THERMOCOUPLE TECHNICAL DATA

THERMOELECTRICITY IN RETROSPECT

The principles and theory associated with thermoelectric effects were not established by any one person at any one time. The discovery of the thermoelectric behavior of certain materials is generally attributed to T. J. Seebeck.

In 1821, Seebeck discovered that in a closed circuit made up of wire of two dissimilar metals, electric current will flow if the temperature of one junction is elevated above that of the other. Seebeck's original discovery used a thermocouple circuit made up of antimony and copper. Based on most common usage and recognition today, there are eight thermoelement types: S,R,B,J,K,N,T and E.

In the ensuing years following the discovery of the thermoelectric circuit, many combinations of thermoelectric elements were investigated. Serious application of the findings was accelerated by the needs brought on during the course of the Industrial Revolution.

In 1886, Le Chatelier introduced a thermocouple consisting of one wire of platinum and the other of 90 percent platinum- 10 percent rhodium. This combination, Type S, is still used for purposes of calibration and comparison. It defined the International Practical Temperature Scale of 1968 from the antimony to the gold point. This type of thermocouple was made and sold by W. C. Heraeus, GmbH of Hanau, Germany, and is sometimes called the Heraeus Couple.

Later, it was learned that a thermoelement composed of 87 percent platinum and 13 percent rhodium, Type R, would give a somewhat higher EMF output.

In 1954 a thermocouple was introduced in Germany whose positive leg was an alloy of platinum and 30 percent rhodium. Its negative leg was also an alloy of platinum and 6 percent rhodium. This combination, Type B, gives greater physical strength, greater stability, and can withstand higher temperatures than Types R and S.

The economics of industrial processes prompted a search for less costly metals for use in thermocouples. Iron and nickel were useful and inexpensive. Pure nickel, however, became very brittle upon oxidation; and it was learned that an alloy of about 60 percent copper,40 percent nickel (constantan) would eliminate this problem. This alloy combination, iron-constantan, is widely used and is designated Type J. The present calibration for Type J was established by the National Bureau of Standards, now known as the National Institute of Standards and Technology (N.I.S.T.).

The need for higher temperature measurements led to the development of a 90 percent nickel-10 percent chromium alloy as a positive wire, and a 95 percent nickel-5 percent aluminum, manganese, silicon alloy as a negative wire. This combination (originally called Chromel- Alumel) is known as Type K.

Conversely the need for sub-zero temperature measurements contributed to the selection of copper as a positive wire and constantan as a negative wire in the Type T thermoelement pair. The EMF-temperature relationship for this pair (referred to as the Adams Table) was prepared by the National Bureau of Standards in 1938. The relatively recent combination of a positive thermoelement from the Type K pair and a negative thermoelement from the type T pair is designated as a Type E thermoelement pair. This pair is useful where higher EMF output is required.

Within the past 20 years, considerable effort has been made to advance the state of the art in temperature measurement. Many new thermoelement materials have been introduced for higher temperatures.

Combinations of tungsten, rhenium and their binary alloys are widely used at higher temperatures in reducing and inert atmospheres or vacuum.

The most common thermoelement pairs are:

W-W26Re	(Tungsten Vs. Tungsten 26% Rhenium)
W3Re-W25Re	(Tungsten 3% Rhenium Vs. Tungsten 25% Rhenium)
W5Re-W26Re	(Tungsten 5% Rhenium Vs. Tungsten 26% Rhenium)

Letter designations have not yet been assigned to these combinations.

The most recent significant development in thermometry was the adoption of the International Temperature Scale of 1990 (ITS-90). The work of international representatives was adopted by the International Committee of Weights and Measures at its meeting September 1989, and is described in "The International Temperature Scale of 1990,"Metrologia 27, No. 1, 3-10 (1990); Metrologia 27,107 (1990).

LAWS OF THERMOELECTRIC CIRCUITS

Numerous investigations of thermoelectric circuits in which accurate measurements were made of the current, resistance, and electromotive force have resulted in the establishment of several basic laws.

Although stated in many different ways, these precepts can be reduced to three fundamental laws:

1. The law of the Homogeneous Circuit
2. The law of Intermediate Materials
3. The law of Successive or Intermediate Temperatures

Law of Homogeneous Circuit

A thermoelectric current cannot be sustained in a circuit of a single homogeneous material, however, varying in cross section, by the application of heat alone.

Two different materials are required for any thermocouple circuit.

Any current detected in a single wire circuit when the wire is heated in any way whatever is taken as evidence that the wire in inhomogeneous.

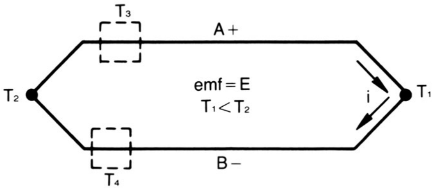

Figure 1. Law of Homogeneous Circuit.

A consequence of this law as illustrated in figure 1, is that if one junction of two dissimilar homogeneous materials is maintained at a temperature T. and the other junction at a temperature T_2, the thermal EMF developed is independent of the temperature distribution along the circuit. The EMF, E, is unaffected by temperatures T_3 and T_4.

Law of Intermediate Materials.

The algebraic sum of the thermoelectromotive forces in a circuit composed of any number of dissimilar materials is zero if all of the circuit is at a uniform temperature.

A consequence of this law is that a third homogeneous material can be added in a circuit with no effect on the net EMF of the circuit so long as its extremities are at the same temperature.

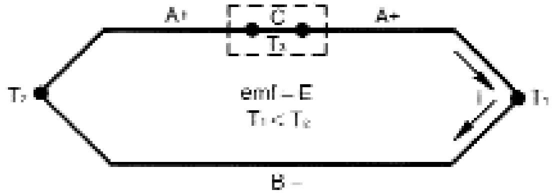

Figure 2. Law of Intermediate Materials.

In figure 2, two homogeneous metals, A and B, with their junctions at temperatures T, and T2 a third metal C, is introduced by cutting A, and forming two junctions of A and C. If the temperature of C is uniform over its whole length, the total EMF in the circuit will be unaffected.

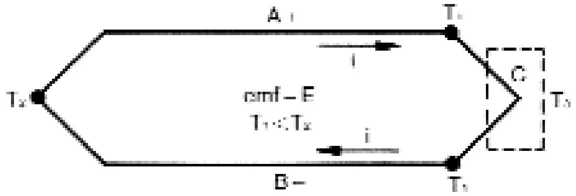

Figure 3. Combining the Law of Intermediate Materials With the Law of Homogeneous Circuit.

Combining the Law of Intermediate Materials with the Law of Homogeneous Circuit, as shown in figure 3, A and B are separated at the temperature T. junction. Two junctions AC and CB are formed at temperature T_1. While C may extend into a region of very different temperature, for example, T_3 the EMF of the circuit will be unchanged. That is, $E_{AC} + E_{CB} = E_{AB}$.

A further consequence to the combined laws of Intermediate Materials and Homogeneous Circuit is illustrated in figure 4.

When the thermal EMF of any material A or B paired with a reference material C is known, then the EMF of any combination of these materials, when paired, is the algebraic sum of their EMF's when paired with reference material C.

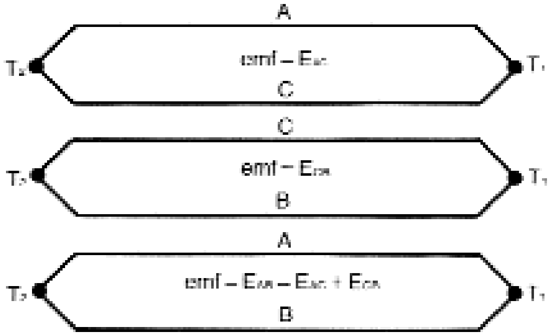

Figure 4. Thermal EMF of two materials with respect to a reference material.

Law of Successive or Intermediate Temperatures

If two dissimilar homogeneous metals produce a thermal EMF of E., when the junctions are at temperatures T_1 and T_2, and a thermal EMF of E_2, when the junctions are at T_2 and T_3, the EMF generated when the junc- tions are at T_1 and T_3, will be $E_1 + E_2$.

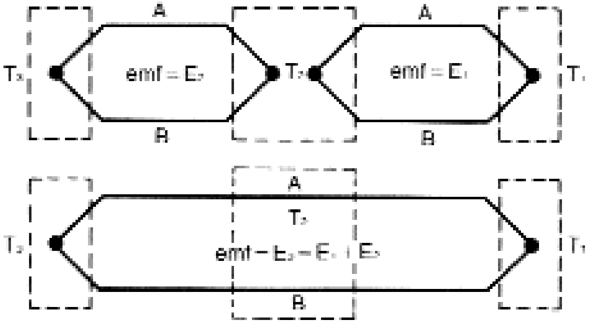

Figure 5. Law of Successive or Intermediate Temperatures.

One consequence of this law permits a thermocouple calibrated at a given reference temperature, to be used at any other reference temperature through the use of a suitable correction.

Another consequence of this law is that extension wires, having the same thermoelectric characteristics as those of the thermocouple wires, can be introduced in the ther-mocouple circuit (say from region T_2 and region T_3) without affecting the net EMF of the thermocouple.

CONCLUSION

The three fundamental laws may be combined and stated as follows: “The algebraic sum of the thermoelectric EMFs generated in any given circuit containing any number of dissimilar homogeneous materials is a function only of the temperatures of the junctions.” Corollary: “If all but one of the junctions in such a circuit are maintained at some reference temperature, the EMF generated depends only on the temperature of that one junction and can be used as a measure of its temperature.”

THERMOELECTRIC EFFECTS

Seebeck Effect

The Seebeck effect, figure 6, concerns the conversion of thermal energy into electrical energy. The Seebeck voltage refers to the net thermal electromotive force established in a thermoelement pair under zero current conditions.

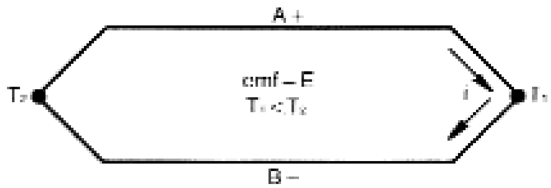

Figure 6. Seebeck Thermal EMF.

When a circuit is formed consisting of two dissimilar conductors A and B, and one junction of A and B is at temperature T_1 while the other junction is at a higher temperature T_2, a current will flow in the circuit. The electromotive force E producing this current i, is called the Seebeck thermal EMF.

Conductor A is considered thermoelectrically positive to conductor B if the current i flows from conductor A to conductor B at the cooler of the two junctions (T_1).

Peltier Thermal Effect.

The Peltier Thermal Effect, figure 7, concerns a reversible phenomenon at the junction of most thermoelement pairs.

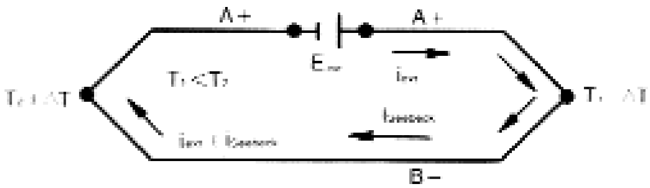

Figure 7. Peltier Thermal Effect.

When an electrical current i_{ext} flows across the junction of a thermoelement pair, heat is absorbed or liberated. The direction of current flow at a particular junction determines whether heat is absorbed or liberated.

If an external current i_{ext} flows in the same direction as the current $i_{Seebeck}$ produced by the Seebeck Effect at the hotter junction of a thermoelement pair, heat is absorbed. Heat is liberated at the other junction.

The Thomson Effect

The Thomson Effect concerns the reversible evolution, or absorption, of heat occurring whenever an electric current traverses a single homogeneous conductor, across which a temperature gradient is maintained, regardless of external introduction of the current or its induction by the thermocouple itself.

The Thomson voltage alone cannot sustain a current in a single homogeneous conductor forming a closed circuit, since equal and opposite EMFs will be set up on the two paths from heated to cooled parts of the circuit.

THERMOELECTRIC CIRCUITS

Series Circuit

A number of similar thermocouples all having thermoelements A and B may be connected in series with all of their measuring junctions at T_2 and their reference junctions at T_1. Such a series, called a thermopile, is shown in figure 8. With 3 thermocouples in series develops an EMF 3 times as great as a single thermocouple is developed.

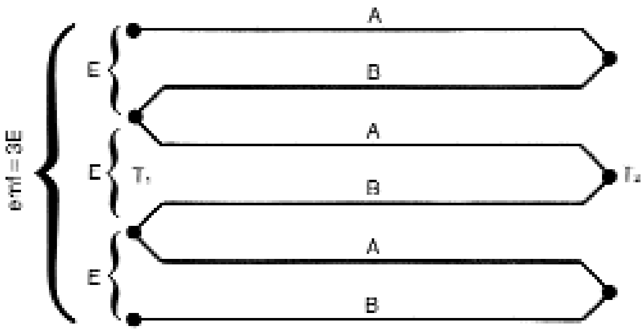

Figure 8. A thermopile of three thermocouples.

Parallel Circuit

If a quantity "N" of thermocouples of equal resistance is connected in parallel with junctions at T_1 and T_2 the EMF developed is the same as for a single thermocouple with its junctions at T_1 and T_2.

If all of the thermocouples are of equal resistance but their measuring junctions are at various temperatures T_2, T_3... T_{n+1}, see figure 9, then the EMF developed will correspond to the mean of the temperatures of the individual measuring junctions.

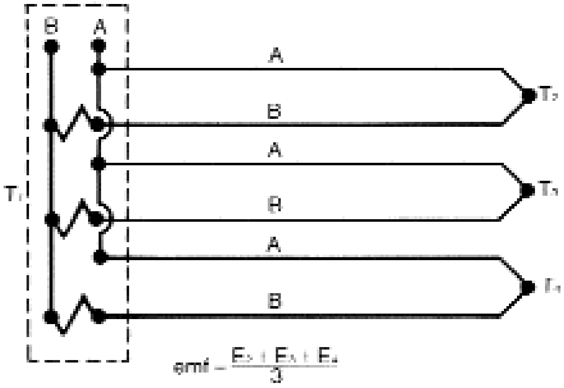

Figure 9. A parallel circuit for mean temperatures.

It is not necessary to adjust the thermocouple resistances when measuring these average temperatures. Instead, swamping resistors may be used. For example, if the thermocouples range in resistance from 5 to 10 ohms, a 500 ohm (±1%) resistor is connected in series with each, and the error in EMF introduced by the inequality in thermocouple resistance becomes an insignificant fraction of the total resistance.

Basic Thermocouple Circuit

Two continuous, dissimilar thermocouple wires extending from the measuring junction to the reference junction, when used together with copper connecting wires and a potentiometer, connected as shown in figure 10, below, make up the basic thermocouple circuit for temperature measurement.

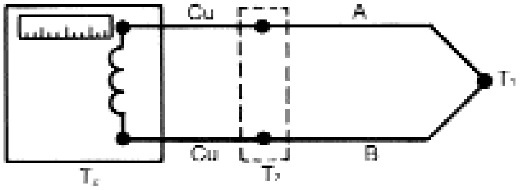

Figure 10. Basic thermocouple circuit

Differential Thermocouple Circuit

Junctions 1 and 2 are each at different temperatures. The temperature measured by the circuit shown in figure 11 is the difference between T_1 and T_2.

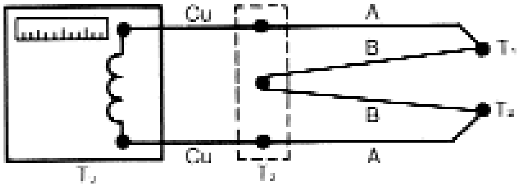

Figure 11. Differential thermocouple circuit

Typical Industrial Thermocouple Circuit

The usual thermocouple circuit includes: measuring junctions, thermocouple extension wires, reference junctions, copper connecting wires, a selector switch, and poten-tiometer. Many different circuit arrangements of the above components are acceptable, depending on given circumstances.

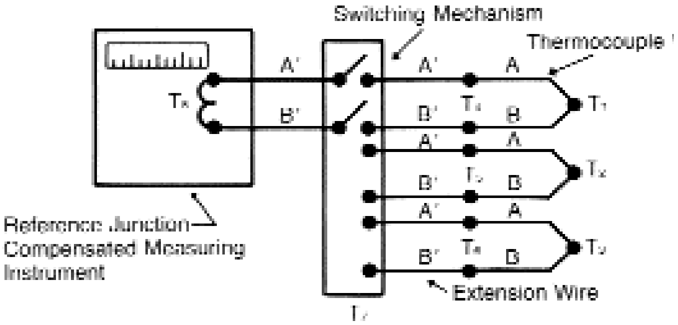

Figure 12. Typical industrial thermocouple circuit