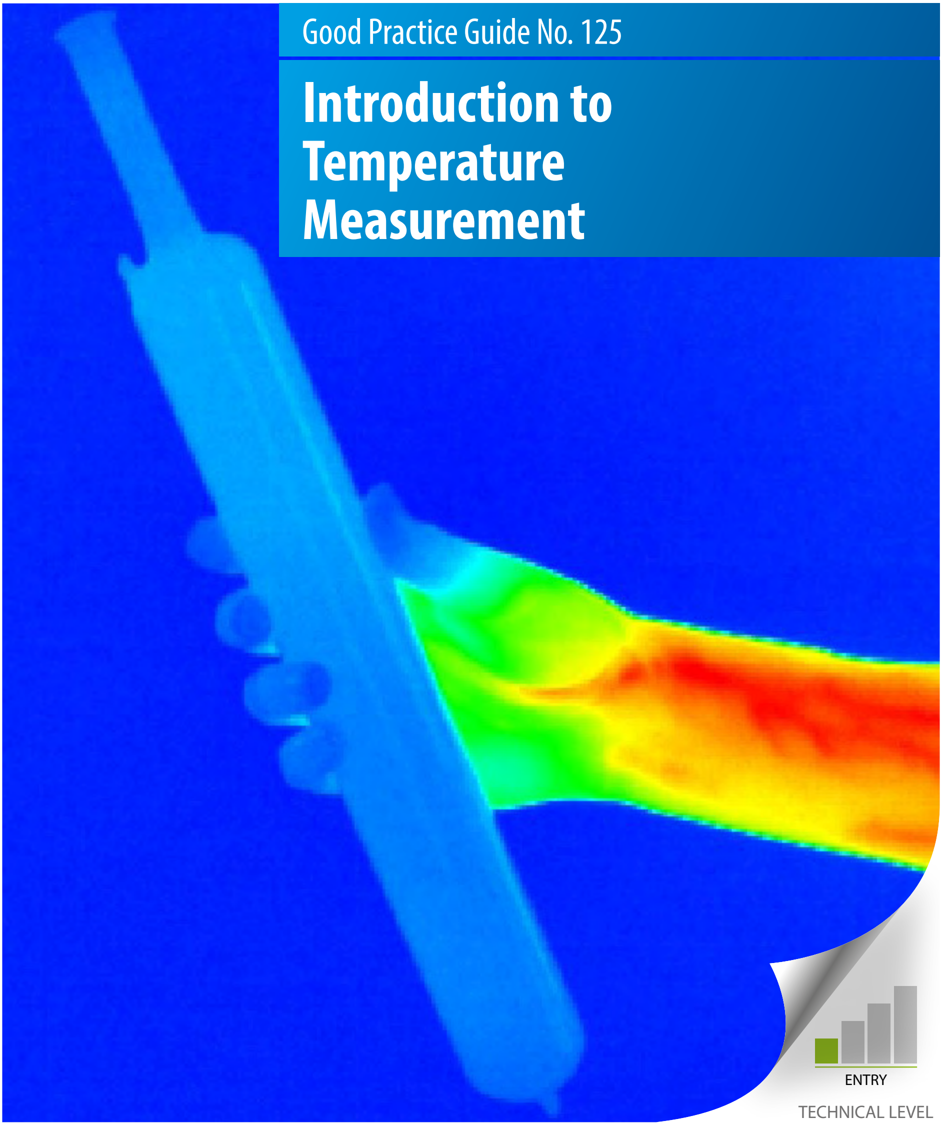
NPL
National Physical Laboratory

Good Practice Guide No. 125

Introduction to Temperature Measurement



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Front cover image: *Image of a triple-point of water cell, taken using a thermal camera (Source: NPL).*

Guide Information

What is it about?

This guide is an introduction to basic concepts and types of instrument used in temperature measurement. For each instrument, the technical features, practical issues, applications and sources of error are discussed.

Who is it for?

This guide is for users who have little or no previous experience in measuring temperature. Fields of application range from clinical practice to industrial processing and scientific research.

What is its purpose?

The purpose of this guide is to provide background knowledge about temperature measurement and to present the options that are available in terms of instruments, procedures and applications.

What is the prerequisite knowledge?

The guide covers topics from entry to intermediate levels. Although it does not require any background in temperature measurement, it assumes that the reader has some scientific knowledge.

Key to icons:


Need to know


Good to know


Checklist

The National Physical Laboratory (NPL)

- NPL is the UK's National Measurement Institute, and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available.
- NPL's mission is to provide the measurement capability that underpins the UK's prosperity and quality of life.

Contents

Introduction

This is an introductory guide that aims to help first-time users who have little or 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 up and down the temperature scale is very broad and none can be treated in detail. However, 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.

The guide opens with some basic background about temperature, why it is important to measure it, the units and scale used, and some of the difficulties that may be encountered.

An important question 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 Chapter II. They mostly use electrical sensors, such as resistance thermometers, for applications requiring good accuracy up to moderately high temperatures (not usually above 600 °C). Alternatively, thermocouples are smaller, more rugged and durable, and can be used at much higher temperatures. However, they are less accurate.

Non-contact infrared radiation thermometry is discussed in Chapter III. It is well adapted for measuring hot, moving or distant objects, and 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. Systems for thermal imaging are also briefly considered.

Chapter IV gives some guidance about how to use contact temperature sensors in gases, liquids and solids, and on surfaces. Some specification standards for the more commonly-used industrial thermometers are introduced. Various options for temperature measurement in healthcare are used to illustrate current practice. A checklist guide for choosing the right sensor is presented at the end of the guide.

Dr Richard Rusby, *formerly the Head of Temperature Standards at NPL, is now a consultant in temperature measurement.*

Chapter I

Temperature and its definitions

- Background to temperature measurement
- Temperature units and scale
- Thermometers

Background to temperature measurement

Why measure temperature?

We are all familiar with the measurement of temperature by nurses, weather forecasters, cooks and gardeners, and most of us own 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 (Figure 1) is not right, it will either fail to produce good material or be wasteful in the use of energy and time, or both. Huge costs are involved in running processes in heavy industry and huge benefits are derived from doing it efficiently. The same applies in the processing of glass, semiconductors, petrochemicals, plastics, pharmaceuticals, food and other products. Similarly, efficient 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 the particular requirements.

Image credit: OkFoundryCompany

Figure 1: *Pouring steel at about 1500 °C.*

Measuring temperature: basic questions

The process of measuring temperature – inserting the sensor and taking a reading – could not in principle be simpler, but in practice there are many reasons why the reading may not be correct. This is a list of important points to consider when measuring temperature:

- ***Does the probe make proper contact?*** Unlike in electricity, where a simple contact produces immediate results, 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 most common causes of error in temperature measurement.

- ***Can the sensor withstand 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 perhaps to 1000 °C or more, possibly at high pressure, is likely to drift or fail because of stresses due to expansion and contraction, contamination, oxidation or corrosion. The higher the temperature, the more resilient the sensor must be and the more precautions must be taken to protect it.
- ***Can we use a remote sensing technique?*** One way of avoiding both of the above 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 – as discussed in Chapter III – but radiation thermometers are now very widely used for general purposes.
- ***Has the thermometer been calibrated?*** The thermometer must be calibrated if it is to read correctly. For the calibration to be 'traceable' to the proper standards, it 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 check of conformity with a standard specification may be sufficient.

Calibration and traceability

The calibration of an instrument is the comparison of a test instrument or artefact against a more accurate standard of measurement.

The most accurate standards – known as 'primary standards' – follow from the definitions of the International System of Units (SI). They require expensive equipment and highly trained metrologists and are realised only at national measurement institutes such as NPL. The primary standards are used as reference standards to calibrate working standards.

Traceability of an instrument is an unbroken chain of calibrations linking its reading to the primary standard. Each comparison in the chain must be accompanied by a statement of uncertainty.

More information on calibration and traceability can be obtained in the e-Learning courses offered by NPL.

What *is* temperature?

Before discussing thermometers and how to calibrate and use them, we need to consider what temperature is and how the temperature scale is set up.

Modern ideas about heat and temperature go back to the mid-nineteenth century when it was discovered 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 when the heat melts a solid or boils a liquid: during a change of phase the temperature remains approximately constant. We can easily understand that heat and temperature are in some way different, because the heat energy in a large object is greater than that in a small object of the same material, even when they are 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, temperature 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 speaking, 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 on 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* – such as 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.

Temperature units and scale

Temperature units

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.

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 kelvin minus 273.15 such that:

$$t \,/\, °\mathrm{C} = T \,/\, \mathrm{K} - 273.15$$

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.

Temperatures are occasionally given in degrees Fahrenheit, though this scale is formally obsolete. Relative to Celsius temperatures, Fahrenheit temperatures are defined such that:

$$t \,/\, °\mathrm{F} = (9/5)(t \,/\, °\mathrm{C}) + 32$$

The triple point of water

The triple point of water is the unique temperature at which the liquid, solid and vapour phases of pure water are in equilibrium.

In a practical realisation of the triple point (*right*), a glass cell contains a sample of pure water under vacuum. To prepare the cell for measurement, an ice mantle is frozen around the central thermometer well 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: any heat flowing in or out just melts or freezes some ice *(right)*. The long thin shape is to allow deep immersion of a thermometer in the well for calibration.

Image credit: National Physical Laboratory

Temperature scale

Since temperatures are not additive and cannot be divided up, unlike metres or amperes, a temperature scale has to be derived from fundamental, thermodynamic 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 for measurement in science, technology and everyday life.

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 at points 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, is available from the International Bureau of Weights and Measures, under 'CCT publications'.

Temperature fixed points

A temperature fixed point is a precise temperature at which a pure substance undergoes a change in its phase.

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'. The ITS-90 specifies that Standard Platinum Resistance Thermometers (SPRTs) are calibrated by measuring them in a series of 'fixed-point' cells covering the range of interest. The SPRTs can then be used as standards to calibrate less precise thermometers.

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. Hence the ITS-90, based on fixed points, can be applied universally.

ITS-90 fixed points

The ITS-90 fixed points are:

- *melting or freezing points* of metals such as tin and zinc, in which the solid and liquid phases are at equilibrium at a pressure of one standard atmosphere, with heat only 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.

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 many cases the thermometer sensor and the instrumentation are integrated into a single package and 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.

Types of thermometer

There are many types of thermometer, notably expansion (e.g. mercury), electrical thermometers and non-contact radiation thermometers.

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 directly, by reading from a scale marked on the glass.

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 from the detector is processed in order to display the temperature.

Properties of a thermometer

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

- ***sensitive*** to temperature but insensitive to things other than temperature, so the measurement should not depend on environmental factors such as humidity, atmospheric pressure or altitude.
- ***repeatable***, so that the measured property of the device has the same value (or very nearly so) whenever the temperature is the same.
- ***calibrated***, so the measured property (length, resistance, voltage, etc.) can be reliably converted to the (ITS-90) 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 variously 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.

Chapter II

Contact thermometers

- Resistance thermometers
- Thermocouples
- Calibration

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 clinical thermometers the reading is often displayed on the probe itself, for which a processor and a battery are needed. More usually, a connecting cable leads from the probe to the indicating unit.

Platinum resistance thermometer

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 and Pt100s, RTDs (resistance temperature detectors). The sensors are usually made with wires or films of 100 Ω resistance at 0 °C and packaged in alumina tubes or on flat substrates, with two or more connecting wires emerging as illustrated in Figure 2. They are then inserted into a steel protective tube to make the complete probe (Figure 3), which can then be connected to the measurement instrumentation.

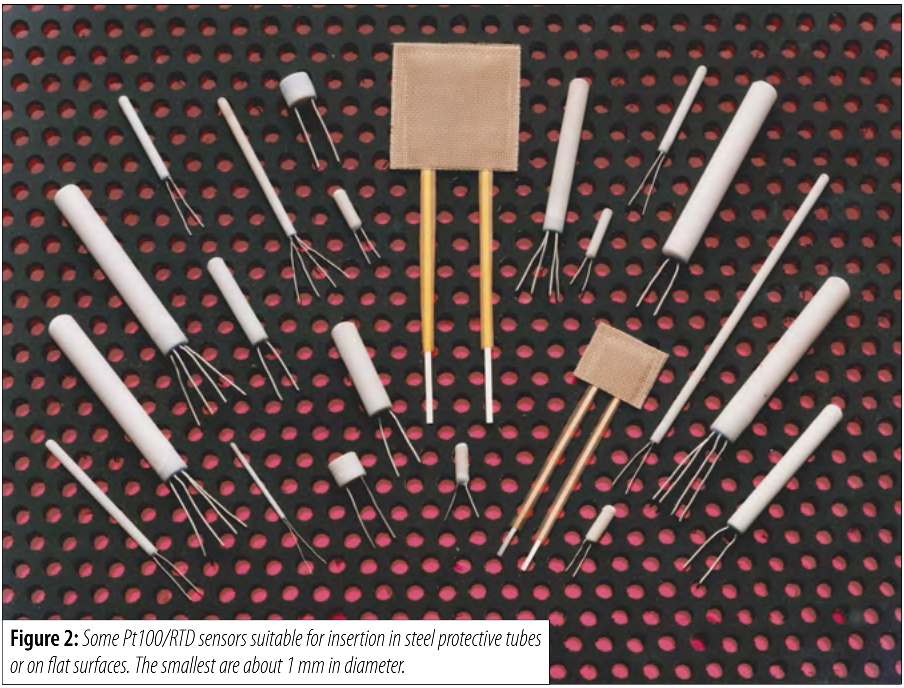

Image credit: Sensing Devices Ltd

Figure 2: *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 in Figure 4. 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.

The measuring instrument and the connections must be chosen to meet the requirement. Most sensors are made with two emerging wires (Figure 2), 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 degrees Celsius may result.

Some compensation for the lead resistances can be achieved by connecting a third lead to one side of the sensor (three-wire connection), but best accuracy requires four wires, where two are used for passing the current in and out and the other two are for sensing the voltage across the Pt100 resistor.

Figure 3: *Mineral insulated probe with potted transition to flexible cable.*

Image credit: Process Parameters

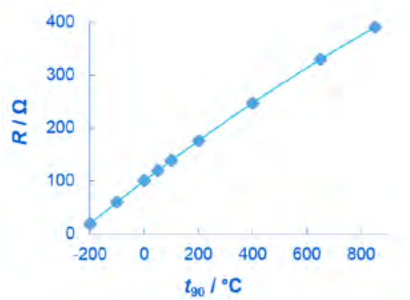

Figure 4: *Resistance (R) versus temperature (t_{90}) for a Pt100 sensor.*

Thermistors

Thermistors (Figure 5) are temperature sensitive resistors made from small beads of various semiconductive oxides. In the more common negative temperature coefficient (NTC) types, the resistance increases very strongly as the temperature falls (Figure 6). They are well suited for use in small probes with fast response, e.g. in medical thermometry, where good sensitivity is achieved over useful though limited temperature ranges. Since the resistances are large, generally several kilohms, two-wire connections can usually be used without significant error.

Thermistors are not standardised, and the manufacturer's specification must be referred to.

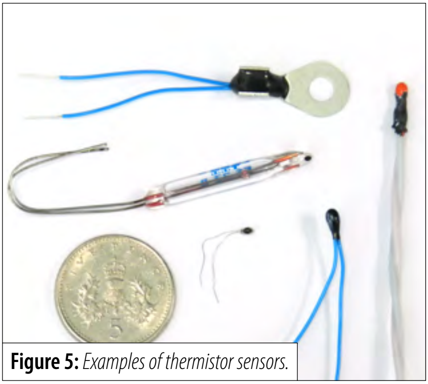

Image credit: National Physical Laboratory

Figure 5: *Examples of thermistor sensors.*

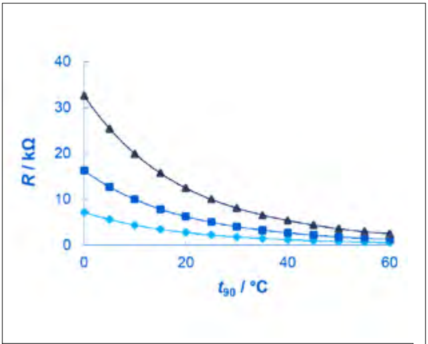

Figure 6: *Three typical thermistor resistance characteristics.*

Thermocouples

Functioning principle

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

In common practice, the thermocouple is connected, as in Figure 7 upper diagram, directly to the measuring instrument which must apply compensation for its 'cold-junction' temperature, t_2. For more accurate use the cold (reference) junctions are controlled or fixed, typically using melting ice at 0 °C, and copper wires then connect to the instrument, as in Figure 7, lower image.

Most of the voltage is generated where the wires pass into the hot (measurement) zone, and ideally there are no temperature gradients near the hot or cold junctions.

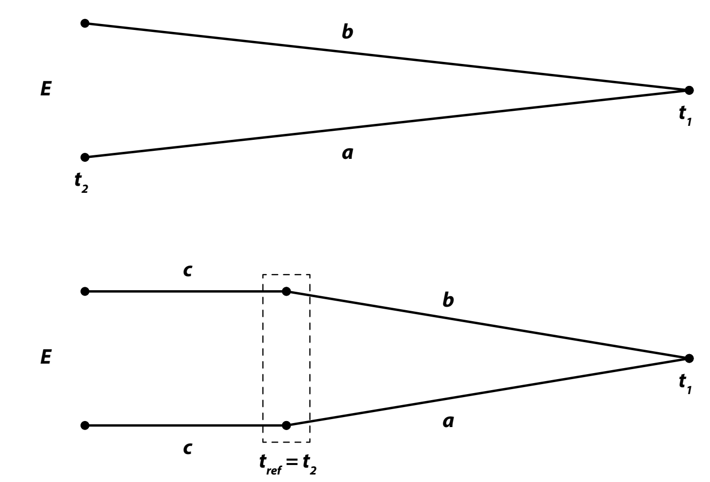

Figure 7: *Schematic diagrams of a thermocouple of wires (a) and (b), used to measure a temperature t_1. The wires are connected directly to a measuring instrument at a temperature t_2, (upper image). Alternatively the 'cold junctions' can be connected at a reference temperature, t_{ref}, usually at 0 °C, to copper wires (c), which connect to the instrument (lower image).*

Advantages

Thermocouples are very convenient temperature sensors because they:

- are simple, small and inexpensive
- can be very rugged in protective metal sheathes (Figure 10)
- can be used to much higher temperatures than resistance thermometers.

The voltages are not large, typically only about 40 µV for every 1 °C of temperature difference between the two ends, but instruments commonly display readings with 0.1 °C resolution.

Types of thermocouple

Ten thermocouple combinations have been standardised in IEC (BS EN) 60584-1 for industrial use:

- Five base-metal (e.g. copper-nickel, nickel-chromium) types J, T, E, K and N. These are relatively inexpensive and can be used (variously) down to –270 °C and up to about 1200 °C.

Thermocouple voltage generation

It is important to note that the voltage in a thermocouple is built up step by step along the lengths of the wires where there is a temperature gradient (Figure 8), *not at the junctions*. The junctions are only needed to make the electrical connections and should be kept free of any temperature gradients (as illustrated in Figure 9).

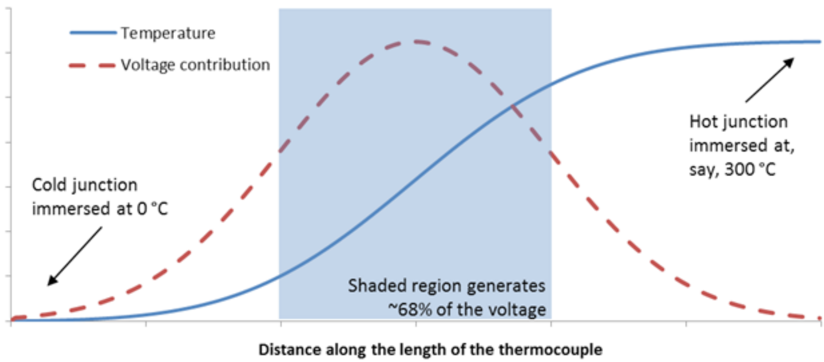

Figure 8: *The voltage contribution (red line) to the overall voltage output of a thermocouple, generated point-by-point along the sensor with a given temperature profile (blue line).*

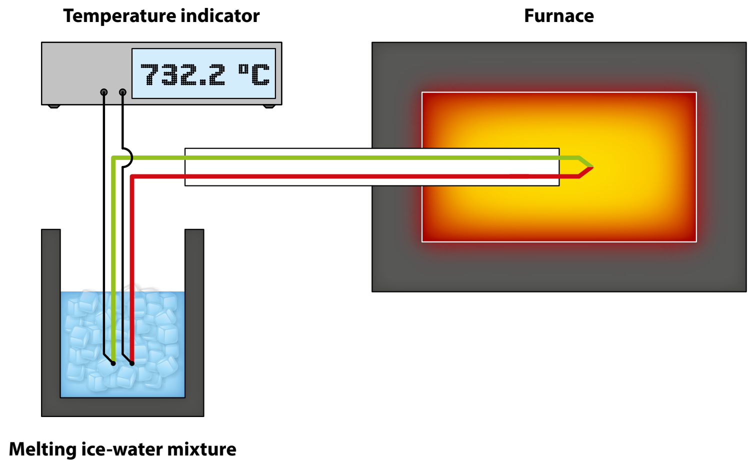

Figure 9: *Illustration of the use of a thermocouple to measure temperature in a furnace.*

- Three others, designated types R, S and B, use wires of platinum and platinum-rhodium alloys. These are expensive, but more stable, and can be used up to about 1600 °C.
- Two thermocouples of tungsten-rhenium alloys, types C and A, can be used up to and beyond 2000 °C.

The values of EMF versus temperature given in the IEC tables are relative to reference junctions at 0 °C.

Image credit: Omega Engineering Ltd

Figure 10: *Metal-sheathed thermocouples with connectors, three in a heavy-duty cover.*

Calibration

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

Calibration using fixed-point cells

Fixed-point cells 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, and it is only suitable for a limited number of high specification thermometers, which are designated as 'standards'.

Calibration by comparison with standards

The alternative, for larger numbers of thermometers of lower specification, is to use a temperature-controlled environment (bath, furnace or 'dry block calibrator'), into which the thermometers to be calibrated are inserted with one or two standard thermometers or thermocouples as reference instruments.

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, and the temperature is determined from the standards. The calibration is thereby achieved.

The thermal environment 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 (Figure 11) 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.

Figure 11: *Stirred liquid bath.*

Image credit: Isothermal Technology Ltd

Dry block calibrators (Figure 12) are portable temperature sources consisting of a cylindrical block, usually of an aluminium, steel or nickel 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.

Figure 12: *Dry block calibrator, in which the controls are at the front, and the sensors are inserted into the block at the rear.*

Image credit: Ametek Inc.

The block sits in an insulated heating unit so that its temperature can be controlled, typically from about 30 °C up to 650 °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 thermometers. Guidance on using and testing these calibrators is available from the European Association of National Metrology Institutes (EURAMET) website under 'Documents and Publications'.

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, their calibration is 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. The sensor must be protected in suitable tubing, though this will also slow the response to changes in the temperature. Thermocouples are conveniently supplied in mineral-insulated metal-sheathed (MIMS) cables, which provide adequate protection and good response.

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 so 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 thermocouple types 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.

Chapter III

Non-contact thermometers

- Brief introduction
- Infrared radiation thermometers
- Blackbody sources
- Selection of an infrared thermometer
- Thermal imaging

Brief introduction

Often it is not convenient to use a probe to measure temperature and a non-contact method is needed. This section briefly discusses the methods and application of radiation thermometry and thermal imaging, which measure temperature by remote sensing of the thermal (heat) radiation emitted without contacting the object under measurement.

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 (Figure 13). 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 consistent. For low temperature applications, it must be cooled to improve the signal-to-noise ratio and to reduce the intensity of its own thermal radiation.

Thermal radiation is mostly in the infrared and is not visible, 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 intensity is strongly dependent on temperature, so radiation thermometry is a sensitive method of temperature measurement, even down to –50 °C.

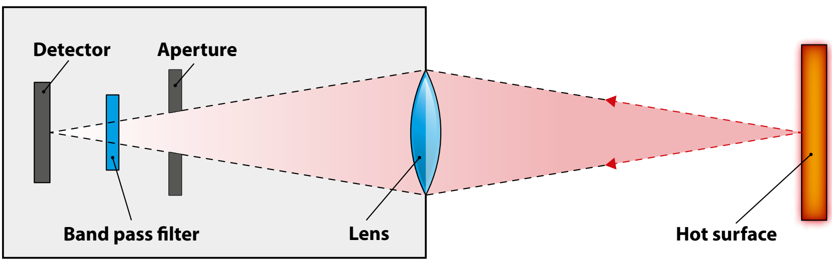

Figure 13: *Schematic arrangement of a radiation thermometer measuring the temperature of a hot sample or object.*

Radiation thermometers must be calibrated using a known source of thermal radiation, such as a blackbody cavity, so that the measured intensity of the radiation can be accurately converted to a temperature. Blackbodies radiate at close to the maximum possible intensity at any given wavelength and temperature, according to Planck's law. They are so called because they are also perfect absorbers of all radiation incident on them, and hence appear perfectly black when cold. In practice, good approximations to blackbody cavities can be made, as is discussed later, but exposed surfaces always emit less radiation than a blackbody at the same temperature and the measurements must be corrected for the 'emissivity' of the surface.

Planck's law

The radiant 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 Planck law for the radiant intensity emitted in a wavelength interval $d\lambda$ may be written

$$L_\lambda (T)d\lambda = \left(\frac{c_1}{\pi\lambda^5}\right) [e^{\frac{c_2}{\lambda T}} - 1]^{-1} d\lambda$$

where c_1 and c_2 are constants.

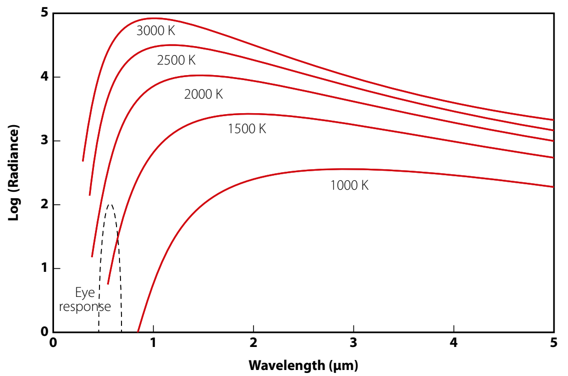

Figure 14: *Planck curves, showing how the intensity of thermal radiation varies with wavelength at various temperatures. The dashed line indicates the wavelength range of visible radiation. Note that the intensity (radiance) is plotted as a logarithm, so each division on the y-axis marks an increase by a factor of ten.*

The figure shows that at any temperature 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 ($\lambda > 0.7$ µm, beyond the eye response), but as the temperature increases, the intensity of the radiation rapidly increases and the peak moves toward shorter wavelengths. The radiance is then very sensitive, increasing roughly exponentially with temperature, but at longer wavelengths the lines are bunched closer together and the sensitivity, $dL_\lambda(T)/dT$, is lower.

Emissivity

Emissivity is the ability of a surface to radiate, and it varies 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.).
- The temperature.
- The wavelength of the radiation.
- The angle of view.

Figure 14 shows us that, at any given temperature, it is generally advantageous to operate at as short a wavelength as possible, because the sensitivity is greater (the curves are more widely separated). A wavelength in the range 0.65 µm to 1.0 µm, using a silicon (Si) photodiode detector, is commonly used at high temperatures, $t > 700$ °C. 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 µm to 5 µm using indium antimonide (InSb) photodiodes, and 8 µm to 14 µm, using cooled mercury cadmium telluride (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.

Disadvantages and sources of error

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.

However, the advantages of radiation thermometers are offset by some significant disadvantages and sources of error.

- ***Emissivity:*** 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*. 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.

- ***Reflections:*** 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.
- ***Environment:*** 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 (in this case there will be some absorption in the fibre, but if it is repeatable it can be included in the calibration).
- ***Optical imperfections:*** 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.

Figure 15 shows a typical calibration arrangement, with two infrared radiation thermometers on moveable mounts in front of a blackbody source. To achieve a smaller target size, an aperture plate would be attached to the blackbody.

Figure 15: *A radiation thermometer being sighted on a blackbody source at about 900 °C.*

Image credit: National Physical Laboratory

Radiation exchange between target, thermometer and surroundings

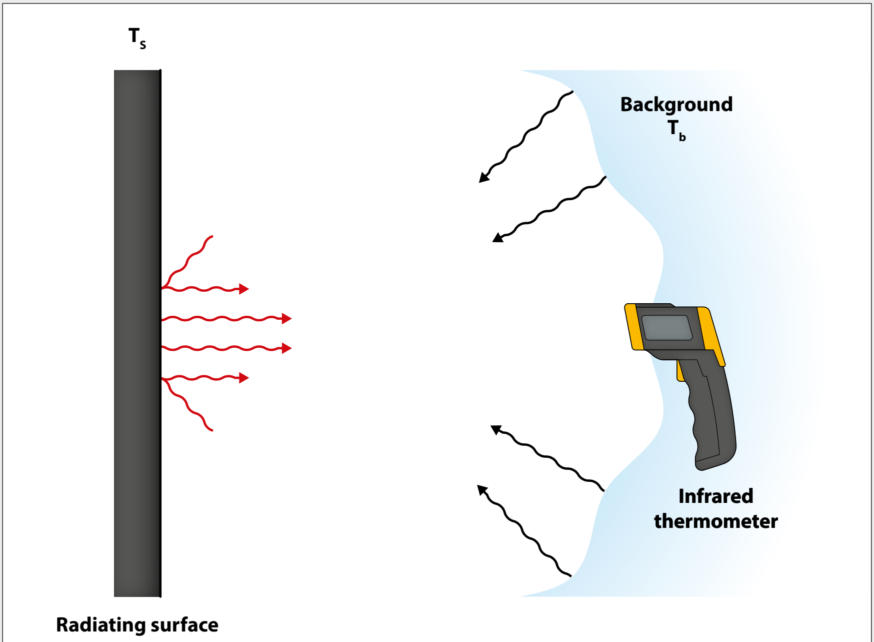

Figure 16: *Schematic picture of a radiation exchange between a surface, its surroundings and an infrared thermometer. The detected radiation is the sum of the emitted radiation and the reflected radiation.*

For a surface at temperature T_s which is not enclosed but radiates freely to its surroundings at temperature T_b (Figure 16), the radiation received by a radiation thermometer focused on the surface can be written as the sum of two parts, the emitted and the reflected radiance:

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

where L_{total} is the radiance of the surface, ε is the emissivity (remember that $0 < \varepsilon < 1$), $L(T_s)$ is the radiance of a blackbody at temperature T_s and $L(T_b)$ is the radiance at the background temperature T_b.

The first term in equation [4], $\varepsilon L(T_s)$, corresponds to the radiation emitted by the surface.

The second term is due to the radiation reflected from the background, and is the product of the radiance at the background temperature (T_b) and the reflectivity of the surface, which is $(1 - \varepsilon)$.

There are three distinct cases of interaction between target, thermometer and surroundings:

- $T_s >> T_b$: In this case, the thermometer measures a hot object in much colder surroundings. 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 – i.e. the Planck curves are more widely separated – and an error in estimating the emissivity produces less error in the value of temperature.
- $T_s \sim T_b$: The temperature of the surface is similar to that of the background. In this case, 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.
- $T_b > T_s$: This is the case when the background is hot compared with the surface, either because the surface is cold or because it is being heated in a hot furnace. In this case, 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 – i.e. the Planck curves are less widely separated – and the effect of errors in estimating the emissivity or the background temperature are less serious.

Blackbody sources

The calibration of radiation thermometers is done using blackbody sources at known or measured temperatures, 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 Planck's law, and it depends only on:

- the wavelength (λ)
- the temperature

The intensity is *independent on the emissivity of the material 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.

Fixed-point blackbodies

In fixed-point blackbodies a small cylindrical cavity, made of graphite, is almost completely surrounded by an ingot of a pure metal (such as copper, silver or gold), which is contained in a graphite crucible (Figure 17). The internal surfaces of the cavity are grooved to further enhance the already high emissivity, and the cavity is viewed though a rhodium aperture. During a melt or a freeze the temperature is uniform and fixed at a known value. Such blackbodies are used in realising the ITS-90 for temperatures above the freezing point of silver (961 °C), and they can also provide useful reference points at lower temperatures, using aluminium, zinc, tin or indium.

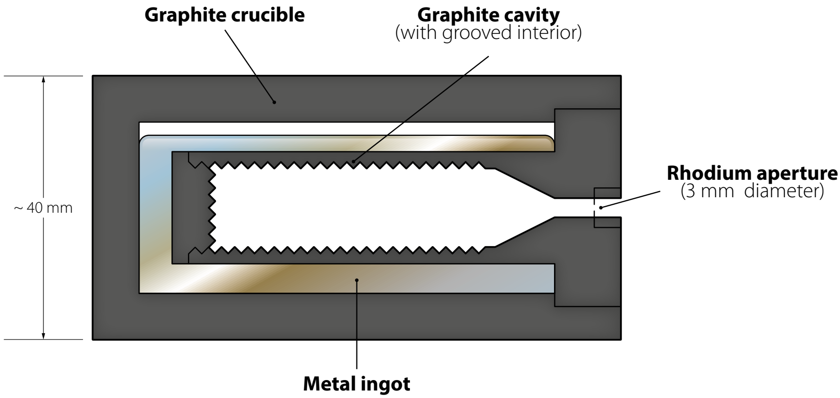

Figure 17: *Schematic diagram of an NPL fixed point blackbody radiator.*

Variable temperature blackbodies

However, most blackbody cavities are variable-temperature sources, made using an oxidised alloy, or a metal painted or coated black, 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. Often the cavity and sensor are calibrated as a system, by comparing the radiated output with that of a reference blackbody. At very high temperatures, up to 3000 °C, blackbodies are generally made of a closed graphite tube which is directly heated by passing a large current through it. These blackbodies must be used in an inert atmosphere to prevent oxidation and erosion of the graphite (Figure 18).

Approximations to blackbody sources

Because cavities are often large and can be slow to operate, 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 as the surface is exposed the emissivity is likely to be substantially less than 1. 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 it with a reference blackbody.

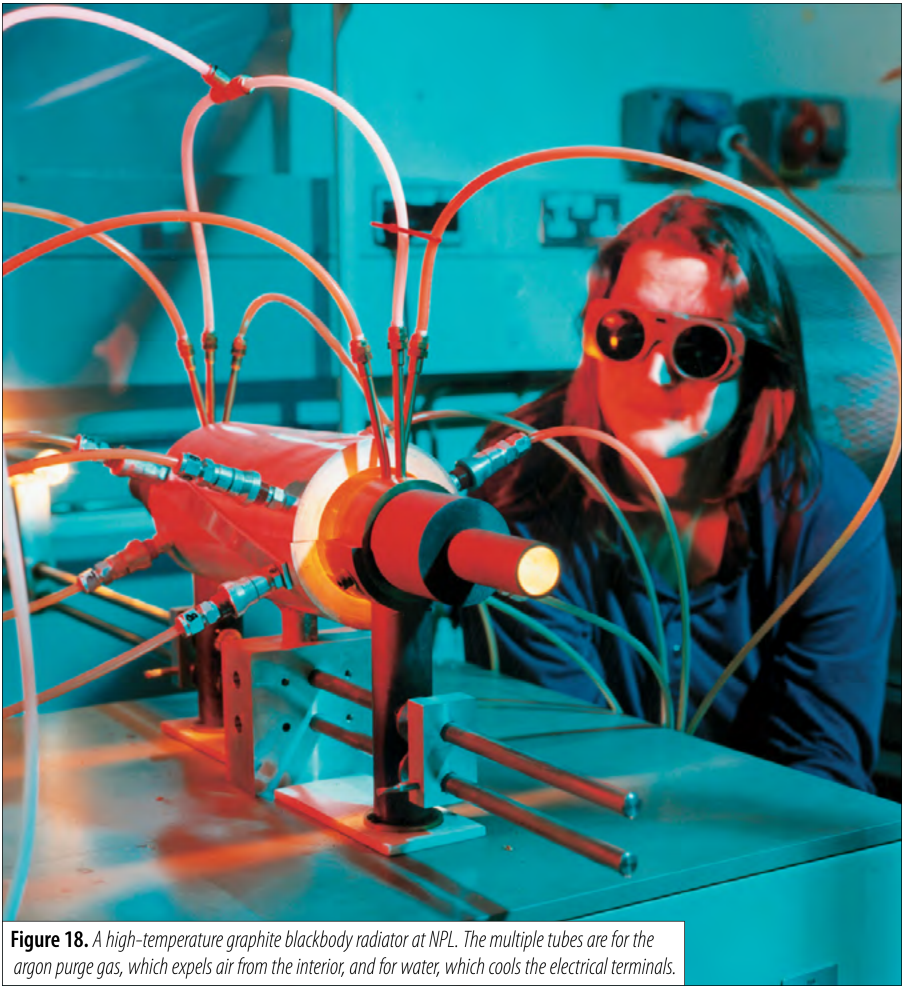

Image credit: National Physical Laboratory

Figure 18. *A high-temperature graphite blackbody radiator at NPL. The multiple tubes are for the argon purge gas, which expels air from the interior, and for water, which cools the electrical terminals.*

Selection of an infrared thermometer

There are many factors to be considered in choosing the best option for an infrared thermometer, depending on:

- the intended target
- the target size
- the target accessibility
- the target temperature

The critical parameters are the operating wavelength, the field of view (the optics to suit the target size and distance) and operability (hand-held or fixed, environmental influences, output options, etc). Some aspects of these are now considered.

Operating wavelength

The operating wavelength range must be chosen to suit the temperature, longer wavelengths and broader wavebands being needed to obtain enough signal at lower temperatures, as explained in the box about the Planck law. 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, as discussed in the box about radiation exchange.

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 area, but portable hand-held thermometers, with a viewfinder, are more versatile and more common.

Target size

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, otherwise the reading may need to be corrected for a 'size-of-source' effect.

Coping with emissivity

Problems due to emissivity have been mentioned already, and there are several options for coping with them:

- ***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 important 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 repeatability of the measurement conditions and the target surface condition.
- ***Make an estimate of the target emissivity, and apply a correction***. Given a value for the emissivity, most thermometers will do this automatically. The temperature values should then be more accurate, 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 temperature (in kelvin).
- ***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.
- ***Enhance the emissivity of the surface***. This can be done by:
  - roughening it
  - oxidising it
  - coating it
  - painting it with a high-emissivity paint

  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.
- ***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 by sighting on these features, 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:

- The two wavelengths must be well separated if the ratio is to have adequate temperature sensitivity. This implies that the emissivities cannot then be assumed to be equal and their ratio must be estimated.
- As the ratio of the two signals is much less sensitive to temperature than either signal alone, an 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 can 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. To the extent that 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.

Thermal imaging

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 substantial area or even a complete scene.

With modern detector arrays it is possible to produce a temperature map with typically 1024 × 768 pixels. This is presented as a picture, but because the camera operates in the infrared, the image is either in shades of grey or false colours.

Thermal imaging is now widely used in:

- ***Qualitative applications:*** 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, to name but a few. These applications rely only on contrast.

- ***Quantitative applications:*** 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 two-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. However, they are now much more affordable, and have become powerful tools in thermal and temperature measurement. Figure 19 shows a fixed thermal imaging system focused on a stream of molten metal.

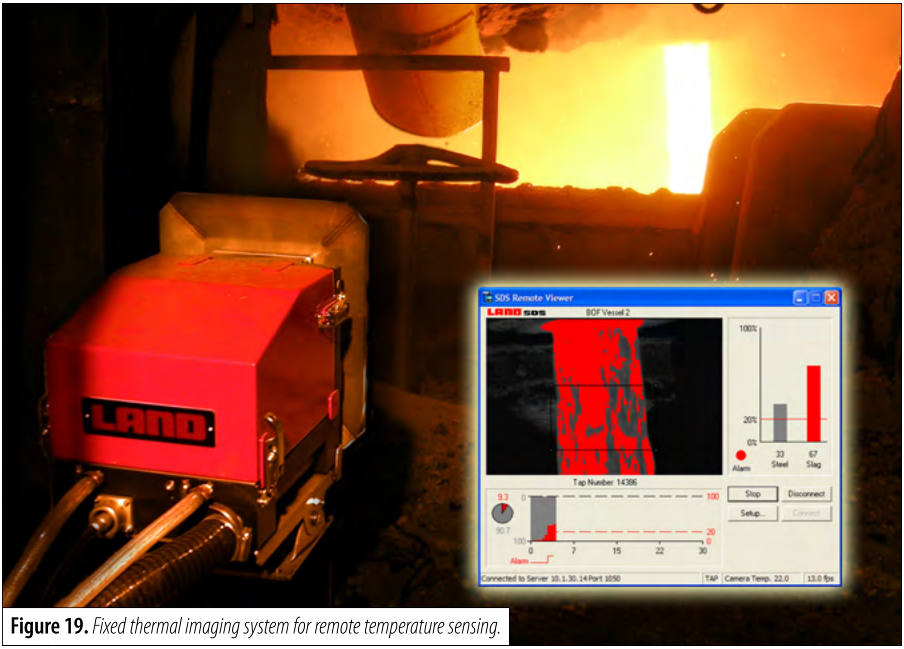

Figure 19. *Fixed thermal imaging system for remote temperature sensing.*

Image credit: AMETEK Land (Land Instruments International)

Chapter IV

Temperature measurement in practice

- Brief introduction
- Measurement in liquids
- Measurement in air and other gases
- Measurement in solids
- Measurement on surfaces
- Industrial measurements and standards
- Measurement in healthcare
- Checklist to choose the right temperature sensor

Brief introduction

Poor contact is the most common source of error in using contact temperature sensors. Ideally, the sensing element should be totally immersed in the measurement medium, with minimal contact to the outside environment. How this may be best achieved (or approximated) depends on whether the medium is a liquid, a gas, a solid or a surface.

This chapter 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. An example of temperature measurement in practice is given with reference to healthcare. Finally, a checklist is given to help in choosing the right sensor for a particular application.

Measurement in liquids

Liquids are very effective media for making contact for two main reasons:

- There is no gap between the medium and a sensing probe which is directly immersed in it.
- 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.

Recommendations for measurement in liquids

- Use a probe whose immersed 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.
- Where possible, allow extra length: an increase of 50 % in the immersion depth could reduce this error by as much as a factor of ten.
- Under steady conditions, test for immersion errors by withdrawing the sensor in steps of 2 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.
- Where a thermowell is used, 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 immersion can sometimes be gained by locating the thermowell at bends or elbows, or inserting it at an oblique angle. Test for immersion errors as suggested above.

Larger errors will arise if the probe has to be inserted into an additional protective tube; for example, if it is too short or 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 it needs to be longer if adequate immersion is to be achieved.

Measurement 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 can cause it to read high.

The sensor should be protected from:

- Lighting and other sources of radiation
- Sunlight
- Draughts
- Convection heaters

Recommendations for measurement in air and other gases

For ambient measurements:

- 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.

In an industrial chamber:

- 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).

In high temperature furnaces:

- 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 within the cable and contaminate the thermocouple wires. The supplier should advise, and some guidance may be found in documentary standards.

Similar considerations apply to air temperature measurements in an environmental chamber or oven, whose temperature may be very different from ambient. Good immersion is more important, and the poor heat exchange with the air means that the effect of heaters can be more significant.

Mineral-insulated metal-sheathed (MIMS) thermocouples are commonly used in industrial sensing, especially at very high temperatures and in reactive gases such as in combustion processes (power generation, aero engines, 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 approximately 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.

Measurement in solids

For hot or cold solids, where there are large heat flows, taking a surface measurement is likely to be problematic. 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', which was briefly discussed in Chapter II.

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.

Recommendations for measurement in solids

- In order 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 be more significant than immersion errors in the probe.

Measurement on surfaces

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

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, e.g. 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.

Sources of error and their minimisation

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

- The probe conducts heat from the surface and cools it.
- If it covers a significant area, it will mask the surface and will change the temperature.
- The sensor in the probe is some distance from the point of contact, and may be significantly cooler.

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, or to compensate for heat flows, 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.

Three options are available for surface measurement as illustrated in Figure 20 and discussed in the box 'Recommendations for measurement on surfaces'.

The first two options (point contact and surface probe) 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 close enough to the temperature of the surface in the presence of heat flows. The third option (extended contact) may be more difficult to engineer, but should give better measurements.

Recommendations for measurement on surfaces

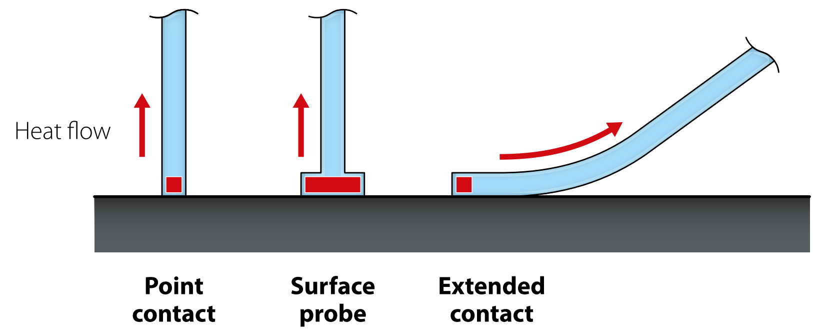

Figure 20. *Options for surface measurement.*

- **Option 1: point contact**. Apply a thin probe, for minimal 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 along the probe and temperature gradients (and hence errors) will be rather significant with this solution, and it is not recommended.
- **Option 2: surface probe**. 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, and it should be applied with a firm pressure. 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.
- **Option 3: extended contact**. 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 thermocouple keeps in contact with the surface for some distance before leading off to a remote indicator, so the region near the hot 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.

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 discussed in C hapter II. 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 of the operation of such apparatus are needed if reliable calibrations are to be obtained.

None of the 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, which were discussed in chapter III. Further research in this area is continuing to address these issues.

Industrial measurements and standards

Wherever possible, industrial process measurement and control uses products and components that 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, such as its ability to withstand temperature cycling, vibration and electromagnetic interference, etc. Instrumentation in the European Union (EU) is subject to directives to ensure that it meets requirements for, among other things, electromagnetic compatibility and health and safety.

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.

Standards for temperature sensors

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 Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). These are subsequently often adopted as European Norms.

In the case of industrial Pt100 sensors, the standard IEC 60751 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 degrees Celsius from –200 °C to 850 °C.

Rather more complicated equations are specified in IEC 60584-1 to relate thermocouple voltages (V) to temperature. 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. MIMS cables are normally used, manufactured according to IEC 61515 and drawn down to a final diameter between 8 mm and 0.5 mm. The optimal diameter is a compromise between good protection, in the larger sizes, and speed of response and 'bendability' at the finer sizes, which can follow an indirect path into the process or complicated machinery such as an aero engine.

Once clear of the high-temperature zone, it is common practice for the MIMS thermocouple to be connected to flexible extension cable, which can be easily run to the instrumentation, where cold junction compensation is applied, as discussed in chapter II. 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.

Measurement in healthcare

Measuring temperature in healthcare is a familiar activity which illustrates the range of options for temperature measurement which are now available, and it is used in this chapter as an example.

Much has changed in clinical temperature measurements since the days when the mercury thermometer was the device of choice and one million of them 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 ISO 80601-2-56 specifies the performance requirements and the methods of testing.

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 until reset (Figure 21). 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 uses the rate of warming to calculate the final reading, 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. The matrix of dots 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 sterilising before re-use. Other devices operating on similar principles, such as temperature-sensitive colour changes in liquid crystal displays, are available for applying to patients’ foreheads or temples, but they are less reliable because the location 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 (Figure 22) 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 cover is attached to the probe for each patient, to avoid transferring infections.

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. Wireless sensors are also available which can monitor other parameters such as heart rate, as well as temperature.

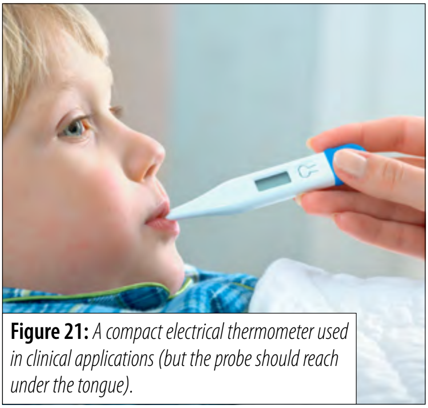

Image credit: © iStock.com/AlexRaths

Figure 21: *A compact electrical thermometer used in clinical applications (but the probe should reach under the tongue).*

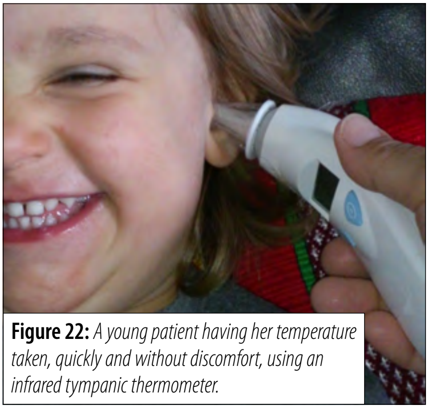

Image credit: National Physical Laboratory

Figure 22: *A young patient having her temperature taken, quickly and without discomfort, using an infrared tympanic thermometer.*

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 (Figure 23, left) is a thermal profile of the author showing the contrast between various sites, with the ear canal and temple which are closer to the normal core body temperature than the more exposed ear lobe and nose. The second picture (Figure 23, right) shows his hands, which are slowly warming up after being cooled in iced water. The technique is used to test for conditions which lead to poor circulation, such as Raynaud's syndrome.

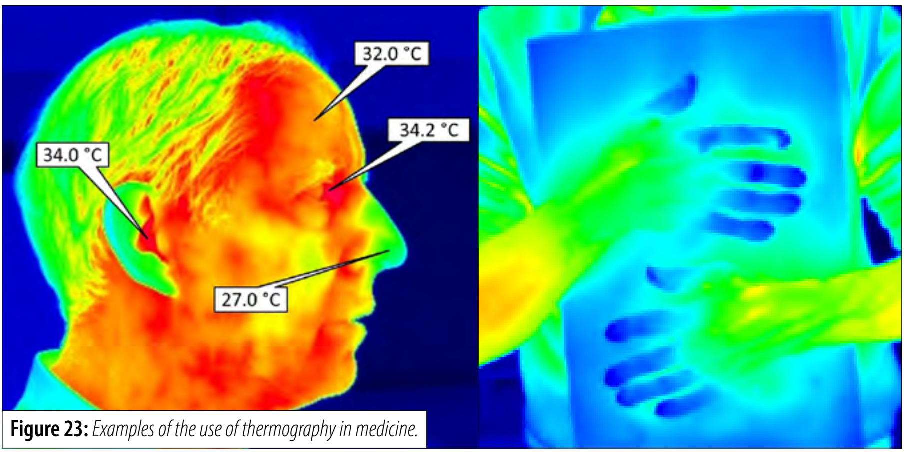

Image credit: National Physical Laboratory

Figure 23: *Examples of the use of thermography in medicine.*

Checklist to choose the right temperature sensor

The following table is a checklist of some key questions to ask before choosing a temperature sensor for a particular application. The list is not exhaustive. The desired answers for a good and meaningful measurement are marked with a dot.

Checklist for the choice of the temperature sensor

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?	●	
Accessibility/contact/ease of installation (size, shape, etc.)		
Can the sensor be mounted in good contact with the measurement site?	●	
Is the immersion adequate, so that heat flows along the connecting leads to not affect the measurement?	●	
Is there provision or space for connections, feed-throughs, etc?	●	
Instrumentation and communication (connection to control point)		
Is instrumentation (hardware and software) available with suitable specifications?	●	
Are the means of connection acceptable (thermally, mechanically, and electrically)?	●	
Compatibility with the environment (atmosphere or medium, material components)		
Is there potential for oxidation or other chemical reaction within the probe?		●
Does the ambient atmosphere need to be controlled?		●
Might any liquids or moisture in the measurement site affect the sensor?		●
Can any other physical influences or conditions affect the measurement (noise, vibrations, electromagnetic fields, thermal or ionising radiations, etc.)		●
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 and/or made fail-safe?	●	
Cost and availability (initial, maintenance, commercial status, testing needed)		
Is the preferred solution affordable or can an acceptable compromise be found?	●	
Can it be bought in from established commercial sources?	●	
Has all necessary testing been satisfactorily undertaken?	●	
Has infrared remote-sensing thermometry been considered?	●	

Further reading

Books

- Quinn, T.J. (1990), *Temperature*, Second edition, London: Academic Press
- Nicholas, J.V. and White, D.R. (2001), *Traceable temperatures*, Second edition. Chichester: John Wiley & Sons
- Michalski, L.; Eckersdorf, K.; Kucharski, J.; McGhee J. (2000), *Temperature Measurement*, Second edition, Chichester: John Wiley & Sons

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 towards industrial application.

Guides

- BIPM (2015), Guide to the realisation of the ITS-90. Accessed on 15 April 2015 from: *http://www.bipm.org/en/committees/cc/cct/guide-its90.html*
- EURAMET (2011), Calibration of Thermocouples, Version 2.1. Retrieved on April 2015 from: *https://www.euramet.org/fileadmin/docs/Publications/calguides/EURAMET_cg-8___v_2.1_Calibration_of_Thermocouples.pdf*
- NPL e-Learning Programme, Introduction to metrology, Module 3: The relevance of the worldwide measurement uniformity. Retrieved from: *http://www.npl.co.uk/commercial-services/products-and-services/training/e-learning/*

International standards

- IEC (BS EN) 60751:2008, *Industrial platinum resistance thermometers and platinum temperature sensors*
- IEC 61515:1995, *Mineral insulated thermocouple cables and thermocouples*
- IEC TS 62492-1:2008, *Radiation thermometers – Part 1: Technical data for radiation thermometers*
- IEC (BS EN) 60584-1:2013, *Thermocouples – Part 1: EMF specifications and tolerances*
- IEC (BS EN) 60584-3:2008, *Thermocouples – Part 3: Extension and compensating cables – tolerances and identification system*
- ISO (BS EN) 80601-2-56:2009, *Medical electrical equipment (Clinical thermometers)*

Useful websites

- NPL Training - online module on temperature measurement : *www.npl.co.uk/publications/good-practice-online-modules/temperature/*
- NPL introduction to temperature and humidity: *www.npl.co.uk/temperature-humidity/*
- NPL science posters: *www.npl.co.uk/educate-explore/posters/temperature/*
- Bureau International des Poids et Mesures (BIPM): *www.bipm.org*
- European Association of National Metrology Institutes (EURAMET) documents: *www.euramet.org/index.php?id=documents*

Contact NPL

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Introduction to temperature measurement

Good Practice Guide No.125

What is it about?

This guide is an introduction to basic concepts and types of instrument used in temperature measurement. For each instrument, the technical features, practical issues, applications and sources of error are discussed.

Who is it for?

This guide is for users who have little or no previous experience in measuring temperature. Fields of application range from clinical practice to industrial processing and scientific research.

What is its purpose?

The purpose of this guide is to provide background knowledge about temperature measurement and to present the options that are available in terms of instruments, procedures and applications.

What is the prerequisite knowledge?

The guide covers topics from entry to intermediate levels. Although it does not require any background in temperature measurement, it assumes that the reader has some scientific knowledge.

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