THERMOCOUPLE FUNDAMENTALS

by RICHARD M. PARK
Chief Engineer
Marlin Manufacturing Corporation
Cleveland, Ohio, U.S.A.

MARLIN COURSE # TECH TEMP 2-1

Table of Contents **page**

Thermocouple Gradient Theory

How a Thermocouple Works

It is commonly known that a thermocouple consists of a pair of dissimilar wires joined at one end. This connecting point is known as a measuring junction, but in fact, the junction itself doesn't really 'measure' anything. It simply joins the two wires at one place, and ensures that there can be no electrical potential difference between the wires at that point. Thus, the sole purpose of the 'junction' is to establish a starting point from which a thermoelectric voltage can be developed.

There is a popular, and very misleading, misconception of how a thermocouple operates. In this erroneous 'model', it is imagined that the thermocouple's 'hot' (measuring) junction somehow functions as an electrical source, and that the junction itself produces the thermocouple's small signal voltage. This concept is simply not true. The actual thermoelectric effect is an extended and continuous one that is distributed along the entire length of the thermocouple conductors. The process is driven by the temperature differences, or gradients, through which these conductors pass.

The key point here is that a thermocouple electromotive force (emf), or voltage, is developed *from* the measuring junction rather than *by* that junction. It follows that throughout the circuit beyond this starting point or junction, the thermocouple conductors must be electrically insulated from each other, and must remain so under all operating conditions, so that a useful output signal may be realized.

One helpful way of visualizing a thermocouple is to consider a hypothetical and greatly idealized application in which there are three temperature zones as shown in Fig. 1. One zone, where the temperature is being measured, is uniformly hot. Another, containing the reference junction and instrument connections, is taken to be at a cooler, and likewise uniform, ambient temperature. And in between is a zone within which the temperature is assumed to vary in a linear manner with distance, decreasing smoothly from the hotter to the cooler temperature.

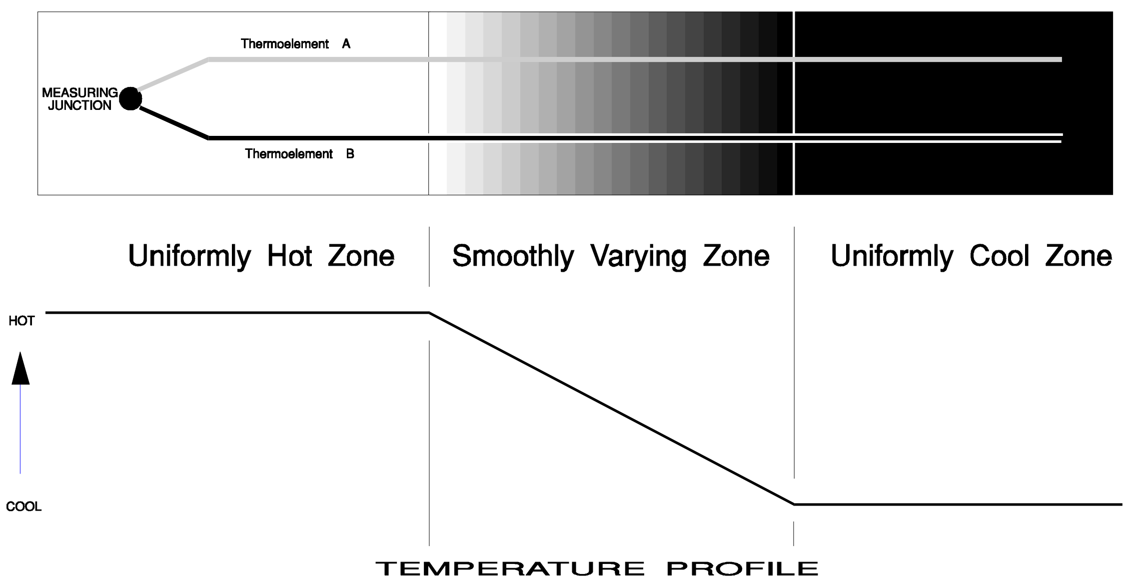


FIG. 1 — *Hypothetical and idealized thermocouple installation.*

Figure 2 shows graphically the relationship between temperature and the emf in each of the thermoelements for the hypothetical thermocouple of Fig. 1.

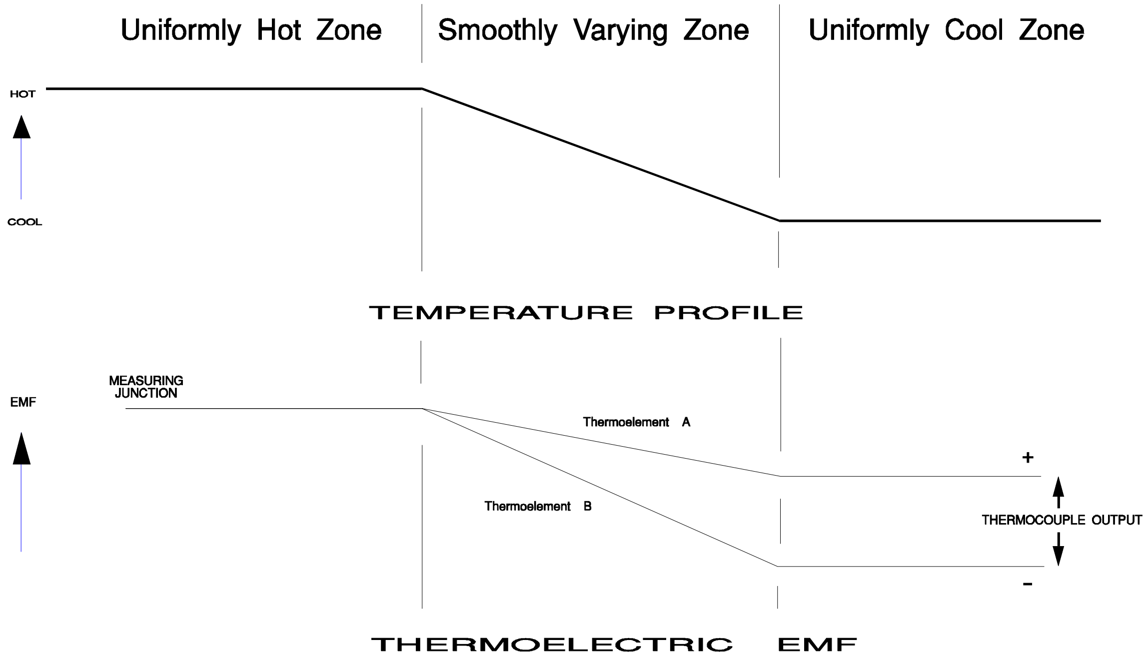


FIG. 2 — *Development of a thermocouple emf.*

Because of the connection at the measuring junction, there is no electrical potential difference between the wires at that point. In fact, no emf difference between the wires can exist anywhere within the uniform, hot zone, because under the assumed temperature conditions there is no thermal gradient there that could produce one. For the same reason, no additional change in emf difference between wires will occur within the uniformly cool, ambient temperature zone.

All thermoelectric activity therefore takes place in the center zone of decreasing temperature. The two thermocouple wires, or thermoelements, are dissimilar by design. That is to say, each conductor is made up of chemical elements that essentially differ from those of the other wire, and the presence of these dissimilarities will cause each element to respond to external stimuli (in this case, a temperature change) in a different way.

The electrical potential emf along any wire will change as the local temperature changes. Thus, a diminishing temperature will result in a reduced emf for both thermoelements, but the amount of this reduction in one wire will not be the same as for the other because of their different compositions. The small net difference in emf change between two dissimilar wires constitutes a thermocouple output signal. For an appropriately chosen thermocouple pair this emf output can be a dependable and repeatable function of the temperature difference between the ends the wires.

Thus we see that when subjected to a temperature gradient, selected wires with different known thermoelectric properties will produce a useful electrical signal that varies with the temperature difference in a predictable way. It should be apparent that if the temperature does not change along a particular length of a thermoelement pair, then the emf will not change along that length. It also follows that a temperature difference of any magnitude cannot produce a thermal emf between two conductors traversing that difference if the conductors are thermoelectrically identical.

Standard T/C Types

While it is true that any randomly chosen pair of dissimilar wires will produce some kind of thermal emf when subjected to a temperature difference from end to end, the emf so produced may be unpredictable and of little use. However, certain thermoelement combinations have been commercially developed over the years that have proved to be useful, reproducible, and readily available.

Eight of the most widely used of these combinations have been assigned letter-designations for ease of reference, and their thermoelectric properties have been standardized. Among these several standard types, differences will be found in their useful operating temperature range, their stability in use, their compatibility with various operating environments, and their cost.

Selection of Thermocouple Type

A primary consideration in choosing which thermocouple type to use in a given circumstance is the range of temperatures over which the device is to be used. Some of the other selection factors to be addressed include suitability for the conditions of use and expected service life.

Listed below are descriptions of the eight letter-designated thermocouple types arranged in order of increasing upper operational temperature limit.

Base metal types

Type **T,** Copper (+) vs. Constantan (nickel-45%copper) (–). This type is moisture resistant, very stable, and useful to 370℃ (700℉) in air, a temperature limit imposed primarily by oxidation of the copper element. When used in vacuum or in reducing or inert atmospheres, operation at somewhat higher temperatures may be possible. It is also suitable for subzero use down to -200℃ (-370℉), but stock materials are not normally pretested in this range, so special selection and additional calibration of materials is usually required for such use. Neither wire is magnetic, but visual identification by metal color is easy.

Type **J,** Iron (+) vs. Constantan (nickel-45%copper) (–). These thermocouples are suitable for use in vacuum, air, reducing, or oxidizing atmospheres to 760℃ (1400℉) in the heavier gage sizes. Rapid oxidation of the iron wire at temperatures above 540℃ (1000℉) limits the expected service life of the finer sized wires. Type J wires of any size should not be used in sulfurous atmospheres above 540℃ (1000℉). Subzero use of this type is limited because of rusting and embrittlement of the iron conductor. The positive (iron) wire is strongly magnetic and the negative one is non-magnetic.

Type **E,** Chromel® (nickel-10%chromium) (+) vs. Constantan (nickel-45%copper) (–). Type E is recommended for use to 900℃ (1600℉) in oxidizing or inert atmospheres. This type is also quite suitable for low temperature work down to about -230℃ (-380℉), and develops the highest output emf of any standardized type. For subzero work, special selection and testing is usually required. Type E thermocouples are vulnerable to sulfur attack and should not be exposed to atmospheres containing this substance. These thermocouples perform best in clean oxidizing atmospheres. They are not recommended for use under partially oxidizing conditions, nor when subjected to alternating cycles of oxidation and reduction, or in vacuum, except for short time periods. The wires of this type can be difficult to identify because neither one is magnetic and coloration is similar, but the negative leg appears a little ‘warmer’ in color than the positive one.

Type **K,** Chromel® (nickel-10%chromium) (+) vs. Alumel® (nickel-5%aluminum and silicon) (–). Thermocouples of this type are suitable for use in oxidizing or inert atmospheres at temperatures up to 1260℃ (2300F), These thermocouples are the traditional base-metal choice for high-temperature work. Type K is quite vulnerable to sulfur attack and should not be exposed to sulfur-containing atmospheres. These thermocouples perform best in clean oxidizing atmospheres and, except for short time periods, are not recommended for use under partially oxidizing conditions, in vacuum, or when subjected to alternating cycles of oxidation and reduction. Identification of these wires is usually made by magnetic response. The positive leg is non-magnetic, while the negative one shows a moderately magnetic response.

®Trademarks of Hoskins Manufacturing Company

Type **N,** Nicrosil (nickel-14%chromium, silicon) (+) vs. Nisil (nickel-4%silicon, magnesium) (–). This type differs from type K by having silicon in both legs and containing magnesium in the negative leg. It was developed to be more stable (exhibit less calibration drift) than type K when used at temperatures above about 1000℃ (1800℉). Type N tolerates operation under partial oxidization better than type K, but should not be used in vacuum or reducing atmospheres. Both type N wires are similar in color and both are non-magnetic, so identification is usually made by gently heating the junction and observing the polarity of the resultant emf.

Noble metal types

The following three letter-designated types are made from the precious metals, platinum and rhodium, and as a consequence are more costly than the base-metal types described above. But these thermocouples do operate at higher temperatures than any of the base-metal types, and it is also possible to recover a significant portion of their initial cost by reclaiming the used scrap metal.

Type **S,** Platinum-10%rhodium (+) vs. Platinum (–). Type S is recommended for continuous use in air or inert atmospheres in the temperature range 0 to 1480℃ (32 to 2700℉). It is quite stable and capable of long operating life when used in clean, favorable conditions. When used above 1100℃ (2000℉), Type S must be protected from exposure to metallic and non-metallic vapors. It is therefore not suitable for direct insertion into metallic protecting tubes. Long operation times at very high temperatures can produce large grain growth leading to mechanical failure of the negative thermoelement. This type has the same uses as type R, but is not interchangeable with it.

Type **R,** Platinum-13%rhodium (+) vs. Platinum (–). This type is recommended for continuous use in air or inert atmospheres in the temperature range 0 to 1480℃ (32 to 2700℉). It is quite stable and capable of long operating life when used in clean, favorable conditions. When used above 1100℃ (2000℉), these thermocouples must be protected from exposure to metallic and non-metallic vapors. Type R is not suitable for direct insertion into metallic protecting tubes. Long periods of operation at very high temperatures can produce large grain growth leading to mechanical failure of the negative thermoelement. This type has the same uses as type S, but is not interchangeable with it.

Type **B,** Platinum-30%rhodium (+) vs. Platinum-6%rhodium (–). Type B thermocouples are recommended for use in clean air at temperatures from 870 to 1700℃ (1600 to 3100℉). They may be used for brief periods in vacuum, but should not be used in reducing atmospheres nor where exposed to nonmetallic or metallic vapors. This type is not suitable for direct insertion into metallic protecting tubes. Type B is more resistant than either type R or S to grain growth that could result in mechanical failure. Under some conditions, type B may also have less calibration drift than type R or S sensors that are subjected to the same use.

Identification of noble metal thermocouple wires is made difficult by the fact that all alloys are nearly identical in color and all are non-magnetic. Sometimes it is possible to distinguish the positive wire from the negative one for types R or S by observing the 'limpness' of the wires. Pure platinum wires tend to be slightly more soft, or limp, while the rhodium-alloyed conductors are a little stiffer, enough so to permit identification. The differences, however, are subtle, and it is not possible to tell one rhodium alloy from another by these means. Proper connections for these thermocouples can be reliably determined by gently heating the junction and observing the resulting polarity on a sensitive indicator.

In a related way, qualitative identification of rhodium alloys may be made by forming a junction between an unknown wire and another whose composition is known. If the wires are the same, no significant emf will result when their junction is heated to a considerable degree.

Accuracy

Thermocouple materials are produced, tested, and sold in two tolerance grades, called standard and special. A table of allowable variations from the NIST-standardized nominal thermocouple tables, or ‘curves’, is given in ASTM Standard E-230 for the several thermocouple types. The emf versus temperature tables themselves, as well as the mathematical functions to derive them are also given in that standard.

The following tolerance table is extracted from the same ASTM standard. The values given in it apply to new and unused thermocouple materials as tested at the time they are produced. Note that where a tolerance is given in percent, the percentage applies to the temperature of interest only when it is expressed in degrees Celsius. The tolerance in degrees Fahrenheit is 1.8 times greater than the tolerance for the Celsius equivalent temperature.

INITIAL CALIBRATION TOLERANCES FOR THERMOCOUPLES

Type	Alloy	Temperature	Standard Limits	Special Limits
T	Copper (+) vs. Constantan (–)	–200°C to 0°C*	±1°C or ±1.5%*	±0.5°C or ±0.8%*
		0°C to 350°C	±1°C or ±0.75%	±0.5°C or ±0.4%
J	Iron (+) vs. Constantan (–)	0°C to 750°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%
E	Chromel®(+) vs.Constantan (–)	–200°C to 0°C*	±1.7°C or ±1%*	±1°C or ±0.5%*
		0°C to 900°C	±1.7°C or ±0.5%	±1°C or ±0.4%
K	Chromel® (+) vs. Alumel®(–)	–200°C to 0°C*	±2.2°C or ±2%*	N.A.
		0°C to 1250°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%
N	Nicrosil (+) vs. Nisil (–)	0°C to 1250°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%
R	Pt/13%Rh (+) vs. Pt (–)	0°C to 1450°C	±1.5°C or ±0.25%	±0.6°C or ±0.1%
S	Pt/10%Rh (+) vs. Pt (–)	0°C to 1450°C	±1.5°C or ±0.25%	±0.6°C or ±0.1%
B	Pt/30%Rh (+) vs. Pt/6%Rh (–)	870°C to 1700°C	±0.5%	±0.25%

* Thermocouple wire is normally supplied to meet tolerances for temperatures above 0°C.
Stock materials may not fall within the sub-zero tolerances given without special selection and testing.

® Trademarks of Hoskins Manufacturing Company

Most tolerances in the table above are listed in ‘degrees *or* percent’. This simply means that the tolerance is the *larger* of: the fixed number of degrees stated; or the percentage of any temperature of interest (when expressed in °C).

These tolerance classes are intended to ensure interchangeability of thermocouple sensors without special calibration testing. But, where required, thermocouples may be custom calibrated with the results of such testing reported to the user. Then, if necessary, corrections based on the test results may be made.

A unique advantage of thermocouples is that ‘lot calibration tests’ may be made of samples from a given spool (or ‘lot’) of wire, and those test results will apply to *all* sensors made from that same lot. In this way significantly closer control of tolerance variations may be gained without incurring the high cost of testing a large number of individual thermocouples.

Practical Assemblies

Design Rationale

The choice of thermocouple type is dependent upon the temperatures and conditions of use. Whatever the choice, it is usually necessary to provide the thermoelement with suitable protection from the often harsh conditions in which temperature measurements must be made. Another important factor in selecting a design can be the ease with which a sensor may be serviced or replaced.

Materials selection

One class of thermocouple material, referred to as 'metal-sheathed', is shown in Fig. 3. It has an integral outer sheath, or tube, whose material is chosen to be compatible with the test atmosphere and to resist deterioration by it. Inside this sealed tube a compacted ceramic (metal oxide) powder supports and insulates the thermocouple wires. These sensors are rugged and may be bent. Materials inside the sheath are made pure and dry at time of manufacture and effective seals are formed at both ends . These seals must remain intact so that the ceramic powder inside remains completely dry, because moisture intrusion is apt to shorten service life.

FIG. 3 — *Metal-sheathed thermocouple (partially sectioned).*

In another frequently used construction, illustrated in Fig. 4, bare thermoelements are simply strung through holes in hard-fired ceramic beads. Under very favorable conditions, it may be possible to insert such a bare, insulated thermoelement directly into a space to obtain temperature measurements. However, in most instances, isolation from the test medium is necessary. Therefore, bare-wire, insulated thermoelements are usually inserted into single, or multiple concentric, closed-end protecting tubes for isolation and protection from the measurement environment. Metal-sheathed assemblies are often installed in such tubes, too. By such means, measurements in very hostile environments can be successfully taken. Where measurements are to be obtained in fluids under pressure, drilled thermowells, machined from solid metal, are sometimes required to obtain the necessary mechanical properties.

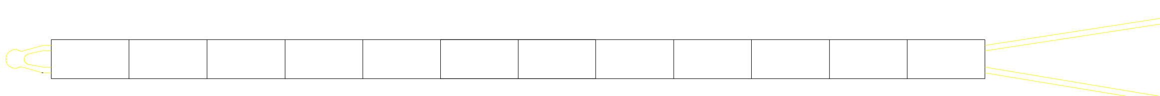


FIG. 4 — *Beaded thermocouple assembly.*

For moderate temperature applications, it may be possible to utilize soft insulated single or duplex thermoelements with a simple welded junction bead at the end, such as shown in Fig. 5. Depending on the type of insulation and conditions of use, these economical constructions may be directly inserted into the medium to be measured, or may be provided with some type of tube or other enclosure for isolation from potentially harmful test atmospheres.

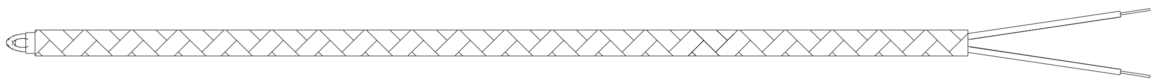
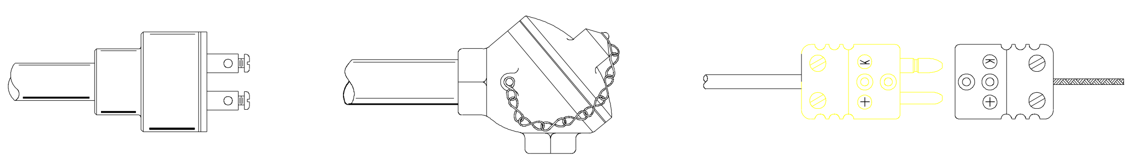


FIG. 5 — *Duplex wire thermocouple.*

Hardware Choices

Once the basic materials selections have been made, the mechanical details of the installation can be determined. Mounting may be accomplished by simply sliding the sensor into a hole, or it may be necessary to rigidly connect it to the process by means of threads or clamps. Pipe fittings are often used for this purpose. Note that the hardware associated with the complete design can often be as important to the success of an application as the choice of thermocouple type inside.

Connecting means for wiring to an instrument often occurs at the outer end of a sensor assembly. In some instances, this may take the form of an open or enclosed connecting head, as in Fig. 6(a) or Fig. 6(b), or a terminal block. At other times a plug and jack type of quick disconnect may be used, similar to Fig. 6(c). It is important that all current carrying portions of the circuit that may be subjected to a temperature gradient should be made of matching thermocouple materials. This is because each incremental length in the circuit must make its contribution according to the temperature difference that it 'sees'. As an exception to the matching materials rule, judicious use can sometimes be made of short, heavy splices containing non-matching materials as long as the connections are well protected and remain essentially isothermal. Where properly applied, such splices may be used without causing a significant error.



(a) *(b)* *(c)*

FIG. 6 — *Thermocouple terminations: (a) Open head; (b) Enclosed head; (c) Plug and Jack .*

Often it is desirable to select wiring used beyond a connecting head or plug that is different in some respects from the construction needed for the thermocouple itself. Because the ambient temperatures in this 'extension' part of the circuit are often less severe than those seen by the thermocouple itself, alternate insulation materials and wire constructions may be appropriate. For example, soft plastic insulation and fine stranded wires may be used for extensions even though they might be unsuitable for the thermocouple itself. Economical extension grade wires are also available that have the same nominal composition as costlier thermocouple grades, but are usually guaranteed over more limited temperature ranges and may also have moderately relaxed tolerance levels.

In those cases where thermocouple wires are made of noble metals or other costly alloys, the extension wires can made be of a totally different material as an economy measure. Such specially produced extension alloys have thermoelectric properties that are closely matched to those of the particular thermocouple type with which they are to be used. These materials are called *compensating* thermocouple extension wires.

Selection Factors

Why choose one T/C over another

The usual goals in picking a thermocouple type are to provide an adequate measurement over the longest possible life, and at the lowest cost. It is prudent, for such comparisons, to consider the *total* cost over some suitable time period. It is easy to overlook such hidden costs as maintenance, testing, and replacement, or loss of production due to down time or as a result of inaccurate readings. Other factors in making the best choice might be the availability of instrumentation, and sometimes a need to standardize on the thermocouple type or types to be used at a given site.

Service life

Useful thermocouple life is a very difficult prediction to make, even when most of the details of an application are known. And unfortunately, such information is often very hard to determine. The very best test for any application is to actually install, use, and evaluate the in-use performance of a design that is thought likely to succeed. The recommendations, and non-recommendations, listed under the thermocouple type descriptions are a good starting place to pick a type to try.

Decalibration & Drift

Stability

All thermocouples are subject to calibration drift with use, it is just a matter of how much, and how fast this may happen. Thermocouple performance is critically dependent upon absolute uniformity of both physical and chemical properties along the entire length of the circuit. When thermoelement materials are produced, careful steps are taken to assure that this uniformity (or homogeneity) is achieved. In use, different parts of the circuit experience different conditions of heat, chemical exposure, etc., and as a result such parts actually do grow to be 'different' from each other physically.

Because the thermoelectric emf resulting from a given temperature difference is sensitive to changes in the chemical and metallurgical properties of the wire, the total emf produced by a used probe can be different from an otherwise identical new one under the same conditions. The changes are usually small (often negligibly small) over appreciable periods of time. But under adverse conditions, it is possible to realize large drifts at rapid rates.

To achieve long and reliable thermocouple life, the usual strategy is to operate the device comfortably under its maximum temperature, and provide it with the cleanest possible environment in which to work. Enclosures, such as sheaths, protecting tubes, and thermowells are the usual means of controlling the conditions that actually surround the thermoelements themselves.

What can go wrong

Protecting tubes, sheaths, and even thermowells can fail due to corrosion or mechanical damage. Processes can go overtemperature and expose thermoelements to higher than anticipated temperatures. If a sensor controlling a process drifts low in its output, the process, in response to its controller may as a result be forced to temperatures higher than intended.

Base metal assemblies are vulnerable to attack by a number of chemical agents. They can also be altered by unfavorable operating conditions. Several examples of specific conditions that must be avoided are enumerated in the thermocouple type descriptions included in this paper. These and other operational problems are further described in ASTM MNL-12, the *Manual on the Use of Thermocouples in Temperature Measurement*. Similar topics are extensively addressed elsewhere in the published literature.

As supplied, noble metal thermocouple wire of good quality has very low impurity levels. Consequently, it is quite susceptible to contamination that can affect its thermoelectric properties. Platinum is especially sensitive to the presence of free silicon, with which it can combine to form a eutectic alloy that will melt at or below normal service temperatures. High-purity insulators and protecting tubes for precious metal assemblies as well as careful attention to cleanliness in handling are therefore essential to help prevent this.

Human error can be a contributing factor as well. Controls may be improperly set, connections may be improperly made, and inappropriate action in response to the operating conditions may be taken by mistake. Redundancy in instrumentation combined with training and responsibility are the usual means to combat these kinds of errors.

Troubleshooting

The approach

There is no better way to go about finding troubles than to use plain common sense. One should ask if the system performance seems reasonable for the conditions? Do changes in the controls produce a logical result? What about the product? Does its condition correspond with what the instruments are saying?

How to test a used T/C

First of all, one cannot ordinarily remove a suspect thermocouple from service and 'test' it in another place. The very fact that the device is used means that it may no longer be homogeneous. Subjecting an inhomogeneous thermocouple to a different set of temperature gradients, even if only subtly different, can result in a different output and reading. So, 'recalibrating' a used t/c will certainly yield a 'number', but that number will probably be meaningless in the thermocouple's place of use.

Perhaps the best way to evaluate a used thermocouple is to 'probe' the location by placing a new, or nearly new thermocouple that is known to be good alongside the suspect one in an operating process and compare the readings. If it is not practical to have two sensors in place at the same time, the next best thing is to remove the suspect probe and replace it with another one known to be good. Then, as long as the good probe is located in the same place as the removed one had been, and the process has not changed during the exchange, the readings from the two probes can be compared.

Note that is not necessary to keep and use an unlimited supply of new probes for these tests. A few suitable replacement devices can be kept on hand and one of them selected for testing use. Under normal circumstances, thermocouple drift, or degradation, is a gradual, and very slow process. A single replacement probe can thus be used a number of times to probe a process before it accumulates very much time at operating temperature, and can usually be considered reliable for a number of such repeated tests. And, when a drifted probe has been found, the test probe may simply be left in place as a working sensor, while the next replacement becomes the test device.

System tests

One very useful instrument for troubleshooting thermocouple systems is a portable temperature indicator. A number of these devices are capable of operating with two or more different thermocouple types, and some offer an ‘output’ function that will produce an electrical output to simulate a thermocouple operating at any temperature of choice.

In use, the instrument is normally ‘clipped on’ to the wires of a circuit being tested at some convenient access point, such as in a connecting head. There, the output of an operating sensor may be monitored and evaluated. Or, using an instrument’s ‘output’ function, a synthesized signal may be sent back to the circuit’s permanent indicator or controller to verify proper operation of the rest of the circuit. When driving a signal back towards an instrument, it is usually necessary to break one side of the circuit to avoid ‘loading’ the portable tester by the low resistance of the thermocouple itself.

Sections of extension wiring in thermocouple circuits may be checked for proper connections with a portable tester, as well. The section being tested should be electrically isolated from the rest of the loop, and one end of an extension wire pair should be shorted together. If a tester is connected to the opposite end of the shorted pair, the tester should indicate the approximate temperature of the shorted end. Note that if both ends of the extension pair happen to be at the same temperature, it may be necessary to warm the shorted end a little and verify that the tester ‘sees’ the temperature change correctly. Note that it is the possibility of an incorrect, reversed connection that is being checked in this test.

Summary

A key to the successful use of thermocouples is the understanding of how and why they operate. Once the basic principle — namely distributed generation of the thermocouple's emf, driven by the temperature gradients, or differences, through which the wires pass — is known and understood, applying thermocouples to most applications becomes straightforward and logical.

Commercially available thermocouples are standardized by letter-designated type and by tolerance levels of conformance to published tables or 'curves' of emf versus temperature. Custom calibration of thermocouple materials is available to answer needs more critical than can be covered by the usual tolerance grades.

An important fact to be remembered is that laboratory calibration of thermoelements is predicated upon good uniformity or homogeneity of the thermoelement being tested. New materials will possess this property, but used materials may not, so it is not normally possible to recalibrate used thermocouples. This is particularly true for base metal types after use at high temperatures.

Thermocouples are available in an almost endless variety of constructions and configurations. It is possible and practical to connect them in special ways to sense either temperature differences or temperature averages over a number of sites. It is even possible to 'gang' these devices together to boost the amount of electrical signal arising from small temperature differences. But applications like these are specialized. The major use for thermocouples is to make reliable and direct measurements of temperature in many diverse applications.

Thermocouples are fundamentally simple devices. They are extremely versatile and rugged, and are capable of operating over a very wide range of temperatures. Thermocouples can be made to very tiny dimensions and into many different forms for standard or special purposes. In addition, they are low in cost and are readily interchanged or replaced. But they do need to be understood, so that they will measure the quantity that is desired with the precision that is required.

References

1. Burns, G.W., et al., *Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90,* NIST Monograph 175, National Institute of Standards and Technology, 1993.

2. *Manual on the Use of Thermocouples in Temperature Measurement, Fourth Edition,* ASTM MNL-12, American Society for Testing and Materials, Philadelphia, 1993.

3. *Annual Book of ASTM Standards, Temperature Measurement,* Vol. 14.03, American Society for Testing and Materials, Philadelphia, (Published annually).