THERMAL-ELECTRICAL PROPERTIES. In an earlier section, we have seen that a temperature rise takes place in current carrying members. The ease with which heat can be dispersed through a material is determined by its *thermal conductivity*. A contact pair of dissimillar metals can also act as a thermocouple under certain conditions and produce a self-generated voltage at elevated temperatures. Thus *thermal emf* (thermocouple effect) and thermal conductivity are properties that should be known and understood. Other important properties are *resistivity* and temperature *coefficient* of *resistance*.

Resistivity. The term resistivity has already been introduced, but is included here in more detail because of the importance of this material property. It can be defined as the property of a material that impedes electrical current when a sample of specified unit dimensions is considered.

$$\rho = \frac{RA}{l} \qquad \text{Eq. 2.1}$$

where ρ = resistivity
A = cross-sectional area
l = length
R = resistance

In the metric system, the units would be :

$$\rho = \frac{RA}{l} \, \frac{(\text{ohm})\,(\text{cm})^2}{(\text{cm})} = \frac{RA}{l} \text{ ohm cm}$$

This is conventionally used for insulators while for conductors the units are normally expressed as microhm cm.

The units used in this country introduce a term circular mil. This is defined as the cross-sectional area of a wire one mil (0.001”) in diameter and is given the abbreviation cir. mil.

$$1 \text{ cir. mil} = \frac{\pi}{4}(0.001)^2 = \frac{\pi}{4} \times 10^{-6} \text{ sq. in.}$$

With this system, the resistivity is defined as the resistance of a round wire one cir. mil in area (one mil in diameter) and one foot long.

$$\rho = \frac{RA'}{l} \, \frac{\text{ohm cir. mil}}{\text{ft.}}$$

By the definition, A' (cir. mil) = d^2 where d is the diameter of the wire expressed in mils.

$$\rho = \frac{Rd^2}{l} \frac{\text{ohm cir. mil}}{\text{ft.}}$$

In practice the situation is usually such that the resistivity is known (from handbook or catalog data), the dimensions are known and the resistance must be determined. In this case we use

$$R = \rho \frac{l}{A} \qquad \text{Eq. 2.2}$$

where if ρ is expressed in ohm cir. mil/ft, l is the length of the specimen in feet and A would equal the cross-sectional area in circular mils. The resultant **R** is, of course, in ohms. In the metric system if ρ is given in microhm-cm, l in cm and **A** in cm^2, the **R** will be in microhms.

It is often necessary to determine the resistance of rectangular conductors. By realizing that Area (cir. mils) = d^2 and that this same area in "square mils" is $\pi d^2/4$, the calculation is readily made. As an example, suppose we wish to calculate the resistance of a Neyoro® G (age hardened) blade that is .005" X .100" X 1.0" long.

$$R = \rho \frac{l}{A} = 87 \frac{\text{ohm-cir. mil}}{\text{ft}} \times 1 \text{ inch} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \frac{1}{5 \times 100 \text{ sq. mils}} \times \frac{1 \text{ sq. mil}}{\frac{4}{\pi} \text{ cir mil}} = .0114 \text{ ohms}$$

Table II-14 shows the conversions to and from the two systems of units.

TO CONVERT FROM	TO	MULTIPLY BY
ohm-cir. mil/ft	microhm-cm	0.1662
ohm-cir. mil/ft	ohm-cm	0.1662×10^{-6}
microhm-cm	ohm-cir. mil/ft	6.015
ohm-cm	ohm-cir. mil/ft	6.015×10^{6}

Table II-14.

Occasionally, instead of resistivity being given in a handbook, the percent conductivity relative to IACS (International Annealed Copper Standard) is stated. IACS is the internationally accepted value for the resistivity of an annealed copper standard at 20°C. Its value is 10.371 ohm cir. mil/ft. Thus, to determine a material's resistivity (in ohm-cir. mil-ft) when % conductivity is given, we merely divide 10.371 by the stated percent expressed as a decimal.

Temperature Coefficient of Resistance. As temperature is increased in metals, the increased thermal agitation tends to decrease the mobility of the free electrons, resulting in an increase in resistivity. This is another way of saying that metal usually have a positive temperature coefficient of resistance. Within a few degrees above or below room temperature (20°C) this change in resistance is ordinarily considered as negligible. However, when temperature differs widely from the reference temperature at which resistivity was determined (usually 20°C), a correction for temperature is necessary. The resistance (R_T) at the given temperature is

$$R_T = R_o [1 + \alpha(T - T_o)] \qquad \text{Eq. 2.3}$$

where R_o = resistance at reference temperature T_o, ohms
α = temperature coefficient of resistance, ohms/ohm-°C
T = temperature at which R_T is to be determined, °C
T_o = reference temperature at which R_o was determined, °C

Values of temperature coefficient of resistance for Neyoro® G and Paliney® 7 for use in Equation 2.3 are given in the tables in section 3.3.1.

Thermal Conductivity. The ease with which heat energy is conducted through a material is measured by its *thermal conductivity*. The thermal conduction process in metals is carried on by free electrons and lattice vibrations. The free electrons are the same ones that determine electrical resistivity so it is not surprising that resistivity and thermal conductivity are related, specifically by the Wiedemann-Franz-Lorenz law. Based on this, R. Holm has suggested that for temperatures above room temperature an approximation of the thermal conductivity (k) can be obtained from

$$k = \frac{7.1 \times 10^{-6}}{\rho} + 0.1 \qquad \text{Eq. 2.4}$$

where ρ = resistivity at 20°C, ohm cm
k = thermal conductivity, watts/cm °C

The second term is an approximation of the average contribution of the lattice. When the units are changed to the more customary calorie cm/cm^2 °C sec (which reduces to calorie/cm °C sec), the calculated results are as shown in Table ll-15.

Alloy	Alloy Condition	Thermal Conductivity (Calculated) Cal/cm °C sec
Paliney® 6	Annealed	0.08
	Age Hardened	0.09
Paliney 7	Annealed	0.07
	Stress Relieved	0.07
	Ductile HT	0.08
	Age Hardened	0.08
Paliney 8	Annealed	0.08
	Age Hardened	0.09
Paliney M	Annealed	0.07
Neyoro® G	Annealed	0.10
	Stress Relieved	0.10
	Age Hardened from Annealed	0.14
	Age Hardened from Cold Worked	0.14
Neyoro 28	Cold Worked	0.19
Neyoro 28A	Cold Worked	0.16
Neyoro 28B	Annealed	0.16
	Cold Worked	0.16
Neyoro 69	Annealed	0.13
	Cold Worked	0.13

Table II-15. Thermal Conductivity Calculated from Eq. 2.4

Thermal EMF. Every material possesses a characteristic energy state determined by its composition, working history, and temperature. When two different materials are in contact, the difference in energy causes a voltage which tends to make the energy states equal. However, the voltage is extremely small when the materials are at the same tempera-ture and is negligible. If, however, *two* junctions are used with one of them at a temperature higher than the other as in Fig. 2-39, there can be an appreciable voltage created. This is called the *thermal electromotive force* (emf) and is the basis for thermocouples.

A typical thermocouple consists of two lengths of one material and a length of a second material connected to the ends of the first. The leads are connected to a potentiometer or some other voltage measuring device. One junction is held at a known temperature, frequently by immersion in an ice-water mixture. The other junction is subjected to the temperature to be measured. The induced voltage is read and, by means of a conversion chart or factor, the difference between the two temperatures is found. The temperature of the unknown will be the algebraic sum of the temperature difference plus the reference temperature.

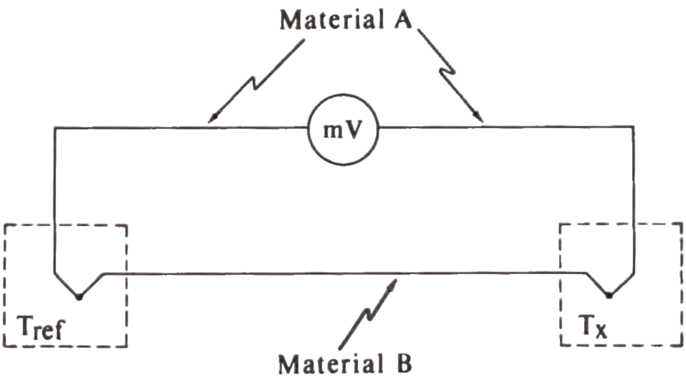

Fig. 2-39. A classical thermocouple circuit.

The most desirable characteristic for thermocouples is a large and constant voltage per degree temperature. With the majority of materials, the voltage per degree is not constant but is a function of temperature. For accurate temperature measurements, tables converting millivolts to temperature are used.

In electrical contact circuitry, it may be necessary to know the approximate voltage that is generated by temperature differences at two metallic junctions. For this purpose tables of voltage produced per °C, with respect to a standard material (platinum or copper) are used. The table values are averages over the temperature range specified. Extrapolation beyond the specified temperature range is quite common.

The need for two junctions at different temperatures deserves emphasis. Without two junctions a termocouple cannot exsist. For example, consider a contact system as shown in Fig. 2-40(a). Contact alloys A and B are attached to a leaf spring member which has a thermal emf characteristic identical with the lead wire. Assume that the space within the dotted lines is all at temperature T_1 and everywhere outside this space the temperature is constant at T_2. Under these conditions no thermal voltage will be seen at the terminals. There is no second junction of Alloys A and B.

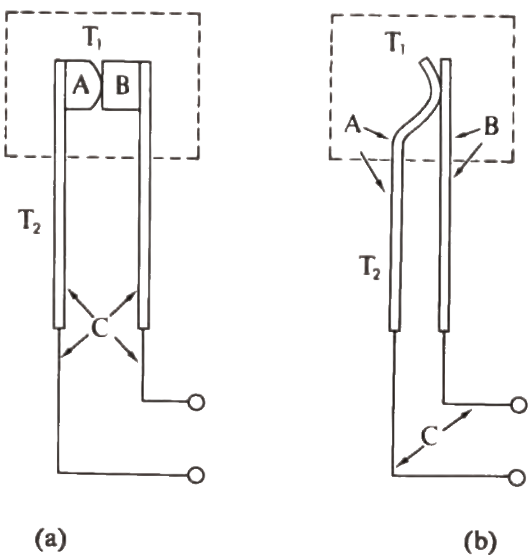

Fig. 2-40. (a) A circuit that will not produce a thermal emf.
(b) An arrangement that will produce a thermal emf.

By contrast, the arrangement shown in Fig. 2-40(b) will produce a thermoelectric voltage at the terminals as it contains an effective second junction of alloys A and B at temperature T_2. Note that the presence of the lead wires does not have any effect on the thermal voltage in the two cases shown, since all the lead junctions are at the same temperature, T_2.

Table II-16 gives the thermal emf of various common materials with respect to platinum. To find the thermal emf between two materials neither of which is platinum, algerbracially subtract the figures given. For Instance, the thermal emf of Paliney®7 annealed to Neyoro®G heat treat would be (-10) - (+4) = -14 μvolts/°C. If the temperature difference between the hot junction and the cold junction were 100°C, the voltage would be 1400 μvolts or .0014 volts

Material	Thermal emf (Microvolts/°C)
Nickel-Chromium, 90/10 and 84/16	+30
Nichrome (58.5 Ni, 22.5 Fe, 16 Cr, 3 Mn)	+25
Platinum Iridium, 85/15	+19
Platinum Iridium, 90/10	+18
Sigmund Cohn #479	+14
Sigmund Cohn #851	+12
Evanohm	+ 9
Copper, pure, work hardened	+ 8
Gold	+ 8
Silver, annealed	+ 8
Rhodium	+ 7
Neydium® 90 (coin silver, work hardened	+ 7
Beryllium Copper 1/4 hard	+ 6
Beryllium Copper Age Hardened from the annealed condition	+ 6
Manganin	+ 6
Beryllium Copper 1/2 hard	+ 5
Phosphor bronze, composition A, 1/2 hard and spring temper	+ 5
Neyoro® G, age hardened	+ 4
Neyoro G, stress relieved	+ 4
Neyoro 28, work hardened	+ 4
Sigmund Cohn #LTC	+ 4
Neyoro G, annealed	+ 3
Neyoro 69, work hardened	+ 3
Platinum	0
Neyoro 28A, work hardened	− 3
Neyoro 28B, work hardened	− 4
Palladium	− 5
Paliney® 7, age hardened	− 8
Paliney 7, ductile HT	− 8
Paliney 7, annealed	−10
Nickel "Silver" 18% (i.e., Nickel Brass) spring temper	−13
Nickel	−15
Paliney 6, annealed	−18
Paliney 6, age hardened	−23
Paliney M, work hardened	−24
Constantan	−38

Table II-16. Thermal emf of Various Materials with Respect to Platinum (0–100°C)