TECHNIQUE SELECTION – TEMPERATURE MEASUREMENT

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There is a wide variety of techniques for the measurement of temperature. Furthermore, within each category there is a large number of devices from which the selection must be made. In the absence of experience this choice can seem formidable. The aim of this chapter is to provide guidelines for the initial selection of a technique for temperature measurement. Using this information the choices within an individual category can then be explored.

1.1 Introduction

The undertaking of any task in science and industry is usually subject to a specification. If this does not formally exist then it should be explored and defined. Aspects that should be considered in the selection of a temperature measurement system, as illustrated in Figure 1.1, broadly include:

- Size and Shape
- Nature of contact
- Temperature Range
- Uncertainty
- Response
- Protection
- Disturbance
- Output
- Commercial availability
- User constraints
- Multiple locations
- Cost.

In defining the specification for the temperature measurement requirement for a given application bounds should be developed for each of these categories so that a given solution can be assessed as to whether it fulfils the specification. If there are deficiencies between a proposed solution and a specification, then the impact of these should be assessed and, if unsatisfactory, another solution developed.

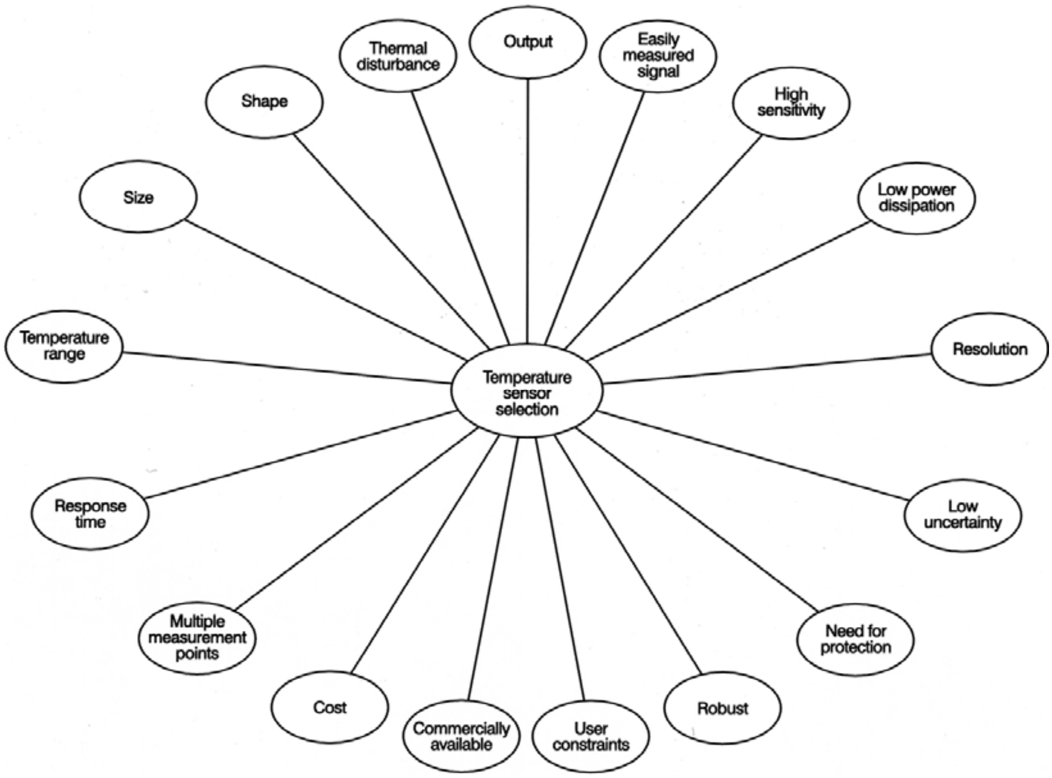


Figure 1.1 Selection considerations

1.1.1 Size and shape

The size and shape of the components of a temperature measurement system, including the transducer, any connection leads and any processing electronics and display can be a significant consideration. It is important to size not only the transducer but also the sensing system. The size of the transducer and its thermal properties will determine the thermal distortion of the temperature field and the transient response of the sensor. Many transducers, such as PRTs and thermocouples, are available in the form of a cylindrical probe that incorporates a protective cover, with diameters typically ranging from 0.25 mm to over 15 mm. In addition to considering whether the diameter of the sensor and its length can be accommodated, thought should also be given to the path of any connection leads, their size and whether it is necessary to protect these from the environment through which they pass. The weight and physical dimensions of any sensing electronics and display can be a factor. Is a plug-in board for a computer desirable, or is a standalone display wanted? If a display is wanted how big does it need to be and can it be located in the available space? A rack-mounted system may be appropriate for some applications. Many of these considerations are, of course, common sense, but the best of professionals can end up with an inconvenient system due to an oversight of such considerations. This is especially true when considering cable runs between the transducer and sensing electronics. For example, during the development of a gas turbine engine, multiple thermocouples may be installed on a turbine blade. The lead-out routes for sensors is often the most challenging aspect. In such an application the leads must have a sufficiently small diameter so that they can be installed in shallow slots and fed through small holes in order to minimize thermal disturbance.

1.1.2 Nature of contact

The various temperature measurement techniques have, for convenience, been categorized according to the level of physical contact between the sensor and the medium of interest. Traditionally, invasive methods have been the first choice for the majority of applications because of economic considerations and the ability of many contact sensors to give a point measurement. The reduction in cost of some of the non-invasive measurement techniques, particularly infrared methods , combined with additional merits of often insignificant thermal disturbance, has made the decision based on economy and performance more competitive. An example is the measurement of food temperature in shop refrigeration display units. Originally a liquid-in-glass thermometer might have been used, although legislation in many countries has forced the replacement of these by RTDs , which can more readily be sterilized to remove harmful bacteria and are more environmentally friendly. An infrared thermometer in such applications could lessen the risk of bacterial contamination even further and could therefore justify the likely five times first-cost price. In some remote or high-temperature applications, non-invasive techniques are the only option and disadvantages of complexity, cost and possibly increased uncertainty have to be accepted.

1.1.3 Temperature Range

Generally a sensor should be selected that can survive the temperatures to which it is exposed. The data given in Figure 1.2 illustrates the temperature range capabilities of various techniques. It should be noted, however, that the majority of the spans presented cannot be achieved with a single sensor. The thermocouple range, for example, shows capability up to 3300°C. A type T thermocouple is useful in the range –262°C to 400°C whilst a type K is useful for the range –250°C to about 1300°C. Figure 11.2 therefore only serves to indicate capability and as an initial guideline. In the case of thermocouples use of Table 5.2 and Figure 5.27 could be made to help to determine which type should be selected.

It is possible and sometimes necessary to use a transducer that ultimately degrades above a certain temperature. An example is the measurement of combustion chamber temperatures. One possibility is to use a MIMS thermocouple, which can survive in the environment at extended temperatures for only a limited time before the

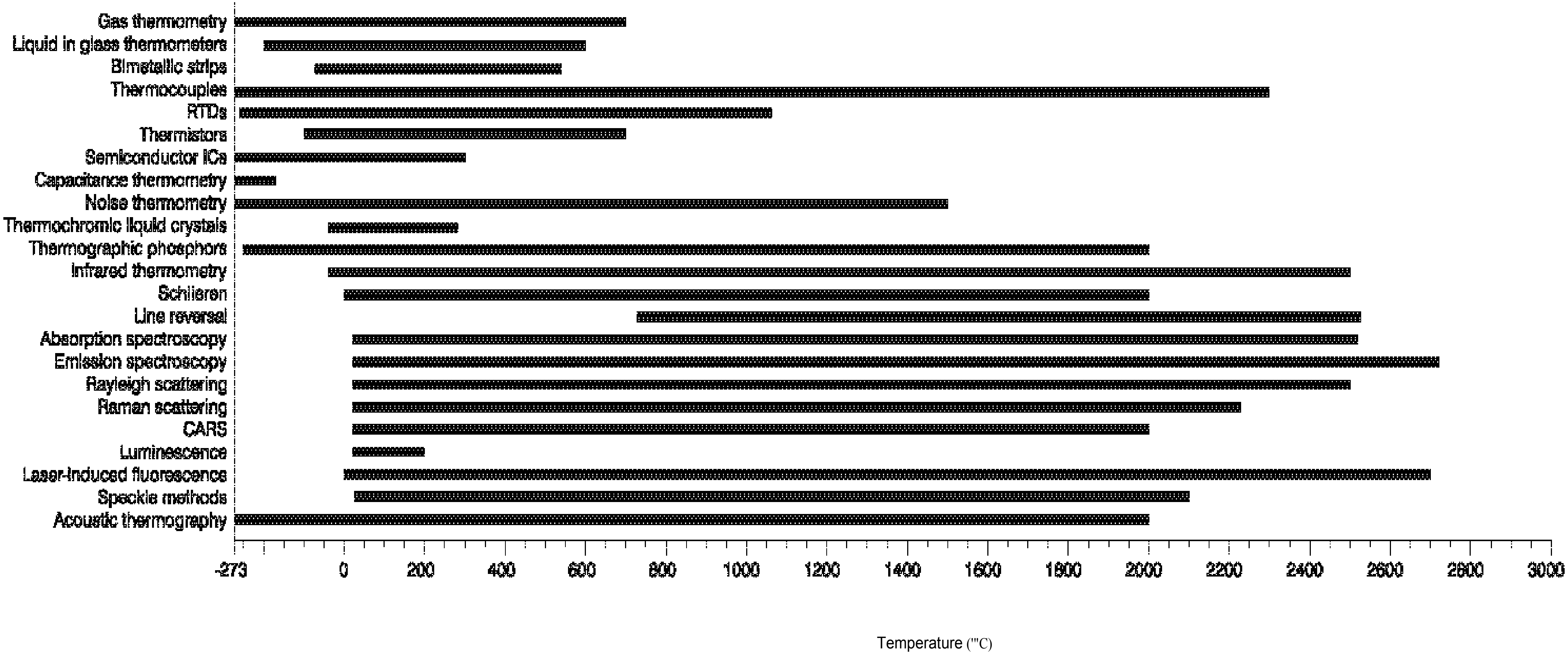


Figure 1.2 Normal temperature range capability of various measurement techniques

sheath or insulation degrades. This period of function before degradation may be long enough to provide a meaningful measurement. Once the transducer has ceased to function it can be replaced.

1.1.4 Uncertainty

The level of uncertainty to which a temperature must be determined should be explored before a sensor is selected. It should be ascertained whether an absolute value of temperature is desired or a temperature difference. If a temperature difference is required, i.e. a comparative measurement, then it should be noted that for some sensors the gradient of the output temperature characteristic remains more stable with time than does the origin. If a low uncertainty is required, then the sensor will need to be calibrated on a regular basis, or replaced by a calibrated substitute. Figure 1.3 provides an indication of the uncertainties of various techniques. The bars show two bands, the best practically achievable, and a more general practical assumed uncertainty.

1.1.5 Response

It is quite possible to install a temperature sensor in an application and not even realize that the temperature is in fact fluctuating significantly because

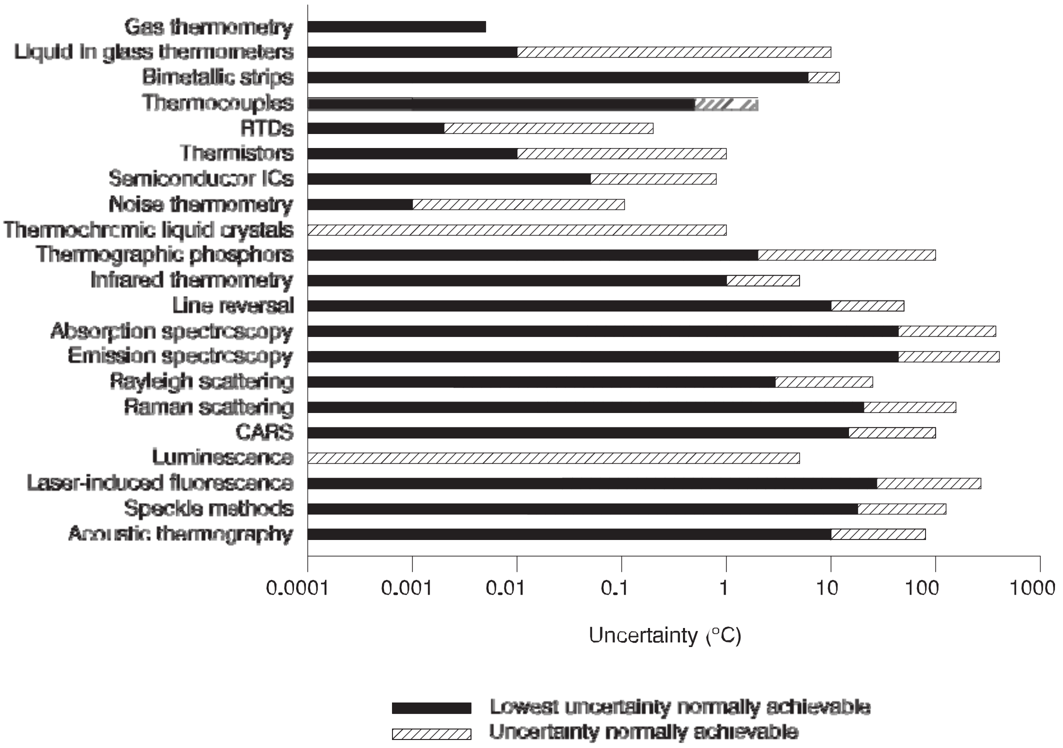


Figure 1.3 Uncertainty capabilities of various temperature measurement techniques. Inner bar represents the lowest uncertainty normally attainable. The outer bar represents normal limits on uncertainty

the transient response of the sensor is so slow that it merely indicates a weighted average temperature. An assessment of the likely temperature fluctuations in an application should be made along with what kind of information is actually required from the measurement. If a weighted average is all that is required then a sensor with a thermal mass low enough to pick this up would be quite appropriate. If, however, an indication of the transient fluctuation is necessary then a sensor with a time constant compatible with the fluctuations should be selected. The lower the product of mass and specific heat capacity, the faster the sensor. If a sensor has a time constant lower than the fluctuation in the temperature of the application there will still be a phase lag between the sensor output and the temperature of the application as well as an amplitude difference between the indicated and the actual temperatures. The smaller the time constant, the lower the phase lag and amplitude difference. Time constants depend on the sensor physical properties, local heat transfer and any signal processing times. For a specific sensor the time constant should be determined taking the boundary conditions of the actual application into consideration.

1.1.6 Protection

For some applications it may be necessary to isolate the sensor from the medium of interest using a protective cover or enclosure. A typical example is the use of a thermowell that protrudes into a fluid. The probe can be installed directly into the well and attain a temperature related to the fluid temperature. Some form of protection for sensors must generally be considered when dealing with corrosive environments such as reducing or oxidizing atmospheres, or extreme temperatures and pressures. Any form of protective coating will have implications on thermal response, thermal disturbance and cost of the system.

1.1.7 Disturbance

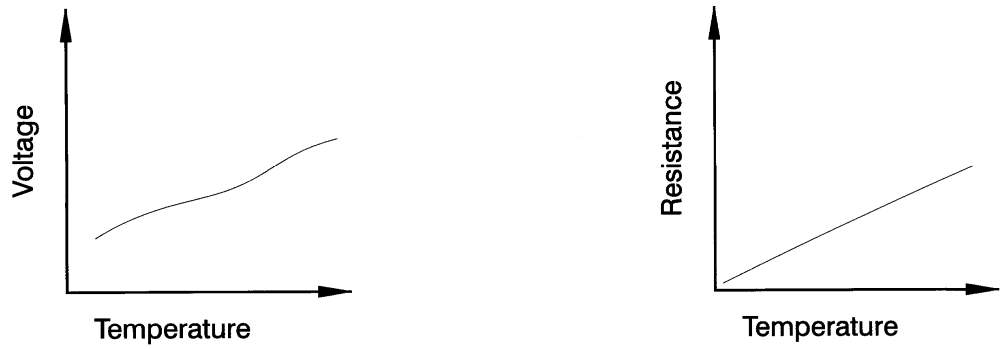
The insertion of a temperature probe into an application will distort the temperature distribution as the thermal properties of the sensor are unlikely to match those of the application and the presence of the sensor may distort the local thermal boundary conditions. A common maxim is that a temperature sensor measures its own temperature. The magnitude of the thermal distortion will depend on the properties of the sensor and its effect on the boundary conditions. Generally, as small a sensor as possible is desirable, preferably with thermal properties similar to those of the application. In addition, care should be taken to minimize the effects of any lead wires on the local system boundary conditions.

1.1.8 Output

The output of each type of transducer is different depending on the type of device. Liquid-in-glass thermometers provide a visual indication of temperature, whilst an RTD gives an output in terms of. Figure 1.4 illustrates the typical outputs for four types of temperature measurement device.

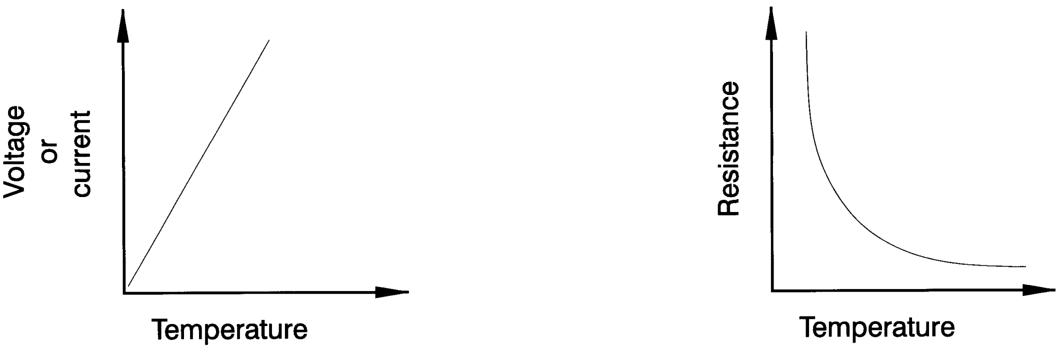
The form of output desired will depend on a number of factors:

1 Is the output to be used for control? If so, an electrical transducer, such as a PRT or thermistor, or mechanical transducer, such as a bimetallic thermometer, may be suitable.
2 Is the output to be recorded? If yes, then a sensor with an electrical output is likely to be most suitable.
3 Must the temperature be displayed at some distance from the point of measurement? If so, then a sensor with a high output, not sensitive to transmission errors, will be most sensible; e.g. an RTD or semiconductor-based sensor.



(a) Thermocouple

(b) PRT



(c) Semiconductor-based transducer

(d) Thermistor

Figure 1.4 Typical output for four types of temperature-sensing device

4 Is high sensitivity, output change/degree temperature change desirable? If yes then an RTD or semiconductor-based device may be suitable

1.1.9 Commercial availability

It is good general practice to use temperature-measuring sensors that are widely commercially available. Such sensors can be readily obtained and replaced as necessary. In particular some sensors are available as stock items. Examples include type J, K, N, R and T thermocouples , standardized thermistors and a number of semiconductor-based sensors. These can be ordered and supplied within a day in many cases. Some of the non- invasive techniques are specialist undertakings, requiring sophisticated equipment and skills that can take months to build up and develop. Even some of the infrared thermometry devices, despite their increased use, can require order times of several months. The selection of a technique must therefore be undertaken with a knowledge of the availability of the devices and the requisite knowledge to install and use them.

1.1.10 User constraints

The level of expertise required to utilize the various measurement techniques described is highly variable. Even highly sophisticated techniques can in some cases be configured in a turn-key system where the user need only switch on the device to monitor the temperatures of interest. Nevertheless the number of considerations described in this chapter give an indication of the possible complexity of temperature measurement. Due thought must therefore be given to user constraints, local expertise, speed of system use, customary usage and traditions, and resistance to rough handling, among others.

1.1.11 Multiple locations

It is often desirable to be able to monitor the temperature at a number of locations on, say, a surface. In such cases a number of the smaller invasive devices such as thermocouples, thermistors or PRTs may be suitable. An alternative is to consider a non-invasive or semi-invasive technique. One example is the use of an infrared thermometer with a traverse system, repositioning the field of view on each area of interest. Another possibility is to coat the surface with thermochromic liquid crystals and use of a video camera to record the spatially distributed temperatures.

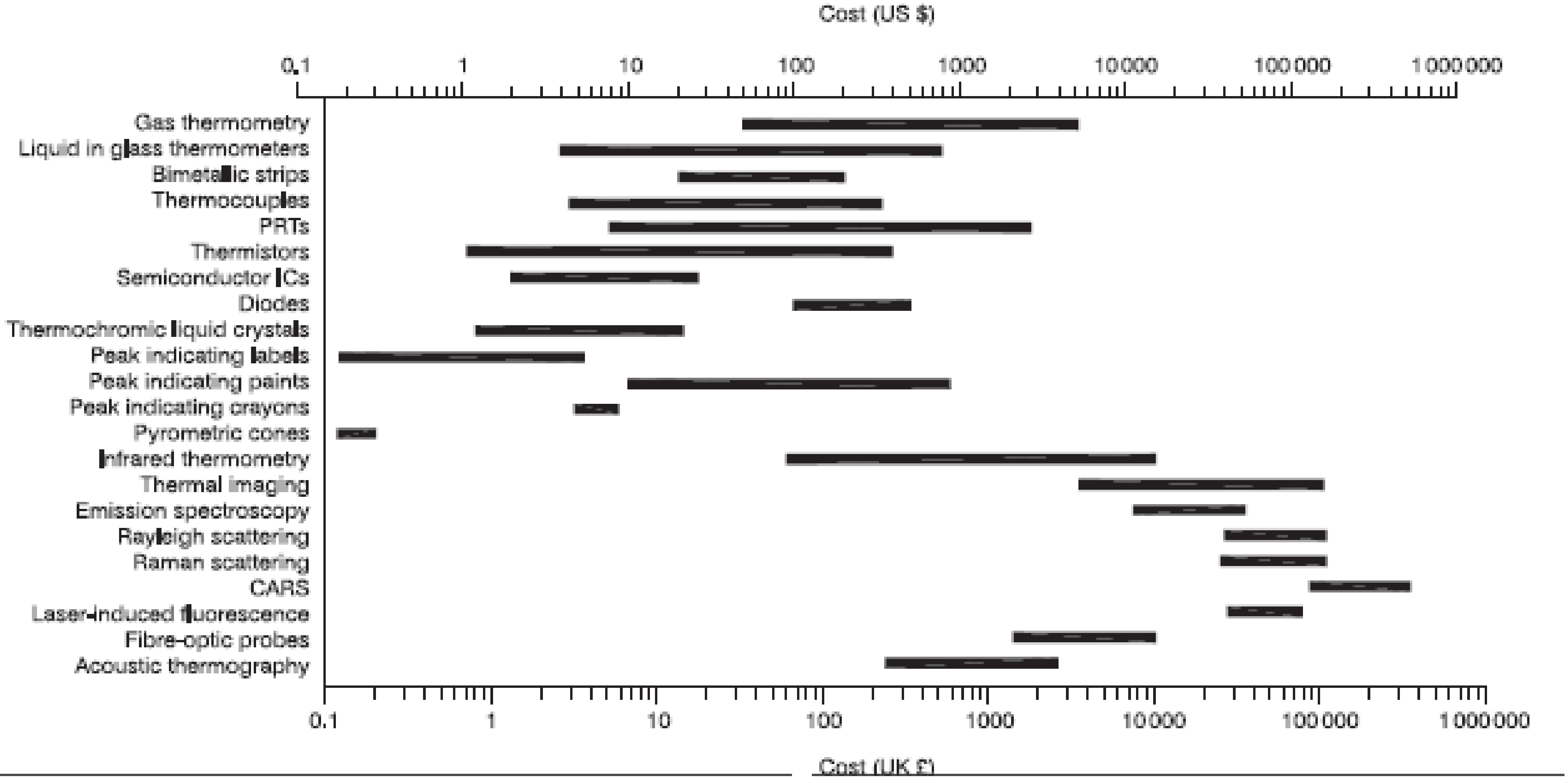


Figure 1.5 Comparison of purchase costs for a variety of temperature-measurement techniques

1.1.12 Cost

Cost is the ever-present driver of many if not all decisions in science and industry. The aim of business is production of profitable money. When considering a temperature measurement, the value of the data should be assessed in order to determine what maximum budget should be allocated to the task. The cost of the various temperature-measurement techniques considered here varies significantly, as does the cost of particular sensors within an individual category. When determining the cost of a temperature measurement, the entire system, the sensor, any connectors and sensing electronics, should be assessed along with the costs of calibration, servicing and use. Figure 11.5 provides an indication of the cost of a variety of techniques. In this figure it should be noted that in some case the cost of the sensor alone is considered, as in the case of a thermocouple, whilst in others the entire measurement system is considered as for infrared thermometers.

1.2 Selection overview

Considerations in the selection of a method for temperature measurement and the associated equipment to suit a particular application include: temperature range, likely maximum temperature, heating rate, response, desired uncertainty, stability, sensitivity, ruggedness, service life, safety, environment and contact methods. The selection of an appropriate technique requires an appreciation of a wide range of different technologies, what is possible and what is available.. The specific requirements of an application can limit the choice of suitable instrumentation. Some applications, for example, preclude the use of invasive instrumentation. Sometimes a full-field temperature map may be required; alternatively, point temperature measure- ments may be acceptable. Very low uncertainty measurements may or may not be worth the investment in equipment. The information given in Table 1.2.0, which is based on a wide range of common selection criteria, can be used to assist in the initial choice of an appropriate technique. Table 1.2.1 provides an overview of typical applications for each type of temperature measuring technique.

In addition to this text a substantial number of sources of information on temperature are available. For general review articles on the subject the reader is referred to Liptak (1995), Webster (1999) and Childs *et al.* (2000). For cryogenic applications, temperatures below 0°C, the reviews by Rubin *et al.* (1970, 1982, 1997) provide a thorough overview. For very high temperature measurements the reader is referred to Farmer (1998). A number of informative textbooks are available including Bentley (1998) and McGee (1988) giving general overviews, Quinn (1990) concentrating on the fundamental aspects of temperature, Kerlin and Shepard (1982) giving an

Table 1.2.0 Guide to the performance of various types of temperature measuring techniques and sensors. After Childs *et al.* (2000)

Method	*Minimum temperature*	*Maximum temperature*	*Response*	*Transient capability*	*Sensitivity*	*Uncertainty*	*High signal*	*Stability/ repeatability*	*Low thermal disturbance*	*Commercially available*	*Relative cost*
Gas thermometer	about –269°C	700°C	slow	×	–	A standard	✓	✓	×	×	v high
Liquid-in-glass thermometer	–200°C	600°C	slow	✓	1°C	±0.02 – ±10°C (ind) ±0.01°C (lab)	✓	✓	×	✓	v low
Bimetallic thermometer	–73°C	540°C	mid	✓	–	±1°C	✓	✓	✓	✓	low
Thermocouple	–270°C	2300°C	very fast	✓	±10 V/°C	±0.5°C – ±2°C	×	✓	✓	✓	v low
Suction pyrometer	–200°C	1900°C+	very fast	✓	–	±5°C of reading	✓	✓	×	✓	mid high
Electrical resistance device	–260°C	1064°C	fast	✓	0.1 n/°C	the standard above 13.81K	✓	✓	✓	✓	mid low
Thermistors	–100°C	700°C	fast	✓	10 mV/K	±0.01 – ±0.05°C	✓	✓	✓	✓	mid low
Semiconductor devices	–272°C	300°C	very fast	✓	±1%	±0.1°C	✓	✓	×	✓	low
Fibre-optic probes	–200°C	2000°C	fast	✓	10 mV/°C	0.5°C	✓	✓	✓	✓	mid high
Capacitance	–272°C	–170°C	fast	✓	good	Poor	✓	×	✓	✓	mid
Noise	–273°C	1500°C	fast	✓	good	Good	×	✓	✓	×	high
Chemical sampling	5°C	2100°C	slow	×	–	±25 K	×	✓	×	✓	mid
Thermochromic liquid crystals	–40°C	283°C	mid	✓	±0.1°C	±1°C	–	✓	✓	✓	low mid
Thermographic phosphors	–250°C	2000°C	very fast	✓	~0.05°C	0.1% –5%	✓	✓	✓	✓	high

Heat-sensitive paints	300°C	1300°C	slow	×	–	±5°C	✓	✓	✓	✓	mid
Infrared thermometer	–40°C	2000°C	very fast	✓	~0.1°C	±2°C	✓	✓	✓	✓	v high
Two colour	150°C	2500°C	very fast	✓	1°C/mV	±1%(±10°C)	✓	✓	✓	×	v high
Line scanner	100°C	1300°C	very fast	✓	–	±2°C	✓	✓	✓	✓	v high
Schlieren	0°C	2000°C	fast	✓	n/a	n/a	visual	✓	✓	✓	mid
Shadowgraph	0°C	2000°C	fast	✓	n/a	n/a	visual	✓	✓	✓	mid
Interferometry	0°C	2000°C	fast	✓	n/a	n/a	✓	✓	✓	✓	high
Line reversal	727°C	2527°C	very fast	×	line of sight av.	±10–15 K	✓				low
Absorption spectroscopy	20°C	2500°C	very fast	×	line of sight av.	15%	✓	✓	✓	✓	low
Emission spectroscopy	20°C	2700°C	very fast	✓	line of sight av.	15%	✓	✓	✓	✓	low
Rayleigh scattering	20°C	2500°C	very fast	×	0.1 mm^3 in 100°C	1%	✓	✓	✓	×	v high
Raman scattering	20°C	2227°C	very fast	×	0.1 mm^3 in 100°C	7%	✓	✓	✓	×	v high
CARS	20°C	2000°C	fast		1 mm^3 in 50°C	5%	✓	@atm	✓	✓	v high
Degenerative four wave mixing	270°C	2600°C	very fast	✓	1 mm^3 in 50°C	10%	✓	@atm	✓	×	v v high
Luminescence	20°C	200°C	fast	✓	1.5 nm in 200°C	±5°C	✓	✓	✓	×	high
Laser-induced fluorescence	0°C	2700°C	very fast	×	–	10%	✓	✓	✓	×	v high
Speckle methods	27°C	2100°C	very fast	×	–	6%	✓	✓	✓	×	v high
Acoustic thermography	–269°C	2000°C	very fast	✓	–	4%	✓	✓	✓	×	high

Table 1.2.1 An overview of typical applications

Medium	*Technique*	*Typical applications*
Solid	Liquid-in-glass thermometers	Body temperatures
	Bimetallic thermometers	Surface and body temperatures
	Thermocouples	Surface and body temperatures
	RTDs	Surface and body temperatures
	Thermistors	Surface and body temperatures
	Semiconductor-based sensors	Body temperatures
	Capacitance	Sample temperatures
	Noise thermometry Quartz	Sample temperatures
	thermometers	Surface and body temperatures
	Paramagnetic thermometry	Sample temperatures
	Nuclear magnetic resonance thermometry	Sample temperatures
	Liquid crystals	Surface temperatures
	Thermographic phosphors	Surface temperatures
	Heat-sensitive paints	Surface temperatures
	Infrared thermometers	Surface temperatures
	Acoustic thermography	Thermal processing
Liquid	Liquid-in-glass thermometers	Typically installed in a thermowell
	Bimetallic thermometers	Typically installed in a thermowell
	Thermocouples	Often integrated into a total temperature probe or installed in a thermowell
	RTDs	Often integrated into a total temperature probe or installed in a thermowell
	Thermistors	Often integrated into a total temperature probe or installed in a thermowell

	Semiconductor-based sensors	Often integrated into a total temperature probe or installed in a thermowell
	Acoustic thermography	Liquid body, oceans
Gas	Liquid-in-glass thermometers	Typically installed in a thermowell
	Bimetallic thermometers	Typically installed in a thermowell
	Thermocouples	Often integrated into a total temperature probe. Combustion chambers
	RTDs	Often integrated into a total temperature probe or installed in a thermowell
	Thermistors	Often integrated into a total temperature probe or installed in a thermowell
	Semiconductor-based sensors	Often integrated into a total temperature probe or installed in a thermowell
	Suction pyrometer	Hot gases, flames
	Chemical sampling	Flames
	Schlieren	Hot gases, flames
	Shadowgraph	Hot gases, flames
	Interferometry	Hot gases, flames
	Line reversal	Flames, hot gases
	Absorption spectroscopy	Flames
	Emission spectroscopy	Flames
	Rayleigh scattering	Plasmas, combustion processes, sooting flames, supersonic flows
	Raman scattering	Reactive flows, flames, atmospheric temperature measurement
	CARS	Flames, combustion chambers, combustion and plasma diagnostics, exhausts, unsteady flows
	Degenerative four-wave mixing	Flames
	Gas thermometer	Gas sample
	Acoustic thermography	Gaseous medium
	Laser-induced fluorescence	Flames, IC engine cylinder measurements
	Speckle methods	Flames
	Luminescence	Flames

accessible introduction to temperature measurement and Nicholas and White (1994) introducing the subject of traceability in measurement. For specialist articles on temperature measurement the series entitled *Temperature. Its Measurement and Control in Science and Industry* (Herzfeld, 1962; Plumb, 1972; Schooley, 1982, 1992), is an excellent starting point for research.

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