with temperature, and there is some difference of opinion as to whether observed values of τ vary significantly with the values of T_1 and T_2 selected for the measurement.

9. LABORATORY EVALUATION OF THERMOCOUPLE PERFORMANCE

Since the performance to be expected of an individual thermocouple in an engine can, to a large extent, be predicted from laboratory tests, a description of facilities used for this purpose at NIST Monograph 175 may be of interest. These facilities are used for thermocouples already calibrated for conventional service, i.e., for which the EMF-temperature relationship is known, but for which additional information is required as to performance in flowing products of combustion.

As indicated schematically in Figure 12, this supplementary facility consists essentially of blowers supplying compressed air to a gas turbine can-type combustor with afterburner, and an exhaust system in which test instruments and standard instruments can be immersed and compared under a variety of controlled operating conditions.

The Inconel test section downstream from the burners has three convenience hatches for installation of the test and reference instruments which, because of the configuration of the exhaust system, receive no direct radiation from the flame. It supports a mechanism, to be described later, for determining response rates. Thermocouples are peened into the walls to indicate the pipe temperature, and external thermal insulation is applied if desired. Similarly constructed test sections 76 mm (3 inches) and 152 mm (6 inches) in diameter are available, and temperatures up to 1093 °C (2000 °F) can be provided at mass velocities up to 3.1 kg/s/m^2 (15 lb/s/ft^2) in the 152 mm (6 inch) section and up to approximately twice this figure in the 76 mm (3 inch) section.

The lower flow channel in Figure 12 is an air-line, used for determining recovery factor, and is described in more detail in 9.2. It is also used for quenching specimens in thermal shock tests.

Fuel and air rates, pressures and velocities are measured by conventional means. Water cooling of valves is accomplished by internal sprays, and the lines downstream of such sprays are sloped to prevent unevaporated water from influencing the temperature of the gas in the test section.

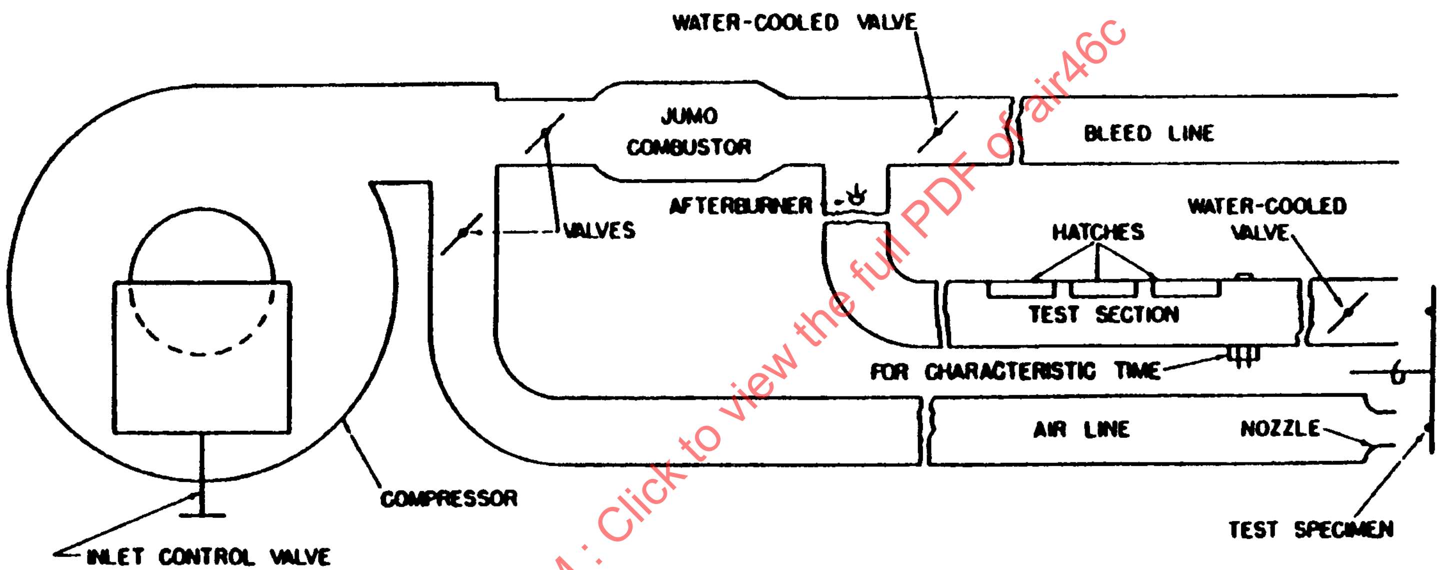

Figure 12 - Composite diagram of supplementary test facilities

9.1 Correction for Radiation and Conduction

For determining the combined correction for conduction and radiation, it is desirable to have a comparison instrument free from losses by either of these processes. Such a laboratory standard for use in flowing gases is shown in Figure 13. It consists essentially of a central, bare thermocouple junction surrounded by two coaxial tubular radiation shields. The inner shield is a silver tube 139.7 x 25.4 x 1 mm (5.5 inches long x 1 inch OD x 0.04 inch) wall thickness. The outer shield is a stainless-steel tube 165.1 x 44.4 x 0.80 mm (6.5 inches long x 1.75 inches OD x 0.03 inch) wall thickness, wound externally with a tapped heating element and having three thermocouples peened into its inner surface. The assembly is mounted coaxially in the 152 mm (6 inch) test section from the central hatch shown in Figure 13.

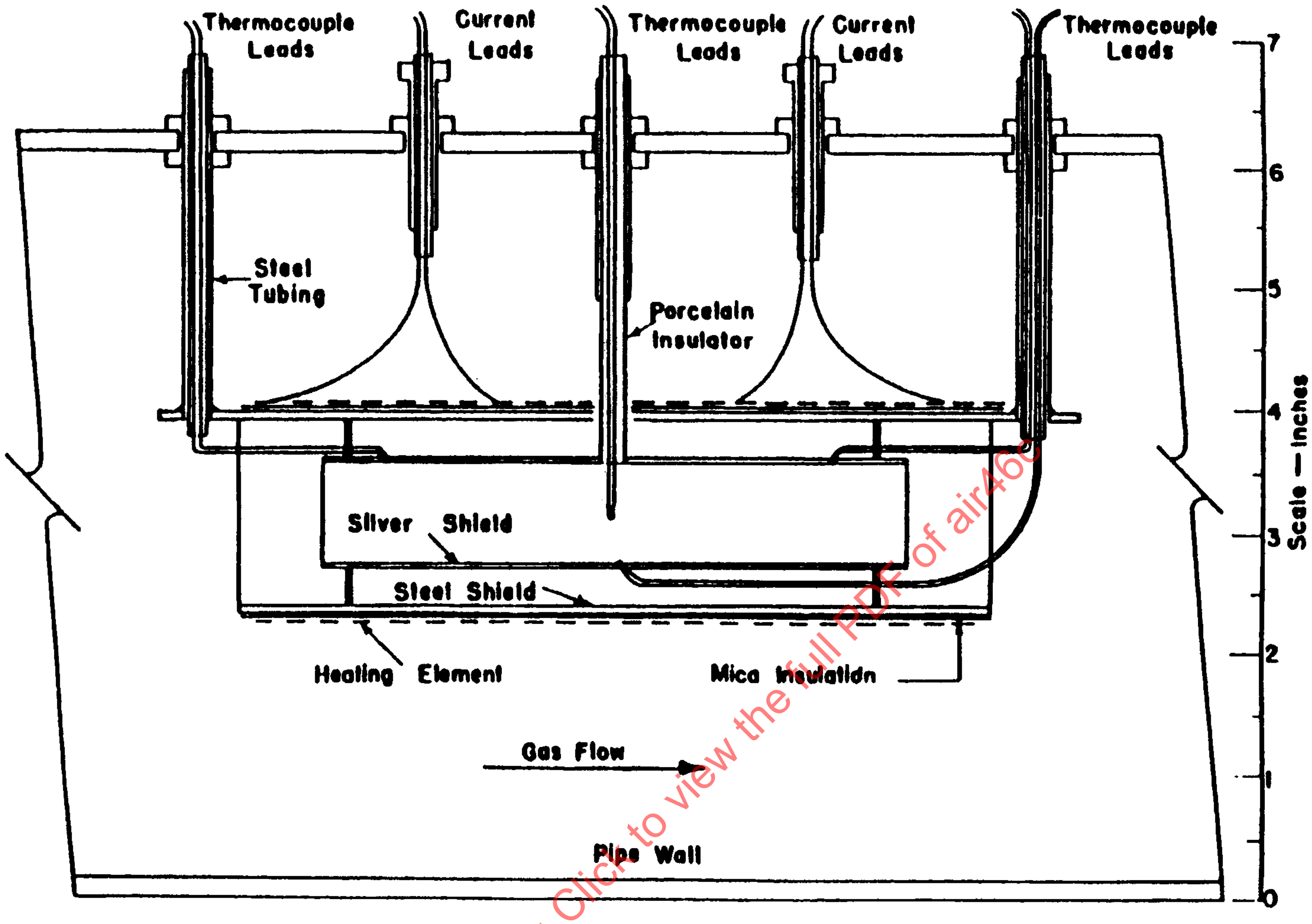

Figure 13 - NBS laboratory standard for determining the combined correction for conduction and radiation

In operation, the outer shield is heated electrically until its temperature is uniform and equal to that indicated by the thermocouple at the centre. Under these conditions, loss from the central junction by conduction and radiation is prevented by the shields. It is apparent that proper operation of such a unit requires considerable time and care, and that it is not convenient for routine calibrations. Hence, it is used only for calibration of more convenient secondary standards, consisting of Type K thermocouples with pressed radiation shields of silver, gold, or platinum.

For calibration, such secondary standards are installed at equal distances upstream and downstream from the laboratory standard. Under various operating conditions, the former are read when the latter are adjusted as already described to read true gas temperature. Gas velocity is kept sufficiently low that impact corrections are small and known. The separate sets of secondary standards, when read differentially, give the axial rate of temperature decrease due to heat loss along the test section. The gas temperatures at the locations of the secondary standards are obtained by applying the corrections for axial gradient to the temperature indicated by the laboratory standard. Wall temperatures are subject to some control by applying more or less thermal insulation, and by dropping the gas temperature suddenly from a high value to that chosen for a particular run.

The corrections applicable to the secondary standards are obtained by subtracting the values which they indicate from the true gas temperature indicated by the laboratory standard, after taking due account of the effects of impact and axial heat loss. Such corrections are determined at various temperature levels, flow rates, and for various values of the temperature difference between the gas and the walls of the test section.

The corrections applicable to gas turbine thermocouples are determined in the same way, the test couples being installed where the laboratory standard was before. True gas temperature is obtained by applying the proper corrections to the indications of the secondary standards. Gas temperatures are currently varied from 538 to 871 °C (1000 to 1600 °F), wall temperatures from 427 to 760 °C (800 to 1400 °F), at mass velocities of 0.41 Kg/s/m², 0.82 Kg/s/m², and 1.23 Kg/s/m² (2 lb/s/ft², 4 lb/s/ft², and 6 lb/s/ft²).

Typical values of the combined correction for conduction and radiation of a bare, loop-type gas turbine thermocouple and of a stagnation-type unit are provided in Table 5 (metric and imperial units):

Table 5 - Combined correction for conduction and radiation of a bare loop type thermocouple

Gas	Wall	Bare, Loop-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities 0.41 kg/s m²	Bare Loop-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities 0.82 kg/s m²	Bare, Loop-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities 1.23 kg/s m²	Stagnation-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities 0.41 kg/s m²	Stagnation-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities in kg/s m² 0.82 kg/s m²	Stagnation-Type Couple Corrections in °C to be Added to the Indicated Temperatures at Mass Velocities 1.23 kg/s m²
815.6	760	11.1	7.8	6.1	13.9	9.4	7.8
815.6	704.4	20.6	14.4	11.7	26.1	17.8	14.4
815.6	648.9	28.9	20	16.7	36.7	25	20.5
815.6	593.3	35.6	25	20.6	45.6	31.1	25
815.6	537.8	42.2	28.9	23.9	52.2	36.1	29.4
760	704.4	10	7.2	6.1	12.2	8.3	6.7
760	537.8	33.3	23.3	18.9	38.9	26.7	21.7
704.4	648.9	8.9	6.1	5	11.1	7.8	6.1
704.4	537.8	21.7	15	12.2	27.8	18.9	15.6
648.9	593.3	7.2	5	4.4	9.4	6.7	5.6
648.9	482.2	18.3	12.8	10.6	23.3	16.1	13.3
593.3	537.8	6.1	4.4	3.3	7.8	5.6	4.4
593.3	426.7	15	10.6	8.3	20	13.9	11.1
537.8	482.2	5.6	3.9	3.3	7.2	5	3.9
537.8	426.7	9.4	6.7	5.6	12.2	8.9	7.2
Gas	Wall	Bare, Loop-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 2 lb/s ft²	Bare Loop-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 4 lb/s ft²	Bare, Loop-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 6 lb/s ft²	Stagnation-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 2 lb/s ft²	Stagnation-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 4 lb/s ft²	Stagnation-Type Couple Corrections in °F to be Added to the Indicated Temperatures at Mass Velocities 6 lb/s ft²
1500	1400	20	14	11	25	17	14
1500	1300	37	26	21	47	32	26
1500	1200	52	36	30	66	45	37
1500	1100	64	45	37	82	56	45
1500	1000	76	52	43	94	65	53
1400	1300	18	13	11	22	15	12
1400	1000	60	42	34	70	48	39
1300	1200	16	11	9	20	14	11
1300	1000	39	27	22	50	34	28
1200	1100	13	9	8	17	12	10
1200	900	33	23	19	42	29	24
1100	1000	11	8	6	14	10	8
1100	800	27	19	15	36	25	20
1000	900	10	7	6	13	9	7
1000	800	17	12	10	22	16	13

These values show that the radiation correction is important, and that it depends strongly on the mass velocity, the temperature level, and the difference in temperature between the junction and its surroundings. While it might at first be thought that the correction for a stagnation probe should be less than for a bare junction because the stagnation chamber is in effect a radiation shield, the above values show that the decreased flow rate over the junction in the stagnation chamber has a greater effect than does the radiation shield.

9.2 Determination of Recovery Factor

The lower flow channel in Figure 12 is a 30.5 cm (12 inch) pipe terminating in a calibrated 10.2 cm (4 inch) nozzle which discharges air from the compressor directly into the atmosphere. A heavy aluminium spool at the nozzle exit is used for mounting instruments for determinations of recovery factor. A heating coil on this spool can be used to bring its temperature to equality with that of the test instrument, thus preventing heat loss by conduction along solid parts of the instrument.

In the 30.5 cm (12 inch) pipe, the velocity is low and the temperature T_t and T_s are nearly alike and directly measurable. The test instrument indicates a temperature T_j at the discharge of the nozzle. The thermal properties of the air are known, and the velocity past the test instrument is known from the calibration of the nozzle and the measured pressure drop across it. The expansion is nearly adiabatic, and the value of T_t measured just upstream of the nozzle applies also at the test instrument. Thus, the value of T_s can be calculated from Equation 14, and all the quantities needed to calculate the recovery factor from Equation 15 are known. Measurements of this type must be made with considerable care, because the differences among T_t, T_s, and T_j are not great.

Recovery factors for gas turbine thermocouples, as determined in air at approximately room temperature, are normally within the range 0.7 to 0.8 for bare, loop-type, V-type and twisted junctions, and from 0.9 to 0.99 for stagnation types.

Figure 14 illustrates the combined effect of radiation and impact upon the temperature attained by a typical, bare Kp-Kn thermocouple (r = 0.65) in flowing gas at a pressure of one atmosphere when the surrounding walls are at a temperature (T_w) of 537.8 °C (1000 °F). One curve in each rectangle gives T_t for the gas, one its T_s, and the third shows the temperature (T_j) attained and indicated by the measuring junction. The upper set of curves applies when T_s is constant at 815.6 °C (1500 °F) and the lower when T_t = 815.6 °C (1500 °F), the latter being the more realistic case. In both cases, the effect of radiation decreases and that of impact increases with velocity, causing the thermocouple in the present example to indicate exactly the static temperature of the gas when the velocity is approximately 243.8 m/s (800 ft/s). This figure is presented primarily to indicate the magnitude of the error that can arise from radiation and impact unless proper corrections are applied.

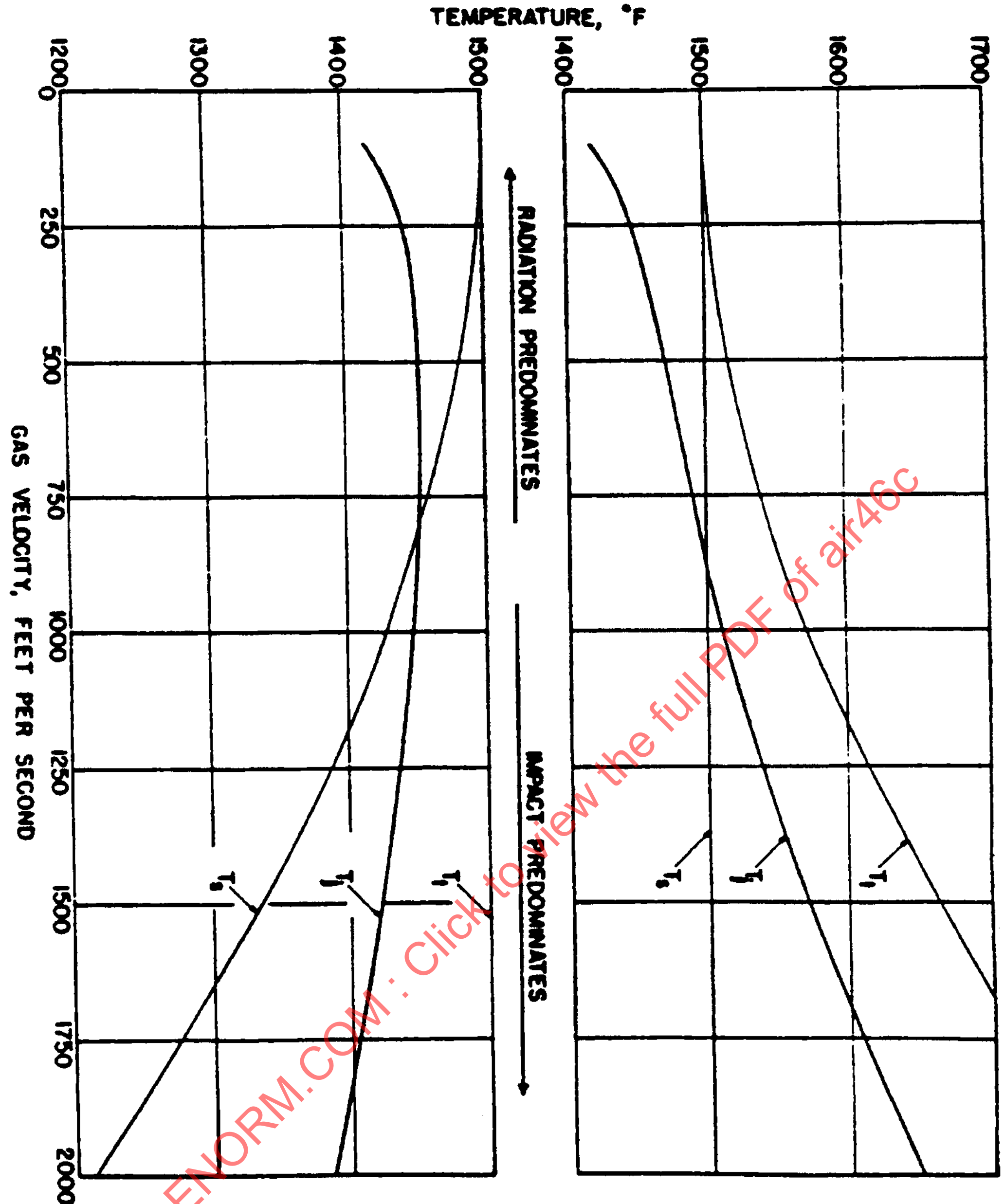

Figure 14 - Combined effect of radiation and impact on the performance of a bare thermocouple with r = 0.65, T_w = 1000 °F, at a static pressure of one atmosphere

The desirability of attempting to determine an average stagnation temperature by having several upstream openings in a stagnation probe is open to serious question. The optimum way to overcome recover errors is to choke the flow of gas over the sensing junction such that the gas velocity is fixed, by fixing the gas velocity the recover error is also fixed and that fixed error may be accounted for with the engine control system.

9.3 Determination of Characteristic Time

Apparatus which has proved suitable for determining characteristic times under conditions simulating those prevailing in engines is shown in Figure 15. An Inconel tube, held in position around the test instrument by a release plate, provides a flow channel for cold air. Upon removing the release plate, the Inconel tube is removed suddenly by a spring, thus exposing the instrument to the stream of hot exhaust gas which had already been established in the test section. During the downward movement of the tube, which requires only about 0.01 second, the supply of cold air is stopped automatically. In this way, a test instrument at a known, moderate temperature (controlled by the rate of air flow through the Inconel tube) can be exposed to exhaust gas at any chosen temperature and mass velocity within the capability of the test system.

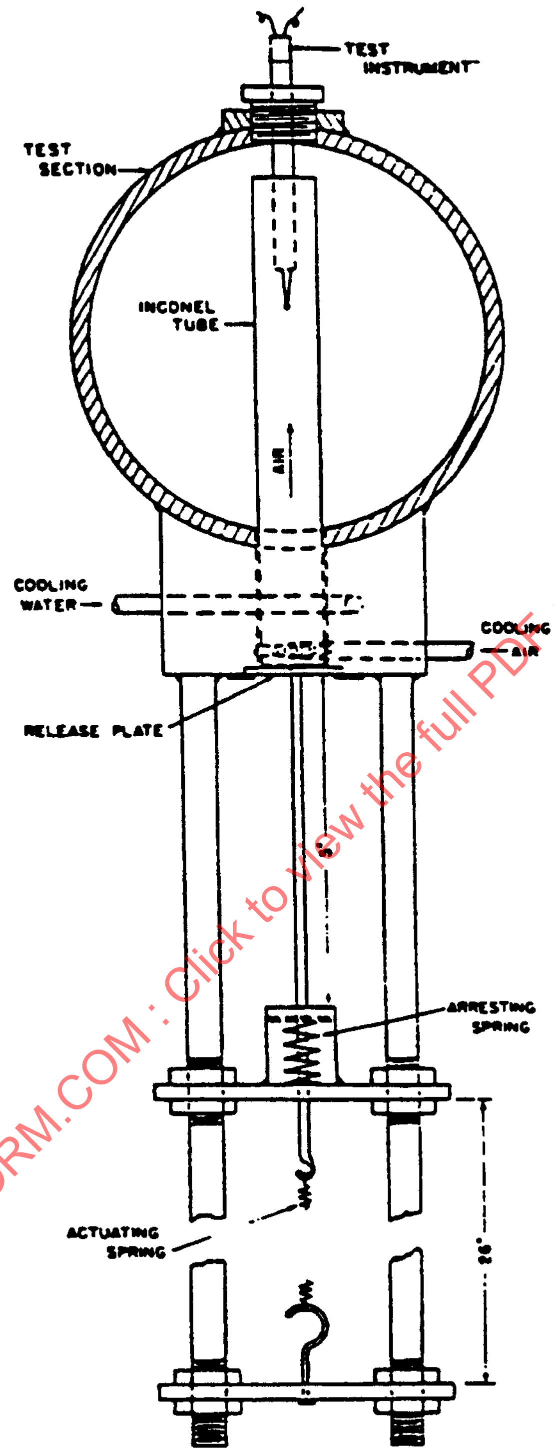

Figure 15 - Apparatus used at NBS for determining characteristic time

The rate of response of a thermocouple is recorded with a direct-inking oscillograph. Since an AC amplifier is used with the oscillograph, it is necessary to first chop the thermocouple EMF. The amplified EMF determines the amplitude of the record, the envelope of which represents EMF as a function of time. For thermocouples in which EMF varies nearly linearly with temperature, it is not necessary to know the amplification factor, and although the initial and final temperatures are usually measured with other instruments, these need not be known.

Typical curves showing the variation of the characteristic time of bare thermocouples with the size of the wire and with flow rate are shown in Figure 16. More detailed discussions of the response characteristics of temperature-sensing elements for use in gas turbine engines will be found in Dahl and Fiock (1950, 1951).

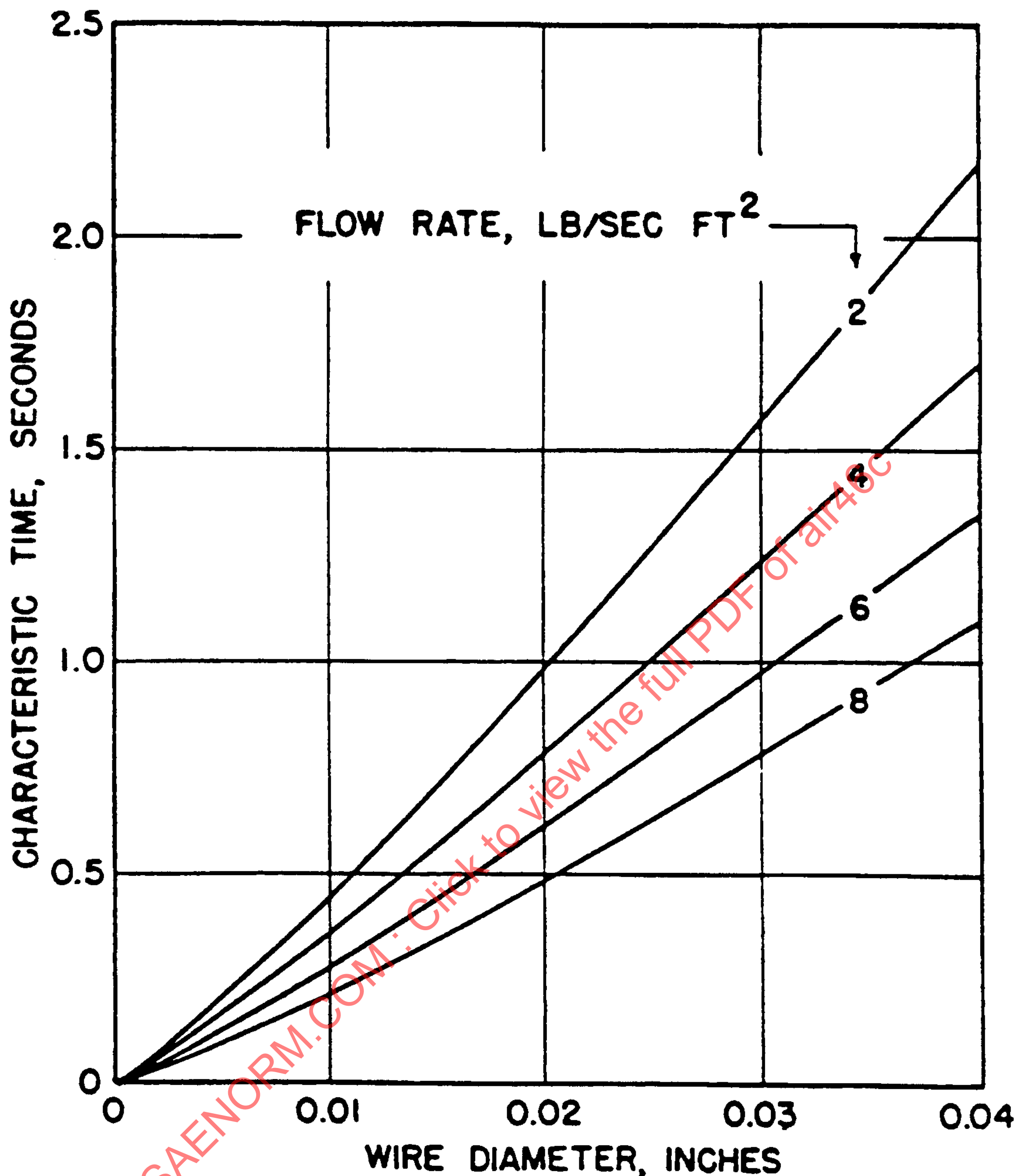

Figure 16 - Variation of characteristic time with wire size and with mass velocity

10. LOCATING THE MEASURING JUNCTION

The measuring junction should be immersed as far as is practicable, to reduce the heat loss by conduction along the thermo elements, insulation, and supporting tube. Locating the measuring junction in a region of high mass velocity is advantageous because the rate of heat transfer from the gas to the junction by convection increases approximately as the square root of this rate. An exception is in regions of transonic flow, as mentioned in the following paragraph. For a given rate of loss from the junction by radiation and conduction, the temperature of the junction approaches that of the gas in which it is immersed more closely as the mass velocity is increased.

Locating a measuring junction in a region where the gas velocity may vary in either magnitude or direction is an undesirable practice. Location in regions where the Mach number is between 0.7 and 1.0 should be avoided, because unstable, local shock waves may cause undesirable changes in the rates of energy exchange between the gas and the junction.

Locating a measuring junction so that it can “see” the flame is to be avoided. Observing this precaution is more important for flames having a high emissivity for total radiation, such as those containing free carbon, than for more common flames which radiate only a few percent of the total energy that would be emitted by a blackbody at the same temperature.

The measuring junction should never be located in a region where it can be struck by liquid fuel. A junction so placed will read low whenever it is wet.

In ground tests under simulated altitude conditions, a pressure-tight seal around the thermo elements is essential, so that no ambient air can leak along these. Leaks there can greatly increase the heat loss from the junction by conduction and possibly cool it by direct impingement.

Do not attempt to measure temperature by locating the measuring junction of a thermocouple in a region of continuing chemical reaction, such as in the primary combustion zone. While gaseous reactions are believed not to be catalysed by Type K alloys, or their oxides, the mere fact that the reactions are continuing indicates incomplete mixing and the absence of equilibrium distribution of energy among the translational, vibrational, and rotational states of some of the gas molecules. Very large gradients are to be expected in reacting gases, so that, for all these reasons, no single translational temperature characterizes such gases. Also, a probe in such a location may act as a flame-holder, and thereby give erroneous temperatures.

11. PARALLEL THERMOCOUPLE NETWORKS

The temperature distribution over any given cross section of the gas stream in a gas turbine engine is not uniform. Some of this non-uniformity is unavoidable, and it is not uncommon to purposely make the gas hotter at the tips than at the roots of the turbine blades. Since the gas temperature is not uniform, measuring it at several locations in an attempt to obtain a representative, average value is highly desirable. This can be done by connecting in parallel a number of thermocouples distributed across the section in some definite pattern. However, the direct measurement of a meaningful average temperature from a single observation of the net EMF of thermocouples in parallel requires certain specific precautions (refer to Dahl and Fiock, 1951). If these are observed and if proper corrections are applied for radiation and impact, the average temperature of the junctions will approximate the gas temperature more or less closely, depending primarily upon the magnitudes of the gradients in temperature and velocity within the gas stream and upon the relative locations of the junctions with respect to these gradients.

In addition to this averaging feature, another marked advantage of connecting thermocouples in parallel is that all but one may fail without rendering the system inoperative. This is particularly desirable in control systems for gas turbine engines, since reliability is essential under operating conditions so severe that the possibility of mechanical failures during service must be anticipated.

The two distinct types of networks currently in use on turbojet engines are the common-terminal and the ladder-type systems.

11.1 Common-Terminal Systems

In this arrangement, all thermocouples are connected directly to a pair of terminals at which the network signal is measured, as shown schematically in Figure 17.

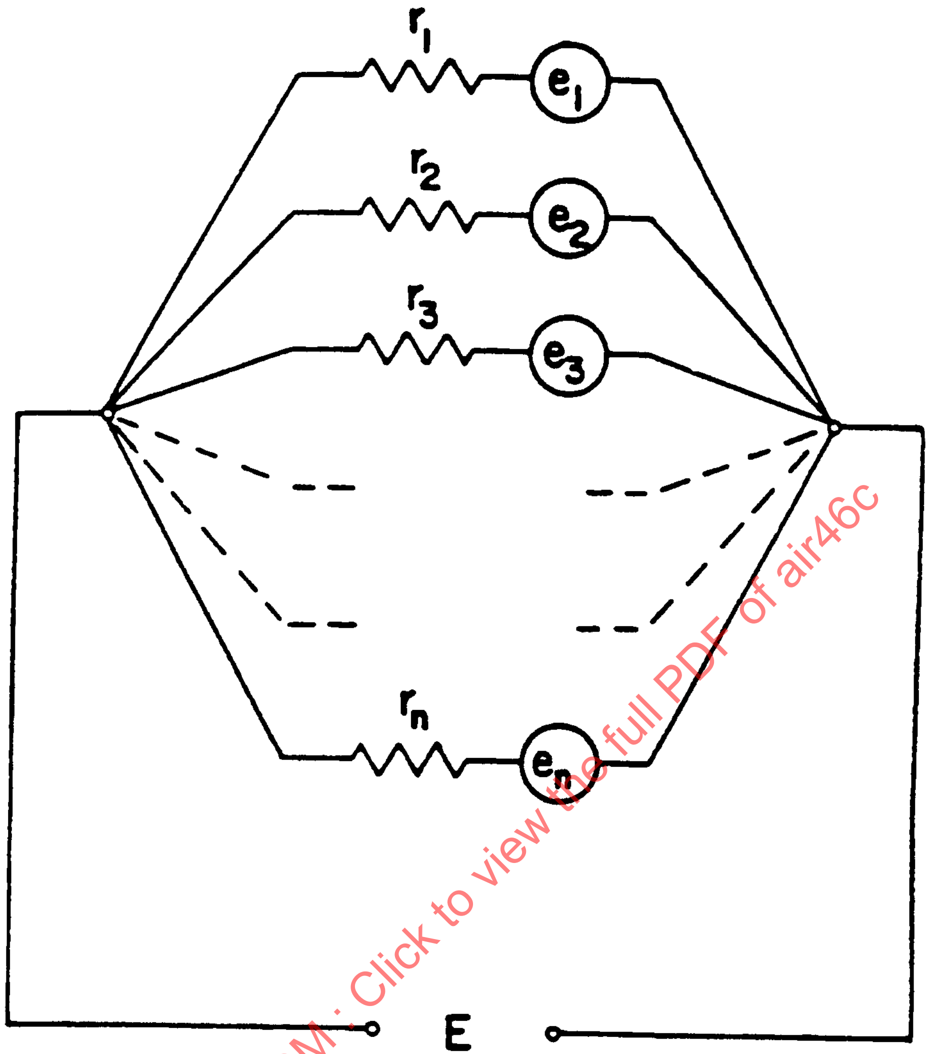

Figure 17 - Common-terminal system

By employing Kirchhoff's laws, Equation 21 can be to determine the EMF of such a network.

$$E = \frac{e_1(r_2 r_3 \ldots r_n) + e_2(r_1 r_3 r_4 \ldots r_n) + - - + e_n(r_1 r_2 \ldots r_{n-1})}{r_2 r_3 \ldots r_n + r_1 r_3 r_4 \ldots r_n + r_1 r_2 \ldots r_{n-1}} \quad \text{(Eq. 21)}$$

Where E is the output of the network and e_1, e_2 ... e_n and r_1, r_2, ... r_n are the EMFs and resistances, respectively, of the individual thermocouples. From Equation 21, it is apparent that if all the r_n are equal, then Equation 21 reduces to Equation 22.

$$E = \frac{e_1 + e_2 + e_3 + - - - + e_n}{n} \quad \text{(Eq. 22)}$$

Thus, when the resistances of all branches between the common terminals are equal, the network will indicate the true arithmetic average of the EMFs of the individual thermocouples.

If the resistances of the thermocouples are not equal, a weighted average EMF will be indicated. The relative weights of the individual thermocouple EMFs are then inversely proportional to the resistances of the thermocouples. For example, consider a four-junction network in which $r_1 = 1.0$, $r_2 = 1.1$, $r_3 = 1.2$, and $r_4 = 1.3$. The output of the network will be as shown in Equation 23.

$$E = \frac{e_1 + \frac{e_2}{1.1} + \frac{e_3}{1.2} + \frac{e_4}{1.3}}{1 + \frac{1}{1.1} + \frac{1}{1.2} + \frac{1}{1.3}} \quad \text{(Eq. 23)}$$

In engine thermocouple networks employing the common-terminal system, the thermocouple resistances are generally made equal by adjusting the physical dimensions (wire length or diameter), or by inserting resistances in the individual thermocouple circuits. Should any of the thermocouples become open circuited, the network will continue to indicate the true average EMF of those which continue to function.

The practical difficulty of running lead wires from a pair of common terminals to each of many thermocouples distributed over the periphery of a gas turbine engine is obvious. Thus, difficulties of constructing a harness having multiple leads may outweigh the disadvantages inherent in circuits which require only a single pair of leads, as is the case of ladder-type systems described below.

11.2 Ladder-Type Systems

The inherent simplicity of using a single pair of leads to which individual thermocouples are attached at intervals along the leads has led to the ladder-type network shown schematically in Figure 18.

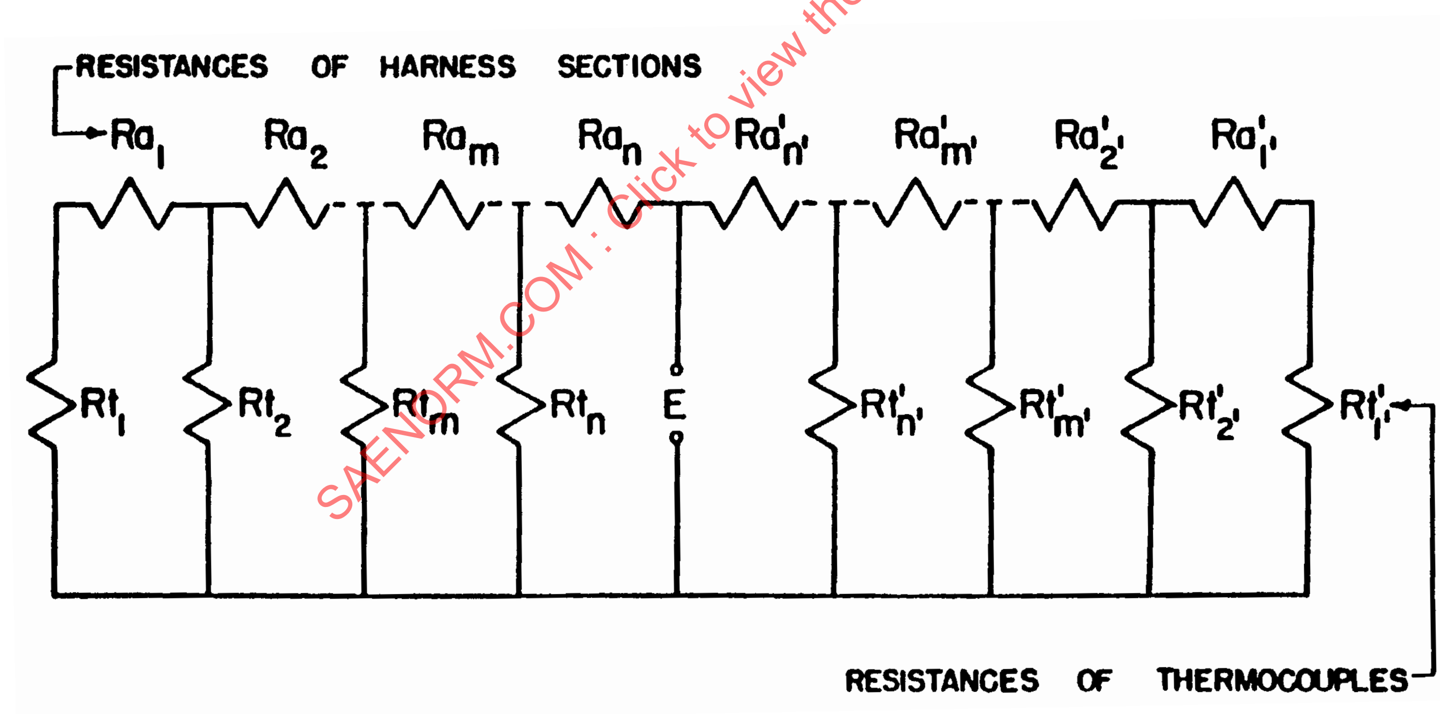

Figure 18 - Ladder-type system

The electrical characteristics of this system are such that only when the resistances between the branch points are zero and when all thermocouple resistances are equal do the individual junctions exert equal weight on the net EMF. If the thermocouple resistances and those between the branch points are all equal, the two junctions adjacent to the measuring terminals have the most weight, and their relative weight increases with the number of junctions. The greater the resistance of the thermocouples as compared with the resistance between branch points, the more closely will the EMF of the network approach the average of the individual EMFs. The EMF of a ladder-type network depends upon the relative position of the measuring terminals with respect to the junctions and of the junctions with respect to the temperature gradients, even if the average of the temperatures of the individual junctions is always identical with the average gas temperature. It is advantageous, in ladder-type networks, to keep the resistances between branch points small compared with the resistances of the individual thermocouples.

Because so many factors influence the weight which an individual junction may exert on the net EMF, the solution to the general equations applicable to such networks becomes very laborious. Analysing specific cases in which certain simplifying conditions are assumed often results in expressions that are more readily solved. This method has been followed in the detailed analysis of ladder-type systems given in Dahl and Fiock (1952).

Varying the resistances of the individual thermocouples in a ladder-type system results in a means to weight the output of each according to its distance from the measuring terminals and thus give equal weight to each. More specifically, let:

n = number of junctions to the left of the measuring terminals

n' = number of junctions to the right of the measuring terminals

Ra_m = resistance of any harness section to the left of the measuring terminals

$Ra'_{m'}$ = resistance of any harness section to the right of the measuring terminals

Rt_m = resistance of any thermocouple to the left of the measuring terminals

$Rt'_{m'}$ = resistance of any thermocouple to the right of the measuring terminals

If the junctions are to have equal weights, the relations shown in Equations 24, 25, and 26 must exist among the thermocouple and harness-section resistances:

$$Rt_m = Rt_{(m-1)} + (m-1)Ra_{(m-1)} \quad \text{(Eq. 24)}$$

$$Rt'_{m'} = Rt'_{(m'-1)} + (m'-1)Ra'_{(m'-1)} \quad \text{(Eq. 25)}$$

$$\frac{Rt_n}{nn'}\frac{Ra_n}{n'} = \frac{Rt'_{n'}}{nn'} + \frac{Ra'_{n'}}{n} \quad \text{(Eq. 26)}$$

The above equations may be applied as follows:

Decide on the number of thermocouples, their spacing, and the location of the lead wires. Based on wire diameter and length, assign values to all harness-section resistances except Ra_n and $Ra'_{n'}$. Depending upon whether it is desirable to assign a value to the sum ($Ra_n + Ra'_{n'}$), or to the individual resistances Ra_n and $Ra'_{n'}$, two cases may be recognized, namely:

a. Assign a value to the sum ($Ra_n + Ra'_{n'}$).

   1. Assume values of Rt_1 and Rt'_1.

   2. Working from the outside in, calculate the resistances of the other thermocouples and Ra_n and $Ra'_{n'}$, using Equations 24, 25, and 26.

b. Assign values to Ra_n and $Ra'_{n'}$.

1. Letting Rt_m be used on the side of the network having the most thermocouples and $Rt'_{m'}$ be used on the side having the lesser number of thermocouples, assign a value to Rt_1.

2. Determine all values on the side of Rt_1.

3. Determine the value of $\frac{Rt_n}{nn'} + \frac{Ra_n}{n'}$.

4. Calculate $Rt'_{n'}$, using Equation 26.

5. Calculate $Rt'_{(n'-1)}$, $Rt'_{(n'-2)}$, etc., down to Rt'_1, using Equation 25.

Although this method for correcting the averaging characteristics of a ladder-type thermocouple and harness system can give accurate averaging for any value of the ratio of thermocouple resistance to harness-section resistance so long as all the thermocouples are functioning, it is still advantageous to keep this ratio high for the sake of the accuracy of the averaging process when one or more of the couples have failed.

Mathematical computation of the circuitry errors of parallel-thermocouple networks is cumbersome, and use of an electrical analog for this purpose is often convenient.

11.3 Electrical Analogue for Parallel-Thermocouple Networks

A schematic diagram of such an analogue is shown in Figure 19.

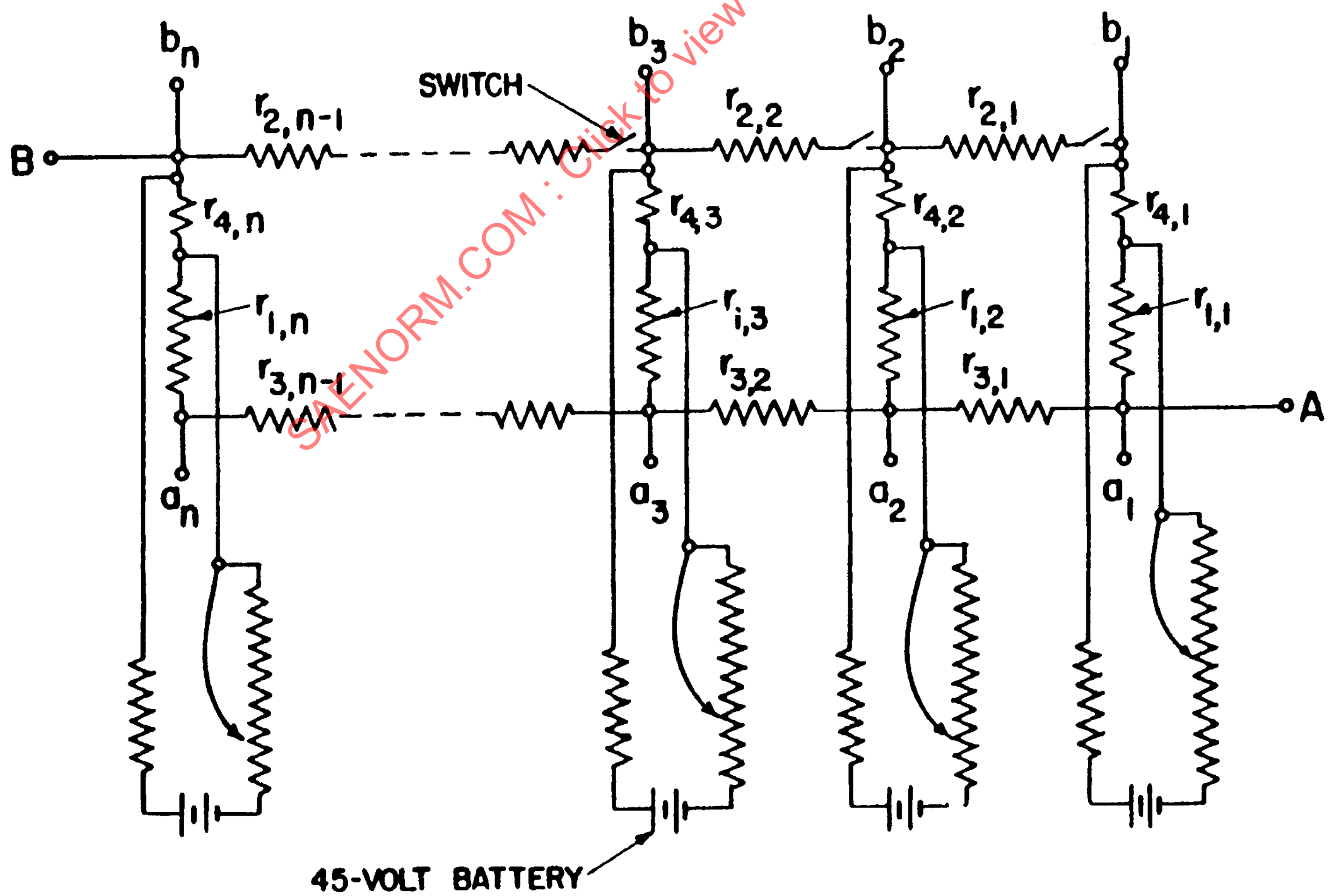

Figure 19 - Schematic of analog for parallel networks