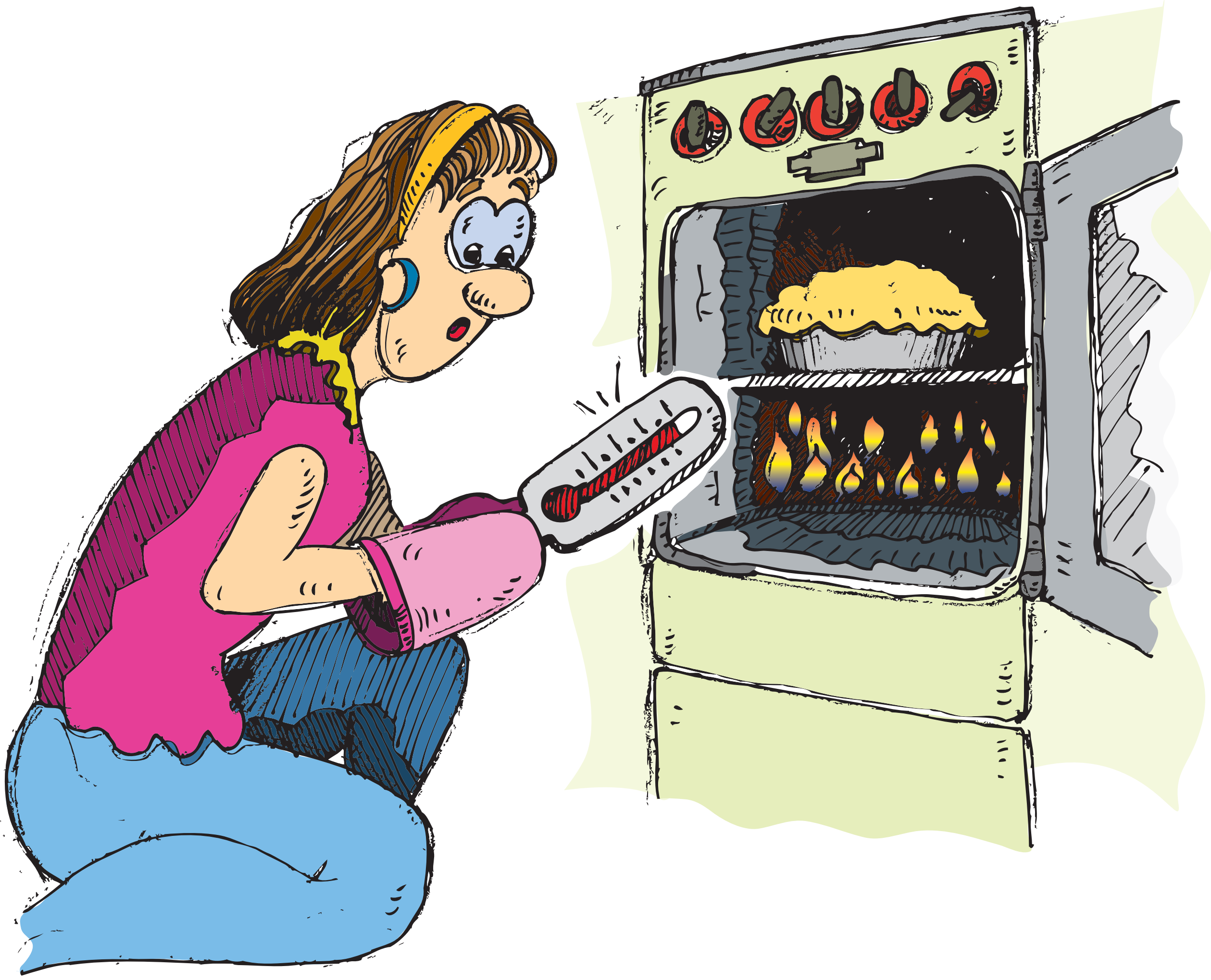
National Physical Laboratory

Good Practice Guide No. 125

The Beginner's Guide to Temperature Measurement

Richard Rusby



National Measurement System

Measurement Good Practice Guide No. 125

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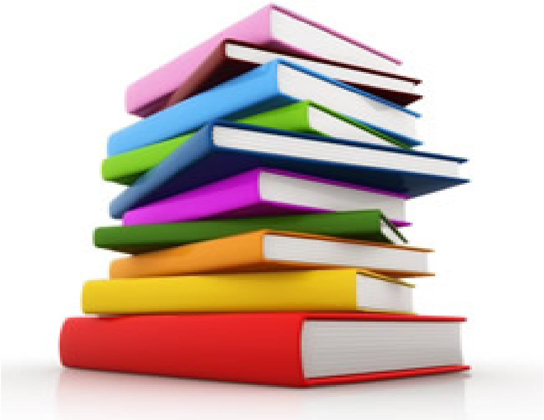
NPL Measurement Good Practice Guides



This is one of a series of NPL guides about measurement. These guides are aimed at everyone who has an interest in measurement, whether in a laboratory, factory, hospital, university, college or in any other walk of life.

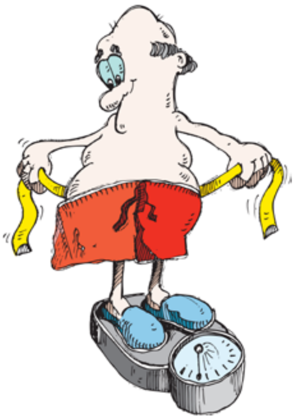
The series includes beginner's guides, which introduce measurement concepts, methods and practices at a basic level. More specialised guides cater for measurement professionals and practicing scientists and engineers who want to go more deeply into an area of measurement. References to additional guides or reading are given where appropriate.

All these guides aim to promote good practice in measurement, and are produced with technical input from specialists in the particular subject covered.

NPL is the UK's national measurement institute. It aims to deliver the highest economic and social benefits through world-leading and responsive science and knowledge services. This series of NPL Good Practice Guides provides one way to transfer knowledge to people who need to make better measurements.

For more information or help with measurement problems visit www.npl.co.uk/contact-us.

Introduction to measurement



Measurement underpins science, technology and industry. It enables processes to be run efficiently, and innovative and competitive products to be made. It impacts strongly on the welfare of a modern society and touches almost every aspect of daily life.

A measurement tells us about a property of something. It might tell us how heavy an object is, or how hot, or how long it is. A measurement gives a number to that property, expressed in the appropriate unit.

The units of measurement are standardised. The International System of Units (SI) is used worldwide so that measurements can be consistent everywhere.

Measurements are only ever estimates. Every measurement is subject to some uncertainty. Perfect measurements cannot be made and so the true value is never known exactly. The uncertainty of a measurement expresses how good the estimate is thought to be.

A measurement result is incomplete without a statement of uncertainty. It is therefore in three parts: a number, a unit of measurement, and an uncertainty. For example, a length may be measured as 2.3 cm $\pm$ 0.1 cm.

The uncertainty of a measurement should suit the need: a school clock need not have atomic accuracy.

Measuring equipment should be calibrated by comparison against a suitable reference which itself has been calibrated. An unbroken chain of calibrations linking back to a national standards body such as the National Physical Laboratory (NPL) is known as measurement traceability.

Good measurement practice can reduce uncertainty and so improve the quality of processes and products.

A Beginner's Guide to Temperature Measurement

Contents

0 About this guide

This is an introductory guide which aims to help first-time users who have no experience of how to measure temperature beyond what they may have picked up in school, college or everyday life. The range of potential applications in science and technology, at low and high temperatures, is very broad and none can be treated in detail, but it is hoped that after reading this guide the user will feel more confident in approaching the task and will find the literature more accessible.

1 Introduction

The guide opens with some basic background to the concept of temperature, why it is important to measure it, and some of the difficulties which may be encountered.

Perhaps the first question for a new user to consider is whether to use a contact method, in which a sensor is inserted or attached to the object or medium whose temperature is to be measured, or whether to use a remote sensing non-contact method.

Contact methods are introduced in Section 1. They mostly use electrical sensors such as resistance thermometers, for applications requiring good accuracy up to moderately high temperatures (usually <450 °C, but sometimes higher). Alternatively thermocouples are smaller, more rugged and durable, and can be used at much higher temperatures, but are less accurate. These sensors are discussed in Section 2. Guidance about how to use them is given in Section 4.

Non-contact infrared radiation thermometry is discussed in Section 3. It is well adapted for measuring very hot, moving or distant objects, and so avoids many of the problems of using contact sensors, but it also has its disadvantages. The basic principles of the method are outlined, and some guidance is given about choosing and using an infrared thermometer.

1.1 What is temperature?

Modern ideas about heat and temperature go back to the mid-nineteenth century when it was first realised that heat is the energy associated with the motion of the atoms or molecules of which everything is made. The more energetic the atoms are, the faster they move (in a gas or liquid) or the more vigorously they vibrate (in a solid). Temperature is related to heat but is different from it. As we all know, the application of heat causes the temperature to rise – except that when the heat melts a solid or boils a liquid, the temperature remains constant!

We can easily see that heat and temperature are different because the heat energy in a large object is greater than that in a small object of the same material at the same temperature.

In simple terms, temperature is often said to be the 'degree of hotness', though exactly what this means is not clear. More scientifically, it is the *potential for heat transfer*, by conduction, convection or radiation.

Thus a temperature difference causes heat to flow, just as a pressure difference causes water to flow in a pipe and an electric potential difference causes a current to flow in a wire. If two objects are placed in contact, heat will flow from the hotter to the colder. Eventually, when no more heat flows, we can say that they are at *thermal equilibrium* with each other and that their temperatures are the same. We use this property in measuring temperature when we place a thermometer in contact with an object: the reading of the thermometer after they have reached equilibrium tells us what the temperature of the object is.

Strictly this is the ideal case – to come to equilibrium they must be isolated from any other objects and their surrounding environment. We would also like the thermometer to be small enough that it does not disturb the temperature of the object under measurement.

Many important consequences follow from these fundamental ideas about heat and temperature, and they are discussed in textbooks of thermodynamics and thermal physics. The important point to note here is that the second law of thermodynamics shows how a 'thermodynamic' (absolute) temperature can be derived as a fundamental parameter of physics and chemistry, *independent of any arbitrary material property* (like the expansion of mercury in glass, or the resistance of a platinum wire). To be meaningful and useful a temperature scale must be based on thermodynamic principles.

1.2 Why measure temperature?

We are all familiar with the measurement of temperature by nurses, weathermen, cooks and gardeners, and most of us have thermometers for everyday purposes. Less familiar, though unsurprising, is the fact that temperature is one of the most important parameters in monitoring or managing processes in science, technology and industry. For example, if the temperature of a molten steel casting is not right, it will either fail to produce good material or be wasteful in the use of energy and time, or both. The same applies in the processing of glass, semiconductors, petrochemicals, plastics, pharmaceuticals, foods, etc. Similarly, low temperature processes are important in air conditioning, cooling and freezing foods and biological samples, liquefying gases for many purposes, and for cooling the superconducting magnets in medical MRI scanners.

These applications take us well outside the range of our normal experience, and often call for precise and accurate thermometers designed to meet particular requirements.

Pouring steel at about 1500 °C

1.3 Basic questions in temperature measurement

The process of measuring temperature - insert the sensing probe and take a reading - could not in principle be simpler, but in practice there are many reasons why the reading may not be correct. The following are some points to consider.

Does the probe make proper contact?
Unlike the electrical case, where a simple touch may be sufficient, heat flow is slow and not easily channelled. Good thermal contact requires that the probe is deeply immersed in the object or process, and for long enough that the sensor near the tip really reaches the temperature to be measured. Poor thermal contact is one of the commonest causes of error in temperature measurement.

Can the sensor stand the environment?
For measurements at or around ordinary ambient temperatures this is not a problem, but a sensor which is used up to several hundred degrees or even to 1000 °C or more is likely to drift or fail because of stresses due to expansion and contraction, or contamination by other materials, or chemical reactions such as oxidation. The higher the temperature, the more resilient the sensor must be and the more precautions must be taken to avoid excessive drift.

Can a remote sensing technique be used?
One way of avoiding both these problems is by remote sensing; that is, using the heat radiated from an object to sense and measure its temperature. This can be very convenient, and it is not as expensive as it was a few years ago. It is not without its problems, see Section 3, but infrared radiation thermometers are very widely used for general purposes.

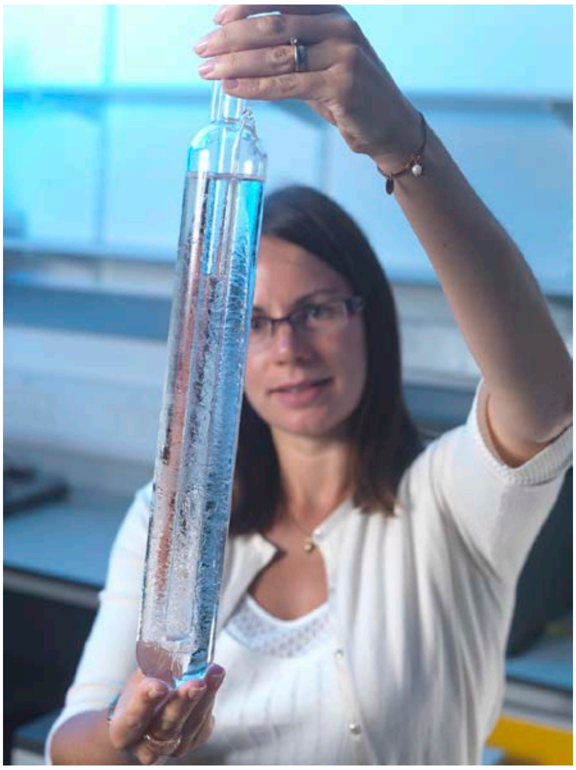
Has the thermometer been calibrated? This means that it has been compared with a standard thermometer at a series of temperatures in the range of use. For the calibration to be 'traceable' to the proper standards the calibration should be done in a laboratory approved for the purpose, and a certificate issued with a statement of the uncertainty achieved. For less exacting requirements a certificate of conformity with a standard specification, supported by factory tests, may be sufficient.

In many cases the thermometer sensor and the instrumentation are integrated into a single package and can be calibrated as a complete system. Where they are separate they may be calibrated separately or together. It is not sufficient to calibrate the sensor and trust that the instrumentation is accurate, or vice versa.

Before discussing thermometers and how to calibrate and use them in more detail, we need to consider the units of temperature, and how the temperature scale is set up.

1.4 Temperature units and the International Temperature Scale of 1990

As with other physical quantities, temperature measurement begins with the definition of a unit. Historically, in the Celsius (centigrade) system the unit was based on the so-called 'fundamental interval' of 100 degrees between the melting point of ice and the boiling point of water, both at standard atmospheric pressure. Since 1954 the adopted unit has been the kelvin, which is defined by assigning the value 273.16 K to the triple-point of water, the unique temperature at which the liquid, solid and vapour phases of pure water are in equilibrium.



The triple point of pure water is the melting temperature of ice at the vapour pressure (i.e. in the absence of air). A glass water triple-point cell like this one contains a sample of pure water under vacuum. To prepare the cell for measurement an ice mantle is frozen around the central tube using solid carbon dioxide (dry ice) at about – 80 °C. When enough ice has formed (taking care not to allow the cell to freeze solid), the cell is placed in ice at 0 °C. Inside the cell the three phases, ice, water and water vapour, settle at the temperature of the triple-point, 273.16 K or 0.01 °C: any heat flowing in or out just melts or freezes some ice. The long thin shape is to allow deep immersion of a thermometer for calibration.

For most everyday purposes, temperatures are still measured in degrees Celsius, using the definition that the temperature t in °C is the temperature T in kelvins minus 273.15:
t / °C = T / K – 273.15.
Thus the triple point of water is both 273.16 K and 0.01 °C exactly. The numbers in the definitions were chosen such that there are still (almost exactly) 100 degrees between the melting point of ice and boiling point of water.

The Fahrenheit scale is formally obsolete, but is occasionally used. Relative to Celsius temperatures, Fahrenheit temperatures are defined such that
t / °F = (9/5)(t / °C) + 32.

Since temperatures are not additive and can't be divided up, like metres or amps, a temperature scale has to be derived from fundamental principles, for example using the physical laws governing the properties of gases or thermal radiation. Such experiments are very difficult and time-consuming, but they nevertheless form the basis of the practical temperature scale that is used in science, technology and everyday life.

Thus the *International Temperature Scale of 1990, ITS-90*, makes use of 'fixed points' whose temperatures have been established in careful experiments and which can be used as reference values up and down the scale. It then defines procedures by which certain *specified practical thermometers* can be calibrated in such a way that the values of temperature obtained from them are *precise and reproducible*, while at the same time *approximating the corresponding thermodynamic values* as closely as possible.

The text of the ITS-90, together with related documents and guidance on how it can be realised, are available from www.bipm.org.

1.5 Fixed points

Fixed points are temperatures at which a pure substance changes its phase. In the ITS-90 they are

- *melting and freezing points* of metals such as tin and zinc, in which the solid and liquid phases are at equilibrium at one standard atmosphere pressure, with heat slowly entering or leaving the sample
- *boiling (vapour pressure) points* of hydrogen and helium at low temperatures, where the liquid and vapour are at equilibrium
- *triple points*, e.g. of water, mercury and argon, where the solid, liquid and vapour phases are all at equilibrium. They are the melting or freezing points at the vapour pressure.

During the phase change a significant amount of heat is absorbed or liberated, and while this is happening the temperature remains almost constant, *i.e.* it is 'fixed'. If a thermometer senses this (known) temperature, its calibration at this point can be determined. A full calibration is obtained by using a set of fixed points covering the range of interest.

Fixed points are also fixed in the sense that they are the same from one day to the next, and from one laboratory to the next, provided that the experiments are carefully done and that the materials are not contaminated.

1.6 Thermometers

A thermometer is a device in which a property that changes with temperature is measured and used to indicate the value of the temperature.

In a mercury thermometer the liquid expands as the temperature increases, so changing the length of the mercury column in the capillary glass stem. The temperature is indicated by a scale marked on the glass, in degrees.

In an electrical thermometer a measurement is made of a resistance or a voltage which depends on temperature, and a conversion algorithm enables the temperature to be displayed.

A radiation thermometer senses the heat radiated and, again, an electrical signal is processed in order to display the temperature.

To be useful, the thermometer must have some other properties. It must be

- *repeatable*, so that the measured property of the device has the same value (or very nearly so) whenever the temperature is the same. In particular, the device should withstand exposure to temperatures within its range of use
- *sensitive* to temperature but *insensitive to things other than temperature*, so the measurement should not depend on factors such as the humidity or pressure
- *calibrated*, so the measured property (length, resistance, etc) can be reliably converted to temperature. If the instrument reads directly in temperature, the calibration shows how accurate the reading is
- *convenient to use*. Factors such as size, ruggedness, speed of response, immunity to electrical interference, etc, and cost, will be important to varying degrees in different applications.

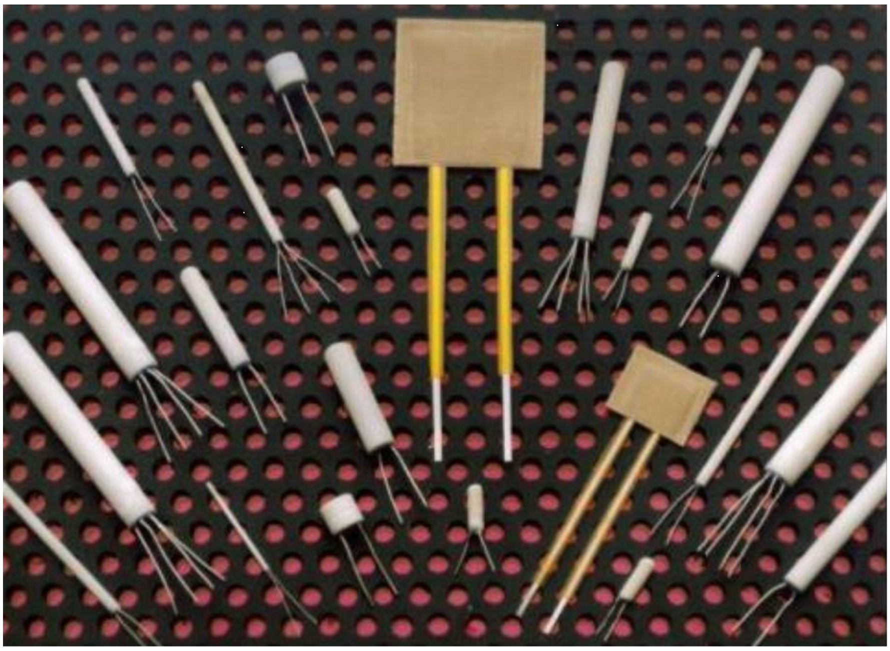
The majority of scientific and industrial temperature measurements use resistance thermometers, thermocouples or radiation thermometers, and the measurements are often automated. They can be used at very low or very high temperatures with good accuracy and the instrumentation can be very sophisticated, with multiple measurement channels and feedback for process control, etc. The next section and Section 4 are concerned with contact thermometers; non-contact radiation thermometers are treated in Section 3.

2. Contact thermometers and their calibration

2.1 Resistance thermometers

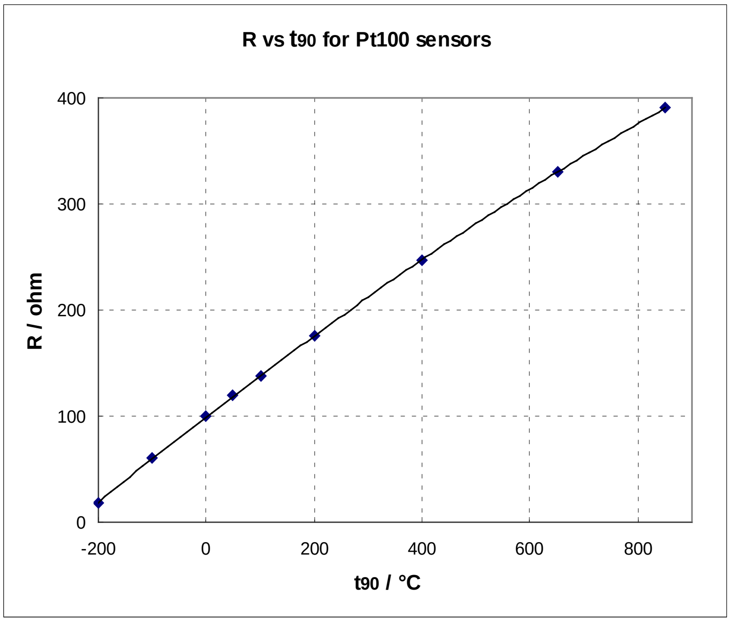
Resistance thermometer sensors use a wire, film, chip or bead whose electrical resistance changes with temperature. The sensor is located near the tip of a closed protective tube, to make a probe which can be inserted into the measurement environment. In medical thermometers the reading is often displayed on the probe itself, for which a battery is needed. More usually a connecting cable leads from the probe to the measuring and indicating unit.

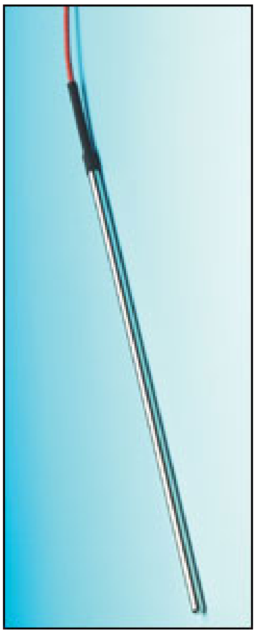
The most accurate thermometers are the Standard Platinum Resistance Thermometers (SPRTs) used as specified in the ITS-90, where uncertainties can be less than 0.001 °C. However, they are only suitable for laboratory use, and in industry more rugged industrial platinum resistance thermometers are used, variously known as IPRTs, Pt100s, RTDs (resistance temperature detectors). The sensors are usually made with wires or films of 100 Ω at 0 °C and packaged in alumina tubes or on flat substrates, with two or more connecting wires emerging as illustrated below. They are then inserted into a steel protective tube to make the complete measurement probe.



Some Pt100/RTD sensors suitable for insertion in steel protective tubes or on flat surfaces. The smallest are about 1 mm in diameter.

Pt100 manufacture is standardised in the international specification IEC (BS EN) 60751, and the resistance-temperature dependence is shown below. Using a typical 1 mA measuring current, a Pt100 sensor has a sensitivity of approximately 0.4 mV/°C, and good temperature resolution can be readily achieved. Over a limited temperature range (- 100 °C to + 250 °C) the accuracy of a measurement can be 0.01 °C or better, rising to a few tenths of a degree at ~ 600 °C, usually limited by the calibration and stability of the sensing probe, and on how it is used. Although the standard specification extends to 850 °C, Pt100s are rarely used above 660 °C.

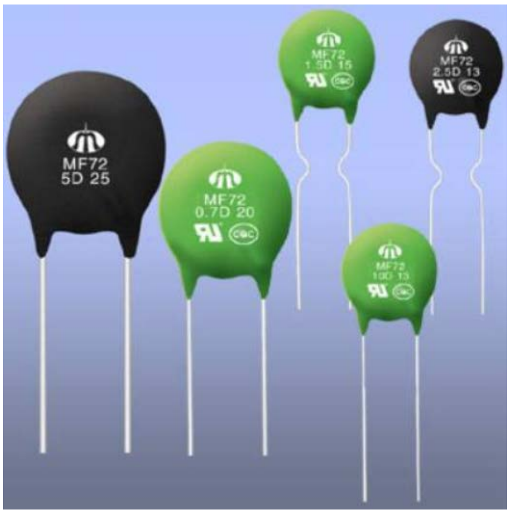




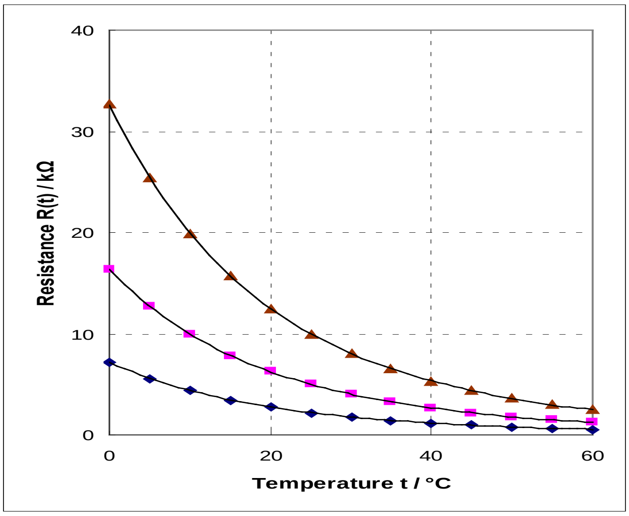
Resistance versus temperature for a Pt100 sensor, and (right) a steel probe with heat-shrink transition to flexible cable, courtesy of TC Ltd (www.tcdirect.com)

The measuring instrument and the connections must be chosen to meet the requirement. Most sensors are made with two wires emerging, but if there are only two wires connecting all the way to the instrument, the resistance of these wires is included in the measurement and errors of a few °C may result. Some compensation for the lead resistances can be achieved by connecting a third lead to one side of the sensor (3-wire connection), but best accuracy requires four wires, two for passing the current and two for sensing the voltage across the Pt100 resistance.

Thermistors are temperature sensitive resistors made from small beads of various semiconductive oxides. In the more common NTC (negative temperature coefficient) types, the resistance increases very strongly as the temperature falls, see the figure below. They are well suited for use in small probes with fast response, eg as current limiters in electronic circuits and in medical thermometry, where good sensitivity is achieved over useful though limited temperature ranges. Since the resistances are large, generally several kilohms, 2-wire connections can usually be used without significant error. Thermistors are not standardised, and the manufacturer's specification must be referred to.



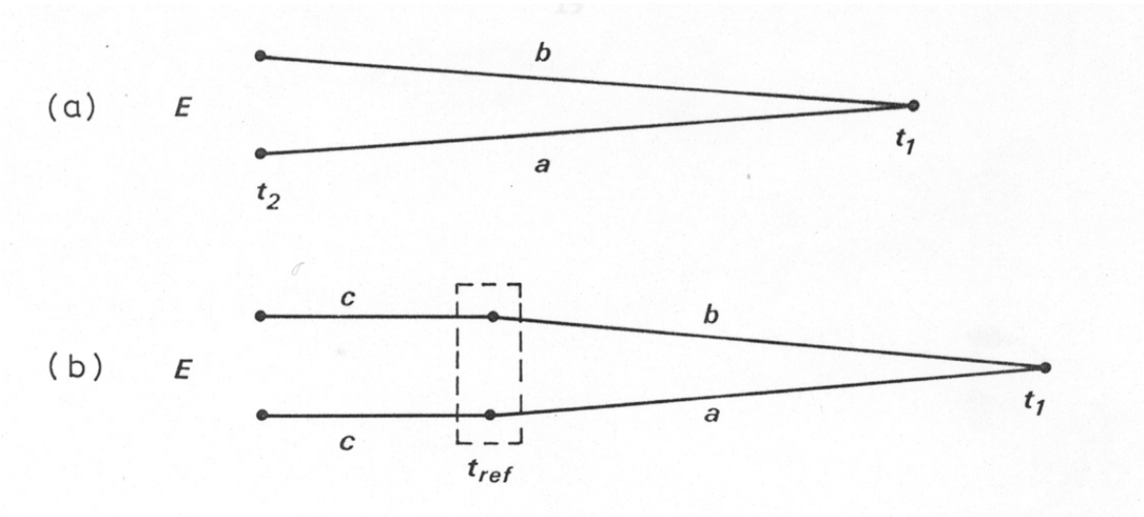
Thermistors for use in current limiting circuits (Cantherm Ltd).



Typical thermistor resistance characteristics.

2.2 Thermocouples

A thermocouple is a temperature sensor based on the Seebeck effect. This is the generation of an EMF (voltage) in electrical conductors along which there is a temperature difference (gradient). In its simplest form, Figure (a) below, a thermocouple consists of two wires which are joined at the end where the temperature is to be measured, the other ends being connected to a voltmeter. The two wires must be of different materials (*a* and *b*), because the measured voltage is the difference between the voltages produced in each wire separately.



Schematic diagrams of a thermocouple (*ab*) is used to measure a temperature t_1, and connected directly to a measuring instrument at temperature t_2, above; and below, where the reference junctions are connected at a fixed temperature, t_{ref}, usually 0 °C, to copper wires (*c*) which then connect to the instrument.

It is important to note that the voltage is built up along the lengths of the wires where the temperature gradient is, *not at the junctions*, which are only needed to make the electrical connections, and should be kept free of any temperature gradients. As a result the measured voltage depends on the temperatures at both ends of the wires. In common practice the thermocouple is simply connected to the measuring instrument, which applies compensation for its 'cold-junction' temperature. For more accurate use the reference junctions are controlled or fixed, typically using melting ice at 0 °C, and copper wires then connect to the instrument. In the illustration below most of the voltage is generated where the wires pass through the temperature drop across the furnace wall, and ideally there are no temperature gradients near the hot junction.

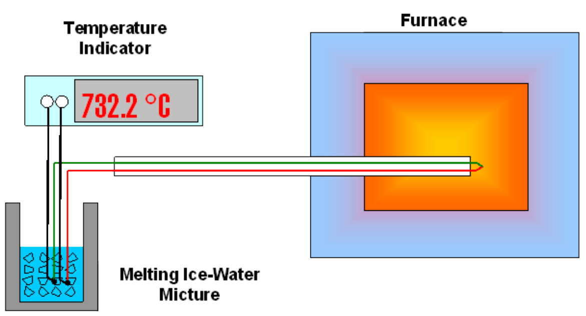


Illustration of a thermocouple measuring the temperature in a furnace

Some metal-sheathed thermocouples with connectors, and one in a heavy-duty cover

Thermocouples are very convenient temperature sensors because they are simple, small and inexpensive, and can be very rugged in protective metal cables. The voltages are not large, typically only about 40 µV for every 1 °C of temperature difference, but instruments commonly display readings with 0.1 °C resolution.

Eight thermocouple combinations have been standardised in IEC (BS EN) 60584-1 for industrial use. Five base-metal (copper-nickel) types are relatively inexpensive and can be used (variously) down to – 270 °C and up to about 1200 °C. Three others, designated Types R, S and B, use wires of platinum and platinum-rhodium alloys, and are expensive but more stable, and can be used up to about 1600 °C. Thermocouples of tungsten-rhenium alloys can be used up to and beyond 2000 °C.

Sensor drift and lifetimes

The reliability of the sensor is a key factor in the performance of a contact thermometer, but as with any material device operated at elevated temperatures, they are liable to drift. Sometimes the drift is hysteretic: the characteristic is slightly different for increasing temperatures compared with decreasing temperatures. This applies to IPRTs where the expansions and contractions of the wires or films are not completely accommodated, and the effects of moisture may also be significant. At temperatures much above 500 °C chemical and physical changes occur increasingly rapidly, and these may show as permanent calibration drift in the sensors. The effect in thermocouples may be delayed by suitably protecting the wires in a steel tube, though this will also slow the response to changes in the temperature.

To help in selecting a sensor, a user will want to know at what temperature, and for how long, the various alternatives can be expected to operate within the specified tolerance, perhaps in a harsh atmosphere or environment. Unfortunately there are no easy answers. There are many different possible sensor configurations (diameters, sheath materials and thicknesses, etc) from many suppliers, and so many different requirements and conditions of use that it is impossible to test or give guarantees for each situation. Even two nominally identical sensors may differ significantly in the time before failure at an elevated temperature. The requirements should be discussed with suppliers, and in critical applications it is advisable to choose a sensor with a margin of safety built in and to undertake preliminary testing before going ahead.

To assist in this, some general guidance is available in documents prepared by IEC and the national standardisation bodies in the USA, UK, Germany and Japan, particularly for thermocouples which are used at high temperatures. Typically they give recommended upper temperature limits for the various types of thermocouple and for a range of common diameters, at which the thermocouple can be expected to remain within the specified tolerance. It must be remembered that the advice is offered in good faith (and not all sources are consistent), and it should be taken as indicative only, to be considered as one factor in coming to a decision.

2.3 Calibration

All the thermometers considered so far must make contact with the process being measured, and they must be calibrated at fixed points or by comparison with standard thermometers.

Fixed points are used for the calibration of platinum resistance thermometers and thermocouples at the highest level. However, only a few thermometers can be measured while the phase change (melting or freezing) lasts and several fixed points are needed to cover a given range. The method is time-consuming and therefore expensive.

The alternative is to use a temperature-controlled environment (bath, furnace or metal block ‘calibrator’), into which the thermometers to be calibrated are inserted with one or two standard thermometers or thermocouples. The bath or furnace is set to control at a series of steady temperatures covering the range of the calibration, which can be chosen at will. At each stable point, measurements are made of all the thermometers in a suitable scanning procedure, the temperature is determined from the standards, and the calibration is thereby achieved.

The thermal environments must be uniform in temperature over the critical volume, and stable (or only slowly drifting) during the measurement period. The uniformity and stability must be checked before use, and the conditions are also tested during the calibration if more than one standard thermometer is used.

Stirred liquid baths, such as this one from Isothermal Technology Ltd, provide the most stable and uniform calibration environments in the range from about − 100 °C up to 500 °C, using alcohol or acetone, water, various silicone oils, and molten salts. They should be deep enough, typically 450 mm, to ensure proper immersion depths for the probes and standards which will be inserted, and the control and measurement procedure can be conveniently programmed. At higher temperatures air-circulating fluidised alumina baths (sand baths) or tube furnaces are used.

The metal block calibrator is a portable apparatus consisting of a cylindrical block, usually of an aluminium alloy about 150 mm long and 30 mm in diameter. This is drilled with holes as required for the probes to be inserted along almost the complete length. The block sits in an insulated heating unit so that its temperature can be controlled from about 30 °C up to 450 °C or higher. When the temperature is steady the calibrations of the test probes are established by comparing their readings with readings of standard probes which are also inserted. This is simple, convenient and inexpensive compared with the use of liquid baths, but the accuracy is limited mainly by the uniformity and stability of the temperature in the block and by immersion effects (heat conduction) in the test and standard probes. Guidance on using and testing these calibrators is available from www.euramet.org under Documents and Publications.

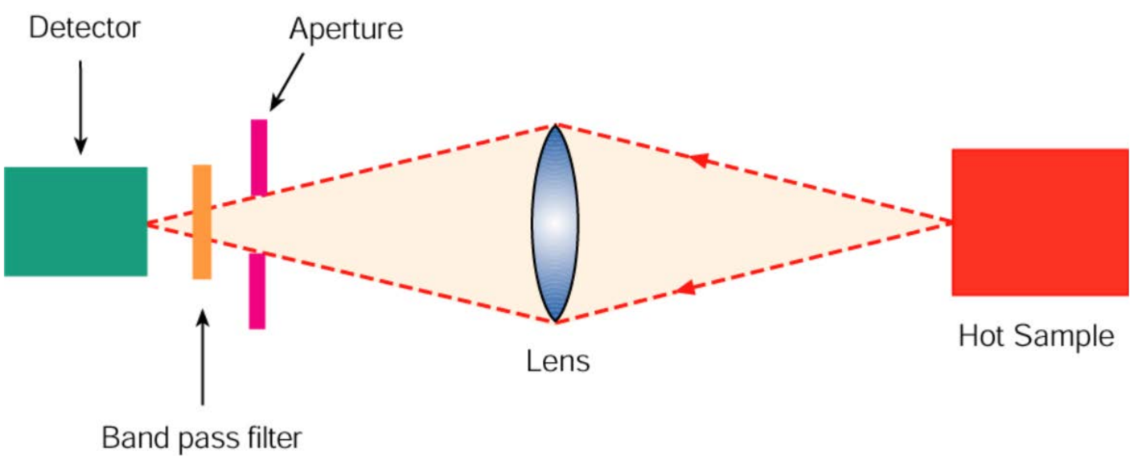
Calibration by comparison allows a higher throughput of thermometers and is amenable to greater automation than using fixed points. It is therefore the preferred method for secondary calibration laboratories and factories.

3. Non-contact thermometry

All objects emit thermal (heat) radiation by virtue of their temperature. This section briefly discusses the methods and application of radiation thermometry and thermal imaging, which measure temperature by remote sensing of this thermal radiation and do not require contact with the object of the measurement.

3.1 Infrared radiation thermometers

Radiation thermometers (infrared thermometers, radiation pyrometers) work like cameras, with an optical system, using lenses or mirrors and a filter which selects the wavelength range (waveband) over which the thermometer is sensitive. The radiation is focused onto a detector whose output indicates the intensity of the radiation and hence the temperature. This may be a 'photo-detector', in which the incident photons give rise to an electric current, or it may be 'thermal', in which case it senses the temperature rise produced by the energy absorbed. The detector is generally temperature-controlled to make its response more repeatable. For low temperature applications, it must be cooled to improve the signal-to-noise ratio and to reduce the intensity of its own radiation.

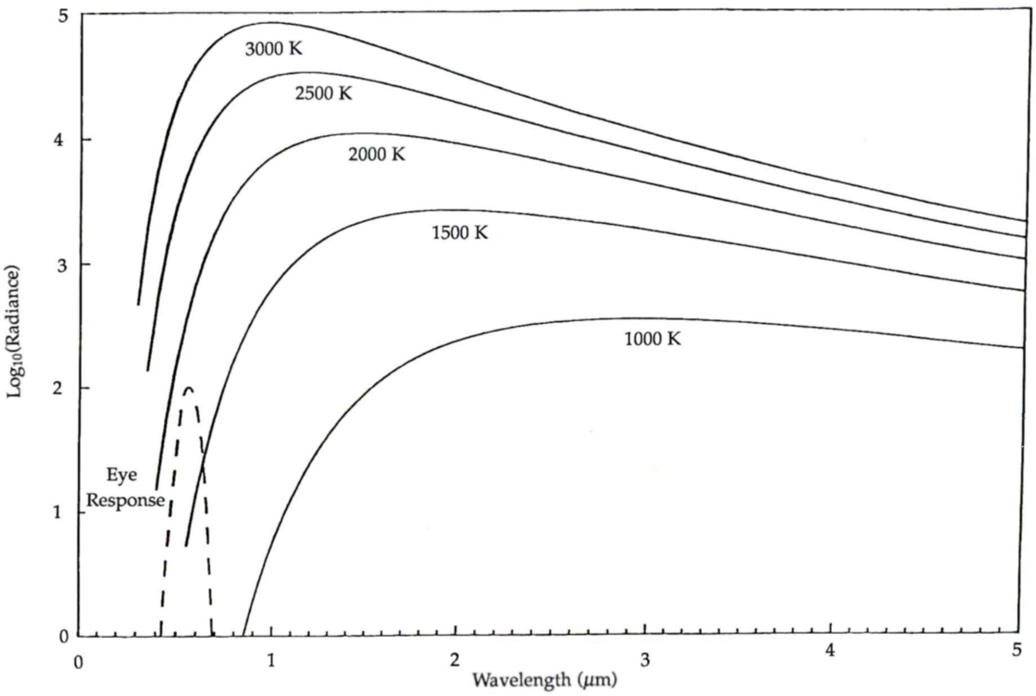


Schematic arrangement of a radiation thermometer

Thermal radiation is mostly in the infrared, but as the temperature increases beyond about 700 °C a dull 'red heat' can be seen, which gradually brightens to orange, yellow and finally a brilliant white heat. The effect is very sensitive and radiation thermometry is a powerful method of temperature measurement, down to – 50 °C or even lower. See Box 3.1 for further details.

Box 3.1: the Planck law

The intensity, $L_\lambda(T)$, of a perfect radiator (a blackbody) is given by the Planck law and depends only on the temperature T (in kelvin) and the wavelength of the radiation λ (in micrometres). The figure shows that the intensity rises to a peak and then falls off as the wavelength increases. At low temperatures the intensity is low and entirely in the infrared (λ > 0.7 μm), but as the temperature increases, the intensity of the radiation rapidly increases and the peak moves toward shorter wavelengths. The sensitivity is then very high, roughly exponential, but at longer wavelengths the lines are bunched closer together and so the sensitivity is lower.



Planck curves:
the intensity of thermal radiation versus wavelength at various temperatures. The dashed line indicates the wavelength range of visible radiation. Note that the intensity (radiance) is plotted as a logarithm, so each division on the y-axis marks an increase by a factor of ten.

Some general features of radiation thermometry are:

1. Radiation thermometry uses the concept of a 'perfect radiator' or blackbody, so-called because it also a perfect absorber of all radiation incident on it, and hence appears perfectly black when cold. In practice (nearly) blackbody sources are used to calibrate radiation thermometers. However, real surfaces emit less radiation than a blackbody at the same temperature, and the measured temperature must be corrected for the 'emissivity' of the surface, see below.

2. At any given temperature, it is generally advantageous to operate at as short a wavelength as possible, because the sensitivity is greater and emissivity and other errors are less serious. A wavelength in the range 0.65-1.0 μm, using a Si photodiode detector, is commonly used at high temperatures.

3. At low-to-moderate temperatures, where the intensity is low, it is necessary to operate some way into the infrared and over a substantial band of wavelengths, to obtain a useful signal. It is also necessary to use parts of the spectrum where the water vapour and carbon dioxide in the atmosphere do not absorb the radiation. Typical thermometer wavelength ranges are 3-5 μm using InSb photodiodes, and 8-14 μm, using cooled HgCdTe photodiodes or thermal sensors. The latter are used for measurements at room temperature, where the peak in the Planck curve is at about 10 μm.

4. Being a remote-sensing method, radiation thermometry can measure very hot objects, or moving objects on a production line. Modern detector arrays allow thermal images (colour-coded temperature maps) of objects, structures or environments to be produced. Thermal imagers are discussed in Section 3.4.

The advantages of radiation thermometers are offset by some significant disadvantages.

1. As has already been mentioned, the radiation emitted from an object depends not only on its temperature but also on the surface properties, *i.e.* on its *emissivity*. This is its ability to radiate, on a scale from 0 to 1:
   0 for a perfectly reflecting surface which emits no radiation, and
   1, the maximum possible, which applies to a perfect blackbody radiator.

   The emissivity depends on the material and its surface condition (roughness, state of oxidation, etc). It also varies with the temperature, the wavelength and the angle of view. When using a radiation thermometer, the emissivity must be known or estimated if an accurate temperature is to be obtained. Sometimes very large errors (tens of degrees is quite common) arise because the emissivity is incorrectly estimated.

2. Secondly, the thermal radiation emitted by heaters or lighting will be partially reflected by the target and add to the radiation which is detected. Large errors can be caused by reflections from furnace heaters at high temperatures, unless precautions are taken. When measuring low temperatures, ‘heaters’ may include lights, human beings or even the ordinary ambient environment. See Box 3.2.

3. Thirdly, the thermometer may be several metres away from the target, and it must have a clear line of sight. Dust, water vapour or carbon dioxide in the atmosphere can scatter or absorb the radiation before it reaches the thermometer, and hence cause an error in the measurement. In some applications an air purge is needed to keep the atmosphere

clear. In others it may be possible to use a fibre-optic light-pipe to transmit the radiation to the remote detector.

4. Finally, imperfections in the optics lead to imperfections in the field of view, so that the 'target size', or 'spot size', of the instrument may be significantly larger than is intended or claimed.

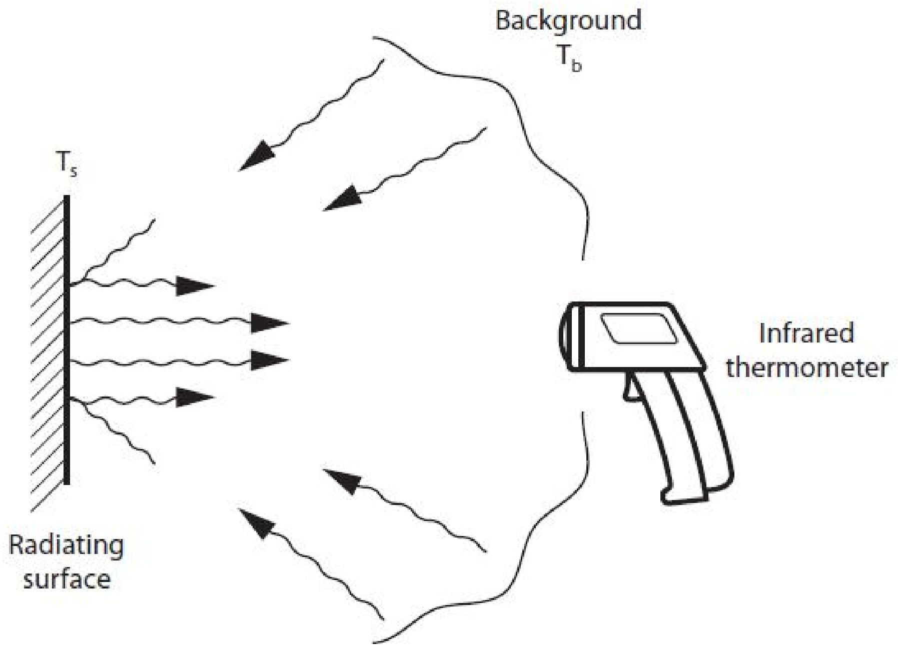
A radiation thermometer being sighted on a blackbody source at about 900 °C

Box 3.2: radiation exchange between target, thermometer and surroundings

For a surface at temperature T_s which is not enclosed but radiates freely to its surroundings at temperature T_b, the radiation received by an infrared thermometer focused on the surface can be written as the sum of two parts:

$L_{total} = \varepsilon L(T_s) + (1 - \varepsilon)L(T_b)$.

The first term is due to the radiation emitted by the surface and is the product of the emissivity (remember that $0 < \varepsilon < 1$) and the blackbody radiance $L(T_s)$ at temperature T_s (in kelvin), given by the Planck law. The second term is due to the radiation reflected from the background, and is the product of the spectral radiance at temperature T_b and the reflectivity of the surface, which is $(1 - \varepsilon)$.



Radiation exchange between a surface, its surroundings and an infrared thermometer. The detected radiation is the sum of the emitted radiation and the reflected radiation.

In the simple case where the thermometer measures a hot object in much colder surroundings we have $T_s >> T_b$. Then the first term dominates and the temperature can be calculated, given an estimated value for the emissivity. In these circumstances it is advantageous if the operating wavelength of the thermometer is short (say, less than 1 μm), because the sensitivity is higher (the Planck curves are more widely separated) and an error in estimating the emissivity produces less error in the value of temperature.

However, if the temperature of the surface is similar to that of the background, $T_b \sim T_s$, the radiation reflected from the surroundings will be significant, and the background temperature must be taken into account. To an extent the background compensates for the effect of the surface emissivity: in the particular case where $T_b = T_s$, we have $L_{total} = L(T_s)$ and the whole system of surface and surroundings behaves as a blackbody cavity at temperature T_s.

Often the background is hot compared with the surface, $T_b > T_s$, either because the surface is cold or because it is being heated in a hot furnace. In these cases the second term will again be significant and may even dominate. It is now advantageous to use a thermometer which operates at a longer wavelength, because the difference in the radiances $L(T_s)$ and $L(T_b)$ is then smaller (the Planck curves are less widely separated), and the effect of an error in estimating the emissivity is less serious.

3.2 Blackbody sources

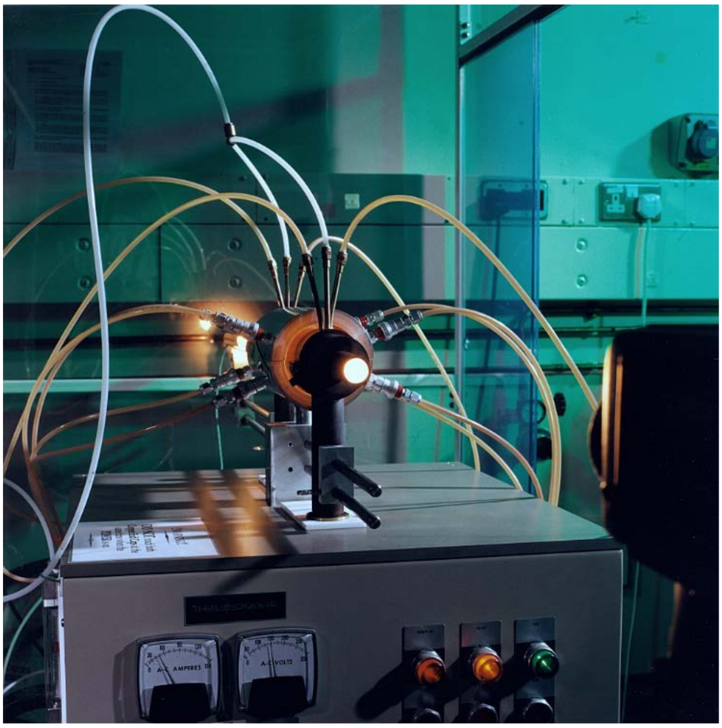
The calibration of radiation thermometers is done using blackbody sources, assuming an emissivity of (or close to) 1. This is a convenient ‘reference condition’ from which calibrations at other emissivities can be readily calculated.

To make a blackbody source we use the concept of the truly blackbody radiation inside a closed cavity at a uniform temperature. The intensity of the radiation is then solely governed by the Planck law: it depends only on the wavelength and temperature, and is *independent of the emissivity of the materials of which the cavity is made*.

The immediate practical difficulty is that if we make a hole in the cavity to observe the radiation, we perturb the field and the radiation we see is no longer the ideal: the emissivity of the partially open cavity is always less than 1. Nevertheless, if the cavity has good geometrical design and is large compared with the aperture diameter, and if the materials used have high surface emissivities (*i.e*. they are intrinsically good radiators), then very high cavity emissivities (>0.9999) can be achieved.

In fixed-point blackbodies the cavity is typically made of graphite and is almost completely surrounded by an ingot of a pure metal, so that during a melt or a freeze the temperature is uniform and fixed at a known value. Such blackbodies are used in the ITS-90 for temperatures above the freezing point of silver (1234.93 K), using cavities made of graphite which has a very high intrinsic emissivity. They can also provide useful reference points at lower temperatures.

However, most blackbody cavities are made using an oxidised alloy, or a metal painted black, and are contained in a temperature-controlled furnace or fluid bath. The temperature is measured using a calibrated sensor, such as a platinum resistance thermometer or a thermocouple, which provides traceability to the ITS-90. Alternatively the cavity and sensor can be calibrated as a system, by comparing the radiated output with that of a reference blackbody. At very high temperatures blackbodies are generally made of graphite which is directly heated by passing a large current through it. These blackbodies must be used in an inert atmosphere to prevent oxidation.



An NPL high-temperature graphite blackbody source

Because cavities are large and slow to use, it has become common to use blackened plates, usually with a grooved pattern cut into them, as near-blackbody sources. The plate is heated from behind, with a sensor embedded near the surface to monitor the temperature. How well the plate approximates to an ideal blackbody depends on the design, but the surface emissivity is likely to be substantially less than 1, and there will also be temperature gradients across the plate, and between the sensor and the surface. As a result it is necessary for the plate to be calibrated by comparing its output with that of a reference blackbody.

3.3 Choosing and using infrared thermometers: coping with emissivity.

There are many factors to be considered in choosing the best option for an infrared thermometer, depending on the intended target, its size, accessibility and temperature.

The operating wavelength range must be chosen to suit the temperature, longer wavelengths and broader wavebands being needed to obtain enough radiation at lower temperatures, see Box 3.1. Subject to that, the wavelength should generally be as short as possible, to achieve the best sensitivity and lowest errors. The main exception to this is where the target will be exposed to radiation from heaters in a furnace, see Box 3.2.

Commercial thermometers are made for short, medium and long wavelengths, in bands chosen to avoid absorption by the atmosphere. Where steam or dirt is present it is desirable to include a dry air purge to keep the line of sight clear and any windows clean. In process control the thermometer is often fixed in place and focused on a specific target, but portable hand-held thermometers, with a viewfinder, are more versatile and are more common.

Suppliers will advise about ‘target size’, meaning the size or area on which the thermometer can focus at a given distance. Remember that the ‘field of view’ does not cut off completely at this size, but some radiation will come from outside it because of inevitable limitations in the optics. If possible the thermometer should be used for surfaces which are significantly larger than the stated target size, or otherwise the reading may need to be corrected for a ‘size-of-source’ effect.

Problems due to emissivity have been mentioned already, and the following are some tips for coping with them.

Options for coping with emissivity

1. Use as short a wavelength as practicable, to minimise the error, and live with it. In many situations, such as process control, the repeatability of the thermometer reading is more import than the actual correct temperature value: the process may work well enough if the measurement is in error by a *consistent* amount. This strategy relies on the measurement conditions, and the target surface condition, being repeatable.

2. It is better practice to make an estimate of the target emissivity, and apply a correction. Given a value for the emissivity, most thermometers have software which automatically corrects the reading. The temperature values should then be more accurate than in Case 1, but they depend on the correct emissivity being chosen, and they still rely on the conditions being repeatable. The advantage of using a short wavelength thermometer is that the temperature error $\Delta T/T$ may be 10-20 times smaller than the emissivity error, $\Delta\varepsilon/\varepsilon$, so an error of 1% in estimating the emissivity gives rise to an error of less than 0.1% of the (kelvin) temperature.

3. Choose a wavelength where the emissivity of the target is naturally high. For example, the emissivity of most glasses and plastics is very high (>0.95) near 5 μm and 3.4 μm, respectively, so infrared thermometers operating at these wavelengths will give more accurate readings.

4. Enhance the emissivity of the surface by roughening it, oxidising it, coating it or painting it with a high-emissivity paint. All these will increase the radiated power and reduce the reflectance, and should therefore reduce the error. However, it is still necessary to estimate the emissivity, and it may not be desirable or possible to treat the surface in this way.

5. Try to enhance the emissivity by geometric means. The free surface emissivity may be low, but if a hole is drilled into it a ‘mini blackbody’ cavity can be created, with much higher emissivity. Again, this may not be desirable or possible, but in some cases the application provides niches or wedges which give some significant emissivity enhancement. The errors can be reduced, even though the effective emissivity must still be estimated.

Two-colour and multi-wavelength thermometers

So far we have only considered monochromatic infrared thermometers, *i.e*. those operating at just one wavelength (or band). Surely if measurements are made at two wavelengths the emissivity can be eliminated by taking the ratio of the two signals? This is the basis of the 'two-colour' thermometer, and indeed if the emissivity is the same at the two wavelengths it would cancel out. However, there are two problems with this. Firstly, the two wavelengths must be well separated if the method is to work at all, and the emissivities cannot then be assumed to be equal. Secondly, the ratio of the two signals is much less sensitive to temperature than either signal alone, so any error in the emissivity assumption is much more serious than for the monochromatic case. In practice the advantages are rarely demonstrated, and it has been shown that extending the argument to several wavelengths makes matters even worse, not better.

However, there are situations where two-colour thermometers have advantages. The first is in measuring small objects, which do not fill the instrument's field of view. Then the filling factor is nearly the same at both wavelengths and it does not affect the ratio. The second is in dirty environments where the atmosphere and windows are partially opaque. If the transmissions at both wavelengths are similar, they largely cancel out. It is still necessary to estimate the ratio of the emissivity of the target at the two wavelengths in order to calculate the temperature, so the fundamental problem of the method remains.

3.4 Thermal imaging and thermography

The idea of radiation thermometry can be extended to measuring not just the temperature at a small spot on a surface, but building up a two-dimensional image of a large area or even the complete surface. With modern detector arrays it is possible to produce a map of the temperature with typically 380 by 290 pixels. This is presented as a picture, but because the camera operates in the infrared the image is either black and white or in false colours.

Thermal imaging is now widely used in surveillance and night vision, search and rescue, building and land surveying, aircraft and missile tracking, detecting hot spots due to failure in electrical equipment and electronic circuits, and in medical thermography. These are often qualitative applications, relying only on contrast. For quantitative thermometry one must be able to convert the signals to temperatures using a calibration procedure. To do this reference is made to a simple internal blackbody source, which is used to link the colours or shades to numerical temperature values. From time to time it is necessary to check this with respect to a calibrated external blackbody source, if possible with a large enough area to fill the complete field of view.

In many respects the instruments can be treated as 2-dimensional radiation thermometers and they share many features. They may be fixed installations, portable or hand-held, and focused on distant or near objects. They are prone to the same sources of error, due to emissivity and reflected radiation, size-of-source, etc. They are now much more affordable, and have become powerful tools in thermal and temperature measurement. The example below shows a portable camera focused on a power line.

Portable thermal imager for remote temperature sensing (Land Instruments International).

4. Contact temperature measurements in practice

We have emphasised already that poor contact is the most common source of error in using temperature sensors. Ideally the sensor should be totally immersed in the measurement medium, with minimal contact to the outside environment. Exactly how this may be best achieved (or approximated) depends on whether the medium is a liquid, a gas, a solid or a surface. This section offers some advice on how to strike a compromise between making good contact and the convenience or practicality of making the measurement. Further guidance is given in textbooks such as *Temperature Measurement* by Michalski and co-authors.

4.1 Measurements in liquids

Liquids are very effective media for making contact. There is no gap between the medium and a probe which is directly immersed in it, and the capacity for heat transfer is high. This is especially true if the liquid is flowing past the probe. For this reason stirred liquid baths are the preferred media for the calibration of thermometers by comparison with standards.

Tip 1: use a probe whose length, in addition to the length of the sensing element inside, is at least 20 times the diameter. This should ensure that the immersion error is no more than 0.1 % of the difference between the liquid temperature and the outside environment temperature. The error will be somewhat larger for static liquids, though some natural convection is always likely to be present.

Tip 2: where possible allow extra length: an increase of 50% in the immersion depth could reduce the error by as much as a factor of ten.

Tip 3: under steady conditions, test for immersion errors by withdrawing the sensor by 2, 4, 6, etc, cm to find out how the measurements are affected. Wait for long enough (several minutes) at each point for the new conditions to settle, and make a further measurement when the probe is reinserted.

The error will be larger if the probe has to be inserted into an additional protective tube; for example, if it is too short and the cable is not compatible with the liquid. In many cases, such as in pressurised chemical reactors, the probe is inserted into a steel ‘thermowell’ which is built into the vessel wall and from which the probe can be removed without affecting the process inside. In this situation the thermowell, and the inevitable air gap between it and the probe, are both additional barriers to heat transfer, which means that deeper immersion is needed.

Tip: the recommended immersion depth should be at least 20 times the diameter of the thermowell, not just the probe. Again, allow extra length where possible. In confined geometries, such as pipes, extra length can be gained by locating the thermowell at bends or elbows, or inserting it at an oblique angle. Test for immersion errors as suggested above.

4.2 Measurements in air and other gases

Measuring the air temperature in a room is a seemingly benign and trivial application, where adequate immersion is almost guaranteed. However, air and gases generally are not efficient heat transfer media so even a modest heat input to the sensor, such as from lighting or other sources of radiation, can cause it to read high. The sensor should be protected from these, as well as from sunlight, draughts and convection heaters.

Tips: suspend the sensor in a protective perforated cage some distance below the ceiling, away from heat sources, doors and windows. It helps if the air is gently circulated in a controlled manner, as this improves both the temperature uniformity and the heat exchange with the sensor, and so makes the measurement more meaningful. It may also be useful to attach fins to the probe, to increase the area for heat exchange. Make sure that the measurement process does not dissipate too much heat in the sensor.

Similar considerations apply to air temperature measurements in an environmental chamber or oven, whose temperature may be very different from ambient. Good immersion may be more easily achievable than in liquids, because the probe is more compatible with the medium, but the poor heat exchange with the air makes small heat flows more significant.

Tips: follow the advice given above for room air, but more vigorous circulation of the air will be needed to achieve uniform conditions. Take particular care to shield the sensor from heaters (using a shiny probe will help).

MIMS (mineral-insulated metal-sheathed) thermocouples are commonly used in industrial sensing, especially at very high temperatures, and in reactive gases such as in combustion processes (power generation, aeroengines, etc). The sheath provides protection against the environment, and electrical insulation in the cable is provided by high purity compacted magnesia or alumina powder. The cable diameter may be ~1 mm in diameter or up to 8 mm, and in practice there may be a difficult compromise between speed of response, which requires a lightweight sensor, and physical and chemical durability, which calls for more substantial protection.

Tips: the sheath material, stainless steel, Inconel or another special alloy, must be chosen to provide an effective barrier to chemical attack from the medium. It should not contain elements, such as manganese, which may diffuse in the cable and contaminate the thermocouple wires. The supplier should advise, and some guidance is given in documentary standards.

4.3 Measurements in solids

The simplest case to consider is of a sensor attached to a solid object in ambient air. This is common where it is important to monitor or control the temperature so as to correct for or reduce changes in length due to thermal expansion. Applications range from small optical apparatus to large engineering structures. It is convenient to use film-type Pt100 sensors which have a flat surface or, for greater sensitivity, thermistors.

In recent years wireless systems using thermistors have become available, with considerable advantages in instrumenting and controlling large facilities. The sensor/transmitter is attached as usual but, being remote, it needs a small battery to operate.

Tips: bond or bind the sensor to the object, using a heat transfer compound where appropriate, and secure the leads along a convenient route to the instrumentation. Lightly cover the sensor to protect it from draughts or external heat sources. Good results should be obtainable provided that interfering heat flows are small - take care that attaching the sensor does not change the temperature of the object, and that self-heating due to the measuring current is not excessive.

For hot or cold solids, where there are large heat flows, a surface measurement is likely to be problematical (see below). A better result is obtained if the probe can be inserted in a hole drilled in the object, deeply enough that immersion errors are small. This is the principle of the ‘metal block calibrator’, discussed in Section 2.3.

Tips: to make good temperature measurements in solids the air gap between the probe and the object (or block in the calibrator) should be small so that they are in intimate contact. In some cases it may be acceptable to improve it by using a heat-transfer fluid or compound, but immersion errors, as indicated above, are still likely to be significant. Immersion tests should be done, as recommended for liquids. However, in this case temperature gradients in the object or block may make it difficult to interpret the results.

In summary, drilling holes and inserting probes in an object to facilitate measurement is invasive, and it cannot often be done in process industry. At high temperatures, as in the steel industry, it is common to use radiation thermometry if the surface is exposed, coupled with theoretical modelling to estimate the internal temperature.

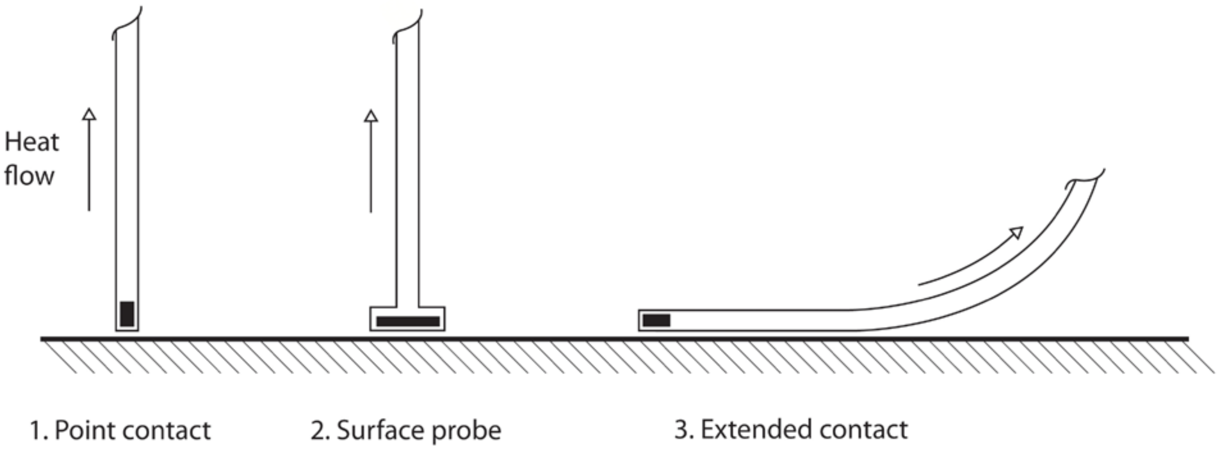
4.4 Measurements on surfaces

The temperature of solid objects is often measured by attaching a sensor to the surface, as was discussed above, but the situation becomes quite complicated when the temperature of the object is very different from the temperature of the ambient environment.

The surface is the interface between the object and its environment (usually air) and, if it is hot, there are large heat flows and temperature gradients. Using a probe to measure the temperature of the interface is therefore problematical because:

- the probe conducts heat from the surface and so cools it,
- if it covers a significant area it will mask the surface and so change the temperature gradients
- the sensor in the probe is some distance from the tip, so is cooler than the tip.

The objective is to minimise these errors by making the sensor temperature as close as it can be to the undisturbed surface temperature. Special 'surface probes' are available with various terminations aiming to increase the intimacy of the contact with the surface, but they inevitably entail compromises between accuracy and practicality. Errors are likely to be several tenths of a degree at best, rising to several degrees as the temperature increases.



Options for surface measurement

The figures above and the text following illustrate some of the options available

Option 1: apply a thin probe, to reduce the disturbance to the surface temperature. A thermocouple junction in the probe can be close to the tip, or even make direct contact with the surface if this is electrically acceptable. However, heat flows and temperature gradients (and hence errors) will be rather significant with this solution, and it is not recommended.

Option 2: for better contact the probe termination should be flat (for a flat surface) and have an enlarged area. The diameter of the probe stem should be as small as practicable, to reduce the heat it conducts away from the surface. The sensor should again be as close to the probe tip as possible, and in this case a thermocouple junction or a flat film-type Pt100 may be suitable. This solution entails greater disturbance to the surface temperature, and heat flow and temperature gradients are still significant problems.

These two options may give results which are quite repeatable but of limited accuracy: a sensor will only measure its own temperature, and it is difficult to get it to the temperature of the surface in the presence of heat flows.

The calibration of a probe for surface measurements should be done using a ‘standard surface’ rather than by immersion in a liquid bath or metal block as in Section 2.3. Some hotplates have been developed as calibration sources, though there is a difficulty in calibrating them (e.g. using an embedded sensor or an infrared thermometer). Investigations with such apparatus are needed if reliable offsets between surface and immersion calibrations are to be obtained.

Option 3: the problem of heat flow is much reduced if the probe makes contact for some distance *along the surface,* before breaking away. In a typical configuration, a thermocouple using fine wires or cable makes contact with the surface under an adhesive patch or another attachment The wires keep in contact with the surface for some distance before leading off to a remote indicator, so the region near the junction is close to the surface temperature. This option is not always convenient, but for measurements of pipes up to about 100 °C, thermocouples in special metal bands, or even Velcro straps, can be wrapped around the pipe. In semiconductor processing, very fine thermocouple wires may be spot-welded to the wafer to ensure good contact with minimal conduction errors.

As can readily be seen, none of these options is a complete solution, and different compromises must be chosen for different applications. We are left with the basic fact that contact sensors are not well adapted to measure surface temperatures. Infrared thermometers *are* adapted to do this but have their own problems, as has already been discussed.

4.5 Industrial measurements and standards

Wherever possible, industrial process measurement and control uses products and components which are bought to meet the specification in a documentary standard. The supplier has to guarantee that the product meets the specification within a stated tolerance, and criteria may be given for the durability of the product in service; for example, its ability to withstand temperature cycling, vibration and electromagnetic interference, etc. Instrumentation in the EU is subject to directives to ensure that it meets requirements for, among other things, EMC compatibility and health and safety.

The specification standards which apply in Europe are either European Norms, designated EN, whereupon they also become British Standards (BS EN), or standards from international bodies such as the International Standardization Organisation (ISO) and the International Electrotechnical Commission (IEC). These are subsequently often adopted as European Norms. Some standards concerned with temperature sensors are listed in Section 5.

As well as ensuring that manufacturers meet the specifications, and therefore that the sensors, thermocouple wires, etc, are interchangeable within the limits of their tolerances, the standards give the mathematical functions which are used to relate the sensor output (resistance or voltage) to temperature.

In the case of industrial Pt100 sensors, the standard uses the Callendar-Van Dusen (CVD) equation, which requires only three parameters to specify the relationship between the resistance $R(t)$ in ohms and the temperature t in °C from –200 °C to 850 °C.

Rather more complicated equations are specified to relate thermocouple voltages to temperature, and these are used as 'reference functions' for the various types of thermocouple, against which manufactured thermocouple wires are checked. If necessary, the small deviations from the standard ($V - V_{ref}$) can be represented by a simple equation which is then added to the reference function (V_{ref}) to give V as a function of temperature.

Industrial thermocouples are often required to withstand harsh conditions of high temperature, vibration and rough use, in oxidising or reactive gases, such as in furnaces or combustion processes. Mineral-insulated metal-sheathed (MIMS) cables are normally used, manufactured according to IEC 61515 and drawn down to a final diameter between 0.5 and 8 mm. These provide good protection and some 'bendability', especially at the finer sizes, so they can follow a devious path into the process.

Once clear of the high-temperature zone, it is convenient to switch to flexible 'extension' cable, which can easily run to the instrument, where 'cold junction compensation' is applied. It is important that the extension cable is made from wires of nominally the same alloys as the main thermocouple, so that the circuit can be considered continuous all the way to the instrument, within a stated tolerance (see Part 3 of IEC 60584).

4.6 Temperature measurements in healthcare

Medical thermometry is a familiar application which illustrates the range of options for temperature measurement which are now available, and it is used in this section as an example.

Much has changed in clinical temperature measurements since the days when mercury thermometers were the device of choice and 1 million were made and tested in the UK each year. In fact, because of concerns over the toxicity of mercury and its improper disposal, such thermometers are prohibited from sale in the EU and are no longer used in the health service. A number of options have been developed to take their place, and the standard BS EN 12470 specifies the performance requirements and the methods of testing. They are now briefly discussed.

Compact electrical thermometers with maximum device

These are constructed to resemble clinical mercury thermometers, and often the tip is made to look like a bulb of mercury. However, as the name implies, they use an electrical sensor, such as a thermistor, whose resistance changes with temperature. 'Compact' means that the measurement, processing and display are all included in the probe, so the device is self-contained. They are inserted under the tongue in the usual way, and once initiated, the maximum reading is displayed. The maximum permissible error in the range 35.5 °C to 42.0 °C is ± 0.1 °C, and the reading should be within 0.1 °C of the final value within 60 seconds. Some devices are equipped with a predictive option, which calculates what the final reading will be, and so the temperature can be displayed significantly sooner.

Phase-change (dot matrix) thermometers

A non-electrical alternative is to use samples of inert chemicals which melt at progressively higher temperatures from 35.5 °C to 40.5 °C in steps of 0.1 °C. They are mounted as small dots in a matrix on a thin plastic spatula with a protective transparent cover. This is placed under the patient's tongue. After a short time the spatula is removed and it can be seen which dots have melted and which have not: the temperature is taken as the melting temperature of the last dot to melt. These are cheap disposable devices and avoid the need for cleaning for re-use. Other devices operating on similar principles are available for applying to patients' foreheads, but they are less reliable because the forehead is more remote from the core body temperature, and hence its temperature is more variable.

Infrared tympanic (ear) thermometers

Tympanic thermometers are now routinely used on hospital wards for monitoring patients' temperatures. They are hand-held infrared thermometers which are applied to the ear, as in the picture, to sense the temperature of the ear drum (tympanum), at close range but without actually contacting it. Again the maximum reading is held and displayed until reset, but in this case the response is almost instantaneous. It is important that the device is applied and angled correctly, if errors are to be avoided. A new plastic cover is attached to the probe for each patient, to avoid transferring infections.

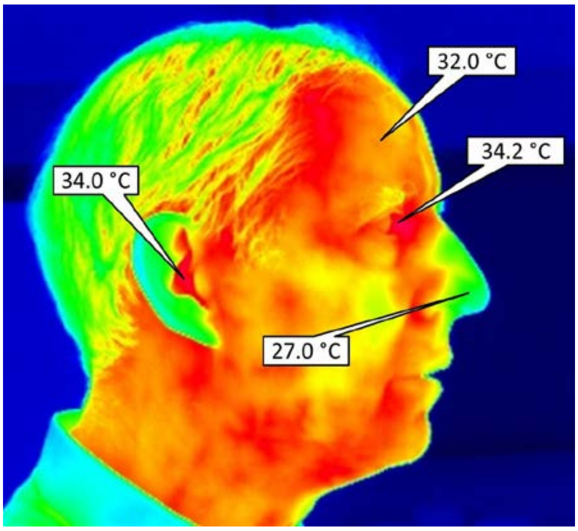
A young lad having his temperature taken, quickly and without discomfort, using an infrared tympanic thermometer

Continuous-reading electrical thermometers

Apart from routine measurement on nurse’s ward rounds, temperatures often need to be monitored on a continuous basis, for example in intensive care units. In these circumstances an electrical probe is likely to be used, applied not in the mouth but at some other more convenient site. The readings will be logged, displayed and stored automatically so that trends can easily be detected.

Thermography

Thermal imaging (thermography) has become widely exploited in clinical medicine, with uses ranging from general healthcare and screening, to detecting circulatory ailments and tumours. The first picture below is a thermal profile of the author showing the contrast between various sites, with the ear canal and temple being closer to the normal core body temperature than the more exposed ear lobe and nose. The second shows his hands slowly warming up after being cooled in water. The technique is used to test for conditions which lead to poor circulation, such as Reynaud’s syndrome.



4.7 Choosing the right temperature sensor

The following table is a checklist of some questions to ask before a temperature sensor is chosen for a particular application. The desired answers are shaded grey.

1. Metrological properties (range, resolution, calibration requirements, etc)	**Yes**	**No**
Does the sensor cover the range with the required resolution, using the intended instrumentation?		
Can a calibration be obtained with the required uncertainty?		
2. Accessibility / contact / ease of installation (size, shape, etc)		
Can the sensor be mounted in good contact with the measurement site?		
Is the immersion adequate (can heat flows along the connecting leads affect the measurement)?		
Is there provision or space for connections, feed-throughs, etc?		
3. Instrumentation and communication (connection to control point)		
Is instrumentation (hardware and software) available with suitable specification?		
Are the means of connection acceptable (thermally, mechanically, electrically)?		
4. Compatibility with the environment (atmosphere or medium, material components)		
Is there potential for oxidation or other chemical reaction?		
Does the atmosphere need to be controlled?		
Might any liquids or moisture in the measurement site affect the sensor?		
Can any other physical influences or conditions (noise, vibration, electromagnetic fields, thermal or ionising radiations, etc.) affect the performance?		
5. Reliability / durability (drift, recalibration interval, time to failure)		
Are the short, medium or long-term properties of the sensor adequate to ensure reliability for a sufficient time?		
Can periodic checks, recalibration or replacement be implemented?		
Can the sensors be duplicated for security, or made fail-safe?		
6. Cost and availability (initial, maintenance, commercial status, R&D need)		
Is the preferred solution affordable, or can an acceptable compromise be found?		
Can it be bought in from established commercial sources?		
Has all necessary R&D been satisfactorily undertaken?		
7. Has infrared remote-sensing thermometry been considered?		

5. Further reading

1. The following books are recommended

Temperature by T. J. Quinn, 2nd Edition, 1990, Academic Press,

Traceable Temperatures by J. V. Nicholas and D. R. White, J. Wiley and Sons Ltd, 2nd Edition, 2001.

Temperature Measurement by L. Michalski, K. Eckersdorf, J. Kucharski and J. McGhee, J Wiley and Son, 2nd edition, 2001.

The first is mainly concerned with the fundamentals of temperature metrology, the second with the requirements of temperature calibration laboratories, while the third has a stronger bias toward industrial application.

2. Documents relating to the International Temperature Scale of 1990, the text and realisation, can be found at www.bipm.org, under CCT publications.

3. The following are international specification standards

IEC 60751: 2008 (BN EN 60751:2008): *Industrial platinum resistance thermometers and platinum temperature sensors*,

IEC 60584-1:1995 (BS EN 60584-1:1996): *Thermocouples – part 1: Reference tables*. Parts 2 and 3 of IEC 60584 are concerned with thermocouple tolerances and extension and compensating cables.

IEC 61515: 1995, *Mineral insulated thermocouple cables and thermocouples*.

IEC TS 62492-1:2008, *Radiation thermometers* – Part 1: *Technical data for radiation thermometers*.

4. Further information may be found on the NPL web site at www.npl.co.uk on the temperature pages, and at www.euramet.org under Documents and Publications.