



ESDU 02006

Issued May 2002

Supersedes ESDU 83032

Temperature measurement: techniques

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TEMPERATURE MEASUREMENT: techniques

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TEMPERATURE MEASUREMENT: techniques

1. NOTATION AND UNITS

		SI Units
a_j	probability rate	1/J
A	constant in Equations (9.3), (9.5), (9.6) and (9.7)	1/°C
A	probability rate factor	J/m ²
B	blue signal intensity	W/m ²
B	constant in Equations (9.3), (9.5), (9.6) and (9.7)	1/°C ²
$B(T)$	second virial coefficient	cm ³ /mol
c	speed of sound	m/s
C	Curie constant	1/K
C	calibration constant	1/m ² mol
C	constant in Equations (9.5) and (9.7)	1/°C ⁴
C	Gladstone Dale constant	m ³ /kg
$C(T)$	third virial coefficient	cm ⁶ /mol ²
C_1	first radiation constant (= 3.7417749×10 ⁻¹⁶ W m ² , Reference 224)	W m ²
C_2	second radiation constant (= 0.01438769 m K, Reference 224)	m K
$D(T)$	fourth virial coefficient	cm ⁹ /mol ³
E	energy	J
E	Young's modulus	Pa
E	spectral emissive power	W/m ³
f	frequency	Hz
F	relation between red, blue and green signals in Equations (18.2) and (18.3)	-
G	green signal intensity	W/m ²
H	hue	-

I	current	A
I	intensity of light or radiation	W/m ²
I	irradiance	W/m ²
k	Boltzmann's constant (=1.380 658×10 ⁻²³ J/K, Reference 224)	J/K
K	bulk modulus	Pa
L	length of test section	m
M	molar mass	kg/mol
M	molecular weight (relative molecular mass)	-
m	mass	kg
n	number of moles of gas	-
n	refractive index	-
N	number of particles	-
p	pressure	N/m ² (Pa)
q	charge of electron (= 1.6×10 ⁻¹⁹ C)	C
R	characteristic gas constant	J/(kg K)
R	ratio of emitted radiation at two wavelengths in Equation (22.3)	-
R	red signal intensity	W/m ²
R	resistance	W
$\mathcal{R}$	universal gas constant (= 8.314 510 J/(mol K), Reference 224)	J/(mol K)
S	entropy	J/K
S	saturation	-
T	kelvin temperature	K
t	Celsius temperature	°C
t	time	J
V	voltage	V
V	volume	m ³
x	mole fraction	-

x, y, z	Cartesian co-ordinates	m
α	angular deflection	-
α	temperature coefficient of resistance	1/°C
β	constant for the particular thermistor material	-
γ	isentropic index	-
δ	constant in Equation (9.4)	-
δ	denotes incremental difference or amount	-
Δ	finite difference or interval	-
ε	emissivity	-
ε	fringe shift	-
λ	wavelength	m
ρ	density	kg/m ³
σ	Stefan-Boltzmann constant (= 5.67051×10 ⁻⁸ W/(m ² K ⁴), Reference 224)	W/(m ² K ⁴)
χ	magnetic susceptibility	-
σ	Rayleigh scattering cross-section	m ² /sr
ω	frequency	1/s

Subscripts

0	at 0 °C
0	reference
1, 2, 3	particular conditions
100	at 100 °C
<i>air</i>	in air
<i>b</i>	black body
<i>F</i>	forward
<i>i</i>	particular point
<i>i</i>	species <i>i</i>
<i>j</i>	quantum state or energy level
<i>L</i>	laser

ref	reference conditions
R	Rayleigh scattered light
R	reference resistor
S	reverse saturation
s_c	screen in Equation (24.5)
s	sensing resistor
T	at temperature T
T	total
V	at constant volume
λ	at specific wavelength

2. PURPOSE OF THIS DATA ITEM

The purpose of this Item is to review the general techniques available for measuring temperature and to consider specific instruments for particular applications. The issues of measurement criteria including uncertainty, thermal disturbance and calibration are described. Based on the relative merits of different techniques, guidance for the selection of an appropriate temperature measurement technique is provided.

2.1 How to Use this Data Item

It is recommended that the user should read the general considerations of temperature measurement (Section 3) and, in particular, note the more important aspects to be considered in selecting a system (Sections 4.1 and 4.2). Descriptions of a wide range of measuring techniques are given in Sections 5 to 32. Each of those sections covers the *basic principle* of operation, the *component parts* of the system, *alternative types*, the *temperature range* covered and *causes of uncertainty*. Section 34 gives Tables providing a summary of each of the measurement techniques described. These tables, in conjunction with the more detailed descriptions of each method in Sections 5 to 32, can be used to select or specify an appropriate system.

The range of techniques described in this Data Item is extensive. Historically the most popular means of measuring temperature have included: thermocouples (Section 8), resistance temperature detectors (Section 9), infrared thermometers (Section 22), liquid-in-glass thermometers (Section 6) and bimetallic thermometers (Section 7). Other techniques are included here in order to present alternatives arising from technological developments to allow the most appropriate method to be considered and selected. Examples such as peak-indicating labels (Section 20) and deforming devices (Section 21) continue to find new applications.

3. INTRODUCTION TO TEMPERATURE

Temperature is one of the seven base SI units (Reference 129). Many physical processes and properties are dependent on temperature and its measurement is crucial in industry and science, with applications ranging from process control to the improvement of internal combustion engines.

The concept of temperature is familiar from day to day experience of hot and cold objects. Indeed temperature can be defined qualitatively as a measure of hotness. Systems or objects can be ranked in a sequence according to their hotness and each system assigned a number, its temperature. Linked to the concept of hotness is heat transfer, the flow of thermal energy. It is common experience that heat transfer occurs between a hot and a cold object. Accordingly, temperature can be viewed as a potential and temperature difference as the force that impels heat transfer from one object or system to another at a lower temperature.

Although temperature is a very familiar concept, its detailed definition has occupied the attention of many scientists for centuries. Much of our understanding has come from the science of thermodynamics. Thermodynamics is the study of heat and work and the relevant physical properties. There are two approaches to thermodynamics, classical and statistical. Classical thermodynamics is predominantly concerned with the use of heating processes to do work, whilst statistical thermodynamics is concerned with linking quantum theory with the properties of matter in equilibrium. Either approach yields the same result for the definition of temperature. A summary of some of the definitions developed to describe temperature is provided in Table 3.1.

TABLE 3.1 Some descriptions of temperature

Temperature is defined as the degree of hotness or coldness of a body.	M. Planck
The temperature of a system is a property that determines whether that system is in thermal equilibrium with other systems.	Reference 55
Temperature is the parameter of state that is inversely proportional to the rate of change of the logarithm of the number of accessible states as a function of energy for a system in thermal equilibrium.	Reference 122

Quantitatively, temperature can be defined from the second law of thermodynamics as the inverse of the rate of change of entropy with energy at constant volume, Equation (3.1) (see, for example, Reference 222); that is

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E} \right)_V \quad (3.1)$$

where T is the absolute temperature (K), S is entropy (J/K), E is energy (J), and V is the volume (m^3) or some other fixed external parameter.

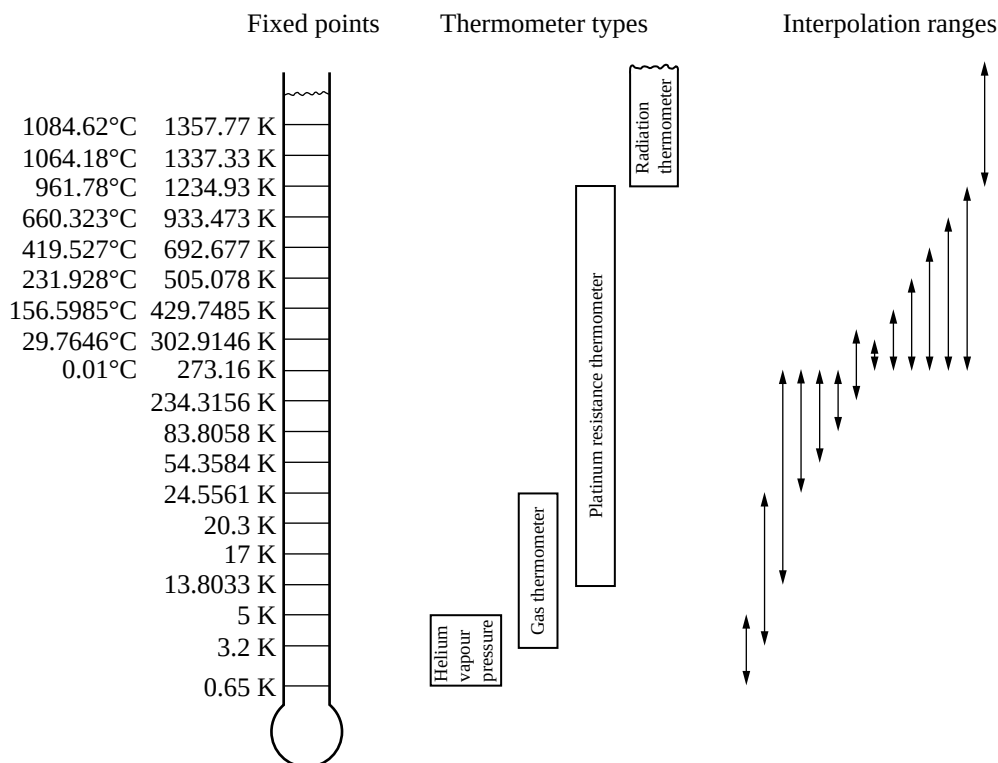
A temperature scale is necessary in order to enable comparison of measurements. A number of temperature scales have been proposed and can be broadly classified as thermodynamic and practical. The unit of thermodynamic temperature, also referred to as kelvin temperature or absolute temperature is the kelvin, symbol K, and is defined in terms of the interval between the absolute zero and triple point of pure water, fixed at 273.16 K; the kelvin is the fraction 1/273.16 of that temperature. In addition to the thermodynamic temperature, the Celsius temperature is defined as equal to the thermodynamic temperature minus 273.15 and the magnitude of one degree Celsius is numerically equal to one kelvin. Within this Item, temperatures are presented using the units kelvins and degrees Celsius, depending on context. Currently common usage of the kelvin is typically for low or cryogenic temperatures below 0 °C and high temperatures, above say 1000 °C.

The International Temperature Scale of 1990 (referred to as the ITS-90 and reported in Reference 121) is intended to be a practical internationally agreed best approximation to the thermodynamic temperature scale. It extends from 0.65 K up to the highest temperature practically measurable using the Planck radiation law and is believed to represent thermodynamic temperature within about ± 2 mK from 1 to 273 K, ± 3.5 mK (one standard deviation limits) at 730 K and ± 7 mK at 900 K. The ITS-90 is constructed using a number of overlapping temperature ranges. The ranges are defined between repeatable conditions using so-called fixed points such as the melting, freezing and triple points of a variety of materials. Fixed points are convenient as the conditions at which, say, the freezing of aluminium occurs can be set up in a highly reproducible fashion. The temperatures assigned to the fixed points are provided from the best estimates, using thermometers of an approved type, at the time of formulation of the ITS-90. Intermediate temperatures between the fixed points are determined by interpolation using specified equations. The five temperature ranges used in the ITS-90 are:

- 0.65 to 5 K, defined in terms of the vapour pressure of helium,
- 3 to 24.5561 K, using a constant volume gas thermometer,
- 13.8033 to 273.16 K, using a platinum resistance thermometer made from material of specified purity,

- 273.15 to 1234.93 K, using a platinum resistance thermometer made from material of specified purity but using different fixed points and interpolating equations from those used between 13.8033 and 273.16 K,
- 1234.94 K and above, using the Planck law of radiation.

An overview of the fixed points, ranges and devices used in defining the ITS-90 is given in Sketch 3.1. Table 3.2 provides details of the fixed points used and the temperatures assigned to these. Previous practical temperature scales have included the International Temperature Scale of 1927 (ITS-27) and the International Practical Temperature Scales of 1948 and 1968 (IPTS-48 and IPTS-68 respectively).

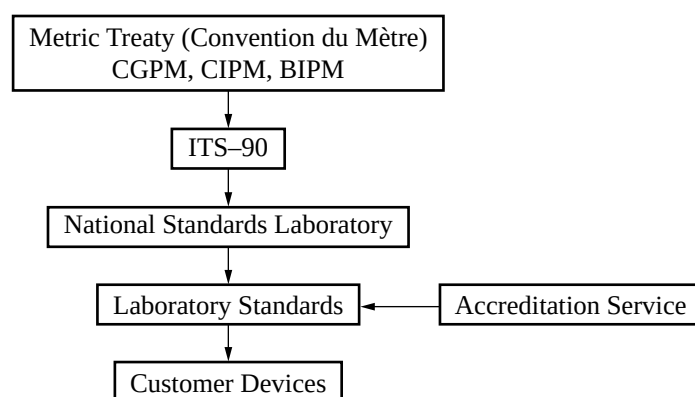


Sketch 3.1 Simplified overview of fixed points and devices used for the ITS-90 (Data from Reference 121. Sketch after Reference 162)

The significance of the ITS-90 is its value in providing a means of traceability between measurements taken in practical applications and its close approximation to thermodynamic temperature. The chain of traceability is illustrated schematically in Sketch 3.2. In order for measurements to be traceable back to the ITS-90, devices used for a given application should be calibrated against devices that have a direct link to the ITS-90. This can be achieved in a number of ways. A typical chain for an industrial measurement device might be calibration against another device that has itself been calibrated by a standards laboratory against a device that has been calibrated by a national standards laboratory. In this way the ITS-90 acts as a transfer standard of near thermodynamic temperatures to popular usage.

TABLE 3.2 Defining points of the ITS-90 (Reference 121)

Number	Temperature (K)	Temperature (°C)	Substance	State
1	3 to 5	−270.15 to −268.15	He	Vapour pressure
2	13.8033	−259.3467	H ₂	Triple point
3	≈17	≈−256.15	H ₂ or He	Vapour pressure
4	≈20.3	≈−252.85	H ₂ or He	Vapour pressure
5	24.5561	−248.5939	Ne	Triple point
6	54.3584	−218.7916	O ₂	Triple point
7	83.8058	−189.3442	Ar	Triple point
8	234.3156	−38.8344	Hg	Triple point
9	273.16	0.01	H ₂ O	Triple point
10	302.9146	29.7646	Ga	Melting point
11	429.7485	156.5985	In	Freezing point
12	505.078	231.928	Sn	Freezing point
13	692.677	419.527	Zn	Freezing point
14	933.473	660.323	Al	Freezing point
15	1234.93	961.78	Ag	Freezing point
16	1337.33	1064.18	Au	Freezing point
17	1357.77	1084.62	Cu	Freezing point



Sketch 3.2 Recommended practice to ensure definition and traceability of temperature measurements. (CGPM = Conférence Générale des Poids et Mesures, CIPM = Comité International des Poids et Mesures, BIPM = Bureau International des Poids et Mesures)

4. MEASUREMENT TECHNIQUES

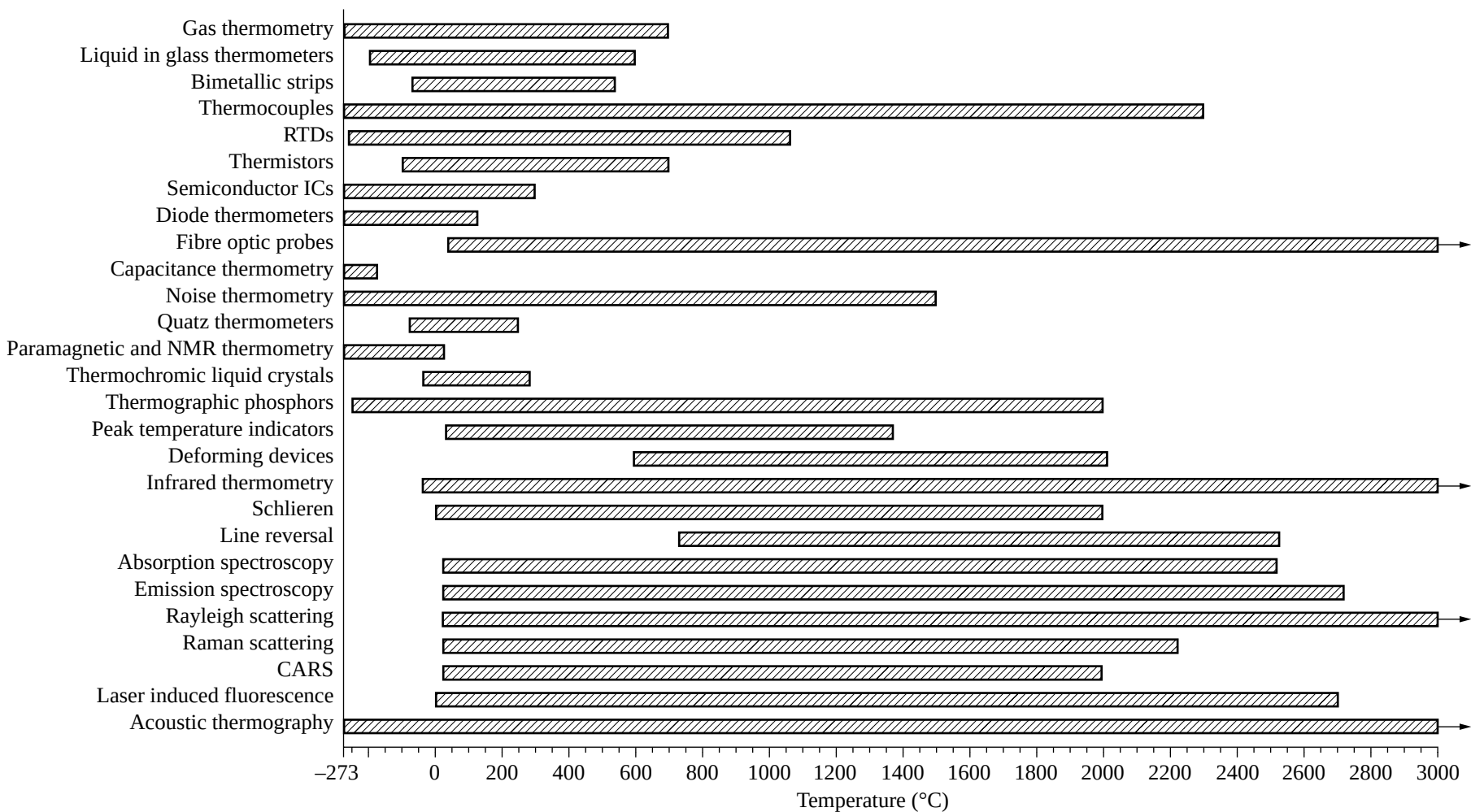
In the selection of a particular method of measuring temperature, consideration may be given to uncertainty, sensitivity, life, size, cost, manufacturing constraints, dynamic response, temperature of operation and robustness. The range of techniques for the measurement of temperature is extensive, utilizing such diverse phenomena as thermoelectricity, temperature-dependent variation of the resistance of electrical conductors, fluorescence and spectral characteristics. For convenience, the various measurement techniques can be classified into three categories depending on the nature of contact which exists between the measuring device and the solid, liquid or gaseous medium of interest.

- (1) *Invasive.* The measuring device is in direct contact with the medium of interest, *e.g.* a thermocouple in a gas stream.
- (2) *Semi-invasive.* The medium of interest is treated in some manner to enable remote observation, *e.g.* surface coatings whose colour changes with temperature.
- (3) *Non-invasive.* The medium of interest is observed remotely, *e.g.* infrared thermography.

4.1 Aspects to be Considered in Selecting a System

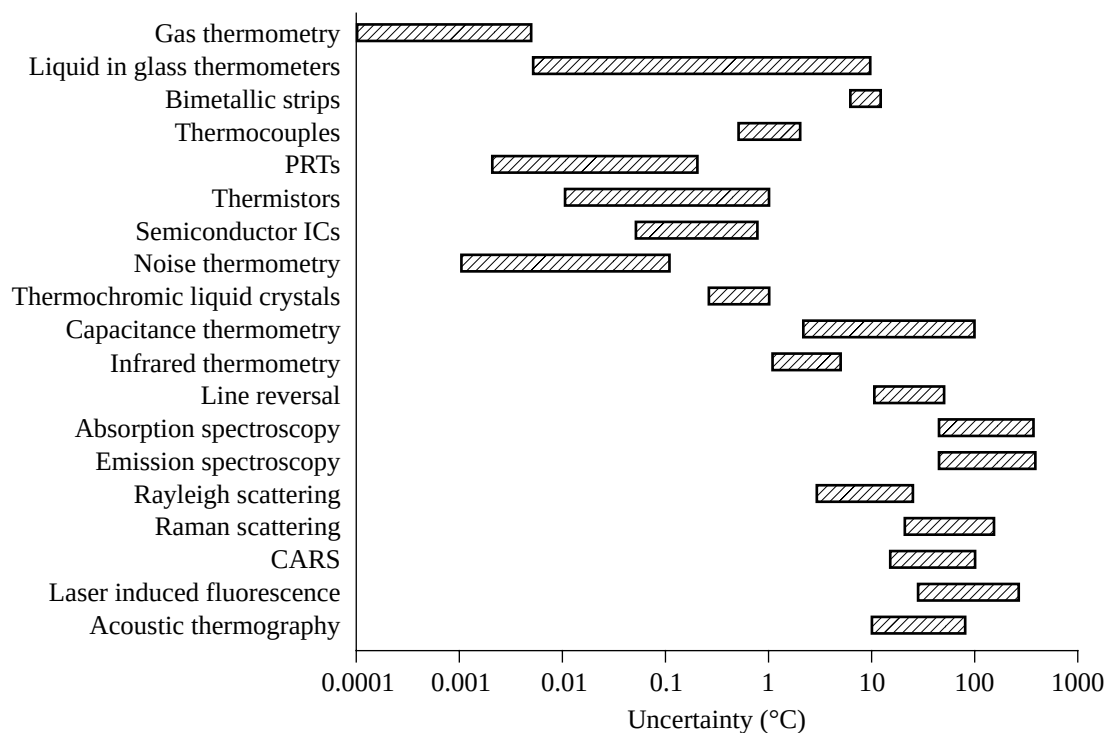
Before selecting a temperature measuring system a number of aspects have to be considered. Some of the issues that might have to be addressed are given below and characteristics of various methods are summarized in the Tables in Section 34.

- (1) What size and shape of sensor is required? If there is no special requirement most types of invasive sensor are available as cylindrical probes which usually incorporate a protective cover. These may range from about 0.25 mm to 15.0 mm in diameter. Items 1 and 2 in the Tables in Section 34 provide details of the form and size of transducers.
- (2) Is an invasive, or non-invasive method the most suitable? In most circumstances, an invasive sensor can be used and this may provide the most economic and the most accurate solution. However, with some more difficult measuring situations, non-invasive methods are essential and any disadvantages such as complexity, cost and increased uncertainty have to be accepted. (See item 3 in the Tables in Section 34.)
- (3) What is the temperature range? Some techniques provide a wide temperature range with a single sensor. Some provide a wide overall temperature range but individual sensors are limited. With others the temperature range possible with the technique itself may be quite limited. Sketch 4.1 illustrates the range of application of various techniques and this information is also tabulated in item 5 in the Tables in Section 34.
- (4) What uncertainty can be accepted? Is the temperature needed with low uncertainty in absolute terms or are temperature differences or changes in temperature really required? With many types of sensor the gradient of the output versus temperature characteristic may remain more stable with time than the apparent origin. If low uncertainty is required then sensors need to be calibrated against known standards before use. If this uncertainty has to be maintained, regular substitution by new calibrated sensors may be needed. Sketch 4.2 provides an indication of the uncertainty normally associated with various temperature measurement techniques and this information is also tabulated as item 6 in the Tables in Section 34.



Sketch 4.1 Approximate temperature ranges for various temperature measurement techniques

- (5) Are steady state or transient phenomena to be measured? Some types of invasive sensor are better suited to fast response, *e.g.* fine thermocouple or resistance wires. (See item 7 in the Tables in Section 34.)
- (6) Will the sensor need protection? Sensors may be fragile and also susceptible to contamination. Many sensors can be fitted in tubes, sleeves or pockets but by so doing their accuracy and response characteristics may be impaired.
- (7) Will the sensor take up the required temperature? This is an important consideration, see Section 4.2.
- (8) Will the presence of the sensor modify the local temperature significantly? If this is likely to be a problem it may be better to consider a non-invasive method (see Sections 22 - 31).
- (9) Can a readily available system be employed? Although special sensors and systems can be designed and manufactured, they are inevitably likely to be more expensive. (See item 9 in the Tables in Section 34 for a guide to the cost of sensors.)
- (10) Is it a multi-channel scheme? If so then in general thermocouple or resistance temperature detectors are more suitable.
- (11) Is a temperature difference to be measured? Common devices used for monitoring temperature differences, also referred to as temperature differentials, are thermocouples and resistance temperature detectors. These devices are described in Sections 8 and 9 respectively and further details can be found in References 56 and 79.



Sketch 4.2 Approximate uncertainty levels associated with various temperature measurement techniques

A nominal temperature range over which the use of each technique is appropriate is given in each of Sections 5 to 31 (each section describing a particular method) and also in the Tables in Section 34. These values provide a reasonable guide but it is not possible to generalize further, as the operating conditions are very relevant. For example, a nickel-chromium/nickel-aluminium thermocouple can be produced from wires down to 25 μm diameter. The thermocouple manufacturer's literature may specify a maximum operating temperature in excess of 1000 $^{\circ}\text{C}$ for these materials. Under controlled conditions in the laboratory such a thermocouple could provide a rapid response sensor which might be entirely satisfactory for a number of tests at this temperature. Nevertheless it would be quite unrealistic to expect it to survive under the conditions obtaining in industrial plant. The requirements for each temperature measurement application should be discussed with the suppliers. Sometimes it may be possible to solve a difficult problem in an unconventional manner. In the steel industry, where the temperature of the molten metal needs to be measured with the minimum of uncertainty, an immersible platinum type thermocouple transducer has been developed that will survive just long enough in the steel melt for the measurement to be completed. It should be recognised that there is ever-increasing scope for the designer to extend, improve or "tailor" the overall performance of systems to achieve a particular result. The incorporation of microprocessors in temperature measuring systems is of considerable value in this regard.

In the consideration of temperature measurement a number of sources of information are helpful. These include reviews on the subject such as Reference 175, 230 and 235 giving overviews, References 23, 61 and 201 concentrating on cryogenic applications (normally taken as temperatures less than the freezing point of water) and Reference 218 concentrating on high temperatures associated with combustion processes and plasmas. Books on the subject include Reference 122 concentrating on fundamental considerations relating to standards laboratories, Reference 58 providing an accessible account particularly for the inexperienced user of temperature sensors, References 213 - 215 providing a wide series of overviews, Reference 106 giving an introduction to temperature measurement and Reference 162 providing insight into the subject of traceable measurement practice. In addition the proceedings of the symposium series entitled Temperature, Its Measurement and Control in Science and Industry (References 13, 30, 62, 139) provide an excellent source of specialised articles on the subject.

4.2 Selection of Method

For many applications there is likely to be more than one method that will provide an adequate determination of temperature. Nevertheless, some thought should be given to the selection of the most appropriate method. Sections 4.2.1 to 4.2.4 describe some of the considerations depending on whether the application is the measurement of temperature in a solid, liquid, gas or of a surface. Table 4.1 is a selection chart that summarizes the characteristics of the majority of methods considered here.

4.2.1 Solids

If the temperature within a solid material is required then some type of transducer needs to be embedded within the material. The choice normally lies between liquid-in-glass thermometers (Section 6), thermocouples (Section 8), resistance thermometers (Section 9) or thermistors (Section 10). Thermocouples are likely to be the most useful in terms of shape or temperature range. Some care is needed to ensure that the transducer assumes the local temperature closely enough. This means that the thermal contact between the transducer and the local material must be satisfactory. In addition, errors arising from the effects of unwanted heat conduction along the connecting wires, or the presence of the sensing probe, should be reduced as far as possible. If the temperature of the solid material is acceptably uniform and the surface is optically accessible, then a non-invasive method, such as infrared thermometry (see Section 22), or a semi-invasive technique, such as the use of thermochromic liquid crystals or thermographic phosphors (Sections 18 and 19), may be suitable. In some cases, for example with production lines or turbine rotors, where the items of interest are moving, a non-invasive method may be essential.

4.2.2 Liquids

The measurement of liquid temperatures usually involves using an immersed transducer. Here the choice is very wide depending on the requirement. If a simple visual indication is required a liquid-in-glass thermometer (Section 6) might well be suitable. Extremely low uncertainty is possible with an appropriate, calibrated instrument. If a large indicator is required then a bimetallic thermometer (Section 7) might be suitable. These instruments are robust and self-contained.

In many applications an electrical signal is required for processing, recording or control purposes. Therefore, an electrically based device is needed, such as for example a thermocouple or resistance thermometer (see Sections 8 to 12). The actual device selected is dependent on the temperature range and the precision required. If the temperatures are changing with time the response characteristics of the sensor must be adequate. Thermocouples or resistance temperature detectors are probably the best choice if a particularly rapid response is needed. It should be borne in mind that the transducer may require mechanical or environmental protection. If this is necessary it is likely to impair the response characteristics. Finally, it is possible in some cases to measure liquid temperatures by surface techniques. Infrared radiation thermometers (Section 22) are used for molten materials such as metals and glass, but considerations of surface emissivity and transparency make these methods less straightforward.

4.2.3 Gases

Many of the considerations that influence the measurement of liquid temperatures also apply to gases. However, the heat transfer potential for similar velocities is generally less with gases than for liquids. Thus the effects of unwanted heat conduction along the sensing probe, or its connecting wires, and radiation exchange are likely to be more serious. Also, high gas velocities can give rise to dynamic heating with an immersed sensor and due allowance must be made for this effect. For simple, isolated measurements, liquid-in-glass or bimetallic thermometers (Sections 6 and 7) may well be adequate. If electrical signals are required, the choice again lies between thermocouples, platinum resistance thermometers, thermistors or transistor instruments (Sections 8 to 11), with the added proviso that thermocouples and resistance wires can be made from very small diameter conductors if required. If protection has to be added, the increase in thermal mass and thermal resistance tends to degrade the response of the sensor more seriously in a gas than in a liquid. For some gas temperature measurements, generally associated with combustion processes, it may be undesirable or impossible to use conventional sensors and use of non-invasive, Sections 24 - 31, or fibre optic techniques, Section 13, becomes necessary. Monitoring combustion temperatures tends to be complicated and expensive and may require the expenditure of a considerable amount of time and effort to produce useful results.

The use of invasive instrumentation involves a disturbance, which manifests itself as a difference between the temperature being measured and that which would exist in the absence of the instrumentation. The temperature reached, for example, by an invasive instrument in contact with a gas stream, is determined by the balance of convective heat transfer from the gas to the probe surface, conduction in the probe itself and its supports and connections, and radiative heat transfer between the probe and its surroundings.

TABLE 4.1 Selection chart. Adapted from Reference 235

Method and Section	Minimum temperature	Maximum temperature	Response	Transient capability	Sensitivity	Uncertainty	High signal	Stability / repeatability	Low thermal disturbance	Commercially available	Relative Cost
Gas thermometer (5)	−269 °C	700 °C	slow	✗	-	A standard	✓	✓	✗	✗	v high
Liquid-in-glass thermometer (6)	−200 °C	650 °C	slow	✓	1 °C	±0.02 - ±10 °C (ind)* ±0.01 °C (lab)*	✓	✓	✗	✓	v low
Bimetallic strip (7)	−73 °C	600 °C	mid	✓	-	±1 °C	✓	✓	✓	✓	low
Thermocouple (8)	−270 °C	3000 °C	very fast	✓	±10 µV/°C	±0.5 °C - ±2 °C	✗	✓	✓	✓	v low
Electrical resistance device (9)	−260 °C	1064 °C	fast	✓	0.1 Ω/°C	the standard above 500 °C	✓	✓	✓	✓	mid low
Thermistors (10)	−100 °C	700 °C	fast	✓	10 mV/K	±0.01 - ±0.05 °C	✓	✓	✓	✓	mid low
Semiconductor devices (11)	−272 °C	300 °C	very fast	✓	±1%	±0.1 °C	✓	✓	✗	✓	low
Diode thermometers (12)	−272 °C	200 °C	fast	✓	high	±50 mK	✓	✓	✓	✓	high
Fibre optic probes (13)	35 °C	4000 °C	fast	✓	10 mV/°C	0.5 °C	✓	✓	✓	✓	mid high
Capacitance thermometer (14)	−272 °C	27 °C	fast	✓	good	poor	✓	✗	✓	✓	mid
Noise thermometry (15)	−273 °C	2500 °C	slow	✓	good	good	✗	✓	✓	✗	high
Quartz thermometry (16)	−80 °C	250 °C	slow	✓	-	0.01 °C	✓	✓	✗	✓	high
NMR thermometry (17)	−270 °C	30 °C	-	-	-	±1 mK	-	-	✓	✓	v high
Thermochromic liquid crystals (18)	−40 °C	283 °C	mid	✓	±0.1 °C	±1 °C	-	✓	✓	✓	low mid
Thermographic phosphors (19)	−265 °C	2000 °C	very fast	✓	~0.05 °C	0.1% - 5%	✓	✓	✓	✓	high
Heat sensitive paints (20)	300 °C	1300 °C	slow	✗	-	±5 °C	✓	✓	✓	✓	mid
Deforming devices (21)	590 °C	2015 °C	slow	✗	~10 °C	poor	visual	✓	✗	✓	low
Infrared thermography (22,23)	−223 °C	5727 °C	very fast	✓	~0.1 °C	±2 °C	✓	✓	✓	✓	v high
Schlieren (24)	0 °C	2000 °C	fast	✓	n/a	n/a	visual	✓	✓	✓	mid
Shadowgraph (24)	0 °C	2000 °C	fast	✓	n/a	n/a	visual	✓	✓	✓	mid
Interferometry (24)	0 °C	2000 °C	fast	✓	n/a	n/a	✓	✓	✓	✓	high
Absorption spectroscopy (25)	20 °C	2500 °C	very fast	✗	line of sight av.	15%	✓	✓	✓	✓	low
Emission spectroscopy (25)	20 °C	2700 °C	very fast	✓	line of sight av.	15%	✓	✓	✓	✓	low
Line reversal (26)	727 °C	2527 °C	very fast	✗	line of sight av.	±10 - 15 °C	✓	✓	✓	✗	low
Rayleigh scattering (27)	20 °C	8727 °C	very fast	✗	0.1 mm ³ in 100 °C	1%	✓	✓	✓	✗	v high
Raman scattering (28)	20 °C	2227 °C	very fast	✗	0.1 mm ³ in 100 °C	7%	✓	✓	✓	✗	v high
CARS (29)	20 °C	2000 °C	fast		1 mm ³ in 50 °C	5%	✓	@atm.pressure	✓	✓	v high
Laser-induced fluorescence (30)	−70 °C	2700 °C	very fast	✗	-	10%	✓	✓	✓	✗	v high
Acoustic thermography (31)	−269 °C	5000 °C	very fast	✓	-	4%	✓	✓	✓	✗	high

* ind = industry
lab = laboratory

4.2.4 Surfaces

The measurement of surface temperature is difficult, particularly if high precision is required. For casual assessments a number of bimetallic instruments (Section 7) are available with flat bases, spring clips and permanent magnets. However, if a substantial temperature difference exists between the surface and the immediate surroundings, uncertainties can arise unless precautions are taken. Under these conditions an improved arrangement is to fit thermocouples (Section 8), platinum resistance thermometers (Section 9) or thermistors (Section 10) equipped with flat or suitably shaped pads. Such pads might be cemented or soldered into place in a fixed installation. These schemes can provide a good thermal contact but the presence of the sensing probe on the surface may well modify the local temperature of the surface, and this would be precisely at the point of the measurement. To obtain the least uncertainty with applied probes it is frequently advantageous if they are small and perhaps recessed in shallow grooves. Connection wires for probes should be run parallel with the surface for some distance. An alternative method of surface temperature measurement is by the non-invasive techniques of infrared radiation or thermal imaging (Sections 22 and 23) although these techniques may be more expensive to implement. At the other end of the scale there is frequently a need for a quick and uncomplicated way of checking the temperature of a surface. Temperature-indicating paints can be applied very readily to provide an indication of the temperatures that are being encountered (Sections 18 to 20).

5. GAS THERMOMETRY

Gas thermometry involves the determination of the temperature of a sample of gas contained within an enclosure. Gas thermometry is a specialised technique and is usually limited to the scientific or standards laboratory.

5.1 Basic Principle

Gas thermometry is based on the ideal gas law:

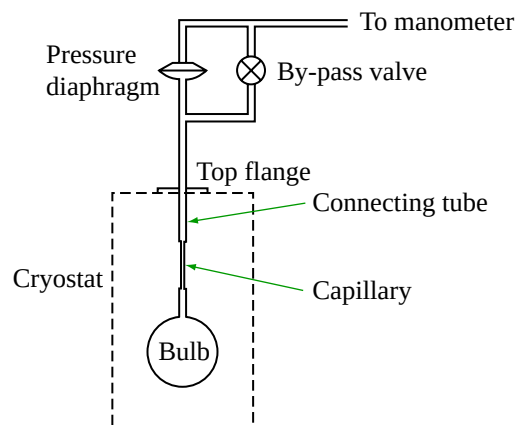
$$pV = n\mathcal{R}T \quad (5.1)$$

where p is pressure (N/m²), V is volume (m³), n is the number of moles of gas ($n = m/M$ (m = mass, M = molar mass)), $\mathcal{R}$ is the universal gas constant (= 8.314 510 J/(mol K), Reference 224), and T is the temperature (K).

By assuming values for the quantity of mass and for the gas constant, the temperature is obtained from a measurement of pressure and/or volume.

5.2 Component Parts

The basic components of a gas thermometer are enclosures to contain the gas sample of interest, under carefully controlled conditions, and a flow circuit to allow the pressure to be measured. Although gas thermometers can be used at temperatures up to 1000 K, the principal application has been in cryogenics and the gas enclosure, commonly known as the bulb, is usually located within a cryostat. Sketch 5.1 illustrates the principal components of a constant volume gas thermometer. Gas thermometers are not generally commercially available. Usually component parts are obtained from a variety of manufacturers and a system assembled to produce a gas thermometer. Some companies such as those specialising in cryostats will assemble a gas thermometry system for a client.



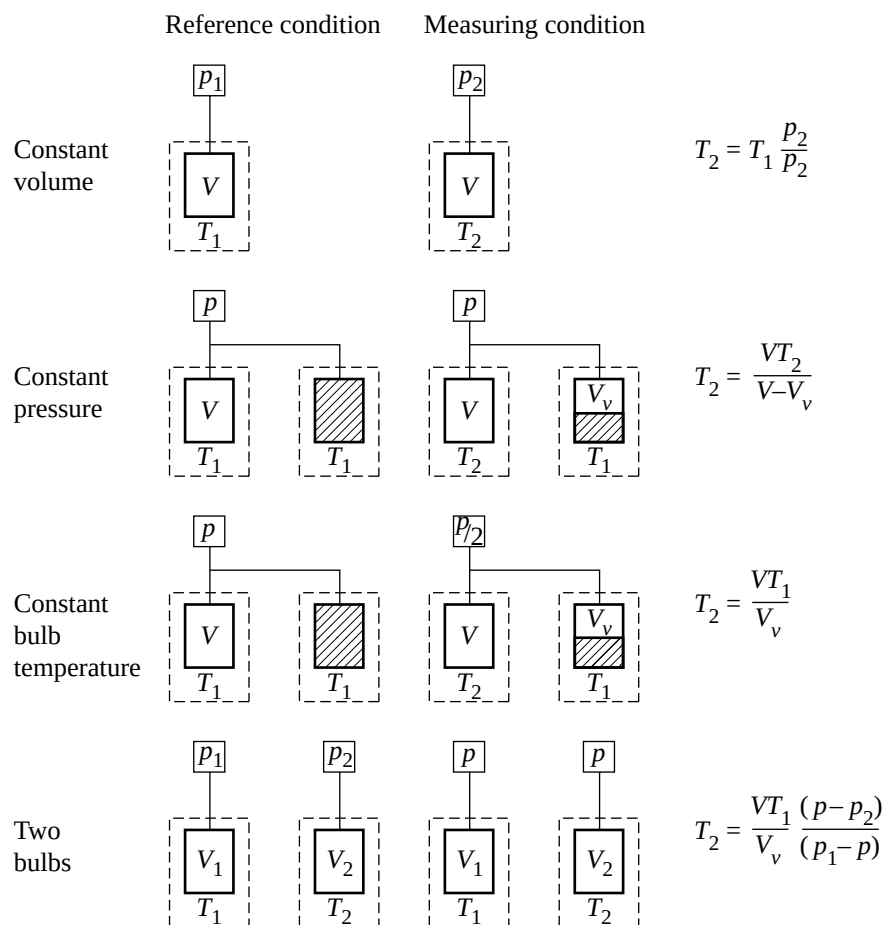
Sketch 5.1 General layout of a gas thermometer

5.3 Alternative Types

If a measurement of temperature is based on the ideal gas equation in the form of Equation (5.1), the uncertainty depends on, amongst other things, the value of the gas constant (see References 37 and 96 for an indication of the improvement in the knowledge of fundamental constants). As a result, a number of methods have been devised that eliminate the need for knowing it. These are:

- constant volume gas thermometry,
- constant pressure gas thermometry,
- constant bulb temperature gas thermometry,
- two bulb gas thermometry.

The four techniques are illustrated in Sketch 5.2. In this sketch, T_1 refers to an accurately known reference temperature, as defined by say a triple point, and T_2 is the temperature to be measured. The diagrams on the left side of the sketch show the schematic arrangement and thermodynamic properties at reference condition; those on the right side, at the measuring condition.



Sketch 5.2 Schematic illustration of four types of gas thermometer.
Adapted from Reference 68

5.4 Temperature Range

Gas thermometers are mostly used for measurements from a few K to approximately 1000 K.

5.5 Causes of Uncertainty

In practice gases do not behave according to the ideal gas equation. The behaviour of real gases can be modelled using the virial equation. A form appropriate to constant volume gas thermometry is:

$$p = \left(\frac{RT}{V} + \frac{B(T)}{V^2} + \frac{C(T)}{V^3} + \frac{D(T)}{V^4} + \dots \right) \quad (5.2)$$

where $B(T)$, $C(T)$, $D(T)$, etc. are the second, third and fourth virial coefficients. These coefficients have been evaluated for a number of gases at various temperatures (see for example References 28, 43, 47, 48, 91, 98 and 101).

The use of the enclosures illustrated in Sketch 5.2 requires determination of the pressures and in some cases the volumes of the enclosures. Corrections are commonly made for the following:

- the dead space in connection tubes (Reference 48);
- thermal expansion of the gas bulb (References 100 and 119);
- the difference in density of the gas at different levels in the pressure sensing tubes (References 48 and 100);
- a thermomolecular pressure correction to account for temperature differences along the pressure sensing tube (References 7, 35, 42 and 48);
- the absorption of impurities in the gas (References 45, 48 and 100).

At the lower temperatures, less uncertainty may be obtained by measuring the vapour pressure of a cryogenic liquid (References 102, 144 and 149). The use of such vapour pressure thermometry in preference to gas thermometry at temperatures below 4.2 K is recommended in Reference 100.

The uncertainty of gas thermometry measurements depends on the care taken and the temperature range. For example Reference 100 reports an uncertainty of 0.5 mK for temperatures between 0.5 K and 30 K. The method is generally expensive and restricted to detailed scientific experiments, calibration and standards laboratories.

5.6 Summary

Gas thermometry involves the determination of the temperature of a sample of gas contained within an enclosure. The technique is based on the ideal gas law and uses measurements of pressure and or volume to allow a calculation of the temperature to be made. The technique is usually limited to the specialist laboratory and significant care is necessary to provide low uncertainties. The performance of gas thermometers is summarized in Table 34.1.

6. LIQUID-IN-GLASS THERMOMETRY

A liquid-in-glass thermometer typically comprises a bulb, stem and thermometric liquid. The thermometric liquid expands with temperature forcing a column of the liquid to rise in a capillary located in the stem. Liquid-in-glass thermometers are commonly used in a wide range of applications from cryogenic temperatures up to approximately 650 °C. Their use at one stage was on the decline but, because they do not require a power supply and can be relatively inexpensive, combined with like-for-like replacement, their future use is currently assured.

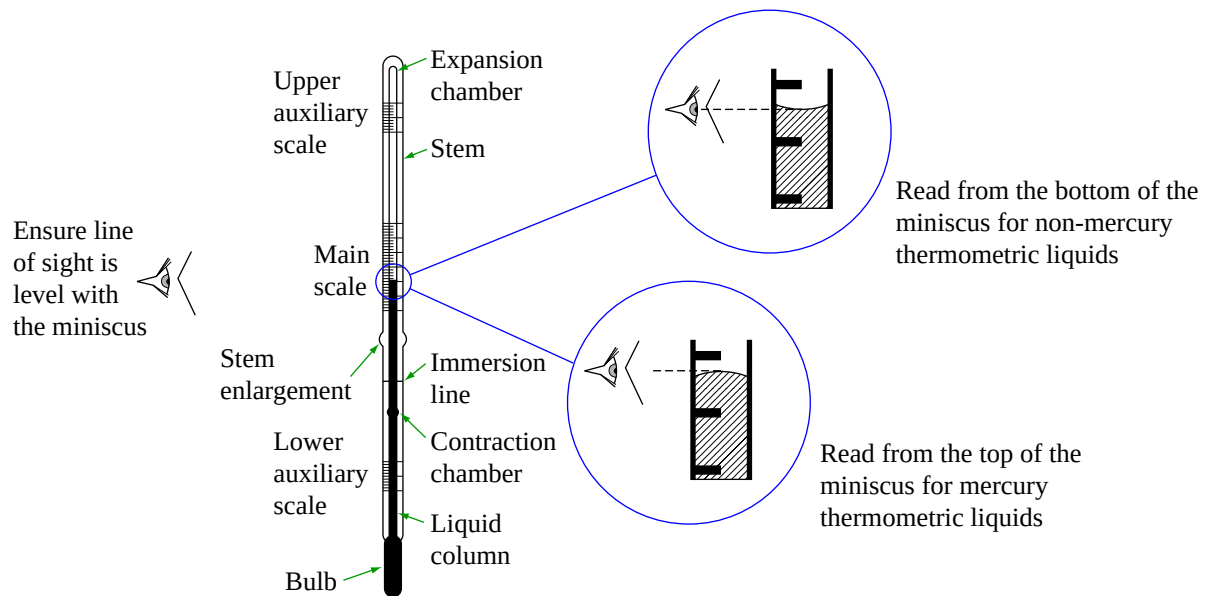
6.1 Basic Principle

Liquid-in-glass thermometers exploit the volumetric expansion of a liquid with temperature. The thermal expansion of a liquid is high in comparison with that of a solid and, with increasing temperature, thermometric fluid contained within a bulb will expand up a capillary tube attached to the bulb. A calibration can be used to associate the column height of the thermometric liquid with temperature.

6.2 Component Parts

There are a wide variety of liquid-in-glass thermometer types but there are various common features. The solid-stem form of a liquid-in-glass thermometer consists of four main components, the bulb, stem, liquid and markings and is illustrated in Sketch 6.1. The bulb is a thin glass container, typically 0.35 to 0.45 mm thick, holding a thermometric liquid such as mercury or an organic spirit. The bulb is connected to a glass stem that contains a small bore capillary tube. The space above the thermometric liquid can be filled with an inert gas or evacuated. As the liquid in the bulb gets hotter it expands and is forced up the capillary stem. The temperature of the bulb is then indicated by the position of the top of the liquid column against a scale engraved or printed on the glass stem. The expansion chamber at the top of the capillary allows for gas compression and gives a slight margin of safety in the case of over-heating the thermometer. The so-called contraction chamber is a widening of the capillary in the main stem, usually below the main scale. As it is an expansion of the bore, the thermometric liquid filling its volume could be equivalent to several centimetres of capillary tube so it shortens the overall length of the thermometer. In addition it serves to prevent all the liquid from retreating into the bulb where gas bubbles become trapped. Some thermometers include one or more auxiliary scales marked on the stem as shown in Sketch 6.1. An auxiliary scale is included for thermometers when the main scale does not include say the ice point and is used for calibration and checking the device. A reference point is sometimes marked on the main or auxiliary scale that is usually at the ice or, less commonly, at the steam point and is used for calibration purposes.

The temperature is read by looking at the position of the meniscus against the temperature scale on the thermometer. The meniscus is the surface shape taken up by a fluid in a container. The flattest part of the liquid meniscus is used for measurement against the scale. Surface tension effects in mercury cause the meniscus to be predominantly convex and the top of the meniscus should be used to read the temperature from the scale as shown in Sketch 6.1. In the case of organic thermometric liquids the bottom of the meniscus is used.

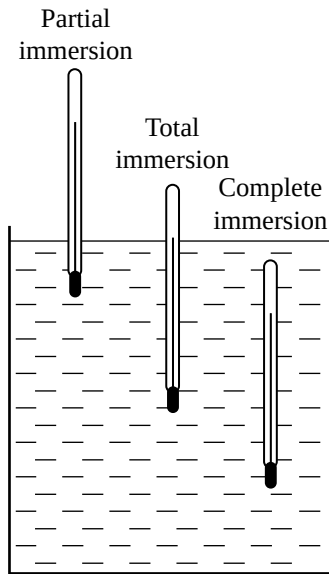


Sketch 6.1 The principal features of an ASTM (American Society for Testing and Materials) specification solid stem thermometer (see ASTM E1-98)²²¹

6.3 Alternative Types

Types of liquid-in-glass thermometers can be categorised according to how the scale is located relative to the capillary tube. For a solid stem thermometer the scale is printed or etched on the stem. For an enclosed scale thermometer the scale is printed on a separate piece of material from the capillary tube. This is attached to the capillary or the bulb and encapsulated within a separate tube. For external scale thermometers the scale is attached to the external body of the thermometer. An alignment mark can be included to indicate that the scale is in the original position relative to the thermometer stem.

Liquid-in-glass thermometers can be further classified according to the level of contact between the medium of interest and the thermometer. Partial immersion thermometers are designed to be used with the thermometer immersed to a specified depth in the medium of interest. This is usually indicated by means of a ring engraved on the stem. Total immersion thermometers should be immersed so that the majority of the column of indicating liquid is submerged in the medium of interest. Complete immersion thermometers must be completely immersed in the medium.



Sketch 6.2 Use of partial, total and complete immersion thermometers

A number of specialist thermometers exist including: Faden thermometers, Beckmann thermometers and clinical thermometers.

6.4 Temperature Range

The range of use of liquid-in-glass thermometers is from about -196°C to 650°C , although no one single thermometer is capable of this entire range. Instead, a variety of stem materials and thermometric liquids are employed specific to particular temperature ranges and uncertainty requirements. Table 6.1 provides a guide to the temperature range of a variety of thermometric liquids.

TABLE 6.1 Apparent thermal expansion coefficients for various thermometric liquids in thermometer glass around room temperature and possible useful temperature ranges. (After Reference 232)

<i>Liquid</i>	<i>Typical apparent thermal expansion coefficient ($^{\circ}\text{C}^{-1}$)</i>	<i>Possible temperature range ($^{\circ}\text{C}$)</i>
Mercury	0.00016	-35 to 510
Ethanol	0.00104	-80 to 60
Pentane	0.00145	-200 to 30
Toluene	0.00103	-80 to 100

Glass is the common choice for thermometers as it is relatively stable in a wide variety of chemical environments. Types of glass used in thermometry include normal glass (soda-lime glass containing zinc oxide and alumina), borosilicate glass, combustion glass, lead glass and silica. Table 6.2 lists the maximum operating temperature for a variety of thermometric glasses.

TABLE 6.2 Common thermometric glasses and temperature limits of operation.
(After Reference 219)

<i>Glass</i>	<i>Maximum operating temperature (°C)</i>
Normal lead glass	400
Jena normal	430
Borosilicate	460
Supremax (silica)	595

6.5 Causes of Uncertainty

Liquid-in-glass thermometers can be calibrated at a number of fixed points and a scale applied to a stem supporting the capillary tube to indicate the range and value of temperature. The uncertainty for industrial glass thermometers depends on the actual device and values range from ± 0.01 °C to ± 4 °C (BS 1041: Part 2, Section 2.1). Laboratory glass thermometers can achieve uncertainty levels of ± 0.005 °C. Uncertainty can occur owing to non-uniformities in manufacture of the capillary bore. If the capillary has a given diameter at the calibration points but its diameter varies in between, then the device will appear accurate at the calibration points but will be inaccurate at intermediate temperatures.

A variety of considerations and error sources exist in the use of liquid-in-glass thermometers as listed below.

- (1) *Stiction*. With all liquid-in-glass thermometers there is a tendency, when temperatures are changing, for the meniscus not to move smoothly along the bore. This can be alleviated by gently tapping the thermometer before making a measurement.
- (2) *Stem corrections*. Not all the thermometric liquid is necessarily at the same temperature as some will be in the capillary tube and the variability in thermal expansion of the thermometric liquid and the stem can cause errors. Corrections are available to reduce the magnitude of this effect if the stem temperature is known.
- (3) *Parallax*. The scale of the thermometer is normally engraved on the outside of the glass stem and errors may occur when estimating the position of the meniscus if the sight line is not precisely normal to the axis of the stem. Care needs to be taken to avoid parallax errors caused by refraction through the glass. The ideal is to view the meniscus at an angle of 90° to the stem. If a 6 mm diameter thermometer, for example, is viewed at 4° to the normal an error of 0.05 °C can occur. For precise work the meniscus should be viewed with a 5 to 10 times magnification microscope. This can be mounted on the stem with a simple spring mechanism to allow it to slide up and down.
- (4) *Column separation*. If the thermometer has been subjected to mechanical shocks or vibration, gaps can occur in the liquid column producing false indications.
- (5) *Secular change*. Changes in the glass structure are known as secular change. Secular change manifests itself by a rise in the temperature indicated by the thermometer and is due to an irreversible contraction of the bulb. During the first year the indicated temperature at the ice point can rise by up to 0.04 °C with a rise of 0.01 °C per year in subsequent years until it stabilises after four to five years. For low uncertainty measurements the extent of secular change should be monitored over the lifetime of a thermometer, say every six months, by checking the water triple point reading and adjustment of the calibration as appropriate.

- (6) *Temporary depression.* If cooling occurs rapidly, structural changes are temporarily frozen in and the glass can take a long time to return to its original size. Consequently a glass thermometer would be temporarily larger than its equilibrium volume at that temperature and the reading would show a low temperature.
- (7) *Pressure effects.* The glass wall of a thermometer bulb is intentionally thin, of the order of 0.35 to 0.45 mm thick, to provide reasonable speed of response. In consequence, it is relatively flexible and sensitive to changes in pressure such as atmospheric pressure or internal pressures.
- (8) *Construction faults and malfunctions.* Faults such as uneven or missing scale divisions, oxidation of the mercury, foreign objects in the bulb or capillary, significant strain in the stem or bulb and a distorted or tapering capillary cannot be rectified without significant manufacturing capability and therefore usually result in the return or controlled discard (following local environmental regulations) of the thermometer.

6.6 Summary

Liquid-in-glass thermometers are increasingly being replaced by relatively cheap resistance devices or by more expensive infra-red devices, giving a digital readout, or by thermally sensitive paint devices which give an obvious visible indication of temperature. Nevertheless there is still an abundance of liquid-in-glass devices and their use, due to simple like for like replacement and due to their non-dependency on a power supply, is set to continue. They have many applications throughout science and industry and certain types of instrument are capable of very low uncertainty. Nevertheless, they have disadvantages in that they are relatively fragile, have a slow response and have to be read by an operator. The performance of liquid-in-glass thermometers is summarized in Table 34.2.

7. THERMAL EXPANSION OF SOLIDS

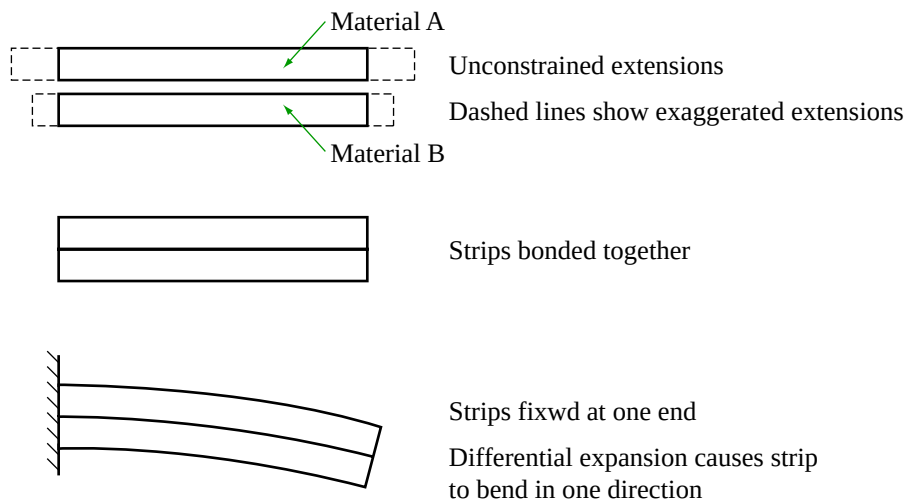
Bimetallic thermometers are commonly used in process control applications. They are robust and do not require an external power supply.

7.1 Basic Principle

These devices take advantage of the difference in thermal expansion between different materials, usually metals. Strips of different metals are bonded together to form a bimetallic strip and when heated the side with the higher coefficient of thermal expansion will expand more causing the assembly to bend (see References 8, 158 and 234). This bending can be translated into a temperature reading by a mechanical linkage to a pointer or other recording device. An advantage of these devices is that they do not require a power supply. Their use as temperature controllers is widespread.

7.2 Component Parts

Bimetallic thermometers use two strips of material with different coefficients of thermal expansion that are bonded together. When the temperature of the assembly is changed, in the absence of external forces, the strip will bend or warp owing to the difference in expansion between the two materials. In its simplest form strips of materials are used supported at one end as illustrated in Sketch 7.1. When the assembly is heated it will deform in the shape of an arc.



Sketch 7.1 Basic components of a bimaterial thermometer

A spiral or helical configuration of a bimetallic strip is useful for indicating temperature on a dial. The spiral serves to allow a long length of the bimetallic strip within a confined geometry and hence results in high sensitivity. This form is commonly used in dial thermometers. These tend to be rugged devices and are used in applications where other sensors might fail. They have the advantage that no power supply is necessary and they do not suffer from the fragility of liquid-in-glass thermometers, for example. In a dial type thermometer one end of the bimetallic strip is fixed to the closed end of a stainless steel tube. The bimetallic strip is wound in a helix so that the deflection of the strip with temperature causes rotation of the free end. This is attached to the shaft of a pointer and a scale is provided on a fascia fixed to the steel tube to indicate the temperature, Sketch 7.2.



Sketch 7.2 Dial type bimetallic thermometer with an adjustable stem and dial to allow flexibility in installation and viewing. Photograph courtesy of WIKA Alexander Wiegand GmbH & Co.

7.3 Alternative Types

To maximise bending of the assembly, materials with significantly different coefficients of thermal expansion are selected. Table 7.1 lists some of the materials used in bimetallic thermometers. Traditionally, as the name implies, only metals or metal alloys have been used such as brass and iron, or invar, an iron nickel alloy with a very low coefficient of thermal expansion. However any two dissimilar materials could be used in theory and use of ceramics and semiconductors to form the differential expansion strip has been demonstrated (see Reference 176). Standards are available for bimetallic strips, see for example References 72 and 181. Dial diameters for commercial gauges vary from 25 mm to 125 mm with stem lengths up to 610 mm.

7.4 Temperature Range

The operating range of a typical commercial product is from -70 to 600°C . The theoretical limit of operation is from about -270°C to the elastic limit of available materials.

7.5 Causes of Uncertainty

The uncertainty in the reading of bimetallic thermometers is associated with mechanical interference, arising say from dirt on the dial indicator mechanism, extreme thermal cycling and general abuse as well as thermal disturbance effects due to the presence of the sensor. If a bimetallic strip is subjected to high temperatures it is possible for the materials to creep, changing the coefficients of linear expansion. Low temperature operation, below freezing point, can introduce instabilities in the reading as the fluid can freeze on the coil impeding the coil motion until the temperature rises. This could be manifest as a hysteresis in the reading.

The uncertainty of a typical commercial product is 1 to 2% of the full-scale deflection with an operating range of -70 to 600°C . However a large length and thin section can be used to provide high levels of sensitivity and a sensitivity of $0.0035^{\circ}\text{C}/\text{mm}$ and a repeatability of 0.027°C are reported in Reference 17.

TABLE 7.1 Properties of selected materials used in bimetallic elements.
(After Reference 234.) Data from Reference 161 and Goodfellows catalogue (2000)

<i>Material</i>	<i>Density</i> (kg/m ³)	<i>Young's modulus</i> (GPa)	<i>Heat capacity</i> (J/kg K)	<i>Coefficient of thermal expansion</i> (K ⁻¹)	<i>Thermal conductivity</i> (W/m K)
Aluminium alloy	2700	61 - 71	896	24×10^{-6}	237
Brass				19×10^{-6}	
Copper	8954	129.8	383.1	17×10^{-6}	386
Chromium	7100	279	518	6.5×10^{-6}	94
Gold	19300	78.5	129	14.1×10^{-6}	318
Iron	7870	211.4	444	12.1×10^{-6}	80.4
Nickel	8906	199.5	446	13.3×10^{-6}	90
Silver	10524	82.7	234.0	19.1×10^{-6}	419
Tin	7304	49.9	226.5	23.5×10^{-6}	64
Titanium	4500	120.2	523	8.9×10^{-6}	21.9
Tungsten	19350	411	134.4	4.5×10^{-6}	163
Invar (Fe64/Ni36)	8000	140 - 150		$1.7 - 2.0 \times 10^{-6}$	13
Silicon	2340	113	703	$4.7 - 7.6 \times 10^{-6}$	80 - 150
n-doped Silicon	2328	130 - 190	700	2.6×10^{-6}	150
p-doped Silicon	2300	150 - 170	770		30
Si ₃ N ₄	3100	304	600 - 800	3.0×10^{-6}	9 - 30
SiO ₂	2200	57 - 85	730	0.5×10^{-6}	1.4

7.6 Summary

Bimetallic thermometers are designed to function as reliable indicators of temperature. The uncertainty is not favourable in comparison with, say, thermocouples or Industrial Platinum Resistance Thermometers (IPTR's). However they respond to temperature changes well because the direct connection between the pointer and the bimetallic coil eliminates any "lost-motion" problems. An advantage is that they require no power supply. A possible disadvantage lies in the fact that the indicator and the transducer are essentially part of the same assembly and this may impose some installation limitations. The performance of bimetallic thermometers is summarized in Table 34.3.

8. THERMOCOUPLES

Thermocouples are a favoured form of instrumentation for temperature measurement owing to their large temperature range, stability and, in many cases, economy. They are widely used with multi-channel data logger systems.

8.1 Basic Principle

The basis of these devices is the Seebeck effect. This is the production of an electromotive force (emf) in a circuit of two dissimilar conductors experiencing a thermal gradient.

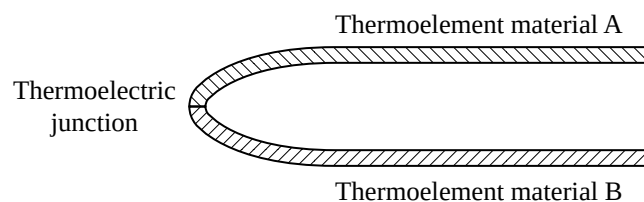
8.2 Component Parts

A thermocouple can be formed by the joining at one end of two dissimilar conductors, see Sketch 8.1. Connection wires can be used to join the free ends to a voltage measurement instrument such as a digital voltmeter (DVM), Sketch 8.2.

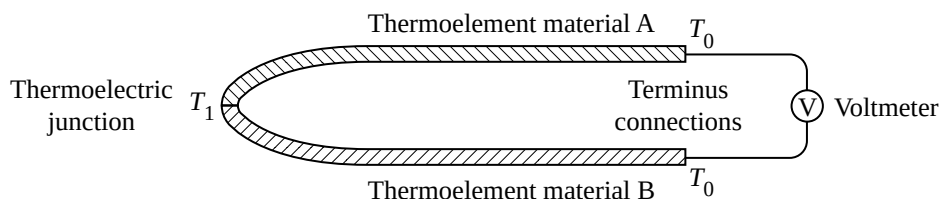
When describing thermocouples the following terminology is sometimes used.

- A *thermocouple* is any pair of dissimilar electrically conducting materials coupled at an interface.
- A *thermoelement*, or leg, is an electrically conducting material used to form a thermocouple.
- An electrical interface between dissimilar electric conductors is a *thermoelectric junction*.
- A free end of a thermoelement is a *terminus*.
- Couplings between identical thermoelements are *joins*.

These terms are not rigidly adhered to in common practice and are often subsumed into the general phrases thermocouple wire, junctions and joins.

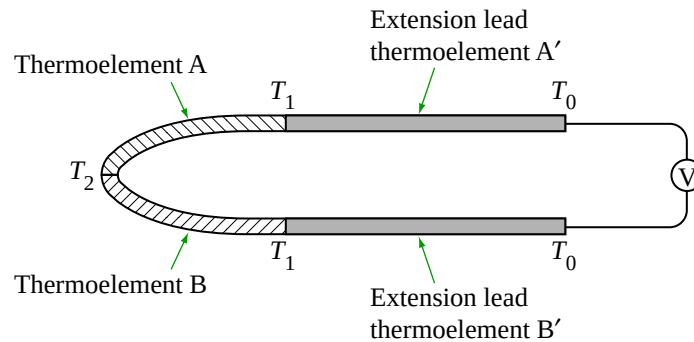


Sketch 8.1 A simple thermocouple formed by joining two wires of dissimilar material



Sketch 8.2 A simple thermocouple circuit incorporating a voltmeter to monitor the thermoelectric emf generated as a result of the thermal gradient between the thermoelectric junction and the terminus junctions

Connection leads known as extension wires are commonly used to connect the thermocouple wire to the voltage measuring device. Extension wire is either manufactured using a wire with a similar physical composition to the thermocouple wire itself but manufactured to a less stringent specification or it is manufactured using a different material altogether. The term 'extension lead' is sometimes used for wires manufactured using the same material as the thermocouple and the term 'compensation lead' for wires manufactured using different materials. However this terminology is not universal and the terms extension and compensation lead, wire and cable are frequently used interchangeably. In most applications the thermal gradient generating the emf is experienced in the first few metres of wire. The remaining length serves the purpose of transmitting the emf to the data acquisition system. The thermoelectric properties of this length of wire are less critical than the part in the region of large thermal gradient. Extension leads tend to be significantly cheaper per unit length than thermocouple wire and in some applications the measurement location and readout instrumentation are separated by a considerable length, justifying the use of an alternative more economic cable for transmission of the emf to the voltage measuring device. The use of extension cable is illustrated in Sketch 8.3.



Sketch 8.3 The use of extension leads in a thermocouple circuit

Tables of data relating the indicated emf to the temperature of the thermoelectric junction have been produced and standardised (*e.g.* IEC 584-1, ASTM E230-96e1, BS EN 60584,; References 174, 180 and 183 respectively). These tables assume that the temperature of the terminus connections, usually known as the reference junction, is at 0 °C. If this is not the case then a correction must be made using the following procedure:

- (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,
- (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. This is the temperature of the thermoelectric junction (also commonly referred to as the tip).

8.3 Alternative Types

Almost any combination of materials could be used to form a thermocouple. However considerations of output, chemical stability and compatibility, and cost limit the choice. A number of thermocouples have been the subject of standardisation and the characteristics for these are listed in Table 8.1. A further number are commonly available from manufacturers worldwide. In addition a large number of combinations of materials have been shown to be useful for specific applications and many of these are reviewed in References 36 and 133. Thermocouples for cryogenic applications are reviewed in Reference 32.

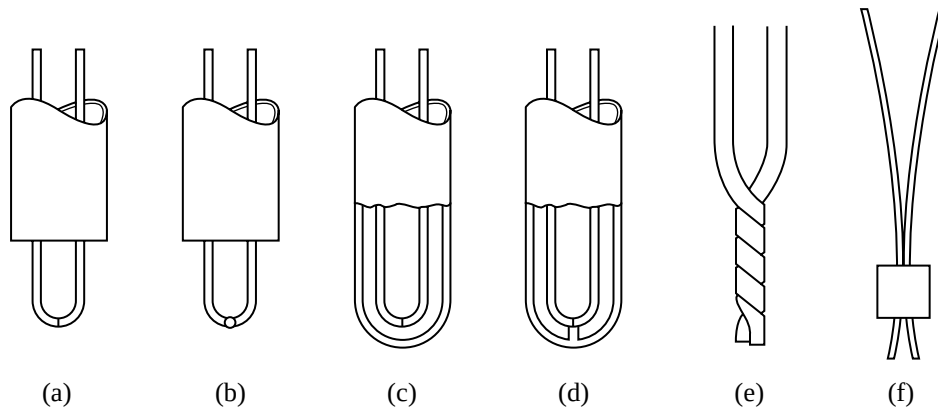
TABLE 8.1 Standardized thermocouples (References 16, 25, 36, 50 and 122)

<i>Temperature range (°C)</i>	<i>Output (μV/°C)</i>	<i>Cost</i>	<i>Stability over the temperature range specified</i>	<i>Standardised letter designation</i>	<i>Common name</i>	<i>Brief description</i>
–262 → 850	15 @ –200 °C 60 @ 350 °C	Low	Low	T	copper/a copper nickel alloy (constantan)	Type T, copper constantan, thermocouples are useful for the –250 °C to 350 °C range in oxidizing or inert atmospheres. Above 400 °C the copper arm rapidly oxidizes. Care needs to be applied to avoid problems arising from the high thermal conductivity of the copper arm. As one lead of this thermocouple is copper, there is no need for special compensation cable. Note that constantan is a general term for a copper nickel alloy with between 35 and 50% copper. The thermoelectric characteristics of each alloy will vary according to the alloying proportions. Although constantan is used in Type T, J and E thermocouples the actual material for each is slightly different.
–196 → 700	26 @ –190 °C 63 @ 800 °C	Low	Low	J	iron/a copper nickel alloy (constantan)	Type J thermocouples are commonly called iron constantan thermocouples and are popular owing to their high Seebeck coefficient and low price. They can be safely used in reducing atmospheres from 0 °C up to 550 °C beyond which degradation is rapid. The maximum temperature for continuous operation is 800 °C.
–268 → 800	68 @ 100 °C 81 @ 500 °C 77 @ 900 °C	Low	Low - Mid	E	nickel chromium alloy (chromel)/a copper nickel alloy (constantan)	Type E, chromel constantan, thermocouples give high output for the range –250 °C to 900 °C. They are ideally suited to temperature measurement around ambient because of the large Seebeck coefficient, low thermal conductivity and corrosion resistance.
–250 → 1100	40 from 250 - 1000 °C 35 @ 1300 °C	Low	Low	K	nickel chromium alloy (chromel)/ nickel aluminum alloy (alumel)	Type K thermocouples are commonly called chromel alumel. They are the most commonly-used thermocouple and are designed for use in oxidizing atmospheres. Maximum continuous use is limited to 1100 °C although above 800 °C oxidation causes drift and de-calibration. Note that the Type K thermocouple is unstable with hysteresis between 300 °C and 600 °C, which can result in errors of several degrees.
0 → 1250	37 @ 1000 °C	Low	Mid - High	N	nickel chromium silicon (nicrosil)/nickel silicon magnesium alloy (nasil)	Type N thermocouples have been developed to address the instability of Type K ³⁹ . They trade linear response for stability and an algorithm is required for conversion between the generated emf and temperature. The voltage temperature curve for Type N thermocouples is slightly lower than that for Type K thermocouples.
100 → 1750	5 @ 1000 °C	High	High	B	platinum - 30% rhodium/platinum - 6% rhodium	Type B thermocouples can be used continuously to 1600 °C and intermittently to 1800 °C. However, owing to a local minimum in its thermoelectric output this thermocouple exhibits a double value ambiguity between 0 °C and 42 °C. However the emf below 100 °C is very low and little concern need be given to cold junction compensation.
0 → 1500	6 from 0 - 100 °C	High	High	S	platinum - 10% rhodium/platinum	Type S thermocouples can be used in oxidizing or inert atmospheres continuously at temperatures up to 1400 °C and for brief periods up to 1650 °C.
0 → 1600	10 @ 1000 °C	High	High	R	platinum - 13% rhodium/platinum	Type R thermocouples give a similar performance to type S, but give slightly higher output and improved stability.

Thermocouples can be categorized as noble metal, base metal, high temperature or refractory metal and non-metal (see Reference 14). Noble metals are relatively inert, although platinum for example oxidizes at 600 °C. Their use in thermocouples stems from their chemical stability and large emf values. Certain base metals such as copper, iron, nickel, aluminum, and chromium, as well as their alloys with additional impurities, can be used to produce materials, *e.g.*, constantan and chromel, with desirable thermoelectric characteristics, particularly for low and moderate temperatures. For high temperature applications, the refractory metals such as tungsten, rhenium, some tungsten and rhenium alloys, and molybdenum can be used. Tungsten and rhenium have very high melting points, 3410 °C and 3280 °C respectively, and have either been used alone or alloyed with other material for thermocouples. Such metals oxidize easily and must not be exposed to oxidizing atmospheres at high temperatures or oxidizing agents. Non-metals such as carbon and boron and compounds such as carbides and borides are generally brittle and have low tensile strengths. Practical thermocouples using non-metals can result in relatively large composite rods.

In addition to the selection of the thermocouple wires to be used, consideration must also be given to the method of joining the wires at the thermoelectric junction, the type of insulation to be used, connectors and installation. The range of connection methods for the thermoelectric junction is illustrated in Sketch 8.4 with the choice depending on the strength of junction and level of thermal contact desired. The range of insulation materials available for thermocouples include Teflon, polyvinyl chloride (PVC), polyimides, fibre glass, fibrous silica and ceramic fibres and the choice depends on the temperature and chemical nature of the application. Protection against harsh environments can be achieved by use of protection tubes, sheaths or thermowells. The characteristics of these are documented in Reference 146.

Thermocouple wire diameters vary from 0.002 mm to 3.2 mm. Large diameters are necessary for long life in hostile environments and smaller diameters give faster speed of response and lower thermal disturbance and a smaller measurement region.



Sketch 8.4 Bead formation options: (a) butt welded, (b) welded bead, (c) butt welded and sheathed, (d) grounded and sheathed, (e) twisted wires, (f) crimped

8.4 Temperature Range

The range of usefulness of thermocouples is approximately -270°C to 3000°C although no single thermocouple is suitable for the entire range.

8.5 Causes of Uncertainty

One of the major concerns in the use of thermocouples is the low output, typically a fraction of a millivolt per degree Celsius making signal to noise and grounding issues of concern. Additional contributions to the uncertainty include cable specification, spurious intermediate junctions, cold junction temperature measurement, voltmeter sensitivity, and cable drift (see References 36 and 227). If a wire is subjected to

high temperatures or stresses the lattice can become modified. Drift caused by annealing of thermocouple materials used in high temperature applications is a common problem. Re-calibration may not compensate for this, as the thermal gradients along the thermoelements in the laboratory calibration may be different from the thermal gradients in the application.

The uncertainty for the standardised thermocouples depends on the specific thermocouple concerned. Several classes of uncertainty exist including Class 1 and Class 2, see Table 8.2. The uncertainty specifications apply for the thermocouple as delivered to the user. Any modifications to the thermocouple structure arising from storage or use by the customer after delivery is not covered.

TABLE 8.2 Manufacturing tolerances for thermocouples (Reference 183)

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

When accounting for the overall uncertainty of a temperature measurement system using a thermocouple the following factors should be combined with a statistical uncertainty approach (e.g. References 166, 202, 223, 225 and 238):

- resolution of the analogue to digital (A/D) converter,
- uncertainty of the A/D converter as specified by the A/D converter manufacturer,
- reference junction uncertainty,
- thermocouple uncertainty based on the Standard limits of error.

8.6 Summary

Thermocouples are commonly used because of their low cost, simplicity, robustness, size and wide temperature range. Their sensitivity is adequate for many applications as is their speed of response but they are less accurate than resistance temperature devices. They require an independent measurement of junction temperature and extension cables can be expensive. The advantages and disadvantages are summarized in Table 34.4 and ESDU 82035, Reference 56, provides details on the operation and application of thermocouples.

9. RESISTANCE TEMPERATURE DETECTORS

Resistance temperature detectors (RTDs) are widely used for measuring temperature. There are various types of resistance based temperature sensors including those using a strip of metal, such as platinum resistance thermometers (PRTs), which are considered in this section, thermistors described in Section 10, and transistor and diode based sensors described in Sections 11 and 12 respectively.

9.1 Basic Principle

The resistance of materials varies with temperature and this phenomenon can be exploited as a measure of temperature.

A common choice of material for RTDs is platinum owing to its stability and temperature range. The equations given in this section are principally relevant to platinum resistance thermometers (PRT's).

The relationship between resistance and temperature can be approximated by

$$R_T = R_0(1 + \alpha t) \quad (9.1)$$

where R_0 is resistance at 0 °C (Ω), R_T is resistance at temperature T (Ω), α is the temperature coefficient of resistance ($\Omega\Omega^{-1}^\circ\text{C}^{-1}$ or $^\circ\text{C}^{-1}$), and t is the temperature ($^\circ\text{C}$).

The temperature coefficient of resistance, α , is calculated from

$$\alpha = \frac{R_{100} - R_0}{100 \times R_0} \quad (9.2)$$

where R_{100} = resistance at 100 °C.

Much of the original work on resistance thermometry was undertaken by Siemens and Callendar and is reported in References 1 to 4. Callendar found that the resistance of platinum could be described by

$$R_T = R_0 \left(1 + At + Bt^2 \right) \quad (9.3)$$

where A and B are constants.

Equation (9.3) can be restated in the form given below which is known as Callendar's equation. This form simplifies the calculations necessary to determine the calibration constants, α and δ (which is a constant).

$$R_T = R_0 \left[1 + \alpha T + \alpha \delta \left(\frac{t}{100} \right) \left(1 - \frac{t}{100} \right) \right]. \quad (9.4)$$

For temperatures below 0 °C, additional terms are necessary and the temperature resistance characteristic is defined by Equation (9.5) which is known as the Callendar-Van Dusen equation.

$$R_T = R_0 \left(1 + At + Bt^2 + C(t - 100)t^3 \right). \quad (9.5)$$

In Equation (9.5) C is a constant and is zero above 0 °C.

Equation (9.5) was the basis of the International Practical Temperature Scales of 1927, 1948 and 1968. This equation has now been superseded by polynomials in the ITS-90. However, it continues to be used to define the resistance temperature relationship for some industrial resistance thermometers. Typical values for the coefficients in Equation (9.5) for a standard PRT (SPRT) and an industrial PRT (IPRT) are listed in Table 9.1.

TABLE 9.1 Typical values for the constants in the Callendar-Van Dusen equation for an SPRT and an IPRT (data from Reference 162)

Constant	SPRT	IPRT
$A / ^\circ\text{C}$	3.985×10^{-3}	3.908×10^{-3}
$B / ^\circ\text{C}^2$	-5.85×10^{-7}	-5.80×10^{-7}
$C / ^\circ\text{C}^4$	-4.27×10^{-12}	-4.27×10^{-12}
$\alpha / ^\circ\text{C}$	3.927×10^{-3}	3.85×10^{-3}

Standards (e.g. BS 1041: Part 3, ASTM E1137 and BS EN 60751) have been produced for PRTs. BS EN 60751 defines a quadratic or cubic for modelling the temperature-resistance characteristic depending on the temperature range. For example:

$$R_T = R_0 [1 + At + Bt^2] \quad \text{for } 0 < t < 850 \text{ } ^\circ\text{C}, \quad (9.6)$$

$$R_T = R_0 [1 + At + Bt^2 + C(t - 100)t^3] \quad \text{for } -200 < t < 0 \text{ } ^\circ\text{C}. \quad (9.7)$$

9.2 Component Parts

The principal components of an RTD are the resistance element, connection leads and some means of measuring the resistance. The resistance element may be a strip of metal bonded or coated on a former or surface, or a length of wire mounted on a former. In order to measure the resistance a current must be passed through the resistance element and therefore connection leads are necessary. A number of methods of resistance measurement are commonly employed including potentiometric and bridge approaches (References 71, 162 and 217).

9.3 Alternative Types

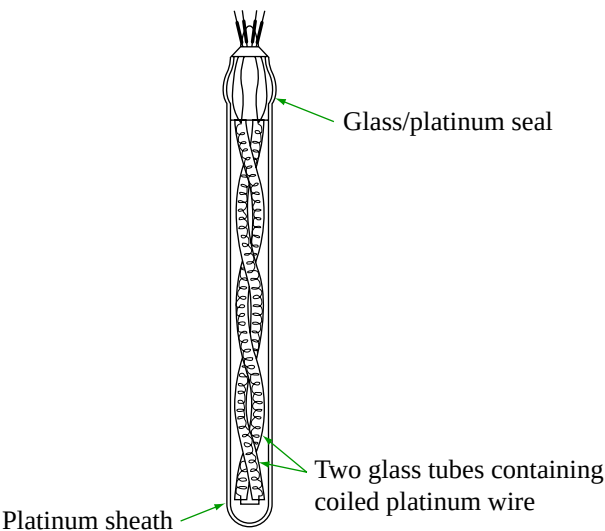
The resistance element of an RTD could in principle be manufactured using any material. However, stability, compatibility, temperature range and economic considerations normally limit the choice to just a few with platinum, copper, nickel, ruthenium, germanium and carbon being the main choices. Copper and nickel are useful in the ranges $-196 \text{ } ^\circ\text{C}$ to $120 \text{ } ^\circ\text{C}$ and $-212 \text{ } ^\circ\text{C}$ to $350 \text{ } ^\circ\text{C}$ respectively (Reference 170), and are cheaper than platinum. Platinum is a common choice for the resistance element of an RTD owing to its chemical stability and wide temperature range in comparison with copper and nickel.

PRTs are available in a wide number of variations depending on the uncertainty and robustness desired for the instrument. The aim in PRT design is to ensure that the sensing element responds to the temperature of the application whilst being unaffected by other environmental factors such as corrosive fluids, vibration, pressure and humidity. Generally the most serious concern in PRT design is strain of the platinum element due to mechanical shock or thermal expansion. In its simplest form a resistance thermometer could comprise

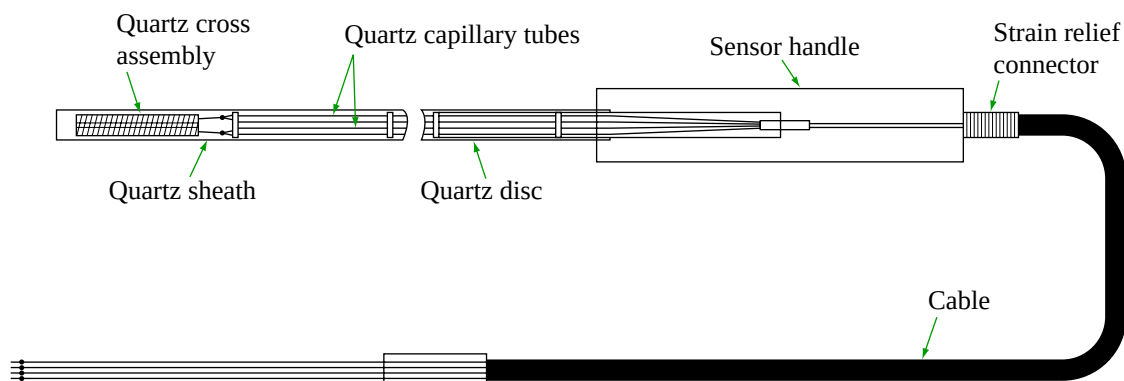
a coil of wire mounted on an electrical insulating support. Such a design, however, would be sensitive to shock and vibrations and knocks could cause unsupported sections of the wire to flex and strain causing work hardening of the wire, which introduces defects in the crystal structure and increases the resistance. An alternative solution is to mount the coil on a solid former. This design is however sensitive to differential expansion between the former and the coil which also serves to work harden the platinum with subsequent uncertainties in the resistivity. Practical PRT designs are a compromise between mechanical robustness and minimisation of strain. Sketches 9.1 to 9.3 illustrate the range of PRT designs available and Table 9.2 provides some information concerning the performance and characteristics of the different types of PRT.

TABLE 9.2 Characteristics for some of the different types of PRT

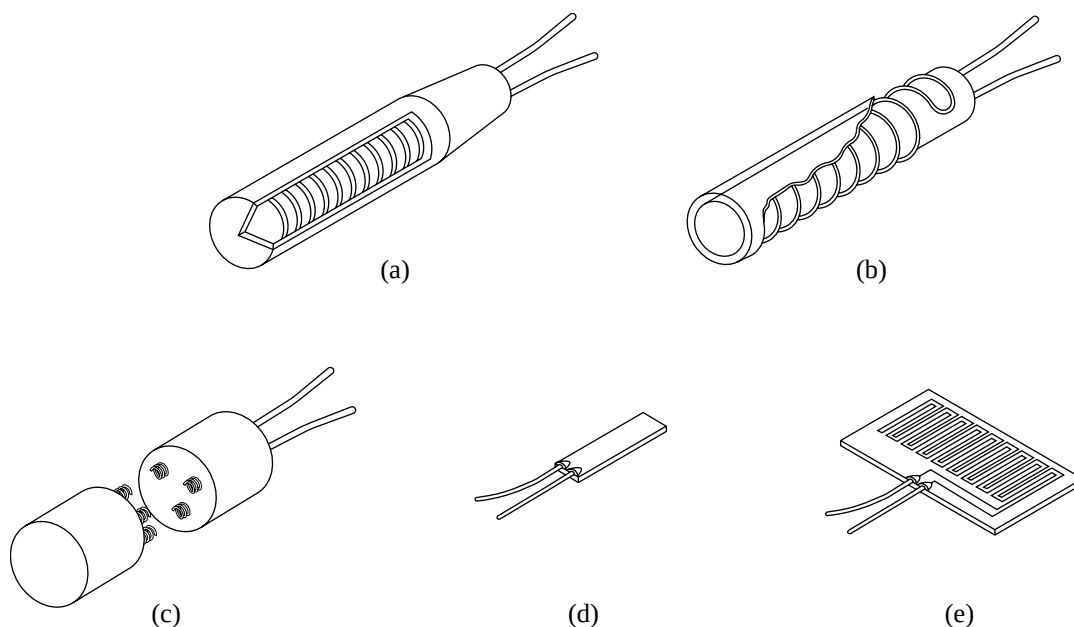
Type	Temperature range	Characteristics
Capsule SPRT	13.8 K - 293 K	Fragile. Must be totally immersed in the medium of interest.
Long stem SPRT	−189.4 °C to 419.5 °C	The platinum transducer is wound on a former contained within a glass or quartz sheath.
High Temperature SPRT	up to 1100 °C	Designed to resist chemical changes at elevated temperatures.
IPRT	−200 °C to 850 °C	Robust.



Sketch 9.1 A typical capsule PRT



Sketch 9.2 Typical construction for a long stem SPRT



Sketch 9.3 Some different designs of IPRTs. (a) Cylindrical PRT with wire set in grooves, (b) Bifilar wound coil, (c) Multi-bore alumina tubing support, (d) Flat pack, (e) Thin film PRT. (Sketches adapted from Reference 39)

Below about 20 K the sensitivity of platinum falls and a number of alternative materials such as rhodium iron, carbon and germanium have been found to form useful resistance elements for RTDs. Above a temperature of 30 K, rhodium-iron alloy gives a similar temperature resistance characteristic to platinum. Below 30 K the sensitivity falls with a minimum between 25 K and 15 K and then rises providing a thermometer with good sensitivity at very low temperatures (References 69 and 143). Germanium RTDs are particularly useful in the temperature range 0.05 K to 100 K with sensitivities of approximately 10^2 to 10^4 Ω/K at 1 K. Certain types of carbon resistors have useful resistance temperature characteristics at cryogenic temperatures.

9.4 Temperature Range

The range of usefulness for the various resistance elements commonly-used is listed in Table 9.3.

TABLE 9.3 Temperature ranges for different types of RTD

<i>Material</i>	<i>Minimum temperature (°C)</i>	<i>Maximum temperature (°C)</i>
Copper	–196	120
Nickel	–212	350
Platinum	–259.35	1508
Carbon	–272	
Germanium	–273.1	600
Rhodium-iron	–272.6	27

9.5 Causes of Uncertainty

Uncertainties inherent with a PRT include immersion errors, lag and settling errors, radiation errors, self-heating, mechanical shock and vibration, thermal expansion effects, contamination, electromagnetic interference, lead wire errors, thermoelectric effects, linearisation errors and strain of the sensing element.

- (1) *Thermal expansion effects.* If the resistance material is not in the fully annealed condition, the resistance versus temperature characteristic becomes less predictable. Strains can arise in the materials as a result of the design and mounting methods. A balance has to be struck between adequate support of the resistance element to cope with operational shocks or vibration, and the maintenance of strain-free conditions.
- (2) *Electrical heating.* An electric current has to flow in the resistance element to develop a temperature related signal for measurement purposes. This generates heat in the element and thus modifies its temperature. The magnitude of this effect is dependent upon the current, the design of the sensor and the nature of its coupling to the local media (Reference 162).
- (3) *Spurious resistances.* The resistance of the connecting wires is included in the overall resistance measurement if a simple two-wire system is used. In addition to their inherent resistance, some parts of the connecting wires will be changing in temperature and their resistance will be changing, probably in an unknown fashion. Three- and four-wire connection schemes can significantly reduce these uncertainties.
- (4) *Oxidation.* Although platinum is relatively stable it can oxidize at elevated temperatures (References 63 and 64).

The combined effects of changes in the overall composition of platinum due to oxidation and thermally induced strain have been investigated in Reference 54. Errors equivalent to several degrees were reported as a result of repeated cycling above 500 °C.

9.6 Summary

Resistance temperature devices can be highly accurate. They are also widely used in industrial applications. The particular design of the sensing element depends on the application, the required uncertainty, sensitivity and robustness. Some advantages and disadvantages associated with this technique are summarized in Table 34.5 and ESDU 84036, Reference 79, provides details of operation and application of resistance thermometry.