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Temperature measurement —

Part 4: Guide to the selection and use of thermocouples

Committees responsible for this British Standard

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Department of Trade and Industry (National Weights and Measures Laboratory)
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Engineering Equipment and Materials Users' Association
GAMBICA (BEAMA Ltd.)
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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 It is a revision of BS 1041-4:1966 which is withdrawn.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 °C up to 3 000 °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 °C to 1 064 °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 μV/°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.s[1)] 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:

$$E = \int_{t_2}^{t_1} S_{\mathrm{a}}\,\mathrm{d}t + \int_{t_1}^{t_2} S_{\mathrm{b}}\,\mathrm{d}t \qquad (1)$$

where

S_{a} and S_{b} are the thermoelectric powers of conductors a and b (in μV/°C)

t_1 and t_2 are the junction temperatures (in °C).

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

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

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

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 µV/°C) and it is related to the thermoelectric power by the equation:

$$\mu = T(dS/dT) \tag{4}$$

where

T is the temperature (in K);

s is the thermoelectric power of the conductor (in µV/°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, $\prod$ (in µV), being equal to TS. Although the heat appears at junctions between conductors, it should be clear that $\prod$ is a temperature dependent property of individual conductors. Since the heating or cooling depends on the Peltier coefficients, $\prod_a$ and $\prod_b$ of the two conductors, such that $\prod_{ab} = \prod_a - \prod_b = T(S_a - S_b)$, 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:

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

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 4937[2]. 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.

5.3.2 ***Tungsten/tungsten-26 % rhenium; tungsten-3 % rhenium/tungsten-25 % rhenium and tungsten-5 % rhenium/tungsten-26 % rhenium***

Of the tungsten-rhenium alloy thermocouples, the tungsten/tungsten-26 % rhenium type is the cheapest but suffers from embrittlement problems in the pure tungsten arm. Tungsten-rhenium alloy thermocouples may be used continuously up to 2 300 °C and for short periods as high as 2 750 °C in vacuo, pure hydrogen, or pure inert gases, though selective vaporization of rhenium may occur at temperatures in excess of 1 800 °C. The American Society for Testing and Materials (ASTM) has published standards for the tungsten-3 % rhenium/tungsten-25 % rhenium and the tungsten-5 % rhenium/tungsten-26 % rhenium thermocouples including tables from 0 °C to 2 315 °C (4 200 °F) with a suggested tolerance of ± 1 % (ASTM Document E988). Beryllia and thoria insulators have been recommended for them, although some reaction may occur between wires and insulator at the upper end of the temperature range.

5.3.3 ***Iridium-40 % rhodium/iridium***

Thermocouples made from varying proportions of rhodium and iridium are the only ones that can be used without protection in air up to 2 100 °C, albeit only for limited periods. They may also be used in vacuo or inert atmospheres. The wires become very brittle and fragile due to grain growth after exposure to high temperatures. There are no standard reference tables, batch calibrations being supplied by the manufacturers. The thermocouple is not recommended for use under neutron irradiation.

5.3.4 ***Platinum-40 % rhodium/platinum-20 % rhodium***

This thermocouple may be used instead of Type B where a slightly higher upper temperature limit is required. It may be used continuously at temperatures up to 1 700 °C and for short periods up to 1 850 °C. Although reference tables exist, it is usual to obtain a batch calibration from the manufacturer. Conditions of use are as for Type B.

5.3.5 ***Nickel-chromium/gold-0.07 atomic % iron and nickel-chromium/gold-0.03 atomic % iron***

Usually referred to (with the incorrect order of the thermoelements) as gold-iron/chromel, such thermocouples were developed for cryogenic work (especially below – 200 °C) since dilute alloys of iron in gold exhibit a remarkably high thermoelectric power compared with other (nonmagnetic) alloys at very low temperatures. They may be used down to 1 K or lower. However, the Seebeck coefficient falls off rather rapidly below 4 K, which is a more usual lower limit. A reference table for the chromel/gold-0.07 % iron thermocouple is given in the ASTM publication STP 470B "Manual on the use of thermocouples in temperature measurement". In Europe a gold-0.03 % iron alloy thermoelement is more commonly used, with a reference table produced by the manufacturer.

6 Durability of thermocouples at high temperatures

6.1 Base metal thermocouples

6.1.1 ***General***

It is not possible to give definitive figures for the length of service to be expected of a thermocouple before replacement becomes necessary. The following factors can have a major effect on the service life of bare thermocouples unless reduced by special protection.

a) *Temperature.* As a general guide, for every 50 °C increase in operating temperature beyond 500 °C, the life expectancy of a base metal thermocouple is approximately halved.

b) *Wire diameter.* The diameter of thermocouple wire has a marked effect on the length of service. Doubling the diameter may produce a two-to three-fold increase in life.

c) *Cycling.* Thermocouples operating under temperature cycling, especially those cycled from ambient to temperatures in excess of 500 °C, may have a 50 % shorter life compared with thermocouples used continuously at the same peak temperature.

Table 3 gives some guidance as to the maximum continuous operating temperatures which bare thermocouples of different types and wire diameters can withstand for a service life of 1 000 h. It should be noted that changes in generated e.m.f. may occur under these conditions and regular calibration should be carried out as indicated in **10.3**.

The service life of bare thermocouples of a given wire diameter can be prolonged by provision of suitable protection to limit the onset or effect of oxidation. Protection may be in the form of close fitting ceramic insulators which help to retain oxidative products such as scale and thus limit progressive attack. More effective protection can be achieved by incorporation into a metal-sheathed mineral-insulated cable. A fuller discussion of these aspects is given in **7.2** and **7.3**.

6.1.2 ***Corrosion in controlled atmospheres***

Although thermocouples are mostly used in air, they are also extensively used in controlled atmospheres for heat treatment and in other hostile process environments. Such atmospheres are often corrosive to base metal alloys which may be used as sheathing materials as well as thermocouple conductors. Inert atmospheres have little or no effect on base metal thermocouple alloys provided that they are dry and do not contain residual oxygen or other contaminating vapours. Base metal thermocouples usually have improved service life under reducing atmospheres, provided again that the gas is dry, although copper develops severe embrittlement in hydrogen above 370 °C. Increased service life can also result from use in vacuo, although Types K, N and E suffer chromium loss at high temperatures through evaporation from the positive element.

Carburizing atmospheres cause corrosion in alloys containing chromium, in which a condition known as green rot develops. Chromium carbide forms along grain boundaries and subsequent oxidation becomes a progressive and rapid intercrystalline attack. The e.m.f. is markedly affected and failure rapidly occurs if the thermocouple wires are exposed to such atmospheres.

A similar attack to that experienced with carburizing atmospheres can occur in moist gases or in atmospheres with low oxygen content. The oxygen preferentially attacks chromium in the alloys, again creating green rot. Alloys containing increased iron and particularly silicon are relatively more resistant to this form of corrosion.

Sulfur occurs in many industrial furnaces, originating either from brickwork or from the charge within the furnace. Hydrogen sulfide gas attacks all base metal thermocouple alloys especially in the temperature range 600 °C to 800 °C. The sulfides of nickel, chromium and copper which are formed oxidize readily and failure rapidly occurs. The thermocouple life can be reduced to as little as 1 h or 2 h depending on the concentration of the sulfur-bearing gases, and the degree of protection given to them by sheaths.

Sulfur dioxide attacks the alloys in a slightly different manner, resulting in rapid intercrystalline corrosion. Alkalis, halogens and cyanides can cause serious corrosion at temperatures above 500 °C. Most molten metals, particularly those with low melting points, and their vapours, attack base metal thermocouple alloys.

Refractory cements consisting of oxides of zirconium, magnesium and aluminium, frequently give rise to sulfurous and carbonaceous gases when heated, and can therefore cause corrosion as described.

6.2 Noble metal thermocouples

Unlike base metal thermocouples, the length of service of thermocouples of platinum-group metals and alloys is not usually limited by oxidation but by mechanical failure due to grain growth or volatilization, or by contamination, which causes calibration drift. In the case of Types R and S it is usual for the pure platinum conductor to fail before the alloy.

To minimize the effects of grain growth and volatilization, specially prepared thermoelement platinum is available which retains a fibrous structure and higher strength at elevated temperatures. Alternatively, a platinum element of larger diameter could be used so as to reduce the service stress level in that element. However, in most cases where stress levels may not be the major factor, it remains usual practice to use wires of diameter between 0.25 mm and 0.5 mm for both elements, as a compromise between cost and performance reliability.

To minimize the effects of contamination the thermocouples should be insulated in close-fitting single-length high-purity recrystallized alumina insulators, and protected by sheaths of the same material. They should never be inserted directly into metallic tubes, and have to be protected from atmospheres containing metallic and non-metallic vapours e.g. lead, zinc, arsenic and phosphorus and from easily reduced oxides e.g. silica and iron oxide particularly when reducing conditions may be experienced. The use of mineral-insulated platinum-rhodium sheathed thermocouples often provides a rugged but still flexible, if expensive, alternative.

Noble metal thermocouples are normally supplied in the annealed condition, but for the most accurate work the wires should be cleaned and annealed before calibration and use, as described in **10.3**. Thereafter under common use in air the e.m.f. drift of Types R and S can be as little as 0.5 °C after 1 000 h at 1 100 °C, for 0.5 mm diameter wires. Larger drifts would occur at higher temperatures or for finer wires. It may be desirable periodically to remove and strip down the thermocouple, prior to cleaning, annealing and recalibrating it. Alternatively, a thermocouple designated as a reference standard instrument when new may be redesignated as a working standard thermocouple after a specified period of use.

Table 4 gives guidance as to the maximum recommended operating temperatures for the standardized noble metal thermocouples of 0.5 mm and 0.25 mm diameter for continuous and intermittent use in air.

6.3 Refractory metal thermocouples

The drift of refractory metal thermocouples is heavily dependent on the operating conditions and insulation material. Oxygen partial pressures greater than 0.1 mbar[3)] are known to cause physical degradation in only a few hours at 1 000 °C. Carbonaceous environments can be expected to cause the formation of embrittling carbides, and hence calibration drift. Atmospheres of dry argon, helium, hydrogen and nitrogen have been found to be suitable.

The length of service of refractory metal thermocouples is often adversely affected by poor design of the hot junction, leading to premature fracture. Correctly prepared units, insulated with high purity beryllia or thoria and operated in a suitable atmosphere, may exhibit drifts of 2 % of temperature after 1 500 h at 2 000 °C. Similar drifts may be expected after 100 h at 2 500 °C or 10 000 h at 1 750 °C.

7 Hardware and fabrication

7.1 General

A practical thermocouple necessarily consists of at least two conductors, made from dissimilar materials, usually insulated, and joined at one end to form the measuring junction. The wire used may range from less than 0.2 mm diameter for research applications, to more than 3 mm diameter for industrial use. Junctions are most effectively made by welding, although soft or hard soldering can be adequate. The welding, or soldering, technique used should be such that minimum change is caused to the composition of the thermocouple wires. Base metal thermocouples are usually welded electrically in an argon atmosphere. Platinum thermocouples may be welded using a small oxy-hydrogen flame.

7.2 Insulators

There is a wide choice of insulating materials for thermocouples. The insulation, where practicable, is colour coded to indicate the thermocouple type. The following materials are those most commonly used.

a) Poly vinyl chloride (PVC) can be used over the temperature range – 10 °C to + 105 °C. It is available either in figure-of-eight or flat-pair configurations.

b) Poly tetrafluoroethylene (PTFE) can be used from – 75 °C to + 250 °C (or to 300 °C for short periods). It is available in flat-pair or twin-twisted forms.

c) Glass-fibre, varnish impregnated, is used from – 50 °C to + 400 °C.

d) Glass-fibre plain (i.e. unvarnished) is usable up to 500 °C.

e) Ceramic insulators are available in various forms and materials. Porcelain fish-beads may be used on the larger sizes of base metal thermocouple wires (≥ 1 mm diameter). Mullite (aluminium-silicate) twin-bore insulators are extensively used with Type K thermocouples in industrial furnaces, either unprotected or housed in metal or ceramic sheaths, depending on the application. Platinum-metal thermocouples are best used in single piece twin-bore high purity alumina insulators in order to minimize the risk of contamination.

[3)] 1 bar = 1×10^5 N/m^2 = 1×10^5 Pa.

f) Mineral-insulated metal-sheathed (MI or MIMS) thermocouples consist of a metal sheath enclosing highly compacted mineral insulant in powder form (usually magnesium oxide) supporting and separating the thermocouple wires. Various forms of construction are possible. Cables are made having from two to six cores, in diameters from 0.5 mm to 8 mm. The junction may either be insulated from the sheath, or bonded to it. The insulated form of junction ensures freedom from ground-loop effects in the associated instrumentation, whilst the grounded junction type has a faster thermal response. It is important for good electrical insulation between the thermoelements and the sheath, especially at high temperatures, that the powder is kept free of moisture.

MI thermocouples have many advantages, namely small size, ease of installation, mechanical strength, reasonable flexibility, good isolation of the junction from hostile environments, choice of outer sheath to suit wide range of operating conditions, high stability, good insulation resistance, reasonable initial cost and ready availability. MI thermocouples are available in the usual material combinations, including platinum-metal types. Sheath materials available include mild steel, stainless steels, inconel, cupro-nickel, nicrosil and related alloys, and for platinum thermocouples, various platinum-rhodium alloys.

7.3 Protection, installation and testing

In some applications the thermocouple can be used without a protective sheath. Typical examples might be a heavy gauge Type K thermocouple used in an electrically heated metal treatment furnace, or a platinum-rhodium thermocouple in a clean research apparatus where the refractory components are made from high-purity alumina. However, in most applications the thermocouple has to be protected from the environment whose temperature is being measured; in many industrial situations a mineral-insulated metal-sheathed thermocouple will be used.

Metal protection tubes may be used with base metal thermocouples up to about 1 150 °C or, with high-purity alumina liners, with platinum thermocouples to the same temperature. Ordinary carbon steel tubes can be used in oxidizing atmospheres up to about 700 °C. Austenitic stainless steels (300 series of BS 970) can be used at temperatures up to about 850 °C, again in oxidizing atmospheres. Ferritic stainless steels (400 series of BS 970) may be used up to about 1 150 °C in both oxidizing and reducing atmospheres. Inconel may be used in oxidizing conditions only at temperatures up to about 1 150 °C.

The protection tube may take the form of a thermowell, which consists of a closed end re-entrant tube designed for the insertion of a temperature sensing element, and provided with means for pressure-tight attachment to a vessel. Various standards for thermowells exist, including BS 2765, as well as specific chemical and petroleum industry standards.

Ceramic protection tubes are required at high temperatures, and they are also often used at lower temperatures in atmospheres which are corrosive to metals. The material most commonly used is mullite, which may be used at temperatures up to 1 600 °C. It has good mechanical strength and reasonable resistance to thermal shock, but because of its silica content it should not be used with platinum thermocouples. An outer sheath of silicon carbide is sometimes used where greater resistance to thermal shock, abrasion, and chemical attached is required. For thermocouples used at temperatures above about 1 200 °C, or where a gas-tight tube is needed, recrystallized alumina is the most suitable sheath material.

The construction and installation of thermocouples, compensating cables and copper lead wires should be such that the wires are protected from the ingress of moisture, from mechanical damage and from the effects of electrical interference. These factors become more important as the length of wire increases. It is recommended that wires intended for long-term installations in particular should be tested after assembly into their final form with the connectors and protective sheaths in place. Possible tests include the following:

a) immersion in water, which should give no significant reduction in the leakage resistance between the thermoelements and the protective sheath;

b) gas pressurization to show mechanical strength or, if helium is used, freedom from leaks;

c) checking the flexibility of the assembled thermocouple by winding it round a suitably-sized mandrel, with a subsequent test for cracks and splits, either by visual inspection or by pressurization with gas;

d) measuring the leakage resistance of the thermocouple at the maximum operating temperature, as all insulating materials tend to become partially conducting at high temperatures.

The presence of moisture in the insulation around the wires used in thermocouple circuits not only reduces the leakage resistance, but may lead to the generation of e.m.f.s by electrolytic action, giving large errors in the indicated temperature. The thermocouple may be protected with insulating materials, such as rubber or plastics, which are impervious to water. Cotton coverings may be impregnated with these materials, and this also prevents fraying of the insulation. It is equally important to ensure that moisture cannot enter at the joints or connections between cables, so these should be sealed. For temperatures up to 300 °C to 400 °C wires may be enamelled for protection.

Although the selection of thermocouple conductors of small diameter may significantly decrease the cost of long runs of wiring, this has the disadvantages of increasing the total electrical resistance of the circuit, and of decreasing its mechanical strength. In the latter respect, moulded insulation would give mechanical protection. For very hazardous installations, the connecting wires should be mounted in metal or plastics conduit, or in flexible stainless steel tubing. Copper leads are available in a continuous copper sheath filled with magnesia or alumina powder as an insulator. A grounded metal sheath, screen or conduit should prevent electrical pick-up from lighting and radio-frequency interference. In every case, installation should be such that it is not possible to strain the connecting wires.

7.4 Thermocouple connectors and switches

The majority of thermocouples are terminated in one of the following ways.

a) *In bare wires.* In laboratory applications the wires are usually each separately twisted with copper wires to form reference junctions which are then inserted in glass tubes into a crushed ice/water mixture at 0 °C. Alternatively the thermocouple may be connected directly to the measuring instrument, if appropriate cold junction compensation is provided. For long runs the wires may be brazed or welded or otherwise connected to extension or compensating cable to form an intermediate junction. The thermoelements should be insulated electrically from one another with sleeving or tape, and thermally insulated from draughts and changes in ambient temperature.

b) *Through connectors of the quick disconnect type.* The pins and sockets of these are made of alloys similar to those used for the thermoelements or, in the case of noble metal thermocouples, of alloys with similar thermoelectric characteristics. The bodies of the connectors, which are usually made of plastics, or ceramics for high temperature applications, should be colour-coded for the different thermocouples. The pins or the bodies are asymmetric so that they can only be joined with the correct polarity. Some models clip together on insertion, so that the connectors cannot be pulled apart accidentally.

c) *Through protective terminal heads.* For heavy duty applications, the thermocouple wires are connected to a terminal block, usually nylon or ceramic, inside a solid aluminium case. Access to the connections is by removal of a protective cover.

All thermocouple connections and switches should be clean and of low resistance, as even very thin oxide films can affect the measurement of the low thermoelectric e.m.f.s generated in most applications. This condition may be met by constructing the switch contacts of corrosion-resistant metals, or by coating them with such metals, and by designing them with a large contact area. Additionally, the closing of the circuit should be made with a wiping action, so that the surface layer is broken, and good metal-to-metal contact achieved. The thermocouple wires should be clamped in position in the switch or connector, to prevent strain on this contact if the wires are accidentally pulled or tightened. It is good practice to switch both thermoelements with a double-pole switch, especially if one side of the circuit is earthed. Low thermal e.m.f. switches can be employed to scan or sample the signals from large numbers of thermocouples. For thermocouples mounted on rotating objects, connection to the measuring instrument may be made through contacts on slip-ring assemblies. These are available for operation up to speeds of 2 000 rev/min, and should generate less than 5 µV of electrical noise in the measuring circuit.

Connectors and switches should not be placed in regions of high temperature gradient and should be kept away from sources of heat.

7.5 Extension and compensating cables

7.5.1 *General*

Extension and compensating cables should incorporate wires having roughly the same thermoelectric properties as the corresponding thermocouple. Extension cable is made from nominally the same conductors as the thermocouple itself, while compensating cable is made from a different pair of alloys. Thus Type K extension cable, designated KX, is made from nickel-chromium and nickel-aluminium (possible slightly sub-standard thermocouple material), while the compensating cable, KC, is made from other conductors (see Table 5).

Extension and compensating cables only have to match the e.m.f. temperature characteristic of the thermocouple wire over a restricted temperature range. Since it is the combination of conductors in the cable whose e.m.f. has to match that of the thermocouple, rather than each conductor separately to match the appropriate thermoelement, it is important that the two junctions in the connectors are at the same temperature. This applies particularly to compensating cable, where substantial errors could otherwise result.

Extension and compensating cables are used in industry for two main reasons as follows.

a) *Cost saving.* It would be prohibitively expensive to run long lengths of platinum-metal thermocouple wire, or heavy-gauge base metal thermocouple wire, all the way to a remote indicator. Instead, there would be a junction box close to the furnace, probably at the thermocouple head, where the transition from thermocouple wire to extension or compensating cable takes place. This is illustrated schematically in Figure 1(c) and Figure 1(d).

b) *Mechanical strength.* Extension and compensating cables are usually made of relatively light multi-stranded wires. This is cheaper, more flexible, and less likely to fracture than if larger diameter single-strand thermocouple wires are carried for any distance.

In the case of the simple furnace pyrometer systems in which the current produced by the thermoelectric e.m.f. is used to drive a moving coil galvanometer directly, the extension or compensating cable can have an important part to play in determining the total electrical resistance of the circuit, and hence in ensuring that the e.m.f. indication is correct.

Manufacturing tolerances for extension and compensating cable are given in IEC 584-3 to which reference should be made for the current specifications. These give the e.m.f. tolerances which apply when extension or compensation cable for the various standardized thermocouples is included in the circuit, in addition to the tolerance for the thermocouple itself. The standards also specify the temperature range over which the cable is expected to meet the tolerance. Thus for example, the Class A tolerance for Type K extension cable, KX, is ± 60 µV, and the cable is restricted to the range – 25 °C to + 200 °C. This is equivalent to about ± 1.5 °C at all measurement temperatures above 0 °C.

As compensating cable cannot so easily match the thermocouple characteristics, no Class A tolerances are given. For Types R and S (for which the same compensating cables are used) two Class B tolerances are given, RCA and RCB (or SCA and SCB), of ± 30 μV and ± 60 μV, which are valid for cable within the ranges 0 °C to 100 °C and 0 °C to 200 °C respectively. These are equivalent to about ± 2.5 °C and ± 5 °C when a temperature of 1 000 °C is measured. Note that these temperature equivalents increase significantly when lower temperatures are measured, and the wisdom or cost-effectiveness of using compensating cable in such measurements may be questionable. IEC 584-3 should be consulted for e.m.f. specifications for compensating cables. The compositions of the conductors in compensating cable are not standardized, but Table 5 indicates the constituents of the alloys most commonly used. The compositions of the copper-nickel alloys are chosen to meet the various e.m.f. requirements.

7.5.2 ***Colour codes***

It has long been the practice to use colour codes for extension and compensating cables, and other thermocouple accessories, so that they may easily be distinguished and identified for what they are. Unfortunately the codes adopted in the past in Britain, the USA, Germany, Japan and elsewhere were not the same and, moreover, they were often mutually incompatible. After many years of trying to reconcile the various interests, in IEC 584-3 the IEC finally adopted a completely new colour code for all standardized thermocouples, with the exception of Type N, and this IEC Standard is recommended for national and international use although, inevitably, the former national codes will linger on. IEC 584-3 also specifies additional optional alpha-numeric identification markings for thermocouple cables.

7.6 Reference junctions

The reference junction(s) have to be situated in an isothermal region whose temperature is known or otherwise taken into account. There are four approaches to achieving this as follows:

a) the junction temperature may be maintained at 0 °C;

b) the junction may be maintained at some other fixed or measured temperature;

c) the junction temperature may be allowed to vary, some compensation being built into the measuring circuit to offset this variation;

d) the junction temperature may be allowed to vary, compensation being effected mechanically in the indicator.

Maintenance of the reference junction at 0 °C is the best approach to achieve accurate results. For laboratory purposes an ice-water bath is convenient and has the considerable advantage that thermocouple reference tables (and most calibrations) have 0 °C as their reference point. The ice point can be measured without difficulty to a tolerance of ± 0.01 °C, and for most thermocouple work crushed tap-water ice is quite suitable. The junctions are inserted in glass tubes into the melting crushed-ice contained in a wide-mouth vacuum flask. A depth of immersion of about 15 cm would usually be appropriate. Some care has to be taken to avoid errors, the most obvious of which is the 4 °C error possible if enough ice melts for the junctions to be immersed in water covered by a layer of floating ice. More subtle is the error caused by the use of fresh ice which may initially be at a temperature considerably below 0 °C. The ice should always be wet but not swimming.

Automatic ice-point devices are more convenient to use than ice-water mixtures, and they are readily available. They make use of semiconductor thermoelectric (Peltier) cooling devices, and use the large expansion of water on freezing to actuate the control system. They can operate very effectively, giving temperature errors of less than ± 0.1 °C but some care needs to be taken with thermal loading and immersion errors as they do not have the thermal capacity of an ice-bath.

With any reference junction operating below ambient temperature the possibility of condensation on the thermocouple wires, leading to a wet junction and hence the possibility of a galvanic cell being set up, has to be guarded against.

As an alternative to maintaining the reference junction at 0 °C it may instead be maintained at a temperature somewhat above the highest likely ambient temperature. This method is most suitable where it is desired to use copper cable in place of long runs of thermocouple wire or compensating cable, or where large numbers of thermocouples are involved, i.e. it is easier and cheaper to provide an enclosure operating at, for example, 50 °C than a cooler of the same capacity. The temperature uniformity and control within the oven obviously has to be such that the overall accuracy of the whole system is not prejudiced. When using reference junctions maintained at a reference temperature above 0 °C in this way with reference tables or instruments applicable to 0 °C, the e.m.f. corresponding to the reference temperature has to be added to the thermocouple output.

With cold junction compensation the temperature of the reference junction (typically the terminals of the measuring instrument) is allowed to vary, the variation being sensed by a suitable device, such as a platinum resistance thermometer (RTD) or a thermistor, situated as near as possible to the junction. By means of appropriate circuitry an e.m.f. is produced which varies with temperature in such a way as to compensate for changes in the temperature of the reference junction. This system can be made to work well over the usual range of ambient temperatures and is widely used in electronic temperature controllers and indicators where an accuracy of a few degrees is acceptable. Electronic reference junction compensators are also available as discrete modules, either mains or battery powered. If large numbers of thermocouples are involved the reference junctions may be arranged inside a single thermally insulated zone box whose temperature is measured. Although cold junction compensation can be acceptable for many applications, its accuracy will depend on the range of reference junction temperatures encountered. It may not perform well if the ambient temperature is subject to rapid changes. The effectiveness of the compensation may be tested by shorting the inputs, whereupon the device should indicate the temperature of the input connections, over the complete specified range of ambient temperature.

Mechanical compensation is used in the furnace pyrometer galvanometer type of instrument. The reference junction here is at the terminals of the instrument, and compensation is applied by means of a bimetallic element acting directly on the hairspring of the indicator. Hence, with no input, such an instrument should indicate the ambient temperature. This is not a particularly accurate method, but is acceptable for the precision of the total system.

8 Electromotive force measurement

8.1 General

Thermocouple e.m.f.s typically range from microvolts to millivolts. The resolution required may vary from a fraction of a microvolt for precision measurements with platinum-group thermocouples to 200 µV or so for simple moving-coil indicators used with Type K thermocouples on industrial furnaces. Instruments employed to measure the e.m.f.s may be classified according to their principle of operation into one of three groups as follows:

a) galvanometric instruments, including furnace pyrometers;

b) potentiometric instruments, including chart recorders;

c) digital instruments, with or without recording systems.

Galvanometric instruments employ moving coil meters to measure the current produced by the thermoelectric e.m.f., and to display it directly as the deflection of a pointer. Generally this group is robust, inexpensive and simple in design, but not very accurate. The non-linear e.m.f. temperature characteristic of the thermocouple can be accommodated either by means of a non-linear scale, by means of non-linear deflection, or by a combination of the two. In addition, a form of cold-junction compensation can be introduced by the use of bi-metallic devices acting on the meter hair springs. These indicators are much used on industrial furnaces and are commonly graduated in 5 °C or 10 °C divisions.

Potentiometric instruments are still used for the most accurate measurements. They operate by balancing the thermocouple e.m.f. against a known fraction of a reference voltage. Laboratory precision instruments are capable of a resolution of 0.1 µV, and an accuracy of about ± 1 µV. However, this is only attainable with a properly maintained and calibrated instrument. Precision potentiometers can also be used as voltage sources for checking other instruments, e.g. digital voltmeters throughout their range, not just at a specific point.

Potentiometric chart recorders are electro-mechanically operated potentiometers and are much used both in laboratories and in process control plant for the continuous recording of temperature. If small temperature changes are to be investigated their effective scale sensitivity may be increased by using a stable voltage to back-off most of the thermocouple e.m.f., the remainder being amplified for the chart. In theory at least, with sensitive modern recorders it is possible to record changes of a fraction of a degree at temperatures of 1 000 °C or more in this way. In practice, however, it is difficult to find a sufficiently stable backing-off voltage source to be able to do this accurately for more than a short period of time.

Digital instruments convert the signal to digital form for display. If this is in volts, the instrument is known as a digital voltmeter (DVM), or, for panel-mounting systems, a digital panel meter (DPM). If the signal is processed to display temperature directly, the instrument is termed an electronic or digital thermometer. Although originally expensive, the price of these instruments has fallen rapidly with improvements in electronic design and with the increasing availability of precise integrated circuits for a variety of functions.

Digital voltmeters are in effect automatic potentiometers. Many are capable of 0.1 μV resolution with an accuracy of a few microvolts over a period of 6 months or so. However, in thermocouple thermometry e.m.f.s have to be measured absolutely and much therefore depends on the quality of the internal voltage reference. This should periodically be checked, for example by measuring the e.m.f. of a basic Weston cell, and for the best results a full calibration should be obtained at regular intervals.

In any precise measurement of small d.c. voltages the influence of stray thermal e.m.f.s have to be guarded against by shielding all connections, terminals, etc., from draughts, and by working in an environment held at a steady temperature. A precision potentiometer facility should always include a multi-pole reversing switch to enable all connections to the instrument to be reversed. A mean is then taken of the forward and reverse readings for each measurement, in order to cancel out the effect of stray e.m.f.s in the measuring system.

8.2 Instrument uncertainty

As the need for accuracy in temperature measurement and control with thermocouples have become increasingly stringent it has become more important than ever to estimate the associated uncertainties. These may be separated into two components, those arising from the thermocouple sensor itself and those from the measuring instrument. In most cases the dominant factors are the uncertainty in the thermocouple characteristics, arising from the manufacturing tolerance or the change in characteristics with use, and uncertainties arising from the use of extension or compensating cable, connectors, switches, etc., in the circuit, and these are discussed elsewhere in this standard.

It is however still necessary to assess the uncertainties involved in the use of the measuring instrument. There are four main considerations as follows.

a) *The resolution and repeatability of the reading of the instrument.* Clearly a digital instrument cannot be read to better than one unit in the least significant figure. The effect of internal electrical noise may result in the error being larger than this. External interference or pick-up on the input signal may have a similar result.

b) *Errors in the zero and scale factor.* In general, errors arising from offsets or drift in the zero readings of modern instruments are unimportant, as electronic techniques for their removal have improved significantly. The error in the scale factor or gain of an instrument may result either from its original calibration or from changes produced by long-term drift of components or by shorter term variations in the ambient temperature.

c) *Linearity errors.* In the case of voltage-reading instruments, linearity errors are a reflection of the variation in gain of the instrument with the amplitude of the input signal. In the case of digital thermometers, in which the response is deliberately non-linear in order to correct for the thermocouple characteristic, the error is normally expressed as the deviation, in terms of temperature, from the standard reference table for the relevant thermocouple type. The function of a class of instruments, often misleadingly called thermocouple calibrators, is to generate voltages corresponding to the thermocouple e.m.f. at selected temperatures. When fed into the input terminals of a digital thermometer, the deviation of the reading from the nominal value is a measure of the linearity error, assuming that the calibrator is correct. It is necessary to avoid thermal e.m.f.s which may affect the reading, and special care has to be taken with instruments with automatic cold junction compensation; the instrument should display the temperature corresponding to the e.m.f which is the sum of the applied e.m.f. and that corresponding to the cold junction temperature.

d) *Errors in the reference junction compensation.* Instruments with this facility should be tested by checking their operation over the specified range of ambient temperature, using a shorted input or an input signal of known magnitude. For a shorted input the instrument should read the temperature of the input connections, over its specified range of ambient temperature.

9 Signal processing and logging

NOTE As signal processing is common to virtually all process control, only a few aspects are discussed.

9.1 Amplification and transmission

The amplification required is usually in the range 10 to 100 and it is often adjustable so as to achieve interchangeability of instruments and sensors. As accuracy of reading in microvolts is important, the amplifier has to possess a low noise level, low input offset drift, and a low input temperature coefficient. The total contribution from these should not amount to more than a few microvolts over the operating temperature range and life of the instrument. This requirement limits the useable types to the best d.c. amplifiers, particularly those with an automatic self-zeroing facility, or to chopper-stabilized types. Satisfactory operation from battery power supplies is required for portable instruments.

An additional advantage obtained with the introduction of an amplifier into the electrical circuit is that it may be used to remove the effects of thermocouple resistance, allowing extended runs or very fine wire thermocouples to be used. In both cases, the increased resistance may lead to high noise levels or pick-up at the input, but these may be handled by incorporating a filter in the input stages.

Alternatively, it is possible to take advantage of the low output impedance of modern amplifiers by placing them close to the point of measurement, and driving the connecting leads to the measuring instrument from the amplifier output. For long runs, or where a very low output impedance is desirable (for example, to reduce the level of noise interference), special buffer amplifier stages, termed "line drivers" may be added to the linear amplifier. If noise is a particular problem, the amplifier may be followed directly by a voltage-to-frequency (V/F) converter, so that the signal is transmitted in pulse form, and is therefore much less sensitive to interference.

Instruments based on these principles, but with the output transformed into a current signal, usually in the range 4 mA to 20 mA, are known as temperature transmitters, and are specified in BS 6175. Cold junction compensation is usually included in the transmitter or in the mounting rack for a group of transmitters. Linearization, however, is not usually incorporated.

9.2 Linearization

One of the important considerations in the original development of industrial thermocouples was to obtain a linear variation of the thermoelectric e.m.f. with temperature. For many modern applications, however, the residual deviation from linearity is significant and has to be taken into account. Where the measuring instrument gives a reading of e.m.f., the operator can simply convert this into the equivalent temperature with the aid of calibration or reference tables. This is accurate and sufficient for many purposes, but generally it is more convenient for the measuring instrument to display temperature directly. The term linearization is usually reserved for the automatic correction of signals to achieve this aim.

In galvanometer systems, the simplest technique involves the use of a non-linear scale on the display. It is also possible to make the response of the galvanometer movements non-linear, but in both cases the correction is relatively crude and not easily adjusted.

Electronic linearization is capable of much greater accuracy. A common technique is to break up the continuous but non-linear variation of e.m.f with temperature into a set of linear segments, continuous at the break points but varying in slope between them. In analog circuitry, the break points are defined by a set of reference voltages applied through diode switches, which add extra resistive elements into the gain-determining feedback network. In digital instruments, the break points may be held numerically in solid state memory and compared with the digital output, thereby largely eliminating the problem of drift in the reference voltages.

The accuracy of the correction depends mainly upon the number of segments. With digital instruments, this can be large and instruments can be produced with characteristics very close to those given by the thermocouple reference tables. Modifying such an instrument to work with a different thermocouple type involves mainly the replacement of the read-only memory (ROM) integrated circuit containing the breakpoint sequence.

Alternatively, linearization may be achieved with a continuous representation of the thermocouple characteristic. In analog circuitry, a number of non-linear circuit elements are available which allow logarithms, exponentials, powers and roots of signals to be obtained. A suitable combination of these with the linear elements enables a continuous representation of the characteristic to be derived. It is difficult, however, to achieve an overall accuracy much better then about 0.2 % to 0.5 % over a temperature range of hundreds of degrees. Some modern measuring instruments employ continuous linearization after analog-to-digital conversion, with a functional representation of the thermocouple characteristic whose coefficients are stored in read-only memory and evaluated by a microprocessor. The mathematical accuracy achieved may be very high and the method avoids the discontinuities in slope associated with the linear segment technique. It is also simple to implement if the instrument design already includes a microprocessor for other purposes.

9.3 Zero suppression

In many applications, accurate temperature measurement is only required over a limited range, generally around an optimum value at which the process or system being controlled is most effective. Below this range measurement is not required, while at higher temperatures it is sufficient to establish an alarm condition. Restricting the temperature range to be displayed enables the resolution of the measuring instrument to be increased and, in principle, higher accuracy to be obtained. However, this has to be obtained by increasing the gain of the system, and the advantage may be offset by an accompanying loss of stability and an increase in the noise level. This is particularly the case where the range required is tens of degrees from ambient temperatures, where the suppression of zero, corresponding to the lower limit of the working range, is large.

In many respects, the techniques employed in the suppression of zero are very similar to those used for reference junction compensation except that the correcting signal is constant and much larger. Both may be combined if the reference junction is controlled at the temperature of the offset zero and the uncompensated signal from the thermocouple displayed directly. This technique is rather limited in the zero suppression which can be achieved, and it is not widely used. For galvanometric displays, a simpler method is to impose a reverse torque on the meter hairspring, such that the meter movement starts at the required lower limit.

In most cases, zero suppression is achieved by subtracting an electrical signal of the required magnitude from the thermocouple e.m.f. The reading displayed is the difference from the offset zero. To avoid damage to electronic circuits or meter movements, off-scale readings may be clamped to a fixed level close to the offset zero.

The resolution of digital instruments is generally so high that zero suppression techniques are not required. In a few cases where it may be of value, it is possible to apply the analog signals subtraction method described, or to subtract the required offset digitally from the output of the analog-to-digital converter. As this device is still required to operate over the complete range, the latter method is only of value where the resolution of the digital display is the limiting factor and this is rarely the case.

9.4 Thermocouple alarm systems

At high temperatures it is often essential that immediate warning is given of failure, to prevent damage to equipment and process resulting from the temperature exceeding the permitted maximum. This is particularly so where the thermocouple forms part of a feedback control system, as its failure could lead to maximum power being applied continuously to the controlled system. At lower temperatures where thermocouple lifetimes are much longer, failure is more often due to mechanical damage either upon installation or during start-up. Under these conditions, faulty thermocouples should be detected by plant engineers in routine tests, before the situation can become hazardous.

In either case, however, it is desirable for measuring instruments to incorporate elements which can detect the breakage of a thermocouple sensor, and initiate the appropriate action. In controlled systems, it is required that the fault will not produce an unsafe condition, and this means that the power supplied should be reduced so that the temperature falls to a safe level. In addition, the measuring instrument may give an audible or visual warning.

The simplest and commonest technique for achieving these aims is to connect a voltage source to the thermocouple input through a high resistance. In normal operation, the thermocouple acts as a low resistance shunt, and the effect is to produce a small, nearly constant, offset. This may be removed by adjusting the zero level at the input. If the thermocouple breaks, however, the voltage source is now in series with the high input impedance of the instrument. The input voltage rises beyond the maximum expected thermocouple signal, and an alarm can be activated. In feedback control systems, the temperature appears to be too high, and the power is reduced or switched off.

This technique has two major defects. If a short-circuit occurs between the thermoelements (apart from at the junctions), the shunt action is maintained while the output from the sensor falls to a low level. The controller, attempting to raise the thermocouple signal, increases the power supplied, irrespective of the real temperature in the hot zone. The second problem occurs in the offset signal produced by the voltage source. If the thermocouple resistance changes, either when the thermocouple is replaced or as its temperature changes, the zero level correction may not be adequate and an error may be introduced into the reading. While the error upon replacement may be removed by further adjustment of the instrument, it is much more difficult to correct for the change of resistance with temperature. In order to overcome these difficulties it may be expedient to incorporate an independent over-temperature unit fitted with its own sensor. This will switch off the power to the heater and, if required, sound an alarm, if the temperature rises above a predetermined level.

9.5 Data loggers

For applications where large numbers of thermocouples are to be monitored or read, scanners and data loggers are required. These consist of electrically controlled sets of switches, which connect each thermocouple channel in turn to the measuring instrument, usually a DVM. The readings are then logged, i.e. printed, plotted or sent to a data storage device. If channels are to be monitored to ensure only that the readings lie between certain levels, this condition may be tested in an auxiliary unit and it is then unnecessary to print or store the readings unless an alarm condition arises. The time interval between consecutive scans can be set in the scanner.

The switches in the scanner have to possess low thermal e.m.f.s in order to avoid errors. Although motor-driven selector switches have been employed, improvements in the design of reed relays have resulted in their general acceptance. These have the advantages of being small, requiring low power input, switching rapidly from one channel to the next, and possessing a long life. Most reed relays have thermal e.m.f.s which, under normal operating conditions, are below 20 μV. Those specially developed for thermocouple switching, and commonly known as low thermal e.m.f. reed relays, possess unwanted thermal e.m.f.s below 1 μV. Input connections to the scanner have to be made in an isothermal region. The temperature in this region has to be monitored with an independent thermometer to provide cold junction compensation, if required.

Since the thermocouples connected to the data logger may be of more than one type, it is usual for the measuring instrument to read voltage only. Linearization may be provided within the data logger, especially if it already contains a microprocessor which can be programmed with the coefficients for the different types and the channel numbers of each type.

10 Thermocouple reference tables, tolerances and calibration

10.1 Tables and tolerances

In order to facilitate the practical use of thermocouples as interchangeable units they are usually made to comply with the e.m.f.-temperature relationships given in IEC 584-1 and BS 4937. These are expressed in the form of tabulated values of e.m.f. resolved to 1 μV at 1 °C temperature intervals, and values of temperature resolved to 0.1 °C at approximately corresponding intervals of e.m.f.

In many applications using microprocessors or small computers the reference tables are not convenient to use, and functional representation of the e.m.f.-temperature relationships is required. IEC 584-1 and BS 4937 give the polynomial functions from which the tables were derived, but since these cover wide temperature ranges they are fairly complicated and may not be convenient to use either. This is especially so because values of temperature cannot be calculated from measured e.m.f.s without iteration. For these reasons simpler equations, valid over reduced temperature ranges and within stated accuracies, are often used as approximations to the specified polynomials.

In practice, thermocouples cannot be made to comply exactly to published tables, and they are therefore supplied, often in pairs of matched conductors, to an agreed tolerance. Normally this would be one of the tolerance classes published in IEC 584-2 and BS 4937-20. Non-standardized thermocouples are usually supplied to the manufacturers' own specifications.

Thermocouple materials are checked by manufacturers at a number of temperatures in the probable range of use, though not usually below 0 °C unless requested. Information on the acceptance tests carried out for thermocouple wire and extension and compensating cable should be available from the supplier. If additional confirmatory tests are required especially below 0 °C or at very high temperatures, then this should be arranged before purchase.

10.2 Calibration

Where the usual tolerances are not sufficient it may be possible to purchase wire from the manufacturer to tighter tolerance as a special order. Usually, however, the wire or the complete thermocouple will have to be calibrated, i.e. the e.m.f. has to be measured at a set of known temperatures. This may be done at a limited number of fixed points such as the melting points of gold and palladium for the calibration of a platinum-rhodium thermocouple, or by comparison with calibrated thermometers or thermocouples at a larger number of points spanning the required range. For the former the calibration data would be used to generate a table or curve of differences or corrections to the reference table. For the latter it may be preferable simply to fit a curve to the calibration data directly, but in either case a full table of the thermocouple e.m.f. versus temperature may be produced.

Platinum-rhodium and refractory metal thermocouples are often calibrated by fixed point techniques. For the greatest accuracy attainable with platinum-rhodium thermocouples (about ± 0.3 °C at temperatures up to 1 100 °C), calibration would be made at the freezing points of zinc, silver and gold (419.527 °C, 961.78 °C and 1 064.18 °C respectively), and possibly also at the freezing point of aluminium (660.323 °C), using substantial ingots of the metals. For calibrations extending to higher temperatures, for which less accuracy can be expected, the so-called wire-bridge method is commonly used. In this method a wire, about 10 mm long and 0.5 mm diameter of a metal whose melting point is accurately known (usually gold or palladium, 1 064.18 °C and 1 553.5 °C respectively) is connected in the junction between the two wires of the thermocouple under calibration, so as to form a short link or bridge. This is placed at the centre of a small tubular furnace set to a temperature just below the melting point of the bridge. The temperature is then caused to increase steadily at about 1 °C or 2 °C/min. Alternate readings are made of the test thermocouple and a second platinum-rhodium thermocouple which monitors the rate of rise of the furnace temperature. When the bridging wire begins to melt, the e.m.f. of the test thermocouple becomes constant for a minute or two and then falls to zero as the circuit breaks, whereas the output of the monitor thermocouple continues to rise at a uniform rate. Since the melt occurs at the junction, the e.m.f. value at the plateau closely corresponds to the melting point value required. It is not necessary for the monitoring thermocouple to be in close contact with the test thermocouple, and the furnace can be quite small, a thermocouple immersion of about 150 mm in length is adequate. It is quite possible by this simple and inexpensive technique to achieve a reproducibility of at least ± 0.5 °C at the gold point and ± 1 °C at the palladium point for new wires. Total calibration uncertainties may be ± 1 °C up to 1 100 °C and ± 2 °C up to 1 600 °C. Platinum melting point (1 767 °C) measurements may be carried out for Type B and refractory metal thermocouples with uncertainties of about ± 2 °C.

Calibrations of base metal thermocouples are more usually carried out by comparison with standards traceable to the International Temperature Scale. These could be thermocouples, platinum resistance thermometers or radiation thermometers. The calibration environment will depend upon the temperature region. From – 100 °C to + 250 °C baths of circulating acetone, water or oil are suitable, in the lower, medium and higher parts of the range, respectively. At lower temperatures other fluids such as iso-pentane can be used, and at – 196 °C a bath of boiling liquid nitrogen provides a convenient environment. All these fluids require appropriate care in handling, and the baths should provide effective temperature control and circulation of the fluid throughout the volume, in order to achieve the required isothermal conditions. From about 180 °C to 550 °C baths containing a molten mixture of sodium nitrite and potassium nitrate salts may be used, provided that proper safety precautions are taken. For the most precise work over this whole range platinum resistance thermometers would be used as the standard thermometers. At least two standards should be used so as to provide an adequate cross-check of the complete calibration system, and all the instruments have to be used at adequate immersion.

As an alternative to baths of circulating liquid, fluidized sand baths are also available. In these a fine powder, usually alumina, is fluidized by passing a current of air through it. By heating the air and suitably arranging the flow, a central region of uniform temperature can be achieved. These baths commonly operate from near room temperature up to 600 °C or sometimes as high as 1 000 °C. Since air is passed through the system rather than recirculated, and has a relatively low heat capacity, the temperature uniformity and stability of sand baths is not as good as that of a good liquid bath. However, it can be improved somewhat by incorporating a small copper or nickel block into which the thermocouples are inserted.

At temperatures above about 600 °C calibration is best carried out in a horizontal tubular furnace of length suitable for the gauge of thermocouple under test. The reference standards would usually be platinum-rhodium thermocouples suitably protected from contamination. The furnace should include a metal block to reduce temperature gradients, with holes into which the standard and test thermocouples are inserted. Nickel is a suitable material for this purpose up to about 1 100 °C.

For calibration by comparison at temperatures above 1 100 °C, it is preferable to use a radiation thermometer standard. In this case the thermocouple under calibration is inserted alongside, and in good thermal contact with, a blackbody cavity contained in a furnace capable of providing minimal temperature gradients over the working zone. The radiance from the cavity is compared with that from a separate reference cavity at a known temperature (possibly a metal freezing-point) and the radiance ratio measured using a precision radiation comparator operating at a known wavelength. The calibration temperatures are then calculated using Planck's radiation equation. Alternatively, a previously calibrated radiation thermometer may be used to give the values of temperature directly.

Cold junctions for calibration purposes are usually ice-water mixtures as described in clause **7.6**. If the thermocouple is used with an extension or compensating cable the latter would preferably be treated as a separate thermocouple and be calibrated over the appropriate temperature range, e.g. 0 °C to 50 °C. However, for many digital thermometers this procedure would not be practicable and the whole system, i.e. thermocouple, extension/compensating cable (if present) and indicator, would be calibrated as one unit. The effectiveness of the cold junction compensation should be tested.

The level of accuracy one can achieve in the calibration of base metal thermocouples varies widely according to the type of thermocouple, the temperature range, the equipment available and the skill of the operator. Base metal types may be calibrated to ± 0.1 °C over a limited temperature range, e.g. – 80 °C to + 100°C, and to a few degrees at temperatures up to 1 000 °C, for Types K and N. However, because of the hysteresis effects discussed in **10.3** and other limitations of use referred to in clauses **5** and **6**, it is not usually worthwhile to obtain accurate calibrations of base metal thermocouples at temperatures approaching the upper limit of their specification. If accurate measurement of temperature is required for prolonged periods above about 600 °C, it is usually more satisfactory to use platinum-rhodium thermocouples.

Calibrations traceable to UK national standards can be carried out by the National Physical Laboratory and by many of the laboratories accredited for temperature measurement under the National Measurement Accreditation Service, NAMAS.

10.3 Pre-treatment and precautions

Any thermocouple which is to be calibrated should be homogeneous. New thermocouple wire should be satisfactory in this respect, but any thermocouple wire that has been in use for a long period at high temperature is suspect. Platinum-rhodium thermocouples can suffer from the effects of rhodium migration and evaporation, although the effects are usually small. They may also become contaminated. Base metal thermocouples on the other hand, especially Type K, can suffer large changes in the e.m.f. output. Inhomogeneous thermocouples, if calibrated and then used under conditions of temperature gradient different from those present during calibration, will give false readings, possibly tens of degrees in error. It is therefore advisable to establish a regime of planned replacement or in situ checks of base metal thermocouples after certain periods of exposure, depending on the requirements of the application. This is especially desirable where chemical contamination may occur, since this is usually irreversible. Physical (metallurgical) inhomogeneity can sometimes be remedied, at least partially, by carefully managed heat treatment.

Before calibration, new or used platinum and platinum-rhodium wires should first be cleaned with an organic solvent. For most purposes it is sufficient then to anneal the platinum wire at 1 100 °C for 15 min and the alloy wire at 1 450 °C for the same time by passing suitable electric currents through the wires, in air. Usually a 10 A to 11 A current is sufficient for 0.5 mm diameter wires. At the end of this anneal the current is gradually reduced to zero over a period of a few minutes. The wires are then inserted into clean (preferably new) insulators and the junction is formed by fusing the wires together. The completed thermocouple should then be annealed at 1 100 °C at maximum immersion. If after a period of use it is desired to recalibrate the thermocouple, it should first be dismantled, then cleaned and annealed as previously described. New insulators should be used.

Base metal thermocouple wire should be suitable for general use in the as-received condition up to the maximum temperature appropriate for the type and size of the conductors.

Between 250 °C and about 450 °C Type K and to a lesser extent Type N thermocouples undergo reversible structural transformations which may change the calibration by several degrees for Type K and by less than 1 °C for Type N. These effects occur in the positive element of Type K and the negative element of Type N. The best results in terms of stability up to 500 °C are achieved by first heat treating the thermocouple at its normal maximum immersion for about 30 min at this temperature, whereupon the ordered condition should be attained. However, a Type K thermocouple may drift out of tolerance during this treatment, and it may be advisable to consult the supplier first; it may be possible to obtain wires which are made so as to be within the tolerance after such treatment. If temperatures much above 500 °C are subsequently encountered, the disordered condition will be reinstated (at least in that part of the wire which exceeds the order/disorder transition temperature). The most reproducible measurements above 450 °C are likely to be obtained if the thermocouple is first annealed at its usual immersion depth for about 24 h at a temperature somewhat above the maximum temperature of use, although again this may cause the e.m.f. output to differ slightly from that indicated by the supplier. Nicrosil may undergo some reversible drift near 750 °C, such that an anneal at this temperature may be desirable.

This discussion of pre-treatment of base metal thermocouples relates to Types K and N because they are the types most likely to be used at elevated temperatures. The limitations of the other types have been discussed in clauses **5** and **6**, and they are not usually overcome by heat treatment.

In calibration (and use) it is essential that thermocouples are sufficiently immersed, so that one can be sure that the junction region of the thermocouple is really at the temperature to be measured. This is obviously more difficult the thicker the wire and for this reason a sheathed industrial thermocouple would usually be dismantled and removed from the sheath before calibration. The larger sizes of mineral-insulated thermocouple can be a problem to calibrate for this reason, as they cannot be dismantled.

In the case of large installations it is often desirable to carry out in situ calibrations, and this is probably the best method of checking the calibration of a base metal thermocouple that has been in use for some time, as the thermocouple is unlikely to be chemically homogeneous. For this it is necessary to arrange matters so that a calibrated reference thermocouple can be inserted into the furnace alongside the thermocouple to be calibrated. Readings are then compared over the working range of temperatures, and the reference thermocouple removed. A less satisfactory alternative would be briefly to replace the thermocouple with one of similar construction and known calibration, and compare readings.

Table 1 — Approximate e.m.f. output of base metal thermocouples (reference junction at 0 °C)

Thermocouple type	Temperature					
	– 200 °C	200 °C	400 °C	800 °C	1 000 °C	1 200 °C
	mV	mV	mV	mV	mV	mV
T	– 5.6	9.3	20.9	—	—	—
J	– 7.9	10.8	21.8	45.5	—	—
E	– 8.8	13.4	28.9	61.0	76.4	—
K	– 5.9	8.1	16.4	33.3	41.3	48.8
N	– 4.0	5.9	13.0	28.5	36.2	43.8

NOTE Reference tables for base metal thermocouples are given in IEC 584-1 and BS 4937.

Table 2 — Approximate e.m.f. output of noble metal and refractory metal thermocouples (reference junction at 0 °C)

Thermocouple type	Temperature						
	400 °C	800 °C	1 200 °C	1 600 °C	1 800 °C	2 000 °C	2 300 °C
	mV	mV	mV	mV	mV	mV	mV
S	3.3	7.3	11.9	16.8	—	—	—
R	3.4	7.9	13.2	18.8	—	—	—
B	0.8	3.2	6.8	11.3	13.6	—	—
Pt-40 % Rh/Pt-20 % Rh	0.2	0.9	2.0	3.6	4.4	—	—
Ir-40 % Rh/Ir	1.9	4.2	6.4	8.6	9.8	11.0	—
W/W-26 % Re	3.3	10.3	18.6	26.8	30.6	34.0	38.4
W-3 % Re/W-25 % Re	6.1	14.2	22.1	29.4	32.7	35.7	39.4
W-5 % Re/W-26 % Re	6.7	14.5	21.8	28.2	31.1	33.7	36.9

NOTE Reference tables for types S, R and B thermocouples are given in IEC 584-1 and BS 4937.

Table 3 — Recommended maximum operating temperatures for bare and protected base metal thermocouple wires operating continuously in air without temperature cycling

Thermocouple type	Diameter						
	3.3 mm	1.6 mm	1.0 mm	0.8 mm	0.5 mm	0.3 mm	0.25 mm
	°C	°C	°C	°C	°C	°C	°C
N: bare	1 100	1 010	960	930	890	840	800
protected	1 250	1 180	1 110	1 040	1 000	950	910
K: bare	1 050	930	900	860	800	750	710
protected	1 150	1 080	1 050	970	910	860	820
E: bare	890	800	750	700	660	620	580
protected	1 000	910	860	810	770	730	690
J: bare	760	760	720	680	650	600	560
protected	760	760	760	760	760	710	670
T: bare	—	400	360	320	280	250	220
protected	—	450	410	370	330	300	270

Table 4 — Recommended maximum operating temperatures for noble metal thermocouple wires operating continuously in air without temperature cycling and intermittently in air

Thermocouple type	0.5 mm diameter		0.25 mm diameter	
	Continuous	Intermittent	Continuous	Intermittent
	°C	°C	°C	°C
S	1 500	1 650	1 400	1 550
R	1 500	1 650	1 400	1 550
B	1 600	1 800	1 500	1 700

Table 5 — Alloys commonly used in thermocouple compensating cable[a]

Type	Temperature range	Positive conductor	Negative conductor
	°C		
KCA[b]	0 to 150	Fe	Cu-Ni[d]
KCB[c]	0 to 100	Cu	Cu-Ni[d]
NC	0 to 150	Cu-Ni[d]	Cu-Ni[d]
RCA and SCA	0 to 100	Cu	Cu-Ni[d]
RCB and SCB	0 to 200	Cu	Cu-Ni-Mn

[a] The applicable e.m.f. tolerances are specified in IEC 584-3.
[b] Previously known as WX.
[c] Previously known as VX.
[d] These alloys are not interchangeable since they have compositions chosen to provide the e.m.f.-temperature relationship appropriate to the particular thermocouple.

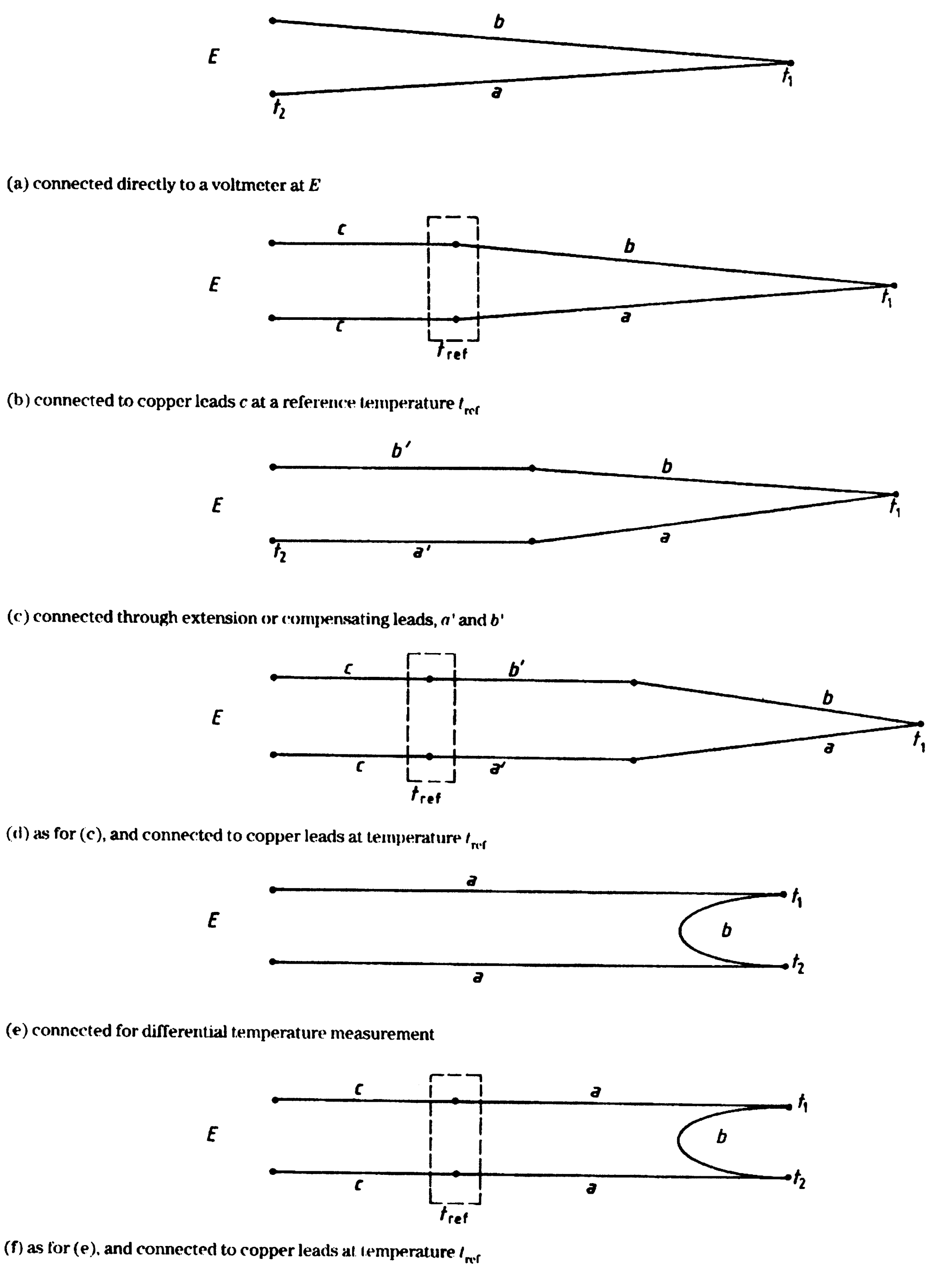

Figure 1 — Basic circuit diagrams for a thermocouple with conductors a and b

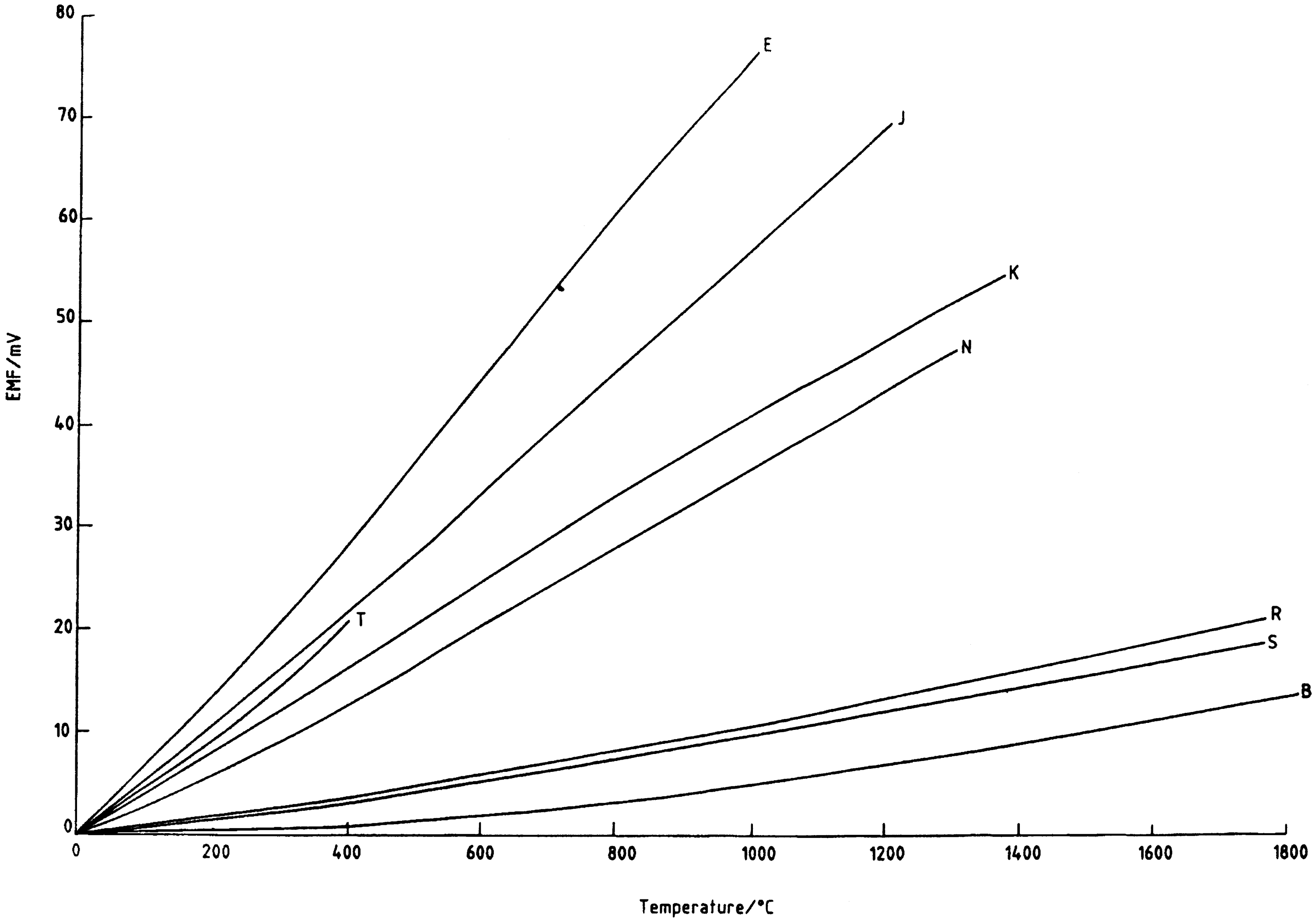

Figure 2 — Electromotive force characteristics of the standardized thermocouples

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Publication(s) referred to

BS 970, *Specification for wrought steels for mechanical and allied engineering purposes.*

BS 2765, *Specification for dimensions of temperature detecting elements and corresponding pockets.*

BS 4937, *International thermocouple reference tables.*

BS 4937-1, *Platinum — 10 % rhodium/platinum thermocouples. Type S.*

BS 4937-2, *Platinum — 13 % rhodium/platinum thermocouples. Type R.*

BS 4937-3, *Iron/copper-nickel thermocouples. Type J.*

BS 4937-4, *Nickel-chronium/nickel-aluminium thermocouples. Type K.*

BS 4937-5, *Copper/copper-nickel thermocouples. Type T.*

BS 4937-6, *Nickel-chromium/copper nickel thermocouples. Type E.*

BS 4937-7, *Platinum — 30 % rhodium/platinum — 6 % rhodium thermocouples. Type B.*

BS 4937-8, *Nickel-chromium-silicon/nickel-silicon thermocouples including composition Type N.*

BS 4937-20, *Specification for thermocouple tolerances.*

BS 6175, *Specification for temperature transmitters with electrical outputs.*

IEC 584, *Thermocouples.*

IEC 584-1, *Reference tables.*

IEC 584-3, *Extension and compensating cables — tolerances and identification system.*

ASTM Publication STP 470B Manual on the use of thermocouples in temperature measurement[4].

ASTM Document E988 Standard temperature-electromotive force (E.M.F.) tables for tungsten-rhenium thermocouples[4].

[4] Available from BSI Sales Department, Linford Wood, Milton Keynes MK14 6LE.

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