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Temperature measurement: thermocouples

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TEMPERATURE MEASUREMENT: thermocouples

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TEMPERATURE MEASUREMENT: thermocouples

1. PURPOSE AND SCOPE OF THIS DATA ITEM

In its simplest practical form a thermocouple can consist of two dissimilar wires connected together at one end with a voltage measurement device across the free ends. A net electromotive force (emf) due to the Seebeck effect will be indicated by the voltmeter, which is a function of temperature difference between the joint and the voltmeter connections.

The purpose of this Data Item, which is one of a series (ESDU 02006²¹ and ESDU 06019²²) concerned with temperature measurement, is to provide background information and practical guidance on designing a temperature measuring system using thermocouples. The nominal temperature range covered by this Data Item is $-272\text{ }^{\circ}\text{C}$ to $2000\text{ }^{\circ}\text{C}$ but the comments apply, in general terms, to all thermocouple systems. It is aimed at the user who wishes to design and install a practical thermocouple system using improved techniques that will allow temperatures to be measured within known tolerances.

The Data Item considers the selection, preparation and installation of thermocouples (Section 4), the use of compensating or extension cables (Section 5), methods of referencing to a known temperature (Section 6) and measurement systems (Section 7). The requirements for reliable systems operating to commercial tolerances are described in Section 8. Various factors that might impair the accuracy and stability of thermocouples are identified together with methods of reducing their effect.

A check list for the design of a thermocouple system is given in Section 9 and a flow chart procedure for selecting appropriate thermocouple materials is provided in Figure 1.

A glossary of thermocouple terms is provided in Appendix E.

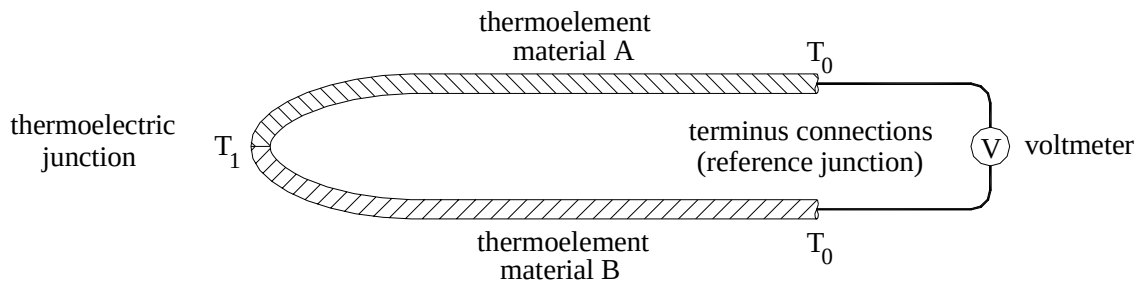
The employment of the techniques described will ensure that the temperature of the measuring junction is within known tolerances. Further techniques and precautions required to make sure that the measuring junction closely assumes the required local temperature of the medium are described in a companion Data Item ESDU 02006 (Reference 21). There is a wealth of information on thermocouple practice in the literature where further details on most items can be found. Reference 19 is a useful source and provides many further references.

Although throughout the Data Item the techniques are discussed in terms of the measurement of temperature, many of the comments are applicable to thermocouples used as sensors in temperature control systems. In this regard, aspects such as time response, temperature equilibrium and stability may be important.

2. HOW A THERMOCOUPLE WORKS

A basic thermocouple circuit is illustrated in Sketch 2.1. Here two wires of dissimilar material, known as thermoelements, have been joined at one end to form a joint known as the thermoelectric junction. The free ends have been connected by, say, copper wire to a voltage measuring device. The net emf observed by this circuit will be proportional to the temperature gradient between the thermoelectric junction and the terminal connections. It is therefore important to know the temperature at the terminus connections and as a result these are often referred to as the reference junctions.

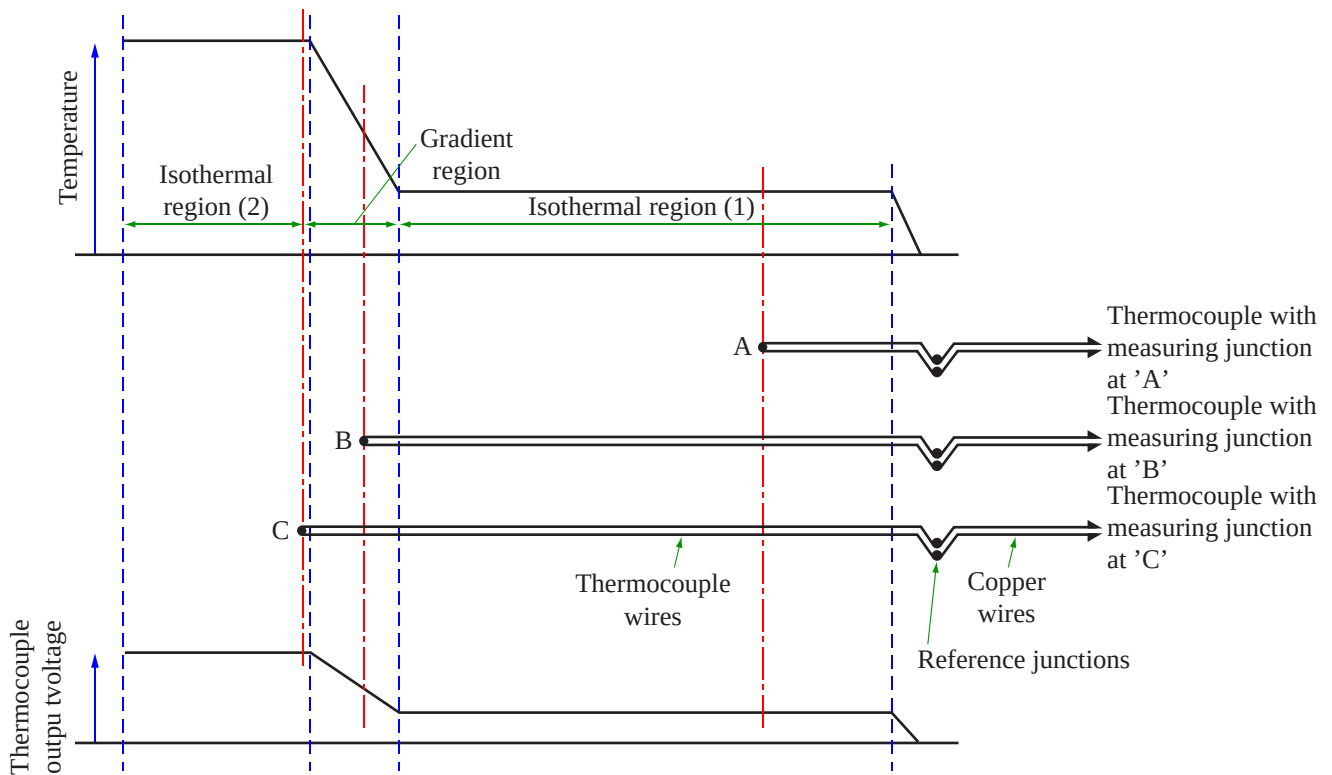
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Sketch 2.1 Basic thermocouple circuit

The phenomenon whereby thermal energy produces an electric current was originally discovered by Seebeck (Reference 1). This effect forms the basis of thermoelectric thermometry. Heat flowing within an electrical conductor also produces a movement of electrons and thus a small electromotive force (emf). Therefore, if a conducting wire is spanning a thermal gradient an emf will exist across its ends. The magnitude and sign of the emf will be dependent on the temperature field and the material of the conducting wire. A complete circuit of just one material placed in a temperature gradient will experience equal and opposite temperature gradients around the circuit and the sum of the emfs will be zero. In a practical thermocouple two materials having different emf/temperature characteristics form the circuit and it is the interaction of these with the temperature gradients that produces the net output voltage. The steepness and distribution of the temperature gradients are of no importance if the conductors have uniform thermoelectric characteristics, *i.e.* are homogeneous. The temperatures of the thermocouple junctions become relevant because they form the limits of the two voltage generating conductors and thus the total temperature difference between the junctions at the ends of the thermocouple conductors determines the magnitude of the thermocouple output. The output is also a function of the absolute temperatures. The widespread belief that the output voltage of a thermocouple is generated at the junction of the dissimilar wires is not correct and is not a useful concept for the understanding of thermocouple operation. Further reading on the fundamentals of thermoelectricity can be found in References 12, 8, 20, 18 and 17.

An illustration of the operation of a thermocouple is shown in Sketch 2.2. Two homogeneous thermocouple wires are situated in an idealised temperature field. If a measuring junction is formed by connecting the wires at position A a voltage will be developed that is a function of the measuring and reference junction temperatures and the thermoelectric characteristics of the thermocouple wires. This voltage will remain the same if the junction at A is situated at any position within the isothermal region (1). Suppose the measuring junction is now formed at B. Here it will experience a higher temperature and the output voltage will be increased. The voltage will continue to increase if the junction is moved further into the gradient, reaching a maximum value at C. The voltage will then remain constant at this new value when the junction is formed anywhere within the isothermal region (2). From this simple model it is evident that only the parts of the thermocouple situated in temperature gradients contribute to the output voltage and no generation occurs in isothermal regions.



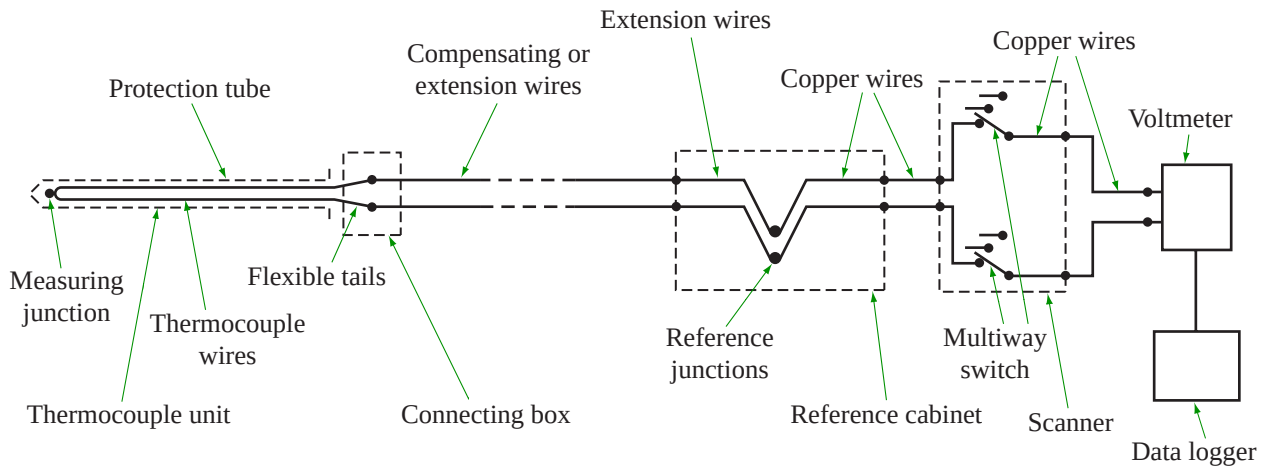
Sketch 2.2 Voltage generation in a thermocouple circuit

In any temperature measuring situation, the precise locations and magnitudes of the temperature gradients are unknown and may possibly vary with time. It is important therefore when designing thermocouple systems to endeavour to provide and maintain a high degree of uniformity of thermoelectric characteristics (homogeneity) throughout the circuits. This will help to promote the correct incremental voltage generation, irrespective of the distribution of the temperature gradients along the thermocouple (see Reference 10). Where local regions with non-matching thermoelectric characteristics are known to be present in the circuit, any spurious voltages that might arise from them can be suppressed by ensuring that the regions are made isothermal.

3. PRACTICAL THERMOCOUPLE SYSTEMS

The ideal thermocouple system would simply comprise two homogeneous thermocouple wires of different materials connected at the measuring junction with copper wires linking the reference junctions to a voltage measuring instrument. While departures from this ideal situation are inevitable with practical systems for reasons of convenience and economy, the effects of such compromises can be reduced by careful design.

A practical thermocouple circuit including a thermocouple unit, compensating or extension wires, a reference device, a switching unit and a data logger is shown in Sketch 3.1. The important requirements for each of these items are discussed in the following sections.



Sketch 3.1 The practical thermocouple

4. THE THERMOCOUPLE UNIT

The measuring junction and the thermocouple wires associated with it are frequently referred to as the thermocouple unit (see Sketch 3.1). In operation, the unit will usually span the majority of the temperature gradient and with homogeneous wires the junction will function as the measuring point of the thermocouple system. Thermocouple units range from a few tens of millimetres to hundreds of metres long. They may take the form of simple bare wire junctions for laboratory applications or a commercially produced beaded assembly in a thermowell for use in plant. A more robust and sometimes more convenient form of construction is as a metal sheathed, mineral insulated cable (M.I.) thermocouple. These are described in Section 4.1.

4.1 Thermocouple Materials

There is an extensive range of material combinations that can conceivably be used for thermocouples (Reference 14) but for most applications the choice can be limited to those shown in Table 4.1. The more popular thermocouples have type designations that are recognised internationally and will conform to the voltage/temperature characteristics provided in the standard tables (ASTM E230-98²⁴, EN 60584-1²⁹ and IEC 60584-1^{34,35,36}) irrespective of the manufacturer. The range of temperatures to which these thermocouples are most suited is given in Table 4.2 together with typical tolerances. These apply to thermocouples installed in the manner recommended by the manufacturers and without further calibration. Sketch 4.1 illustrates the output characteristics of the thermocouples and Table 4.3 shows their sensitivities at selected temperatures.

Selected values from the IEC 60584.1^{34,35,36} voltage temperature characteristic tables have been reproduced in Appendix F. The data are in the form of look up tables and assume the simple circuit of Sketch 2.1 with the reference junction at 0 °C. The procedure to convert a measured emf into a value of temperature for a particular type of thermocouple involves identifying the nearest value of emf in the tables to the measured value and use of linear or bilinear interpolation to determine the corresponding temperature. Example 1 in Appendix H illustrates the procedure for determining temperature using these tables.

If the reference junction is at some temperature other than 0 °C then the reference tables given in Appendix F cannot be used directly and a correction must be made. The temperature of the reference junction must be measured by an independent means or its value estimated. This temperature must then be used to determine the emf that would occur for the thermocouple if the tip was at the reference temperature and the reference junction was at 0 °C. This value of emf must then be added to the measured value and the tables used to determine the temperature of the tip.

The procedure to account for a reference junction with a temperature other than 0 °C can be summarized as:

- (1) measure the emf across the terminations,
- (2) measure the reference temperature at the terminations by some independent means such as using a thermistor,
- (3) convert the reference temperature into an equivalent emf using the tables given in Appendix F,
- (4) add the measured emf to the equivalent emf to give a total emf,
- (5) convert the total emf to a temperature using the tables given in Appendix F. This is the temperature of the thermoelectric junction (also commonly referred to as the tip).

This procedure is illustrated by Example 2 in Appendix H.

A list of links to some thermocouple manufacturers, suppliers and information sources operating at the time of going to press are listed for convenience in Appendix G.

Taking the noble metal thermocouples first, Pt-Rh/Pt thermocouples are widely used in the temperature range 0 to 1500 °C and can be used intermittently for temperatures up to 1650 °C. The manufacturers will guarantee conformity with the relevant tables ASTM E230-98²⁴, BS EN 60584-1²⁹ and IEC 60584-1^{34,35,36} subject to the tolerances shown in Tables 4.2 and 4.3. Unfortunately, for historical reasons there are two formulations for the positive limb, Pt-10%Rh (Type S) and Pt-13%Rh (Type R) with slightly different voltage/temperature relationships. It is preferable to standardise on one type in a given organisation as the wires are indistinguishable without recourse to calibration or chemical analysis.

TABLE 4.1 International Thermocouple Type Designations

<i>Materials</i>	<i>Polarity</i>	<i>International type designation</i>	<i>Some alternative names</i>
Pt-10%Rh Pt	(+) (-)	S SP SN	} Le Chatelier
Pt-13%Rh Pt	(+) (-)	R RP RN	
Pt-30%Rh Pt-6%Rh	(+) (-)	B BP BN	
Pt-40%Rh Pt-20%Rh	(+) (-)		
Ir-40%Rh Ir	(+) (-)		} Feussner
Ni-Cr Cu-Ni	(+) (-)	E EP EN	
Ni-Cr Ni-Al	(+) (-)	K KP KN	
Ni-Cr-Si/Ni-Si		N	
Cu Cu-Ni	(+) (-)	T TP TN	Copper Constantan, Advance, Copel
W-3%Re W-25%Re	(+) (-)		
W-5%Re W-26%Re	(+) (-)		

Chromel, Alumel and Copel are Trade Marks of the Hoskins Manufacturing Company. T1, T2 and Advance are Trade Marks of British Driver Harris Limited.

TABLE 4.2 Manufacturing Tolerances for ASTM Thermocouples (ASTM E 230 – 98²⁴)

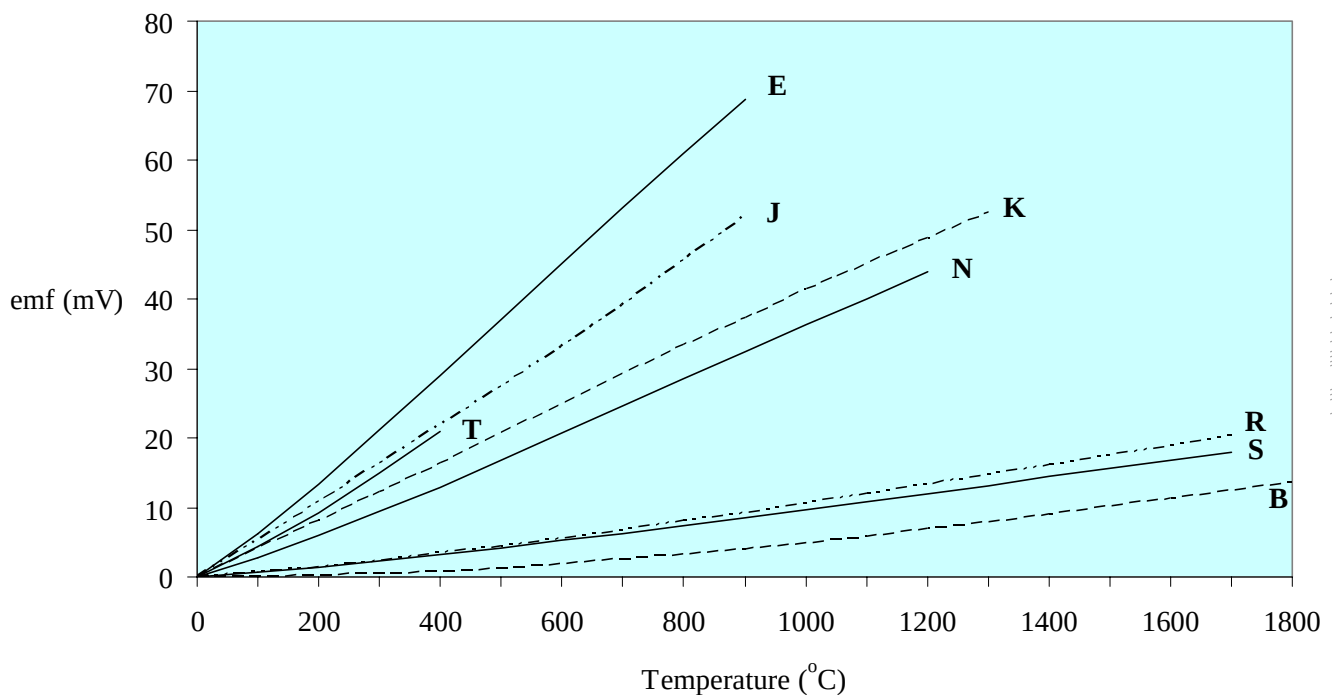
Type	Temperature range (°C)	Standard tolerance (°C)	Special tolerance (°C)
B	870 to 1700	±0.5 %	±0.25 %
E	-200 to 0	±1.7 or ±1.0%	
	0 to 870	±1.7 or ±0.5%	±1.0 or ±0.4%
J	0 to 760	±2.2 or ±0.75%	±1.1 or ±0.4%
K	-200 to 0	±2.2 or ±2.0%	
	0 to 1260	±2.2 or ±0.75%	±1.1 or ±0.4%
N	0 to 1260	±2.2 or ±0.75%	±1.1 or ±0.4%
R	0 to 1480	±1.5 or ±0.25%	±0.6 or ±0.1%
S	0 to 1480	±1.5 or ±0.25%	±0.6 or ±0.1%
T	-200 to 0	±1.0 or ±1.5%	
	0 to 370	±1.0 or ±0.75%	±0.5 or ±0.4%

**TABLE 4.3 Manufacturing Tolerances for Thermocouples
(BS EN 60584-2²², IEC 60584-2³⁴, 60582-2 – am1^{35,36})**

Type	Tolerance Class 1	Tolerance Class 2
B	-	±0.25% (600 °C to 1700 °C)
E	±1.5 °C (-40 °C to 375 °C) ±0.4% (375 °C to 800 °C)	±2.5 °C (-40 °C to 333 °C) ±0.75% (333 °C to 900 °C)
J	±1.5 °C (-40 °C to 375 °C) ±0.4% (375 °C to 750 °C)	±2.5 °C (-40 °C to 333 °C) ±0.75% (333 °C to 750 °C)
K	±1.5 °C (-40 °C to 375 °C) ±0.4% (375 °C to 1000 °C)	±2.5 °C (-40 °C to 333 °C) ±0.75% (333 °C to 1200 °C)
N	±1.5 °C (-40 °C to 375 °C) ±0.4% (375 °C to 1000 °C)	±2.5 °C (-40 °C to 333 °C) ±0.75% (333 °C to 1200 °C)
R	±1.0 °C (0 °C to 1100 °C) ±(1+0.003(t-1100)) (1100 °C to 1600 °C)	±1.5 °C (0 °C to 600 °C) ±0.25% (600 °C to 1600 °C)
S	±1.0 °C (0 °C to 1100 °C) ±(1+0.003(t-1100)) (1100 °C to 1600 °C)	±1.5 °C (0 °C to 600 °C) ±0.25% (600 °C to 1600 °C)
T	±0.5 °C (-40 °C to 125 °C) ±0.4% (125 °C to 350 °C)	±1.0 °C (-40 °C to 133 °C) ±0.75% (133 °C to 350 °C)

TABLE 4.4 Sensitivities of Some Thermocouples at Selected Temperatures

Temperature (°C)	Sensitivity ($\mu\text{V}/^\circ\text{C}$)									
	Pt-10%Rh/ Pt Type S	Pt-13%Rh/ Pt Type R	Pt-30%Rh/ Pt-6%Rh Type B	Pt-40%Rh/ Pt-20%Rh –	Ir-40%Rh/ Ir –	Ni-Cr/ Cu-Ni Type E	Ni-Cr/ Ni-Al Type K	Cu/ Cu-Ni Type T	W-5%Re/ W-26%Re –	Ni-Cr-Si/Ni- -Si Type N
-200	–	–	–	–	–	25.1	15.3	15.7	–	10
0	5.4	5.3	0	0.4	2.0	58.6	39.5	38.7	13.5	26
200	8.5	8.9	2.0	0.6	5.0	74.0	40.0	53.2	17.2	33
400	9.6	10.4	4.1	1.0	6.1	80.1	42.2	61.6	19.0	37
800	10.9	12.3	7.9	2.2	5.9	78.6	41.0	–	19.2	39.5
1200	12.0	13.9	10.4	3.6	5.4	–	36.5	–	17.2	37.5
1600	11.9	13.9	11.6	4.5	5.3	–	–	–	14.9	–
2000	–	–	–	–	5.3	–	–	–	12.2	–



Sketch 4.1 The output characteristics of some thermocouples

For higher temperatures thermocouples are marketed with rhodium alloyed to both limbs. A Pt-30%Rh/Pt-6%Rh (Type B) thermocouple will operate continuously at temperatures between 1000 °C and 1600 °C and intermittently to 1750 °C while a Pt-40%Rh/Pt-20%Rh thermocouple will function up to 1700 °C and 1850 °C intermittently. For temperatures up to 2000 °C an Ir-40%Rh/Ir thermocouple is available (see Table 4.1). The manufacturers have published information on the performance of these thermocouples (References 2 and 3) and Reference 19 is a further source. Tungsten-rhenium thermocouples are also used in this temperature range. For example, W-3%Re/W-25%Re and W-5%Re/W-26%Re thermocouples in sheathed form are used for some nuclear applications.

For the majority of industrial measurements base metal thermocouples are satisfactory with the Type E (References 2 and 3) thermocouple in M.I. form offering the most stable system. It has a temperature range from cryogenic temperatures up to 900 °C. The output is the highest of the base metal thermocouples which reduces the significance of spurious voltages that may be present in the circuit. Although both materials suffer ordering changes *i.e.* changes in the atomic structure (see Appendix A) these are substantially similar in sign and magnitude and cancel to a certain extent. The materials also have a low thermal conductivity, an advantage in most measurement situations.

An alternative and widely used thermocouple is the Type K. In sheathed (M.I.) form it can be used for temperatures up to 1100 °C and this can be extended to approximately 1200 °C with special sheath materials. Nevertheless, the positive Ni-Cr limb is subject to ordering change and this must be borne in mind when the user is seeking high accuracy and stability with time.

Type T thermocouples are widely used for temperatures in the range -200 °C to 400 °C. As one material is copper the referencing requirements are simplified, but its high thermal conductivity can be a disadvantage in some applications. Between 200 °C and 400 °C the negative Cu-Ni conductor might also be influenced by ordering change.

The tolerances given in Table 4.2 and 4.3 are for thermocouples as supplied from manufacturers. Individual calibration of the thermocouples might reduce uncertainties to approximately one third of these values. A flow chart providing for the selection of thermocouple systems is given in Figure 1.

Thermocouple materials exhibit varying degrees of resistance to attack from corrosive or oxidising environments. Temperature and the diameter of the wires are additional factors. For example, copper and iron are susceptible to corrosion and this can limit their usefulness as a thermocouple material in bare wire form. Manufacturers' advice should be sought if thermocouple wires are to be exposed in any application. A preferred alternative is to use sheathed (M.I.) thermocouples whenever possible. With this form of construction the thermocouple wires are embedded in an inert powdered insulant, usually magnesium oxide, and this is surrounded by a metal sheath. The method of cable production, either by drawing or hammer swaging, ensures very close compaction of the insulant with virtually no voids. In this way the thermocouple materials are hermetically sealed from the surroundings and the durability of the sheath becomes the main consideration. A typical range of sheath materials is given in Table 4.5 together with maximum operating temperatures. There may be compatibility considerations with some environments and the supplier should be consulted if conditions are, for example, of an acidic or reducing nature. Nevertheless, the sheathed (M.I.) types of thermocouple are convenient and robust. They can be obtained with sheath diameters ranging from 0.25 to 19.0 mm. Examples of this type of thermocouple are shown in Sketch 4.2.

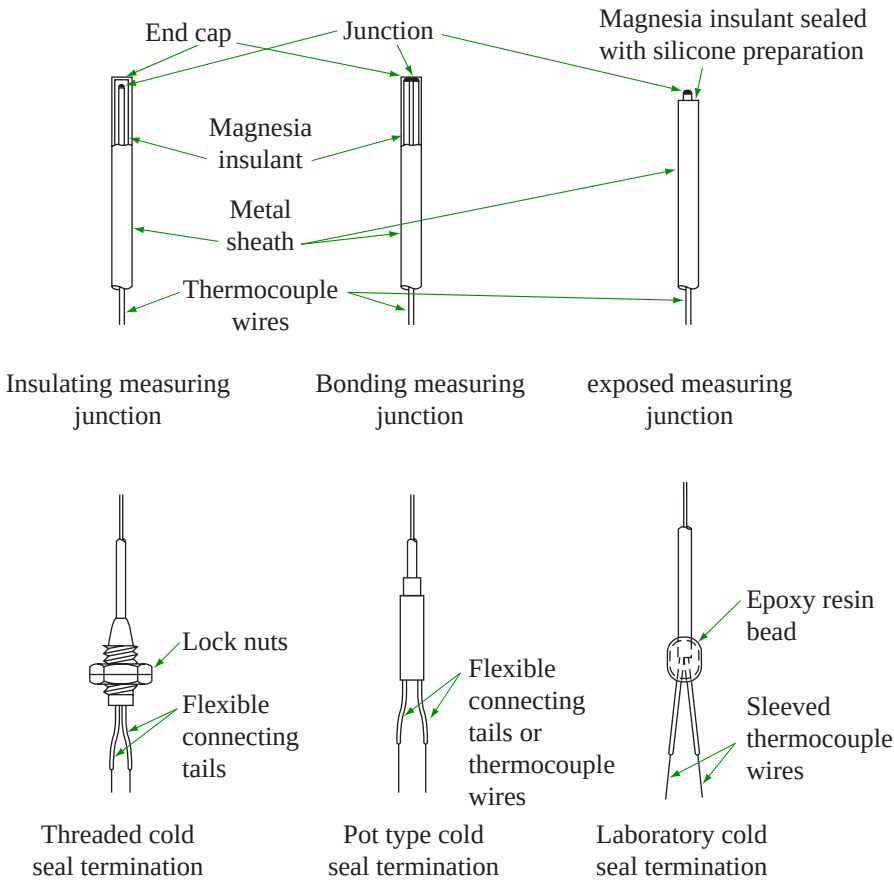
The foregoing comments apply to temperature measurements to be undertaken in reasonably commonplace situations. The requirements for highly specialised thermocouple measurements are not included in this Data Item. Some further comments on the problems arising with measurements in nuclear environments or in intense magnetic fields are given in Appendix A.

TABLE 4.5 Mineral Insulated Thermocouple Sheath Materials

Maximum operating temperature in air (°C)	Sheath material
> 2000	Molybdenum (Mo)
> 2000	Tantalum (Ta)
> 2000	Tungsten (W)
> 2000	W-5%Re/W-26%Re
1700	Pt-20%Rh
1550	Pt-10%Rh
1225	Hastelloy X*
1150	Stainless steel
	AISI Type 310/324
1100	Inconel†
925	Stainless steel 316
800	Stainless steel 321
600	Mild steel
400	Cupro-nickel

* Hastelloy X is a TradeMark of the Haynes International.

† Inconel is a Trade Mark of Special Metals Corporation.



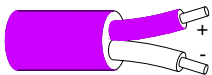
Sketch 4.2 Examples of sheathed, mineral insulated thermocouple units

The Type N thermocouple Nicrosil/Nisil (References 4, 11 and 16) is a development of the Type K thermocouple where careful alloying techniques have resulted in much improved bare wire oxidation resistance at high temperature. A change in chromium content in the positive limb has suppressed the voltage changes due to the effect of ordering.

Where high accuracy is required for large projects it is a good plan to use the same materials throughout. In the case of sheathed (M.I.) thermocouples the production may be planned with the manufacturer such that the cable starting materials emanate from the same melts of the thermocouple alloys. Representative thermocouples can be calibrated to provide information for the entire scheme.

Colour codes defined in IEC 584.3³³ and ISA MC96.1³⁷ for standardised thermocouple wire are given in Table 4.6.

TABLE 4.6 Thermocouple Colour Codes to IEC 584.3:1989³³ and ISA MC96.1³⁷

Thermocouple Type	International Colour Code IEC 584.3:1989 ³³	International Colour Code IEC 584.3:1989 ³³ Overall/Positive (+)/Negative (-)	ISA MC96.1 ³⁷ T/C	ISA MC96.1 ³⁷ T/C Overall/Positive (+)/Negative (-)
B		Grey, + Grey, - White	Not Defined	Not Defined
E		Purple, + Purple, - White		Brown, + Purple, - Red
J		Black, + Black, - White		Brown, + White, - Red
K		Green, + Green, - White		Brown, + Yellow, - Red
N		Pink, + Pink, - White		Brown, + Orange, - Red
R		Orange, + Orange, - White	Not Defined	Not Defined
S		Orange, + Orange, - White	Not Defined	Not Defined
T		Brown, + Brown, - White		Brown, + Blue - Red