

Temperature measurement —

Part 4: Guide to the selection and use of thermocouples

Committees responsible for this British Standard

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- British Gas plc
- British Pressure Gauge Manufacturers' Association
- Department of Energy (Gas and Oil Measurement Branch)
- Department of Trade and Industry (National Weights and Measures Laboratory)
- Energy Industries Council
- Engineering Equipment and Materials Users' Association
- GAMBICA (BEAMA Ltd.)
- Health and Safety Executive
- Institution of Gas Engineers

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- British Cable Makers' Confederation
- British Valve and Actuator Manufacturers' Association
- Department of Trade and Industry (National Engineering Laboratory)
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Foreword

This Part of BS 1041 has been prepared under the direction of the Industrial-Process Measurement and Control Standards Committee. It is a revision of BS 1041-4:1966 which is withdrawn. It should be noted that the title has been restyled for consistency with other parts of BS 1041.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 26, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

0 Introduction

Thermocouples are by far the most common temperature sensors in industrial use. They possess the virtues of simplicity, ruggedness, low cost, small physical size, wide temperature range (from about $-270\text{ }^{\circ}\text{C}$ up to $3\,000\text{ }^{\circ}\text{C}$) and convenient electrical output. These properties make them very suitable for multi-point temperature measurement and monitoring in large and complex process plant, and for an enormous variety of industrial, technological and scientific applications.

The thermocouple has a long history, the original paper by Seebeck having been published in 1822 and the relationship between the three principal thermoelectric effects having been established by William Thomson (later Lord Kelvin) in 1854. The platinum-10 % rhodium/platinum thermocouple, which was for a long time specified as the interpolating instrument in realizing the International Temperature Scales in the range from $630\text{ }^{\circ}\text{C}$ to $1\,064\text{ }^{\circ}\text{C}$, was originally developed by Le Chatelier in 1886. Most of the commonly used base metal thermocouples were developed during the first decade of the twentieth century.

For a proper understanding of how thermocouples function and how to use them, it is essential to realize that thermoelectricity is a bulk property of metallic conductors in the same sense as thermal conductivity and electrical conductivity. Although thermoelectric effects manifest themselves in circuits comprising two or more dissimilar conductors, they are not due to any special properties of the junctions between the conductors. The junctions, which for successful measurements have to be at uniform temperatures, are needed only to complete the measuring circuit and are thermoelectrically inactive. In fact there will be contact potentials at junctions between different metals, but these are not thermoelectric in origin and they are not significantly temperature dependent. Therefore when all contact potentials in a circuit loop are summed, their net result is effectively zero.

By contrast, the chemical state and physical condition, e.g. strained or annealed, of the conductors in regions where they experience temperature gradients, can have a profound effect on the electromotive force (e.m.f.) generated. Great care should be exercised in how the conductors are treated in these regions and users should be aware of possible effects due to physical and chemical changes which may occur in use.

Before embarking on descriptions of thermocouples and their application a brief account is given of the principal thermoelectric effects, since this should be helpful in achieving an understanding of good practice in thermocouple thermometry. Reference should be made to textbooks on thermoelectricity and, more generally, on the electrical properties of metals and alloys, for detailed theoretical discussion.

Thermocouples are used in so many and varied circumstances that it has only been possible to cover the common principles in this standard. It is hoped that it will be a useful aid to understanding the characteristics that are of practical importance so that the most appropriate choices of thermocouple and instrumentation can be made, and their effective application achieved.

1 Scope

This part of BS 1041 provides guidance on the selection and use of thermocouples. It provides an introduction to the operating principles of thermocouples and their application to the measurement of temperature. A brief review of thermoelectricity and basic thermocouple circuits and an overview of the materials commonly used in thermocouples in various temperature ranges, with their strengths and weaknesses are included. The fabrication of thermocouples, associated hardware, measurement techniques, tolerances and calibration are described.

2 Definitions

For the purposes of this British Standard the following definitions apply.

2.1 thermoelectricity

- 1) Electricity generated in a conductor by virtue of a temperature difference (temperature gradient) within it.
- 2) The branch of science concerned with electric effects produced in conductors by means of heat.

2.2 thermoelectric e.m.f.

the electromotive force established in a conductor by virtue of a temperature gradient within it (the Seebeck effect)

2.3 thermoelectric power

the thermoelectric e.m.f. produced in a conductor per unit temperature difference

NOTE 1 Thermoelectric power is also known as thermopower or the Seebeck coefficient.

NOTE 2 Thermopower is the thermoelectric sensitivity, and values are usually given in $\mu\text{V}/^\circ\text{C}$, thus the term “power” is misleading.

2.4 thermocouple

a thermoelectric device for measuring temperature, consisting of a pair of dissimilar conductors (thermoelements) connected together at the measuring junction which is maintained at the temperature to be measured, the circuit loop being closed at a reference junction between the two conductors, or at two reference junctions to a third conductor

NOTE 1 An instrument is connected at a convenient point in the circuit loop so as to measure the net thermoelectric e.m.f. (or sometimes the thermoelectric current) developed in the circuit. If the thermoelements are connected directly to the measuring instrument, the terminals of the instrument constitute the reference junctions.

NOTE 2 The e.m.f. produced depends on the thermoelements used and on the temperatures of the measuring and reference junctions.

NOTE 3 The measuring and reference junctions are often referred to as the “hot” and “cold” junctions respectively, though in many circumstances, especially in measuring temperatures below 0°C , the opposite applies.

2.5 thermoelements

the two conductors used in a thermocouple, one of which is designated “positive”, the other “negative”, according to the polarity of the net e.m.f. developed

3 Thermoelectricity

3.1 The Seebeck effect

A conductor contains electrons which are continually in motion in all directions. These motions are such that in the absence of any external electromagnetic or thermal stimulus there is no net transport of electrons, or current. However, if an electric potential difference is applied, the motions are modified and a current flows. If a temperature gradient is established in the conductor the motions are again modified, this time with the result that heat is conducted and a gradient in electron density is set up. Since electrons are charged it follows that an electric potential difference will be established, which may be positive or negative depending on the details of the electronic structure of the conductor.

As it is difficult to demonstrate the existence of this potential difference in an isolated conductor, the circuit has to be completed with a second conductor which will necessarily experience the same temperature gradient. In order not to counterbalance the effect, this has to be of a different material, i.e. one forms a thermocouple and observes the difference in the thermoelectric e.m.f.s¹⁾ generated in the two conductors.

This is the basic thermoelectric effect which was discovered by Seebeck and which bears his name. The magnitude of the e.m.f. generated depends on the thermoelectric powers of the two conductors and on the temperature gradient to which they are exposed. For the case where the conductors are connected to a high impedance voltmeter [as shown in Figure 1 a)] the e.m.f., E (in μV) may be written as follows:

$$E = \int_{t_2}^{t_1} S_a dt + \int_{t_1}^{t_2} S_b dt \quad (1)$$

where

S_a and S_b are the thermoelectric powers of conductors a and b (in $\mu\text{V}/^\circ\text{C}$)

t_1 and t_2 are the junction temperatures (in $^\circ\text{C}$).

Equation 1 is more strictly correct than the following alternative equations:

$$E = E_{ab}(t_1) - E_{ab}(t_2); \text{ or} \quad (2)$$

$$E = E_{ab}(t_1) + E_{ba}(t_2). \quad (3)$$

Equation 1 shows that E is the sum in the circuit loop of the e.m.f.s built up in the two separate conductors, the junctions exist only to connect them together. Equations 2 and 3 on the other hand suggest that E is the difference between junction e.m.f.s, E_{ab} , between the two conductors at temperatures t_1 and t_2 . Circuit analysis can proceed as if this is the case, but those concerned with making, calibrating, installing and using thermocouples will need to bear in mind the source of the e.m.f.s, and to exercise care in how they treat conductors in regions of temperature gradient. Junctions, being the points of measurement (or in terms of equation 1, the initial and final limits of the integrations) should always be isothermal and therefore should not themselves contribute to the e.m.f. As a consequence, the junctions may be formed in any manner that is electrically, mechanically and chemically effective and appropriate.

¹⁾ Since a thermocouple is, like a battery, an active generator of electric potential difference, its output is more properly termed an electromotive force, or e.m.f., than a voltage.

Since thermopower is a property of bulk conductors and not of junctions, it follows that the conductors of a thermocouple should be homogeneous. The thermoelectric power can be very sensitive to chemical composition and physical condition. If either of these varies along the length of a conductor of a thermocouple, the output may be dependent on the temperature profile, i.e. on exactly where the temperature gradient is. This has obvious implications for the manufacture and correct use of thermocouples.

3.2 The Thomson and Peltier effects

Two other thermoelectric effects arise in the conductors of circuits in which a current is caused to flow.

If a portion of a conductor in a temperature gradient along which an electric current is flowing is considered, the electrons enter with a certain energy and pass on to the next portion of the conductor with a different energy by virtue of the temperature change. The energy which they have either lost or gained appears as heat liberated or absorbed.

This is known as the Thomson heat after William Thomson (Lord Kelvin) who first postulated its existence. It is often referred to as the specific heat (heat capacity) of electricity. The Thomson coefficient, usually written μ , is the heat gain per unit volume per unit current per unit temperature gradient (in $\mu\text{V}/^\circ\text{C}$) and it is related to the thermoelectric power by the equation:

$$\mu = T(dS/dT) \quad (4)$$

where

T is the temperature (in K);

s is the thermoelectric power of the conductor (in $\mu\text{V}/^\circ\text{C}$).

Although the effect is generally quite small, it is through the Thomson effect that absolute thermoelectric power is best measured. The current is passed through the conductor, first in one direction and then in the opposite direction, in order that the Thomson heat, which is reversible, can be distinguished from the Joule heating which, being proportional to the current squared, is irreversible. The calorimetric measurements are not easy and in consequence absolute thermoelectric powers are not accurately known, but once measurements have been made for one material other thermoelectric powers can readily be measured relative to this reference material, using the Seebeck effect.

If instead of a single conductor in a temperature gradient we consider a current flowing across an isothermal junction between two conductors, heat is also liberated or absorbed. This is because electrons in different metals have different heat capacities even at the same temperature. This evolution or absorption of heat at junctions is known as the Peltier effect, named after its discoverer, and it too is reversible with the direction of the current. It is related to the thermoelectric power, the Peltier coefficient, Π (in μV), being equal to TS . Although the heat appears at junctions between conductors, it should be clear that Π is a temperature dependent property of individual conductors. Since the heating or cooling depends on the Peltier coefficients, Π_a and Π_b of the two conductors, such that $\Pi_{ab} = \Pi_a - \Pi_b = T(S_a - S_b)$, it is not useful in absolute measurements. It is however of considerable technological importance in small scale refrigeration by Peltier cooling.

In summary, the three thermoelectric effects arise because the diffusion of electrons under a temperature gradient and the flow of electrons in an electric field, which are primarily responsible for thermal and electrical conductivity in conductors, are not independent. Electrons will transport both heat energy and electric charge by whatever means they may be caused to move.

4 Basic thermocouple circuits

4.1 General

The simplest thermocouple circuit making use of the Seebeck effect is shown in Figure 1 (a). The two conductors are connected together at the measuring junction at temperature t_1 and are directly connected at temperature t_2 to a voltmeter whose input impedance is large compared with the circuit resistance. The measurement of the temperature t_1 requires, among other things, that t_2 be independently measured, or controlled at a known temperature. Often an electronic circuit is included which compensates the measurement of t_1 for any departure of t_2 from a reference value. This is known as cold junction compensation, and is discussed in 7.6.

Figure 1 (b) explicitly shows the use of a reference junction. The two conductors a and b are each connected to conductor c (which would usually be copper) at a uniform temperature, t_{ref} . This could be in a temperature controlled chamber, or zone box, although for greater precision the reference junctions would be inserted, in insulating glass tubes, in melting ice. These techniques are described in more detail in 7.6.

Figure 1 (b) illustrates a consequence of the basic thermoelectric effect, the so-called “Law of intermediate metals”. It follows from equation 1, which can be extended to any number of conductors in a circuit, that if in any conductor the two ends are at the same temperature, the limits of integration are equal and that term in the equation is zero. Therefore one may introduce any number of conductors into a thermoelectric circuit without affecting the output, provided that both ends of each conductor are at the same temperature. Care should be taken that all additional conductors in the circuit are, like the thermoelements, physically and chemically homogeneous otherwise the net e.m.f. generated in the conductor may not be zero even if the two ends are at the same temperature.

The circuits shown in Figure 1(c) and Figure 1(d) are similar to those in Figure 1(a) and Figure 1(b) except that additional conductors a' and b' are connected to the thermoelements a and b . It is often desirable to connect the thermocouple probe ab to longer lengths of cable without having to take great care that the change-over temperature is known and taken into account. This requires that the thermoelectric properties of the additional conductors should not differ by more than an acceptable amount from those of a and b . For this purpose extension and compensating cables are produced. The former use wires of nominally the same conductors as a and b , while in the latter they are different materials whose net thermoelectric power is similar to that of the thermocouple itself. For obvious reasons the use of extension and compensating cable is only advisable over restricted temperature ranges and in cases where a degraded accuracy is acceptable.

The use of extension and compensating cable illustrates another consequence of the basic thermoelectric effect, sometimes referred to as the Law of successive conductors. It follows from equation 1 that if two or more successive conductors in a circuit have identical thermoelectric powers (at all temperatures in the range of integration) then the net e.m.f. generated is not dependent on the temperatures of the junctions between them. The practical limitations to the use of the extension and compensating cables naturally depends on how similar the thermoelectric powers are.

4.2 Measurement of temperature differences

It is often said that thermocouples measure temperature differences and, indeed, at least two temperatures will be relevant in any measurement with a thermocouple. If equation 1 is integrated on the assumption that both S_a and S_b are constant, i.e. independent of temperature, then:

$$\begin{aligned} E &= S_a (t_1 - t_2) + S_b (t_2 - t_1) \\ &= (S_a - S_b) (t_1 - t_2) \end{aligned} \quad (5)$$

The measured e.m.f. is thus the product of the differences between the two thermoelectric powers and the two temperatures.

In practice thermoelectric powers are not independent of temperature and the measured e.m.f. is not simply proportional to the temperature difference. Over short temperature ranges, however, it may be possible to regard the thermoelectric power as constant, or to adopt an average value, in which case a thermocouple is a very convenient device for measuring temperature differences directly.

Figure 1(e) and Figure 1(f) give the basic circuits for differential thermocouples in the cases where conductor a is connected directly to the voltmeter, as would especially be appropriate for copper in a copper/copper-nickel thermocouple, or incorporating reference junctions to a third conductor, c . Extension or compensating cable (of conductor a' only) could in principle be included, although the resulting uncertainties may be too large compared with the difference $(t_1 - t_2)$ which is to be measured.

5 Thermocouple materials and their characteristics

5.1 General

Many combinations of metals, alloys and semiconductors have been used as thermocouples in scientific and industrial temperature measurement from well below 0 °C up to 2 300 °C and beyond. Each has been employed to satisfy as far as possible the various, often conflicting, requirements of sensitivity, range of use, chemical and physical stability in the process environment, availability in the required form, etc.

Base-metal alloys are the most widely used materials up to about 1 200 °C, though platinum-group metals and alloys would be preferred in applications requiring higher accuracy, especially at temperatures beyond the usual range of platinum resistance thermometers. Some types can be used up to 2 000 °C. At still higher temperatures it is necessary to use refractory metals and alloys. In this context “refractory” means “difficult to melt” and usually refers to tungsten, rhenium and their alloys and sometimes to molybdenum. Semiconductors, which can have very high thermoelectric powers, are mainly used in specialized devices near ambient temperature but, being specialized, they are not discussed further in this standard.

The principal qualities and limitations of the more important thermocouples in current use are discussed in 5.2 and 5.3. Compositions of alloys are given in percentages by weight unless otherwise stated. Compositions are not given for the base metal alloys because, with the exception of Type N, these are not specified in the standard and different manufacturers supply alloys with slightly different compositions.

5.2 Standardized thermocouples

5.2.1 General

Of all the thermocouple materials which have been employed and for which an extensive literature exists, only eight combinations have been fully standardized, although a number of others are also available commercially. Tables and polynomial expressions for the e.m.f.-temperature characteristics of the eight standardized thermocouples are given in Parts 1 to 8 of BS 4937²⁾. Their approximate e.m.f. outputs are given in Table 1 and Table 2, and plotted in Figure 2.

A thermocouple is designated by its material components, thus “positive thermoelement/negative thermoelement”. Standardized thermocouples are also designated by letter, e.g. Type K, and individual thermoelements are often specifically referred to by adding the letters P and N for positive and negative respectively, thus KP and KN. Thermocouple extension and compensating cable, and other associated components such as connectors, is usually identified by colour coding (see, e.g. IEC 584-3).

5.2.2 Type S: platinum-10 % rhodium/platinum

This is the thermocouple originally developed by Le Chatelier in 1886 and used to define the International (Practical) Temperature Scales from ITS-27 to IPTS-68 in the range from 630 °C to the freezing point of gold, 1 064 °C. It is suitable for use in oxidizing or inert atmospheres and may be used in reducing conditions provided that care is taken that insulators and sheathing materials are free of silicon. It may be used continuously at temperatures up to 1 500 °C and for brief periods up to 1 650 °C. For high temperature work it is advisable to use insulators and sheaths made of high purity recrystallized alumina to protect the thermoelements from contamination by metallic vapours, etc, which can cause deterioration and lead to a reduction in e.m.f. for a given temperature. Continual use at high temperatures can cause excessive grain growth and weakening of the pure platinum arm. There is also the possibility of diffusion of rhodium from the alloy into the pure platinum conductor, which again leads to a reduction in e.m.f. output.

Wires of 0.5 mm diameter are usually recommended as a compromise between economy and performance reliability. The thermocouple is not recommended for use under neutron irradiation.

5.2.3 Type R: platinum-13 % rhodium/platinum

This thermocouple may be used under the same conditions as Type S. However, it does have the advantages of slightly higher e.m.f. output and rather better stability than Type S. There are no real technical (as opposed to historical) reasons for the continued existence of both types, though in the UK Type R has been preferred because of its better stability.

5.2.4 Type B: platinum-30 % rhodium/platinum-6 % rhodium

The conditions of use of this thermocouple are similar to those for Types S and R, though since both thermoelements are alloys the upper limit is not restricted to the melting point of platinum. The mechanical strength of the thermocouple is greater, and e.m.f. drift due to diffusion of rhodium may also be less significant. Consequently the range of use extends to higher temperatures, 1 600 °C for continuous use and 1 800 °C for intermittent use. The e.m.f. output is less than that of Types S and R, and the combination would not normally be used below 600 °C. However it has the advantage that since the e.m.f. output is less than 3 µV below 50 °C, cold junction compensation is not usually necessary.

²⁾ IEC 584-1 is a related standard to BS 4937.

5.2.5 Type J: iron/copper-nickel (iron/constantan)

This thermocouple is particularly suited for use in reducing atmospheres, and it may also be used in vacuo or in inert atmospheres. It should not be used in sulfur-bearing atmospheres. Under oxidizing conditions both thermoelements oxidize, especially above 550 °C, and care needs to be taken in cryogenic use to avoid rusting of the iron which would result from condensation of water. This thermocouple is usually supplied as a matched pair because of variability in the thermoelectric power of iron wires.

Iron undergoes a magnetic transformation at 769 °C and a crystal transformation near 910 °C, both of which affect its thermoelectric power. Use of this thermocouple is therefore best restricted to lower temperatures. It is not recommended for use under neutron irradiation because of transmutation in the constantan.

Generally the thermoelectric output of a Type J thermocouple decreases with use. For example, a thermocouple made with 3.3 mm diameter wires can be expected to drift out of tolerance within a few hundred hours at 750 °C.

5.2.6 Type T: copper/copper-nickel (copper/constantan)

This thermocouple is much used in laboratory and small scale industrial temperature measurement over the range – 250 °C to + 400 °C, the upper limit being set by oxidation of the copper arm. Stability and reproducibility of ± 0.1 °C is possible in the range – 200 °C to + 200 °C. The thermocouples may be used in inert atmospheres or in vacuo up to 700 °C (although the tables given in BS 4937-5 and IEC 584 have an upper limit of 400 °C), but the copper is subject to severe embrittlement in hydrogen above 370 °C. It is not recommended for use under neutron irradiation.

The high thermal conductivity of the copper arm should be taken into account in considering thermal contact with the process and the depth of immersion required. Note that the copper-nickel alloy used for the negative arm is not interchangeable with that for Type J.

5.2.7 Type E: nickel-chromium/copper-nickel

This thermocouple has the highest output of the standardized thermocouples. The usable range extends from cryogenic temperatures up to about 900 °C in oxidizing or inert atmospheres, or 1 000 °C for intermittent use, and good stability can be achieved. It should not be used in sulfur-bearing atmospheres or in alternately oxidizing and reducing conditions. It is not recommended for use under neutron irradiation.

5.2.8 Type K: nickel-chromium/nickel-aluminium

This type is by far the most common thermocouple in industrial use. It may be used continuously in oxidizing or inert atmospheres at temperatures up to about 1 050 °C, and intermittently to 1 200 °C. It is also suitable for cryogenic use. It should not be used in sulfur-bearing atmospheres, or in alternately oxidizing and reducing conditions.

The positive thermoelement undergoes a reversible and time-dependent metallurgical order/disorder transformation between 300 °C and 500 °C such that on cycling through this temperature range, changes in calibration equivalent to several degrees may occur. If a thermocouple is to be used within but not beyond this range, better reproducibility would be obtained by first annealing it at 500 °C for about 30 min. However, consultation with the supplier is advisable if the thermocouple is required to match the e.m.f. specification after this treatment.

The output of a thermocouple made with 3.3 mm diameter wires may increase by the equivalent of 12 °C after about 1 000 h at 1 050 °C, due to oxidation. In general, for use above 800 °C in all atmospheres the thermocouples should be protected, as in the mineral-insulated metal sheath format (see 7.2).

5.2.9 Type N: nickel-chromium-silicon/nickel-silicon (nicrosil/nisil)

This thermocouple was developed to overcome the limitations in oxidation resistance and metallurgical stability of the other base metal thermocouples. It can be used continuously up to 1 100 °C and intermittently up to 1 250 °C, and also at cryogenic temperatures. Compared with Type K, Type N has better stability in the range 300 °C to 500 °C and at higher temperatures the oxidation resistance is much enhanced through the formation of a protective oxide film. Elements which are liable to undergo transmutation are avoided so that the thermocouple also has improved stability under neutron irradiation.

As well as giving the e.m.f.-characteristic of Type N, BS 4937-8 specifies the compositions (with tolerances) of nicrosil and nisil, in order that the full advantages of physical and chemical stability can be realized in practice.

5.3 Non-standardized thermocouples

5.3.1 General

Over the years many non-standardized thermocouples have been used for a variety of purposes. The non-standardized thermocouples given in 5.3.2 to 5.3.5 are available commercially.