THERMOCOUPLES

Thermocouples are relatively inexpensive devices used to measure temperatures for a wide variety of applications, ranging from furnace control to equipment calibration. They can be made to fit just about any application. Unlike many temperature-measuring devices, the thermocouple is not subject to self-heating problems. A thermocouple is based on the finding of Seebeck, who showed that a small electric current will flow in a circuit composed of two dissimilar conductors when their junctions are kept at different temperatures (1). When one junction is hotter than the other, an electromotive force (emf) is produced that is proportional to the difference in temperature between the measuring junction (hot junction) and the reference junction (cold junction). This condition is known as the Seebeck emf, and the output is measured in millivolts. The pair of conductors that constitute the thermoelectric circuit is called a thermocouple. Thermocouples are the most widely used method of measuring internal temperatures in solid bodies. There are many different types of thermocouples that measure temperature over a range as low as −190°C and as high as 2000°C (2).

The measurement of temperature is thought to be a simple process, but this is a popular misconception. There is a need for controlled, reliable, and reproducible temperature-sensing devices for science, engineering, and industry. There are seven types of instruments used to measure temperature: thermocouple thermometers, radiation pyrometers, resistance thermometers, liquid-in-gas thermometers, filled-system thermometers, optical pyrometers, and bimetal thermometers, and they all have advantages and disadvantages (3). The thermocouple is by far the most widely used device for temperature measurement because of its favorable characteristics that include good accuracy, coverage of a wide range of temperatures, fast thermal response, durability, high reliability, low cost, and versatility. This article concentrates only on the history, theory, junctions, calibration, and applications of thermocouples.

HISTORY OF THERMOCOUPLES

One person did not establish the principles or theory underlying thermoelectric effects. It was established by several scientists working over a span of many years beginning with Alessandro Volta, who concluded in 1800 that the electricity which caused Galvani's frog to twitch was due to a contact of two dissimilar metals (3). This conclusion was the forerunner of the principle of the thermocouple. Others who built on this base were Thomas Johann Seebeck (1821), Jean Charles Althanase Peltier (1834), and William Thomson—later Lord Kelvin (1848–1854). During this same period, Jean Baptiste Joseph Fourier published his basic heat-conduction equation (1821), Georg Simon Ohm discovered his equation for electric conduction (1826), James Prescott Joule found the principle of the first law of thermodynamics and the important I^2R heating effect (1840–1848), and Rudolf Julius Emanuel Clausius announced the principle of the second law of thermodynamics and introduced the concept of entropy (1850) (4,5).

Seebeck Effect

Thomas Johann Seebeck discovered the existence of thermoelectric currents while observing electromagnetic effects associated with bismuth–copper and bismuth–antimony circuits (4,5). His experiments showed that when the junctions of two dissimilar metals forming a closed circuit are exposed to different temperatures, a net thermal emf is generated which induces a continuous current. Measurements of the Seebeck effect can be made in terms of either the closed-circuit current or the open-circuit current. The Seebeck effect concerns the net conversion of thermal energy into electric energy with the appearance of an electric current. The Seebeck voltage refers to the net thermal electromotive force set up in a thermocouple under zero-current conditions. The direction and magnitude of the Seebeck voltage E_S, where E represents the thermoelectric emf, depends upon the temperature of the junctions and upon the materials making up the thermocouple. For a particular combination of materials A and B and for a small temperature difference dT, we obtain

$$dE_S = \alpha_{A,B}\, dT \tag{1}$$

where $\alpha_{A,B}$ is a coefficient of proportionality called the Seebeck coefficient and is also commonly called the thermoelectric power (1). The Seebeck coefficient is obtained in one of two ways:

1. As an algebraic sum ($\alpha_{A,B}$) of relative Seebeck coefficients (α_{AR}) and (α_{BR}), where for a given temperature difference and at given temperature levels, emfs of each of the substances, A and B, making up the thermocouple are obtained with respect to an arbitrary reference material, R.
2. By numerically differentiating tabulated values of E_S versus T for a given reference temperature, T_R, according to the relation

$$E_S = \int_{T_R}^{T} \alpha_{A,B}\, dT \tag{2}$$

In either case, The Seebeck coefficient represents the net change in thermal emf caused by a unit temperature difference as in

$$\alpha_{A,B} = \operatorname*{limit}_{\Delta T \to 0} \frac{\Delta E_S}{\Delta T} = \frac{dE_S}{dT} \tag{3}$$

If $E = aT + 0.5bT^2$ is determined by calibration, then $\alpha = a + bT$.

The Seebeck coefficient is a function of temperature level only based on the validity of the experimental relation

$$E_S = \int_{T_2}^{T} \alpha\, dT = \int_{T_1}^{T} \alpha\, dT - \int_{T_2}^{T_1} \alpha\, dT \tag{4}$$

where $T_1 < T_2 < T$. It follows that α is entirely independent of the reference temperature employed.

Peltier Effect

Jean Charles Althanase Peltier (1834) discovered interesting thermal effects when he introduced a small, external electric current in Seebeck's bismuth–antimony thermocouple (3,6). His experiments showed that when a small electric current is passed across the junction of two dissimilar metals in one direction, the junction is cooled and thus absorbs heat from its surroundings. When the direction of the current is reversed, the junction is heated as well as its surroundings. The Peltier effect takes place whether the current is introduced externally or is induced by the thermocouple. There are certain thermoelectric neutral points where no Peltier effect is apparent for special combinations of metals at certain temperatures.

The Thomson Effect

William Thomson—later Lord Kelvin—came to the conclusion that an electric current produces different thermal effects, depending upon the direction of its passage from hot to cold or from cold to hot, in the same metal (3,6). Thomson reasoned that if an electric current produces only the reversible Peltier heating effect, then the net Peltier voltage will equal the Seebeck voltage and will be linearly proportional to the temperature difference at the junctions of the thermocouple. Thomson also concluded that the net Peltier voltage is not the only source of emf in a thermocouple circuit but that a single conductor itself must also be a seat of emf.

The Seebeck, Peltier, and Thomson effects, together with several other phenomena, form the basis of functional thermoelectric modules.

THEORY OF THERMOCOUPLES

Electromotive Force (emf)

The emf is the energy per unit charge that is converted reversibly from chemical, mechanical, or other forms of energy into electrical energy in a conversion device such as a thermocouple. The basic principle of thermoelectric thermometry is that a thermocouple develops an emf, which is a function of the difference in temperature of its measuring (hot) junction and reference (cold) junction. If the reference junction temperature is known, the measuring junction's temperature can be measured by measuring the emf generated in the circuit. Therefore, we need an instrument capable of measuring emf.

There are three types of emf-measuring instruments in use in industry: deflection meters (millivoltmeters), digital voltmeters, and potentiometers. However, only two of them—digital voltmeters and potentiometers—are used where precision and accuracy are required for measuring thermal emfs. Digital voltmeters are high-impedance devices, and the readings are essentially independent of external circuit resistance. Potentiometers are used when the greatest accuracy is required in measuring emfs because its readings are free from uncertainties arising from changing circuit resistance (3).

Two metals, A and B, form an electric circuit with junctions that have temperatures t_1 and t_2. In general, if the junction temperatures t_1 and t_2 are not identical, an emf will exist in such a circuit (7). The magnitude of the emf will depend on the metal used, the amount of temperature difference between t_1 and t_2, and the actual temperature values of t_1 and t_2. By including a suitable device to indicate any emf or flow of current that may occur in the circuit, the temperature difference $t_1 - t_2$ can be measured. The term thermoelectric power (e) as applied to such a circuit for a given pair of metals and a specified average temperature is defined as the ratio of the magnitude of the thermoelectric emf (E) to the temperature difference, $t_1 - t_2$ between the junction (see Fig. 1).

There are several basic laws that define thermoelectric circuits. These laws have been established experimentally and are generally accepted despite the lack of theoretical development.

Law of Homogeneous Metals. 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 (4).

This law requires two different materials for any thermoelectric circuit (i.e., a thermocouple). No voltage V_{ij} can appear if wires A and B are chemically and physically the same, regardless of the values of T_1 and T_2. This law provides that the position of the voltmeter (Fig. 2) does not affect the emf V_{ij} as long as both wires attached to the voltmeter are homogeneous. The voltmeter could be placed anywhere along wire A or B or at either junction.

Experiments have been reported suggesting that a nonsymmetrical temperature gradient in a homogeneous wire

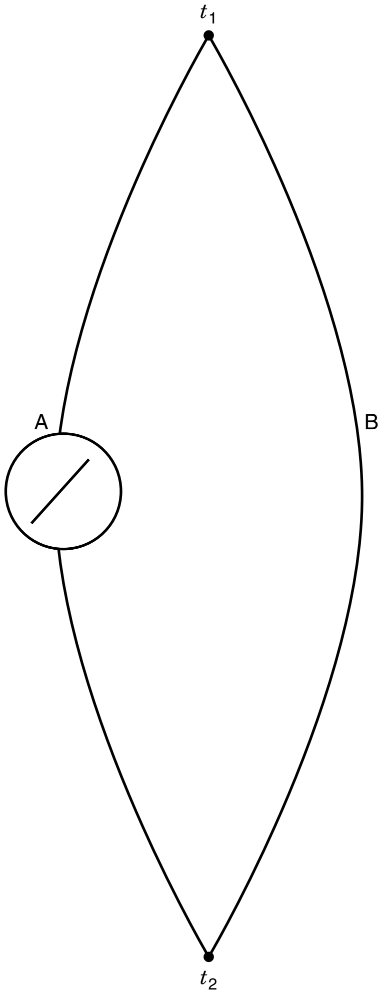

Figure 1. Thermoelectric circuit.

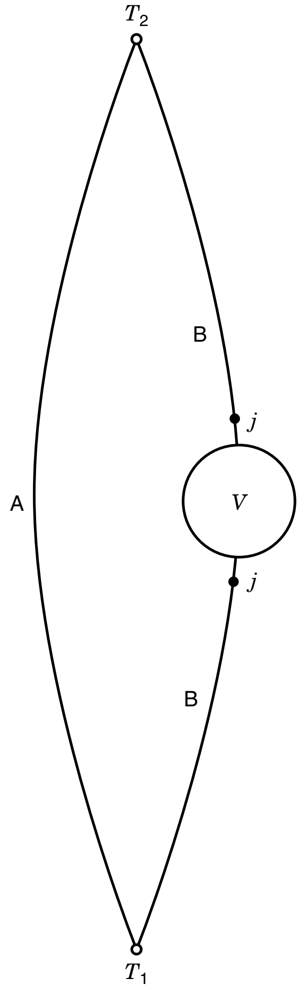

Figure 2. Thermocouple thermometer circuit. Dissimilar wires A and B are joined at temperatures T_1 and T_2. The original current-flow circuit of Seebeck has been modified by the insertion of a high-impedance potentiometer V to emphasize the present-day thermometry technique.

gives rise to a measurable thermoelectric effect. However, there is evidence that indicates that any emf observed in such a circuit arises from the effects of local inhomogeneities, and any current detected in such a circuit when the wire is heated is taken as evidence that the wire is inhomogeneous.

Law of Intermediate Metals. 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 (7).

This law implies that a third homogeneous material can always be added in a circuit with no effect on the net emf of the circuit as long as its extremities are at the same temperature. A junction whose temperature is uniform and which makes good electric contact does not affect the emf of the thermoelectric circuit regardless of the method used in forming the junction. This is significant in that is allows for cheaper materials to be used as extension wires.

This law also implies that if the thermal emfs of any two metals with respect to a reference metal are known, then the emf of the combination of the two metals is the algebraic sum of their emfs against the reference metal.

Law of Intermediate Temperatures. If a given two-junction circuit produces an emf V_1 when junction temperatures are T_1 and T_2 and produces an emf V_2 when its junction temperatures are T_2 and T_3, then the same circuit will produce an emf equal to $V_1 + V_2$ when its junction temperatures are T_1 and T_3 (1).

This law is very important in case an engineer wanted to use a specific thermocouple circuit with a different reference junction temperature than the one for which a set of emf–temperature values is known. The temperature–emf relationship for a specific thermocouple combination is a definite physical property and thus does not depend on details of the apparatus or method used for determining this relationship. Figure 3 lists the emf curves for ISA standard thermocouples.

THERMOCOUPLE JUNCTIONS

The are numerous variations on the construction for joining the two dissimilar wires that make up a thermocouple. Thermocouples are available in four main junction types: exposed- or bare-wire junction, grounded junction, ungrounded or isolated junction, and reduced diameter junction.

Exposed- or Bare-Wire Junction

In this type of junction, the sheath and insulating material are removed to expose the thermocouple wires (3). These wires are joined to form a measuring junction. While the thermocouple will have a fast response, the exposed ceramic is not pressure-tight, will pick up moisture, and will be subject to mechanical damage and expose the thermocouple to the environment (Fig. 4).

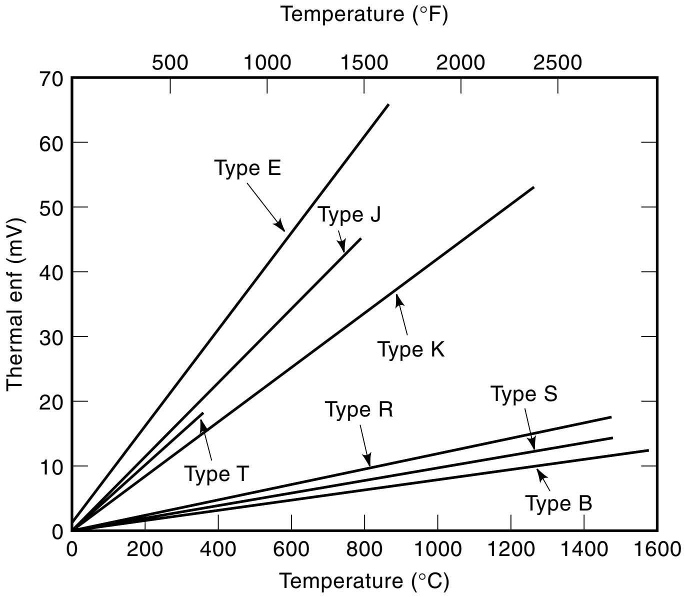

Figure 3. Thermal emf curves for ISA standard thermocouples. [Based on IPTS-68 (1974).]

Figure 4. Exposed- or bare-wire junction.

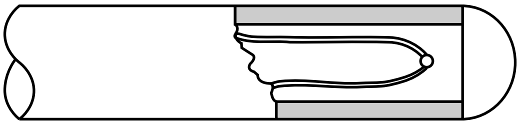

Figure 6. Ungrounded junction.

Grounded Junction

A closure is made by welding in an inert atmosphere so that two thermocouple wires become an integral part of the sheath weld closure (3). The wires are grounded to the sheath. This type of junction will give a slower response than an exposed wire, but the insulation is pressure-tight (Fig. 5).

Ungrounded or Isolated Junction

This type of junction is similar to the grounded junction except that the thermocouple wires are first made into a junction, which is then insulated from the sheath and the sheath enclosure (8). The closure is formed by welding without touching the thermocouple wires, and this results in an ungrounded thermocouple to the sheath material. This junction has a much slower response than the grounded junction but is still pressure-tight, protected from mechanical damage and the environment (Fig. 6).

Reduced Diameter Junction

This junction may be either grounded or insulated, and it is used where a fast response is required (3). It is more commonly used when a heavier sheath or wires are desired for strength, life, or lower resistance over the balance of the unit (Fig. 7).

CALIBRATION OF THERMOCOUPLES

Thermocouple wire is available commercially for measuring temperatures in the range of −190°C to 2000°C in matched pairs to conform to published standard tables. Each wire is calibrated separately, and then selected wires from two materials are paired such that the temperature–emf relationship for each pair does not deviate by more than the established standard tolerances. Common tolerances are usually ±0.25% to ±0.75%.

The National Institute of Standards and Technology (NIST, formerly NBS) can provide temperature calibration when maximum authenticity is required for highly accurate temperature measurement applications. The temperatures covered by NIST are from −196°C to 1566°C, and a minimum length of 3 in. and a maximum of 24 in. wire is required.

The calibration of standard thermocouples consists of the determination of their emf values at a sufficient number of temperatures that they may be used to measure temperatures on a particular scale with a certain accuracy. This process may include annealing, test junction assembly, emf measurement, and construction of emf–temperature tables or equations. A diagram of a thermocouple calibration system is shown in Fig. 8 (9).

Figure 5. Grounded junction.

Annealing

Most base-metal thermocouples are annealed during manufacturing. Annealing is considered to be satisfactory for most thermometric purposes, so that the calibration process for base-metal thermocouples usually does not include an annealing step. For noble-metal thermocouples, annealing has been demonstrated to be effective in promoting more uniform calibration results. NIST anneals all noble-metal thermocouples prior to calibration. The thermocouples are heated to about 1450°C in air by passage of electric current through their length while they are suspended loosely between supports. After approximately 45 min, they are annealed at 750°C for about 30 min and then cooled to room temperature.

Thermocouple Extension Wires

Thermocouple extension wires, also known as extension wires or lead wires, are electric conductors for connecting thermocouple wires to the temperature-measuring and temperature-control instrument. Extension wires are usually supplied in cable form, with positive to negative wires electrically insulated from each other. The chief reasons for using extension wires are economy and mechanical flexibility. Economy-base-metal thermoelements ($10 per pound) are always used as extension wires for noble-metal thermocouple wires ($700 per troy ounce). Mechanical-flexibility insulated solid or stranded wires in sizes from 14 to 20 gauge are used as extension wires. This lends mechanical sturdiness and flexibility to the thermocouple circuitry while permitting the use of larger-diameter base-metal thermocouples for improved oxidation resistance and service life, or smaller-diameter noble-metal thermocouple wire to save cost.

Test Junction Assembly

If a thermocouple is to be calibrated by comparison with a standard thermocouple, then the test wires are usually welded to the measuring junction of the reference thermocouple. By creating a single measuring-junction bead containing all of the thermocouples to be measured, an engineer can eliminate the temperature gradients between the pairs.

Cold Junction Compensation

As a differential output transducer, the voltage output of a thermocouple is dependent on the temperature at both the hot and cold junctions. The freezing point of water, 0°C (32°F), was selected as a convenient cold junction reference.

Figure 7. Reduced diameter junction.

To construct an ice bath reference junction, both legs of the thermocouple are fused to copper wire to form a transition junction. The leads are then waterproofed and the transition junction is immersed in an ice bath (Fig. 9). The open-circuit voltage appears across the copper leads exiting from the ice bath.

The copper leads are used to connect to the emf readout device. This procedure avoids the generation of thermal emf at the terminals of the readout instrument. Voltages measured in this way may be directly converted into temperature by using NBS millivolt–temperature reference tables (7).

THERMOCOUPLE APPLICATIONS

The Instrument Society of America (ISA) assigned a letter designation to each of several types of thermocouples (Table 1). This allows the specification of an emf–temperature relation for each type of thermocouple without specifying its position. By specifying the emf–temperature relations by the letter designation rather than by the compositions, the ISA could ensure that manufacturers could deviate from other compositions that may be trademarked and still meet the published table values. The ISA thermocouples are accepted by NIST in the consensus temperature standard ANSI MC 96 and the useful ranges for thermocouple thermometers as established by the ASTM Committee E-20.

Representative samples of wire of each thermocouple type were studied extensively at NIST in order to develop reference tables of emf versus temperature over the useful range for each type of thermocouple. The reference tables are published along with Seebeck coefficient data in the NIST Monograph 125 issued in 1974.

Base Metals for Thermocouples

Base metals are the metal that is in greatest abundance for a given metal (10,11). However, when discussing base metals in terms of thermocouples, corrosion properties are what is most important for the material used. Base metals used for thermocouples that readily oxidize and are highly corrosive are iron and constantan. The corrosion characteristics of thermocouples are listed in Table 2.

Noble Metals for Thermocouples

Noble metals are metals whose potential is highly positive relative to the hydrogen electrode; they have high resistance to chemical reaction, particularly to oxidation and to solution by inorganic acids (10,11). These metals are sometimes referred to as precious metals and are relatively scarce and valuable such as gold, silver, and platinum and are listed in Table 2.

Type K Thermocouples (Chromel-P Versus Alumel)

This type of thermocouple is regarded as the most versatile thermocouple because of its combination of high sensitivity, stability, oxidation resistance, and price. Type K thermocouples are recommended for use in an oxidizing or completely inert atmosphere over the temperature range of −200°C to 1260°C (−330° to 2300°F). Type K thermocouples should not be used in atmospheres that are reducing, alternately oxidizing and reducing, or vacuum for long periods of time since vaporization of chromium from the positive element may alter calibration used in thermometry applications in the −270° to 1372°C temperature range.

Type E Thermocouple (Ni–Cr Versus Cu–Ni)

Type E thermocouples have proven to be most useful in terms of lower wire conductivity and higher Seebeck coefficient. They are recommended for use over the temperature range of −200°C to 900°C (−330° to 1600°F) in oxidizing or inert atmospheres. These thermocouples are suitable for subzero temperature measurements since they are not subject to corrosion in atmospheres with high moisture contents. Type E thermocouples develop the highest emf per degree of all the commonly used types of thermocouples.

Type T Thermocouple (Copper Versus Constantan)

Type T thermocouples are resistant to corrosion in moist atmospheres and are suitable for subzero temperature mea-

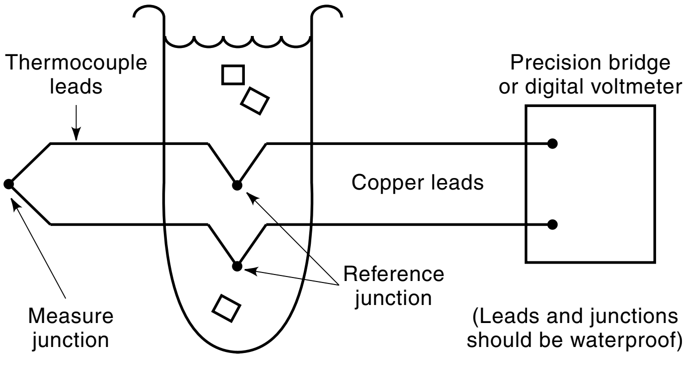

Figure 8. Thermocouple calibration system.

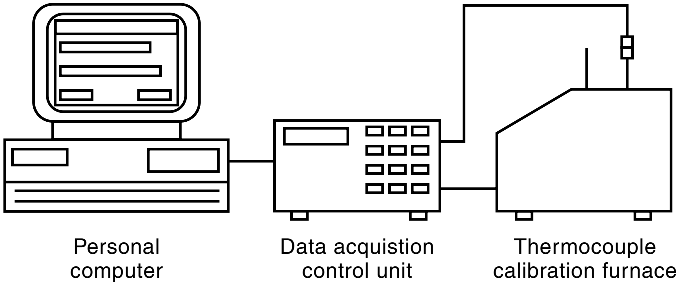

Figure 9. Ice bath circuit.

Table 1. ISA Standard Thermocouples

ISA Designation	Approximate Composition (Positive Leg Listed First)	Useful Temperature Range (°C)
Base metal types		
Type E	(Ni + 10% Cr) vs. (Cu + 43% Ni)	−270 to 1000
Type T	Cu vs. (Cu + 43% Ni)	−270 to 400
Type J	Fe vs. (Cu + 43%Ni)	−270 to 1200
Type K	(Ni + 10% Cr) vs. (Ni + 2% Al + 2% Mn + 1% Si)	−270 to 1372
Noble metal types		
Type S	(Pt + 10% Rh) vs. Pt	−50 to 1767
Type R	(Pt + 13% Rh) vs. Pt	−50 to 1767
Type B	(Pt + 30% Rh) vs. (Pt + 6% Rh)	0 to 1820

surements. They can be used in a vacuum and in oxidizing, reducing, or inert atmospheres over the temperature range of −200° to 370°C (−330° to 700°F). This type of thermocouple, along with Type E and Type K, are widely used in cryogenics, and its temperature range of use is between −270° and 400°C.

Type J Thermocouple (Iron Versus Constantan)

These thermocouples are suitable for use in vacuum and in oxidizing, reducing, or inert atmospheres over the temperature range of 0° to 760°C (32° to 1400°F). This thermocouple is not recommended for use below the ice point because rusting and embrittlement of the iron make it less desirable.

Type R and S Thermocouples (Platinum Versus Platinum–Rhodium)

Type R and S thermocouples are recommended for continuous use in oxidizing or inert atmospheres over the temperature range of 0° to 1480°C (32° to 2700°F). The continued use of these thermocouples at high temperatures causes excessive grain growth, which can result in mechanical failure of the platinum element.

Type B Thermocouple (Platinum–Rhodium Versus Platinum–Rhodium)

These thermocouples are recommended for continuous use in oxidizing or inert atmospheres over the temperature range of 870° to 1700°C (1000° to 3100°F). There are also suitable for short-term use in a vacuum. They should not be used in reducing atmospheres nor in those containing metallic or nonmetallic vapors.

Special Problems with the Use of Thermocouples

The thermocouple possesses an apparent simplicity that often deceives its users (1). The sensor appears to be a tiny detector that evaluates the temperature exactly at the location of the measuring junction. In certain commercially available thermocouple systems, the reference junction is contained within a digital voltmeter so that there is no messy ice bath to manipulate. There are several problems that are unique to thermocouples. Each problem arises from the nature of thermocouple measurements and the fact that the thermometric quantity is measured in terms of a small steady voltage. Any spurious source of voltage in the thermocouple circuit directly contributes to the temperature measurement error.

Some of the primary sources of thermocouple error areas follows:

1. Deviations from specifications in wire manufacture.
2. Use of low-impedance measuring instrumentation, leading to “loop-current” errors that arise from the flow of substantial currents within the thermocouple circuit.

Table 2. Corrosion Characteristics of Common Thermocouples (12–13)

Type of Thermocouple	Influence of Temperature and Gas Atmospheres
Type S, R, and B Platinum vs. platinum–rhodium	1. Resistance to oxidizing atmosphere: very good. 2. Resistance to reducing atmosphere: poor. 3. Platinum corrodes easily above 100°C. Should be used in gas-tight ceramine protecting tube.
Type K Chromel-P vs. alumel	1. Resistance to oxidizing atmosphere: good to very good. 2. Resistance to reducing atmosphere: poor. 3. Affected by sulfur, reducing, or sulfurous gas, SO_2 and H_2S.
Type J Iron vs. constantan	1. Oxidizing and reducing atmospheres have little effect on accuracy. Best used in dry atmospheres. 2. Resistance to oxidation: good up to 400°C but poor above 700°C. 3. Resistance to reducing atmosphere: good (up to 400°C).
Type T Copper vs. constantan	1. Subject to oxidation and alteration above 400°C, due to copper; above 600°C, due to constantan wire. Contamination of copper affects calibration greatly. 2. Resistance to oxidizing atmosphere: good. 3. Resistance to reducing atmosphere: good. 4. Requires protection from acid fumes.

3. Presence of electromagnetic interference, whether at the measuring junction or along improperly shielded extension wires.
4. Use of switching apparatus that introduced spurious and sometime variable voltages.
5. Use of extension wires that do not match the emf–temperature relation of the thermocouple wires themselves or that introduce unwanted emf's in their connections to the circuit.

SUMMARY

The use of thermocouples for temperature measurement provides a reliable and reproducible measurement for a variety of applications in many different disciplines. This article discussed the history of thermocouples, theory of thermocouples, thermocouple junctions, calibration of thermocouples, and thermocouple applications. Since the materials used to make thermocouples are relatively inexpensive and readily available, their use is widespread for scientific and industrial applications. From as low as −190°C to as high as 2000°C, thermocouples are used for just about every low-cost temperature measurement application.

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