

REVIEW ARTICLE

Review of temperature measurement

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A variety of techniques are available enabling both invasive measurement, where the monitoring device is installed in the medium of interest, and noninvasive measurement where the monitoring system observes the medium of interest remotely. In this article we review the general techniques available, as well as specific instruments for particular applications. The issues of measurement criteria including accuracy, thermal disturbance and calibration are described. Based on the relative merits of different techniques, a guide for their selection is provided. © 2000 American Institute of Physics. [S0034-6748(00)03708-4]

NOMENCLATURE

B constant

c speed of light (3×10^8 m/s)

h Planck's constant (6.626×10^{-34} J s)

E Young's modulus

$E_{\lambda,b}$ blackbody emissive power

k Boltzmann's constant (1.38×10^{-23} J/K)

K bulk modulus

p pressure

\mathfrak{R} characteristic gas constant

R resistance

R_0 resistance at T_0

R_T resistance at T

T temperature

V volume

V_v variable volume

u speed of sound

γ isentropic index

λ wavelength

ρ density

σ Stefan-Boltzmann constant (5.67×10^{-8} W/m² K⁴)

ω frequency

I. INTRODUCTION

Temperature is one of the fundamental thermodynamic properties. The unit of thermodynamic temperature, also referred to as Kelvin temperature or absolute temperature, is kelvin (K) and is defined in terms of the interval between the absolute zero and triple point of pure water, 273.16 K; kelvin is the fraction 1/273.16 of that temperature. In addition to the thermodynamic temperature, the Celsius (°C) temperature is defined as equal to the thermodynamic temperature minus 273.15 and the magnitude of 1 °C is numerically equal to 1 K. The current international temperature scale, ITS-90, defines a scale of temperature in five overlapping ranges.¹ These are

- (1) 0.65–5 K using vapor pressures of helium,
- (2) 3–24.5561 K via an interpolating constant volume gas thermometer,
- (3) 13.8033–273.16 K using ratioed resistances of platinum resistance thermometers calibrated against the triple points of various materials,
- (4) 273.15–1234.93 K using platinum resistance thermometers calibrated at fixed freezing and melting points, and
- (5) above 1234.94 K using the Planck law of radiation.

The range of techniques for the measurement of temperature is extensive, utilizing such diverse phenomena as thermoelectricity, temperature dependent variation of the resistance of electrical conductors, fluorescence and spectral characteristics. Additionally, the requirements for a temperature measurement may allow direct contact with the medium. Alternatively this may not be possible or desirable and a noninvasive method may be used. For convenience the various measurement techniques can be classified into three categories depending on the nature of contact which exists between the measuring device and the solid, liquid or gaseous medium of interest.

- (1) Invasive. The measuring device is in direct contact with the medium of interest, e.g., a thermocouple in a gas stream.
 - (2) Semi-invasive. The medium of interest is treated in some manner to enable remote observation, e.g., surface coatings whose color changes with temperature.
 - (3) Noninvasive. The medium of interest is observed remotely, e.g., infrared thermography.
- Invasive, semi-invasive and noninvasive temperature measurements are discussed in Secs. II, III and IV, respectively.

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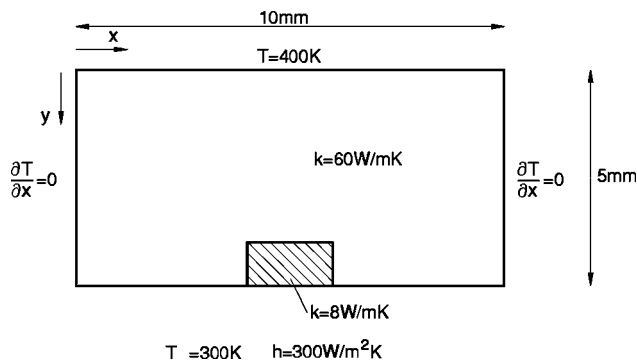


FIG. 1. Boundary conditions for a chrome steel component with a thermocouple installed in a channel filled by ceramic paste.

It is estimated that temperature measurement accounts for 75%–80% of the worldwide sensor market.² In the selection of a particular method of measuring temperature, consideration may be given to accuracy, sensitivity, life, size, cost, manufacturing constraints, dynamic response, temperature of operation and robustness. The accuracy of a measurement technique depends on a number of factors such as calibration against the absolute temperature scale, thermal disturbance due to the method of installation, transducer output monitoring and instability effects. These aspects are considered in Secs. II–IV for the individual categories of measurement discussed and in Sec. V, which provides a guide to the relative merits of the different measurement techniques that are available.

II. INVASIVE TEMPERATURE MEASUREMENT TECHNIQUES

Invasive instrumentation involves the installation of a physical sensor on or within the component, like a turbine blade or a medium of concern as with an exhaust gas. The range of invasive instrumentation is diverse: gas and liquid-in-glass thermometers, thermocouple and resistance temperature devices are commonly known examples. While some of these devices, such as gas thermometers, are more suitable for a calibration laboratory, they are included here for completeness and for their role in defining the accuracy of other sensors.

The use of invasive instrumentation involves a disturbance, which manifests itself as a difference between the temperature being measured and that which would exist in the absence of the instrumentation. The temperature reached, for example, by an invasive instrument in contact with a gas stream is determined by the balance of convective heat transfer from the gas to the sensor surface, conduction in the sensor itself and its supports and connections, and radiative heat transfer between the sensor and its surroundings. Figures 1 and 2 illustrate the thermal distortion caused by the insertion of thermocouple wires encapsulated in ceramic paste in a steel block for steady state conditions. Prior to installation the temperature profiles would have been horizontal for the boundary conditions imposed. At the middle of the ceramic filled channel the temperature calculated is 373.6 K. This compares with a temperature of 377.4 K at this location in the absence of the thermal distortion.

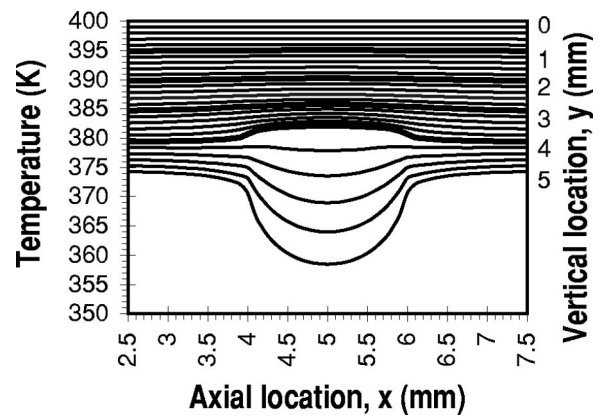


FIG. 2. Calculated thermal disturbance caused by the installation of thermocouple wires encapsulated in ceramic paste in a chrome steel component.

A. Temperature measurement by thermal expansion

The expansion of materials with temperature can be utilized to measure temperature. Fluid thermometry covers a range of devices from the constant volume and constant pressure gas thermometers used in calibration to liquid-in-glass thermometers. The expansion of solids is used in devices such as bimetallic strips.

1. Gas thermometry

The ideal gas law forms the basis of gas thermometry; the temperature is obtained from a measurement of pressure and/or volume. Used directly in this way, the accuracy depends on, among other things, the value of the gas constant.^{3,4} As a result, a number of methods have been devised that eliminate the need for knowing it. The four tech-

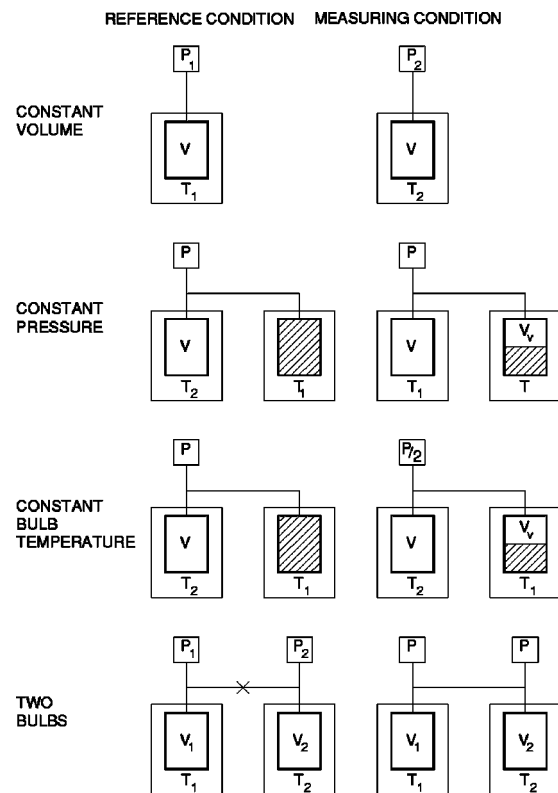


FIG. 3. Schematic of four types of gas thermometer (adapted from Ref. 5).

niques illustrated in Fig. 3 operate on the principle of maintaining either a constant pressure or a constant volume and/or a constant bulb temperature. In Fig. 3, T_1 refers to an accurately known reference temperature, as defined by, say, a triple point, and T_2 is the temperature to be measured. The diagrams on the left side show the schematic arrangement and thermodynamic properties at the reference condition; those on the right side, at the measuring condition.

The most common method is constant volume gas thermometry. For this method, a bulb containing the gas is immersed into a fluid at the known reference temperature T_1 , and the pressure p_1 is measured under conditions of thermal equilibrium and again at temperature T_2 , from which

$$T_2 = T_1 \frac{p_2}{p_1}. \quad (1)$$

For a constant pressure gas thermometer, there are two bulbs and one is always immersed at the reference temperature T_1 (where for $T_2 > T_1$, $V_v = 0$). When the sensing bulb is at T_2 , the pressure is maintained constant by allowing the volume V_v to vary. The temperature T_2 is then given by

$$T_2 = \frac{VT_1}{V - V_v}. \quad (2)$$

In a constant bulb-temperature device, one bulb is always immersed at T_1 and the other always at T_2 . At the reference condition the variable volume $V_v = 0$; at the measuring condition V_v expands until the pressure reaches half that at the reference condition and so

$$T_2 = \frac{VT_1}{V_v}. \quad (3)$$

In the two-bulb device, the separate pressures p_1 and p_2 are measured at the reference condition and the common pressure p at the measuring condition from which

$$T_2 = \frac{V_2 T_1 (p - p_2)}{V_1 (p_1 - p)}. \quad (4)$$

Use of Eqs. (1)–(4) to determine T_2 of course assumes ideal behavior of both the gas and the equipment. The practical application is not so simple and for accurate measurements consideration must be given to both the nonideal nature of real gases and inherent inadequacies of the equipment used. The behavior of real gases may be modeled using the virial equation. This can be expressed in a number of ways; a form appropriate to constant volume gas thermometry (and for modifying the gas thermometry equations given above) is

$$p = \left(\frac{RT}{V} + \frac{B(T)}{V^2} + \frac{C(T)}{V^3} + \frac{D(T)}{V^4} + \dots \right), \quad (5)$$

where $B(T)$, $C(T)$, $D(T)$, etc. are the second, third and fourth virial coefficients. These coefficients have been evaluated for a wide range of gases at various temperatures (see, for example, Refs. 6–12).

Examples of the utilization of constant volume gas thermometry are reported by Guildner and Edsinger,⁷ by Berry,⁹ Kemp *et al.*¹⁰ and in Refs. 13–16. It is used to define the

ITS-90 between 3 and 24.5561 K.¹ Corrections to account for the behavior of the measuring apparatus include

- (1) the dead space in connection tubes;⁹
- (2) thermal expansion of the gas bulb;^{17,18}
- (3) the difference in density of the gas at different levels in the pressure sensing tubes;^{9,17}
- (4) a thermomolecular pressure correction to account for temperature differences along the pressure sensing tube;^{9,19,20}
- (5) the absorption of impurities in the gas.^{9,17,21}

Gas thermometers are mostly used for measurements in the range of a few K to approximately 1000 K. At the lower temperatures, better accuracy may be obtained by measuring the vapor pressure of a cryogenic liquid.^{22–24} The use of such vapor pressure thermometry over gas thermometry at temperatures below 4.2 K was recommended by Pavese and Steur.¹⁷

The accuracy of gas thermometry measurements depends on the care taken and the temperature range. For example Pavese and Steur¹⁷ reported an accuracy of 0.5 mK for temperatures between 0.5 and 30 K. The method is generally expensive and restricted to detailed scientific experiments, calibration and standards laboratories.

2. Liquid-in-glass thermometers

Liquid-in-glass thermometers permit a quick visual indication of temperature that can with care be very accurate. The traditional liquid-in-glass thermometer comprising a reservoir and capillary tube supported in a stem follows the designs proposed by Daniel Fahrenheit in 1714. A number of types of thermometer exist including total, partial, and complete immersion, depending on the level of contact between the medium and the sensor.

Liquid-in-glass thermometers can be calibrated at a number of fixed points and a scale applied to a stem supporting the capillary tube to indicate the range and value of the temperature. The accuracy for industrial glass thermometers depends on the actual device and values range from ± 0.01 to ± 4 °C.²⁵ Laboratory glass thermometers can achieve accuracy levels of ± 0.005 °C. Inaccuracy can occur due to non-uniformities in the manufacture of the capillary bore. If the capillary has a given diameter at the calibration points but varies in between, then the device will appear accurate at the calibration points in use but will be inaccurate at intermediate temperatures. The design and use of liquid-in-glass laboratory thermometers are detailed by Refs. 25–29. Mercury-in-glass thermometers are increasingly being replaced by relatively cheap resistance devices (see Sec. II C) giving a digital readout or by thermally sensitive paint devices which give an obvious visible indication of the temperature (Sec. III A). Nevertheless there is still an abundance of liquid-in-glass devices and their use, due to simple like for like replacement, will continue.

3. Thermal expansion of solids

These devices take advantage of the difference in thermal expansion between different materials, usually metals.

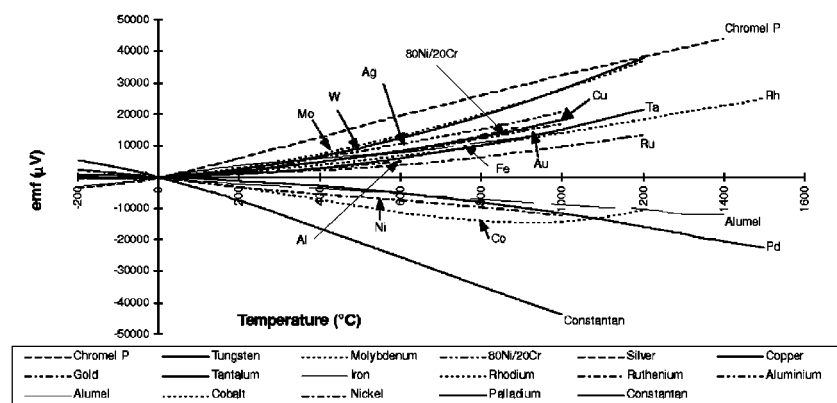


FIG. 4. Variation of thermoelectric power with reference to platinum with a cold junction at 0 °C for a selection of materials.

Strips of different metals are bonded together to form a bimetallic strip and when heated the side with the higher coefficient of thermal expansion will expand more causing the assembly to bend.^{30–32} This bending can be translated into a temperature reading by a mechanical linkage to a pointer with an accuracy of approximately ± 1 °C. An advantage of these devices is that they do not require a power supply. Their use as temperature controllers is widespread.

B. Thermoelectric devices

Thermocouples are frequently referred to as the workhorse of temperature measurement with different devices capable of monitoring temperatures between -270 and 3000 °C. Thermocouples are commonly used because of their low cost, simplicity, robustness, size, and temperature range. Their sensitivity is adequate for many applications as is their speed of response but they are less accurate than resistance temperature devices; they require an independent measurement of junction temperature and extension cables can be expensive. The basis of these devices is the Seebeck effect. This is the production of an electromotive force (emf) in a circuit of two dissimilar conductors experiencing a thermal gradient.

The variation of thermoelectric power is illustrated in Fig. 4 which gives the emf generated by a thermoelement relative to platinum with one junction held at 0 °C and the other at an increasing temperature. This chart can be used to aid the selection of combinations of materials in the design of thermocouples. Often the goal is maximum thermoelectric emf in which case a thermocouple pair should be selected, one with a large positive and one with a large negative emf. The thermocouple materials must however be chemically compatible and Miedema³³ and Pollock³⁴ have provided information on many suitable alloy combinations.

Thermocouples can be categorized as noble metal, base metal, high temperature or refractory metal, and nonmetal.³⁵ Noble metals are relatively inert, although platinum, for example, oxidizes at 600 °C. Their use in thermocouples stems from their chemical stability and thermoelectric power (see Fig. 4). Certain base metals such as copper, iron, nickel, aluminum, and chromium, as well as their alloys with additional impurities, can be used to produce materials, e.g., constantan and Chromel, with desirable thermoelectric characteristics, particularly for low and moderate temperatures. For

higher temperature applications, the refractory metals such as tungsten, rhenium, some tungsten and rhenium alloys, and molybdenum can be used. Tungsten and rhenium have very high melting points, 3410 and 3280 °C, respectively, and have either been used alone or alloyed with other material for thermocouples. Such metals oxidize easily and must not be exposed to oxidizing atmospheres at high temperatures or oxidizing agents. Nonmetals such as carbon, boron, and carbide and boride compounds are generally brittle and have low tensile strengths. Practical thermocouples using nonmetals can result in relatively large composite rods.

The number of thermocouple material combinations available is extensive; the characteristics of over a 150 were tabulated by Kinzie.³⁶ The criteria for thermocouple selection include cost, maximum and minimum operating temperatures, chemical stability, material compatibility, atmospheric protection, mechanical limitations, duration of exposure, sensor lifetime, sensitivity, and output emf.³⁷ Descriptions of the various commonly available standardized thermocouples are presented in Table I. It should be noted that only type *E*, *T*, and *K* thermocouples have proven themselves useful for cryogenic use.³⁸ There are several special gold–iron alloys that supplement the type *E* in the cryogenic region. The properties of a variety of thermocouples for operation at more elevated temperatures are presented in Table II.

Variations in the homogeneity of the alloys used for thermocouple cable have resulted in the use of standards for defining thermocouple wire conformity see, for example, Refs. 46–48. For type *K* and *N* thermocouples class 1 thermocouple wire material conforms to ± 1.5 °C or $0.004T$ for $T > 375$ °C; class 2 thermocouple wire material conforms to ± 2.5 °C or $0.0075T$ for $T > 333$ °C.

Practical monitoring of a thermoelectric emf requires some form of circuit.⁴⁹ The circuits in Fig. 5 with $T_1 > T_2$ illustrate the modifications to the basic circuit to form a practical measurement circuit. Figure 5(a) shows the generation of a thermoelectric emf in a circuit formed by two homogeneous but dissimilar metals experiencing a thermal gradient. The introduction of a third metal in the circuit, as illustrated in Fig. 5(b), does not change the thermoelectric emf produced if there is no net thermal gradient across its junctions. The circuit shown in Fig. 5(c) uses an extension of the principle illustrated in Fig. 5(b) where a conductor that does not experience a net thermal gradient does not contribute to the

TABLE I. Standardized thermocouples (Refs. 36 and 39–42).

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

thermoelectric emf. This circuit can form the basis of a practical thermoelectric measuring circuit as shown in Fig. 5(d) where additional electrical elements are added to monitor the potential difference. For this circuit to provide meaningful results the temperature T_2 must be known and is often called the reference junction temperature. In some laboratory conditions, an ice water bath or Peltier cooler is used to maintain T_2 at 0 °C. In the vast majority of applications, however, a reference junction voltage corresponding to T_2 is provided by an electronic bridge circuit incorporating a resistance temperature device; it is usually, but not always, adjusted to

0 °C. The circuit is mounted at the location of the measuring instrument's input terminals where the resistance temperature device can sense that temperature. The measuring instrument can be a digital voltmeter (DVM) or the amplifier/analog digital converter combination of a direct reading (in temperature) temperature controller or readout. The input impedance of the voltage measuring instrument has to be large compared to the resistance of the thermocouple and its extension wires. This condition is easily met in practice and will prevent a significant current from flowing through the circuit, which could cause other thermoelectric effects and/or

TABLE II. A selection of thermocouple materials for operation at higher temperatures.

Material	Temperature limit (°C)	Output (mV) at 1000 °C	Oxidizing atmosphere ^a	Reducing environment ^b	Source
SiC–SiC	1760	500	Yes	Yes	Kinzie (Ref. 36)
W–CuNi	2200	14.5	No	Yes	Michalski <i>et al.</i> (Ref. 43)
W97Re3–W75Re25	2500	18.226	No	Yes	Michalski <i>et al.</i> (Ref. 43)
C–C	1760	25	Yes, short time	Yes	Kinzie (Ref. 36), Duffey <i>et al.</i> (Ref. 44)
C–W	1800 ^a –2500 ^b	32	Yes	Yes	Kinzie (Ref. 36)
W–Mo	2400	–1.46	No	Yes	Michalski <i>et al.</i> (Ref. 43)
SiC–C	1900	300	Yes, short time	Yes	Kinzie (Ref. 36), Duffey <i>et al.</i> (Ref. 44)
Ir–Rh	2200	5	Yes, short time	Yes	Michalski <i>et al.</i> (Ref. 43), Duffey <i>et al.</i> (Ref. 44)
W–Re	2300	15	No	Yes	Duffey <i>et al.</i> (Ref. 44), Villamyor (Ref. 45)
W–Ir	2200	14.25	No	Yes	Michalski <i>et al.</i> (Ref. 43)
ZrB ₂ –ZrC	2980	10	Yes	Yes	Kinzie (Ref. 36)
CbC–ZrC	3300	Duffey <i>et al.</i> (Ref. 44)

^aO₂, H₂O, CO, or CO₂.^bH₂, Ar, N₂, inert or vacuum.

cause an IR drop across the thermocouple and its leads. Voltages produced by metallic thermocouples are not high, generally about 10–80 $\mu\text{V}/^\circ\text{C}$, however, a DVM with a not uncommon resolution of 10 μV can resolve 0.25 $^\circ\text{C}$ for a type K thermocouple.

Many applications require the thermocouple wires to be electrically or chemically isolated from the environment or medium of interest. Examples of insulation materials include PVC for temperatures between -30 and 105 $^\circ\text{C}$, Teflon for -273 – $+250$ $^\circ\text{C}$, glass fiber for -50 – 400 $^\circ\text{C}$, and polyimide for -269 – 400 $^\circ\text{C}$. Alternatively, a metal sheath encapsulating a mineral insulation such as magnesium oxide which supports and electrically isolates the thermocouple can be used to 1250 $^\circ\text{C}$.⁵⁰ Higher temperatures can be achieved using all-ceramic sheaths. The external noise effects of electrical and magnetic fields on low emf outputs can be of great significance. Twisted pair cable can be used to cancel spurious emfs. Grounding of thermocouple circuits is therefore an important consideration and was discussed by Benedict and Russo⁵¹ and by Claggett *et al.*⁵² The requirements of electrical or chemical isolation and good thermal contact are often in conflict, giving rise to thermal disturbance errors.

Major contributions to the uncertainty in measurement

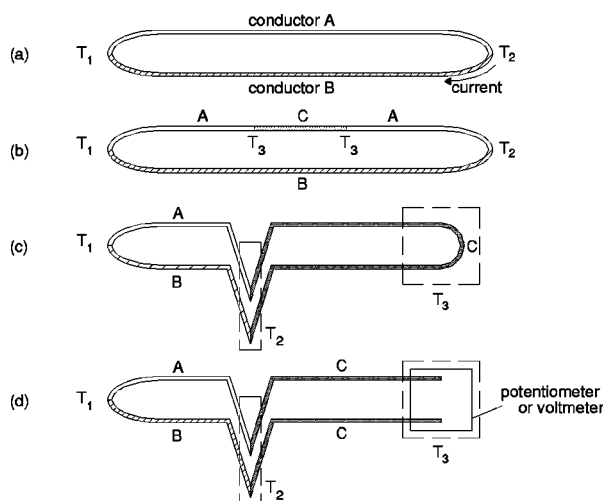


FIG. 5. Thermocouple circuit formation (after Ref. 36).

when using thermocouples include cable specification, spurious intermediate junctions, cold junction temperature measurement, voltmeter sensitivity, and cable drift.^{36,37} If a wire is subjected to high temperatures or stresses the lattice can become modified. Drift caused by annealing of thermocouple materials used in high temperature applications is a common problem. Recalibration may not compensate for this, since the thermal gradients along the thermoelements in the laboratory calibration may be different from the thermal gradients in the application.

C. Electrical resistance devices

The temperature dependence of electrical resistance is fundamental to the operation of many devices. The resistance of a conductor is related to its temperature because the motion of free electrons and of atomic lattice vibrations is also temperature dependent. Any conductor could in theory be used for a resistance temperature device (RTD). But practical considerations of cost, temperature coefficient of resistance (a large value leads to a more sensitive instrument), ability to resist oxidation, and manufacturing constraints limit the choice. Copper, gold, nickel, platinum, and silver are the most widely used. The relevant properties for these materials are given in Table III. Copper is sometimes used for the range -100 – 100 $^\circ\text{C}$ and is relatively cheap. Nickel and its alloys are also relatively low in cost, and have high resistivities and high values of temperature coefficient of resistance. However the variation in electrical resistance with temperature is nonlinear and sensitive to strain. The resistivity of platinum is six times that of copper, it is rela-

TABLE III. Values of resistivity (at 293 K) and temperature coefficient of resistance for a variety of materials (Ref. 55).

Material	Resistivity ($\Omega\text{ m}$)	Temperature coefficient of resistance (K^{-1})
Copper	1.7×10^{-8}	3.9×10^{-3}
Silver	1.6×10^{-8}	4.0×10^{-3}
Nickel	59×10^{-8}	6.0×10^{-3}
Platinum	11×10^{-8}	3.85×10^{-3}
Gold	2.4×10^{-8}	3.4×10^{-3}

tively unreactive and because it has a well-established temperature coefficient of resistance it is a common choice for temperatures between -260 and 962 °C. But some devices are capable of operating beyond this range.^{53,54} For cryogenic applications, certain carbon radio resistors make excellent inexpensive temperature sensors. The resistance–temperature characteristics of germanium, rhodium–iron alloys, and ruthenium oxide make them particularly suitable for cryogenic applications.

Resistance temperature devices can be highly accurate. They are also widely used in industrial applications. The particular design of the sensing element depends on the application, the required accuracy, sensitivity, and robustness.

1. Platinum resistance thermometers

The highly accurate devices used for defining temperature standards must be used in carefully controlled laboratory conditions.¹ These are referred to as standard platinum resistance thermometers (SPRTs). They are used in defining the international temperature scale between the triple point of hydrogen, 13.8023 K, and the freezing point of silver, 1234.93 K, within an accuracy of $\pm 2 \times 10^{-3}$ K at the lower end of the scale and $\pm 7 \times 10^{-3}$ K at the upper end of the scale.¹ These must be manufactured using high purity platinum and great care taken to ensure the assembly is strain free.¹⁸ The sensing element for a SPRT typically consists of a coil of fine gauge (around 0.075 mm diam) platinum wire wound onto a structure made from either mica or pure quartz glass.^{56,57} SPRTs compatible with ITS-90 are constructed from platinum with a temperature coefficient of resistance of $3.986 \times 10^{-3}/\text{K}$ at 273.16 K.¹⁸

The strain free designs of a SPRT would not survive the shock and vibration encountered in the industrial environment. The industrial platinum resistance thermometer (IPRT) typically comprises a platinum wire encapsulated within a ceramic housing or a thick film sensor coated onto a ceramic surface. The actual sensing element of an IPRT is further protected from the environment by a metal (e.g., Inconel™) sheath. The achievable accuracy for a commercially available IPRT is of the order of ± 0.01 – ± 0.2 °C over the range of 0–300 °C.⁵⁸

Standards^{59–61} have been produced for PRTs. The latter defines two classes of accuracy for PRTs; for T measured in °C, these are class A devices where the accuracy is within $\pm(0.15 + 0.002|T|)$ and class B devices, with accuracy $\pm(0.3 + 0.005|T|)$.

Platinum has a reasonably linear resistance–temperature characteristic and assuming a linear relationship for the range 0–100 °C results in an error of less than 0.4 °C at 50 °C. Standard⁶¹ defines a quadratic or cubic for modeling the temperature–resistance characteristic depending on the temperature range. For example

$$R_T = R_0[1 + AT + BT^2], \quad \text{for } 0 < T < 850 \text{ °C}, \quad (6)$$

$$R_T = R_0[1 + AT + BT^2 + C(T - 100)T^3], \quad \text{for } -200 < T < 0 \text{ °C}. \quad (7)$$

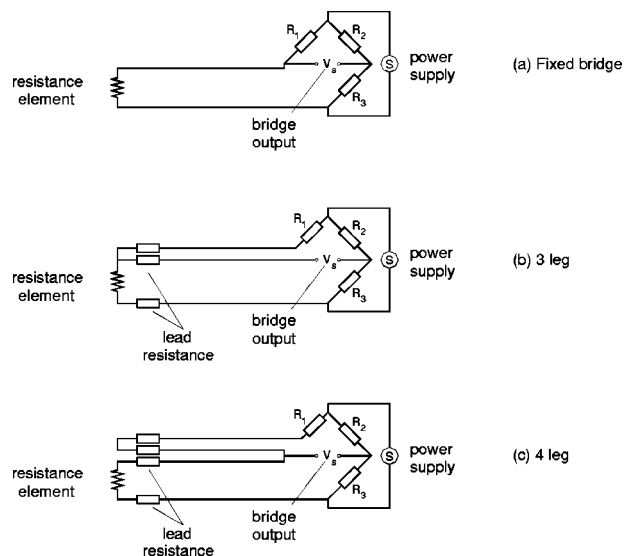


FIG. 6. Resistance temperature device circuits.

However, for the high precision required in SPRT devices conforming to ITS-90, up to a 15th order polynomial is necessary.¹

Various options are available for measuring the electrical resistance of a RTD depending on the desired accuracy and some of these are illustrated in Fig. 6. In the fixed bridge circuit the value of R_1 is adjusted until the current flow through the bridge output, if a galvanometer is used or the voltage read, is zero. Under these conditions the value of R_1 equals the unknown resistance and the temperature can be determined from a calibration equation, such as Eq. (6) or (7) above. This circuit suffers from inaccuracies in accounting for lead wire resistance and is not used for accurate measurements. In the three-leg RTD circuit, the lead resistance of the middle leg is common to both halves of the bridge. Its resistance cancels out when the bridge is balanced and reduces lead wire error considerably. The four-leg configuration gives the best performance, eliminating lead wire resistance uncertainties. With a four-wire RTD, in which two leads are connected to each end of the sensor, one can connect a constant current supply to two of the leads and use a DVM to measure the voltage from the sensor's other two leads. If the input impedance of the DVM is 100 MΩ or higher, there is a negligible loading error from even a 1 kΩ RTD and negligible lead-wire resistance errors. The output sensitivity for a 100 Ω PRT fed with a current of 1 mA will typically be 400 μV/°C at 0 °C. It is possible to use ac supplies with bridges, potentiometers, and four-wire current/voltage systems and this has the advantages of easier amplification and avoidance of spurious dc signals. The inductive ratio bridge, for example, is an ac method incorporating precision wound resistors for the ratio arms. It is capable of high accuracy and high stability. Methods using both dc and ac bridges were reviewed by Wolfendale *et al.*⁶² and by Connolly.⁶³

A SPRT used for interpolating the ITS-90 must be calibrated at the defined fixed points. Procedures for conditioning the PRT and achieving fixed points were outlined by Connolly.⁶⁴ IPRT devices can be calibrated by means

of comparison with another device or against a number of fixed points. For temperatures between -40 and 250 °C, comparison can be made against another thermometer (for example, a SPRT) in a stirred liquid bath containing, say, silicone oil, water, or alcohol, depending on the temperature range. For higher temperatures fluidized beds and heat pipe furnaces are more suitable. The ice point of water provides a reference temperature with an uncertainty of 0.002 °C, assuming appropriate procedures are followed. There is an alternative calibration point (now preferred): the commercially available water triple point cell with its lower uncertainty.⁶⁵

Errors inherent with a PRT include self-heating, oxidation, corrosion, and strain of the sensing element. In order to measure the resistance a current must be passed through the device and this can result in local heating.⁵⁰ Minimizing the current and ensuring good thermal contact between the sensor and surrounding medium reduces self-heating errors. Platinum although considered relatively stable can oxidize at elevated temperatures.^{66,67} The combined effects of changes in the overall composition of platinum due to oxidation and thermally induced strain have been investigated by Trietly.⁶⁸ Errors equivalent to several degrees were reported as a result of repeated cycling above 500 °C.

The PRT is suitable for use at low temperatures as identified by its use for the ITS-90 down to 13.81 K. Below 20 K the sensitivity drops off, but there are other resistance devices with favorable characteristics at low temperatures such as rhodium iron, doped germanium, and carbon resistors. Above 30 K, rhodium iron alloy (0.5% iron in rhodium) provides a similar resistance-temperature characteristic to platinum. Below 30 K, the sensitivity drops to a minimum between 25 and 15 K and then rises again giving a thermometer with good sensitivity at low temperatures.^{69,70} Germanium resistors are commercially available and have a relatively wide temperature range, 0.05 – 325 K. Doped germanium is commonly used with commercial devices, typically consisting of a chip of the semiconductor encapsulated in a 3 mm diam 8.5 mm long cylinder (e.g., GR-200A, from Lake Shore Cryotronics Inc.). Germanium RTDs are particularly suitable for temperature measurements in the range of 0.05 – 30 K, giving sensitivities of approximately 10^2 – 10^4 Ω/K at 1 K. Certain types of carbon radio resistors from Allen-Bradley have been identified (following the original work of Clement and Quinell⁷¹) as having a useful resistance-temperature characteristic at low temperatures. Other RTDs widely used in cryogenics include ruthenium oxide thick film resistors, Cernox zirconium oxynitride sensors, and carbon glass thermometers, which consist of fibers trapped in a glass matrix. All three types are commercially available and were developed to minimize high magnetic field effects on the thermometers.^{72–76}

2. Thermistors

If accuracy is less critical, then a cheaper form of resistance temperature device than platinum resistance thermometers is the thermistor. Thermistors consist of a semiconductor whose resistance is sensitive to temperature. Modern thermistors are usually mixtures of oxides of nickel, manga-

nese, iron, copper, cobalt, magnesium, titanium, other metals, and doped ceramics. They are manufactured by sintering particles in controlled atmospheres. Thermistors can have both positive or negative temperature coefficients. A typical resistance temperature characteristic is 1 Ω/ 0.01 °C. Thermistors are commercially available in bead, disk, rod, washer, and flake form. Beads as small as 0.07 mm in diameter on leads of 0.01 mm diameter are possible. These devices can be encapsulated in epoxy resin, glass, or be painted. Stable thermistors are available using mixed metal oxides for temperatures less than approximately 250 °C. For temperatures above 300 °C the refractory metal oxide devices are appropriate, while for temperatures of the order of 700 °C, devices utilizing zirconia doped with rare earth oxides can be used. For low temperature applications, nonstoichiometric iron oxides can be used.

To a first approximation the temperature can be determined from the relationship given in Eq. (8) as follows:⁷⁷

$$R_T = R_0 \exp \left[1 - B \left(\frac{1}{T} - \frac{1}{T_0} \right) \right], \quad (8)$$

where R_0 is the resistance at T_0 and B is a constant for the particular thermistor material.

The resistance characteristic of a thermistor expressed by Eq. (8) is negative and nonlinear. This can be offset if desired by using two or more matched thermistors packaged in a single device so that the nonlinearities of each device offset each other. Thermistors are usually designated by their resistance at 25 °C, with common resistances ranging from 470 Ω to 100 kΩ. The high resistivity of thermistors negates the need for a four-wire bridge circuit. The accuracy of these devices can be as good as ± 0.01 – ± 0.05 °C,⁷⁸ although commercial applications often result in an accuracy of the order of ± 1 °C. The disadvantage of thermistors is their susceptibility to decalibration and drift due to changes in the semiconductor materials.

D. Semiconductor devices

For applications in the temperature range of -55 – 150 °C where a stable device with an accuracy of about ± 0.8 °C is desired, a junction semiconductor device can be useful. Junction semiconductor devices such as transistors and diodes exhibit temperature sensitive characteristics that can be exploited for temperature measurement. A band gap voltage reference⁷⁹ can be used to generate a temperature sensing output proportional to absolute temperature. One such device, the LM335, is a two terminal integrated circuit temperature sensor that behaves like a Zener diode with a voltage output of 110 mV/°C. Another device, the LM35, behaves like a three terminal reference and has an internal offset so that the voltage is zero at 0 °C, with the device output being 10 mV/°C and an accuracy of ± 0.8 °C. The AD590 is a two terminal device that acts as a constant current element passing a current of 1 μA/°C. The temperature range of these devices is limited by the silicon transistors used. For the AD590 the temperature range is -55 – 150 °C. The advantages of these devices are their linearity, simple circuitry, and good sensitivity.

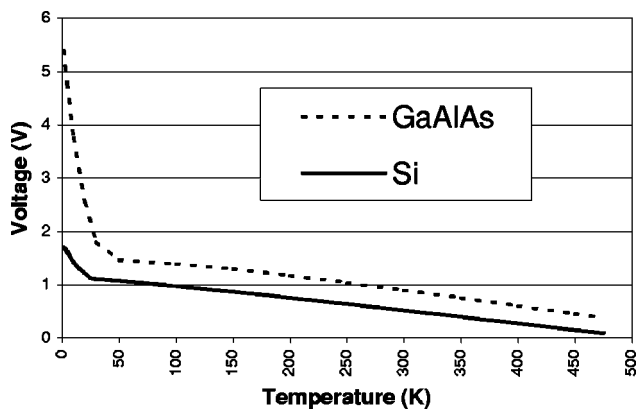


FIG. 7. Characteristic voltage temperature relationship for GaAlAs and Si semiconductors.

1. Diode thermometers

The forward voltage drop across a *p-n* junction increases with decreasing temperature. For some semiconductors, the relationship between voltage and temperature is almost linear; in silicon this occurs between 400 and 25 K with a corresponding sensitivity of approximately 2.5 mV/K. The two most commonly used semiconductors for thermometry are GaAs and Si. The typical voltage sensitivities for these devices are illustrated in Fig. 7. For silicon at temperatures below about 25 K, when the forward voltage approaches 1.1 V, the characteristic function for the voltage temperature relationship changes. As can be seen in Fig. 7, Si diodes give a lower output than GaAs diodes but have better stability and are cheaper and more easily interchangeable. Generally rectifying diodes are used and these can be potted in a small container. Commercial versions are available, for example, the 1.25 mm in diameter and 0.75 mm high DT-420 device, from Lake Shore Cryotronics. Zener diodes have also been used to indicate temperature.⁸⁰

The virtues of diode thermometers are their low price, a simple voltage temperature relationship, a relatively large temperature range (1–400 K), no need for a reference bath or junction, relatively high sensitivity, an accuracy better than ±50 mK,⁸¹ and simplicity of operation with a constant current source and a digital voltmeter. Measurements down to 1 K do however require careful calibration. Errors can occur if the supply current is not a true dc but has an ac component due to, say, noise induced in the circuit from improper shielding, electrical grounds, or ground loops.⁸¹ To minimize

noise effects, all the instrumentation should be electrically shielded and proper grounding techniques used.⁸² The diode current supply should have a single ground, generally at the voltmeter, which then requires a floating current source. A current between 1 and 100 μA can be used but it generally needs to exceed 10 μA in order to overcome noise problems. However, this can cause problems associated with self-heating at very low temperatures.

E. Fiber optic probes

In order to monitor surface temperatures or gas temperatures such as in observing combustion processes it is possible to use an optical fiber to channel thermal radiation into a narrow wavelength band from the location of concern to a measurement sensor.⁸³ Typical fiber optic sensors include those based upon optical reflection, scattering, interference, absorption, fluorescence, and thermally generated radiation. One commercial system marketed consists of a cavity built onto the end of an optical fiber as illustrated in Fig. 8. The blackbody emitter is integrated onto the tip of a single crystal sapphire optical cavity joined to an optical fiber. The cavity closely approximates a blackbody and the optical fiber transmits the radiant energy to a photodiode or photomultiplier. This measures the intensity of the radiation emitted at a particular wavelength and converts the signal using the laws of radiant emission. These devices can measure temperatures from above 100 °C to approximately 4000 °C. Different methods for various applications are available: phosphor tipped fiber optic temperature sensors for the measurement of blackbody radiation and interferometric sensors for the measurement of phase differences between transmitted and received laser light.⁸⁴ The accuracy of these devices is dependent on the type of sensor used. For a sapphire rod device at 1000 °C,⁸⁵ an accuracy of 1 °C is reported, but the accuracy is limited to the accuracy of the temperature standard. For high temperature probes (100–1600 °C), Ewan⁸⁶ has reported on the design of two types: a water-cooled low temperature fiber and an all ceramic construction probe. A book by Grattan and Zhang⁸⁷ serves as a comprehensive introduction to this technology.

F. Capacitance thermometers

The electric permittivity of certain materials such as strontium titanate can be highly dependent on temperature over a certain range. A practical sensor can be formed from

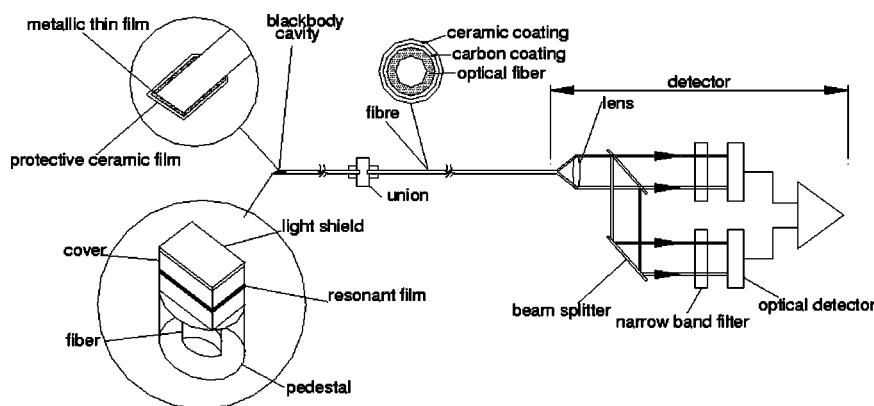


FIG. 8. Fiber optic temperature probe for a thin film blackbody sensor (Accufiber/Luxtron Inc.) or a Fabry–Pérot interferometric encapsulated sensor.

encapsulated samples of the material (with a capacitance of a few nanofarads) and lead wires to a bridge circuit energized at approximately 100 V. Capacitance thermometers provide good sensitivity below 100 K but the output voltage becomes irreproducible after thermal cycling, so calibration against another type of sensor is often necessary. Capacitance thermometers do however exhibit virtually no magnetic field dependency. They are thus useful as control devices in high magnetic fields where other types of device may fail or produce erroneous signals.⁸⁸ The permittivity–temperature characteristics have been studied for a variety of materials.^{89–97} Commercial devices are available from Lake Shore Cryotronics Inc.

G. Noise thermometry

The fundamental principle exploited in noise thermometry is the random voltage generated by Brownian motion of conduction electrons.^{98,99} The method, the measurement of the mean square Johnson noise voltage across a resistor, represents one of the few practical alternatives to gas thermometry for the precise determination of thermodynamic temperature. The sophistication required for the instrumentation to do this has limited the technique to mostly standards laboratory applications. This is in part due to the small value of noise voltages (for $T = 1$ K, $7 \mu\text{V}$ across a bandwidth of 2π MHz, with $R = 1 \text{ M}\Omega$)¹⁰⁰ and also the need to eliminate or compensate for other types of noise. Except at low temperatures the accuracy obtained from noise thermometry does not match that from other, often easier, methods such as the RTD.

In principle the temperature range of application of noise thermometry is wide, from a few mK to over 1500 °C. The type of circuitry used depends on the temperature range and was reviewed by Kamper,¹⁰¹ by Blalock and Shepard,¹⁰² and by White *et al.*¹⁰³ For low temperature measurements, at less than 1 K, two types of absolute noise thermometers have proved useful according to Soulen *et al.*¹⁰⁴ Both measure the noise voltage generated by a resistor using a superconducting quantum interference device (SQUID). In one type the resistor is inductively coupled to the SQUID. In the other, a resistive SQUID (RSQUID), the resistor is connected directly across a Josephson junction (two superconductors separated by a thin insulating layer). Menkel *et al.*¹⁰⁵ reported on the use of a RSQUID device for temperatures up to 4.2 K; Macfarlane *et al.*¹⁰⁶ have for the range of 10–50 K.

Above 273.15 K there are two options. The first compares the measured open-circuit Johnson noise voltage (at the unknown temperature) across a sensing resistor to that of a reference resistor. In the second, the temperature is obtained by measuring the open-circuit Johnson noise voltage and the short circuit Johnson noise current.¹⁰²

H. Quartz thermometers

The phenomenon utilized in quartz thermometers is the highly reproducible variation of the natural vibration frequency of piezoelectric quartz samples.¹⁰⁷ Agatsuma *et al.*^{108,109} have reported the packaging of a YS cut crystal in

a small thermometer and Hewlett Packard has produced a commercial quartz thermometer (model 2804 A).

I. Paramagnetic and nuclear magnetic resonance thermometry

For many materials the magnetic susceptibility, defined as the ratio of magnetization to the applied magnetic field, varies inversely with temperature as defined by

$$\chi = \frac{C}{T}, \quad (9)$$

where χ is the susceptibility, C is the so-called Curie constant, and T is the absolute temperature. The procedure used in paramagnetic thermometry involves placing an appropriate sample of material, which is in close thermal contact with the medium of interest, between the coils of a mutual inductance bridge. A Hartshorn mutual inductance bridge was used by Durieux *et al.*¹¹⁰ More recently a ratio-transformer version has been utilized.¹¹¹ The sample must be a paramagnetic material such as cerium magnesium nitrate (CMN), chromic methyl ammonium (CMA), or manganous ammonium sulfate (MAS). CMN is the most common and is useful at temperatures up to 4.2 K and in particular for the measurement of ³He and ⁴He temperatures, (see e.g., Refs. 112–115). Klemme *et al.*¹¹⁶ reported on the development of new materials, PdMn and PdFe, that allow high resolution measurements in the range 1.5–3 K with application to measurements in outer space. The reproducibility of this method can be better than 0.5 mK below 50 K with an uncertainty of 1 mK in the range of 18–54 K.¹¹⁷ The overall uncertainty also depends on the bridge circuitry and the stability and accuracy of the associated constants. Cetas¹¹⁷ has demonstrated this method for measuring temperatures up to 90 K.

III. SEMIINVASIVE TEMPERATURE MEASUREMENT TECHNIQUES

Some temperature measurement scenarios permit the application of a temperature sensitive material to a surface. The variations in optical properties of the surface coating can then be observed remotely. These surface coating methods are classed as semi-invasive here since the technique involves modification of the component of interest and therefore some disturbance to the temperature field. A number of heat sensitive materials exist, including thermochromic liquid crystals, heat sensitive crystalline solids and paints, and thermographic phosphors.

A. Thermochromic liquid crystals

Liquid crystals have proved useful for experimental investigations and medical applications where the range of temperature variation of interest is limited. Liquid crystals are substances with a molecular structure intermediate between that of a crystalline solid and an isotropic liquid. They possess some of the mechanical properties of liquid and the optical properties of crystalline solids. Of particular relevance to heat transfer studies are the cholesteric (or chiral nematic) liquid crystals, which are optically active since they react to changes in temperature and shear stress by reversible

changes of color. These cholesteric crystals are popularly called thermochromic liquid crystals. Due to their organic nature, they degrade when exposed to ultraviolet (UV) light and are prone to chemical contamination. The practical solution to this problem, one adopted by manufacturers, is to encapsulate the crystals in polymer spheres. The encapsulated thermochromic liquid crystals are commercially available in the form of a water-based slurry that can be painted or applied with an airbrush to the surface of interest.

The observed color of a liquid crystal is a function of several variables including the orientation of the crystals, the spectral nature of the light illuminating the surface, and the spectral response of the sensing device. The molecular orientation of thermochromic liquid crystals is altered by temperature and manifests itself in a variation of the spectral reflectivity. The colors can be recorded by means of a video camera and can be stored in terms of the primary colors: red, green, and blue (RGB). The frames can later be digitally analyzed using a computer and frame grabber and the data converted from RGB to values of hue, saturation, and intensity (HSI). Comparison of the hue values with calibration results gives the surface temperature for each pixel location. Descriptions of thermochromic liquid crystal techniques (application, calibration, the recording and measuring systems, and the analysis) have been given by Camci,¹¹⁸ by Hippensteele *et al.*,¹¹⁹ and by Baughn.¹²⁰

The data reduction technique for thermochromic liquid crystals was detailed by Ireland *et al.*^{121,122} The rate of thermal response of crystals, which is dependent of their viscosity, can be of the order of 5 ms to seconds.¹²³ The accuracy of liquid crystals is the subject of debate; an accuracy of $\pm 1^\circ\text{C}$ for the range of -40 – 283°C is quoted by Michalski *et al.*⁴³

B. Thermographic phosphors

Thermographic phosphors can be used to indicate temperatures from cryogenic levels to 2000°C . The technique exploits the thermal dependence of phosphor fluorescence and generally involves depositing a thermographic phosphor such as $\text{Y}_2\text{O}_3:\text{Eu}$ on a surface and observing it remotely via an optical detection system. This technique can offer sensitivities of 0.05°C and an accuracy of 0.1% – 5% of the Celsius temperature reading.¹²⁴ One of the merits of this technique is its independence of emissivity. The feasibility of employing thermographic phosphors on a rotating turbine at up to $10\,500$ rpm and a maximum temperature of 1000°C has been demonstrated by Tobin *et al.*¹²⁵

C. Heat sensitive paints

If an application merely requires an indication of the maximum temperature attained, then the use of nonreversible heat sensitive crystalline solids may be suitable.¹²⁶ At a particular temperature these melt. They are commercially available in a variety of forms including crayons, pellets, and paints and have been used for indicating temperatures on gas turbine blades and in rocket motors for several decades.

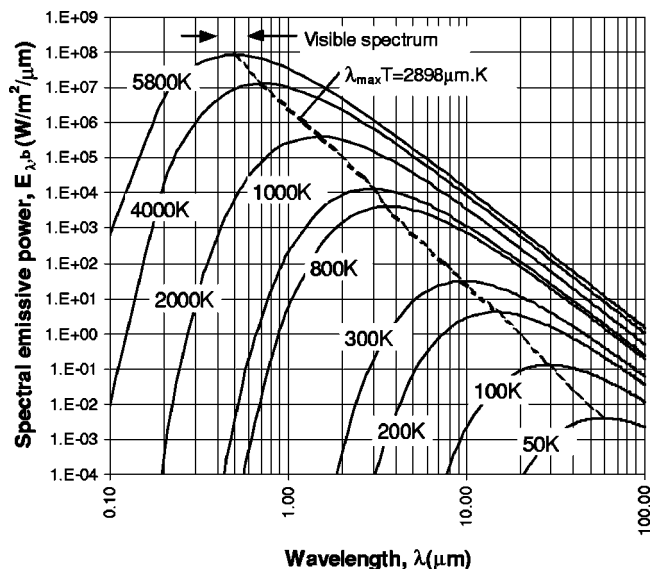


FIG. 9. Planck's distribution.

Paints are available for continuous operation at temperatures from 120 to 400°C or discontinuous use from 40 to 1350°C . The accuracy is approximately $\pm 5^\circ\text{C}$.

IV. NONINVASIVE TEMPERATURE MEASUREMENT TECHNIQUES

Invasive or contact instrumentation must be capable of survival at the temperature concerned. In high temperature or chemically reactive applications such as flames or plasmas, invasive instrumentation can degrade with time; above the material limits, it can disintegrate completely. Noninvasive methods are not bound by this constraint. In addition noninvasive instrumentation can be useful in determining the temperature of moving components without the need for telemetry or slip-ring systems. Both temperature measurements at a point and the variation over a region, by scanning, can be made. Most noninvasive techniques measure temperature from the electromagnetic spectrum. Infrared devices are sensitive to that part of the spectrum. Optical techniques such as absorption and emission spectroscopy, scattering and luminescence, according to Gallery *et al.*,¹²⁷ are sensitive in the visible region mostly because lasers are used as part of the system. One notable exception is acoustic temperature measurement, which relies on the measurement of the speed of sound. Some optical techniques are highly expensive, requiring a laser, high quality optics, and specialized data acquisition equipment.

A. Infrared thermography

Temperature measurement systems based on monitoring thermal radiation in the infrared spectrum are useful for monitoring temperatures in the ranges from 50 to 6000 K. An infrared measurement system comprises the source or target, the environment, the medium through which the radiant energy is transmitted, usually a gas, and the measurement device. The measurement device may include an optical system, a detector, and a control and analysis system.

All matter emits radiant energy or thermal radiation as a consequence of its absolute temperature. The known electromagnetic spectrum extends from gamma rays with wavelengths of the order 10^{-12} m, x rays, ultraviolet, visible light, and infrared to microwaves and radio waves with wavelengths of hundreds of meters. The portion of the spectrum extending from approximately 0.1 to 100 μm which includes a portion of the UV, the visible, and the infrared spectrum, is given the term thermal radiation. Within this band only 0.7–20 μm is used in most temperature measurements because the devices available are not sensitive enough beyond about 20 μm .

The variation of thermal radiative power with wavelength for a blackbody is given by Planck's distribution, Eq. (10), and is illustrated in Fig. 9 for blackbody temperatures between 50 and 6000 K.

$$E_{\lambda,b} = \frac{2\pi hc^2}{\lambda^5 [\exp(hc/\lambda kT) - 1]} \text{ (W/m}^3\text{)}. \quad (10)$$

The fraction of blackbody emission in a spectral band between λ_1 and λ_2 is given by

$$\frac{\int_0^{\lambda_2} E_{\lambda,b} d\lambda - \int_0^{\lambda_1} E_{\lambda,b} d\lambda}{\sigma T^4}. \quad (11)$$

Equation (11) is useful in determining the proportion of blackbody emission between two wavelengths. This information can then be used to determine whether a particular detector has an appropriate spectral sensitivity and whether the optical path transmits this radiation. Radiation detectors can be broadly grouped into three categories: disappearing filament optical pyrometers, thermal detectors, and photon or quantum detectors.

The disappearing filament optical pyrometer is similar to a refracting telescope, the difference being that an electrically heated tungsten filament is placed in the focal plane of the objective lens and a red filter is located between the lamp and the eyepiece.¹²⁸ The pyrometer is sighted on the target and the image is formed in the same plane as the lamp filament. The magnified image of the lamp filament is superimposed on the target. By adjusting the current through the filament, its luminance or brightness can be matched to that of the target. The red filter ensures that the image is nearly monochromatic so no color difference is observed and the image appears to disappear against the target. By viewing a blackbody at known temperatures calibration of the device can be obtained. The accuracy of commercial devices can be $\pm 1^\circ\text{C}$ at 775°C and $\pm 5^\circ\text{C}$ at 1225°C . For temperatures above $1300\text{--}1400^\circ\text{C}$, a gray absorbing filter may be placed between the lamp and the objective lens to extend the range.

Thermal detectors convert the absorbed electromagnetic radiation into heat energy, causing the detector temperature to rise. This can be sensed by its effects on certain physical properties, such as electrical resistance used by bolometers, thermoelectric emf, used by thermocouple and thermopile detectors, and electrical polarization used by pyroelectric detectors. The principal application of thermal detectors is for measurement of low temperatures where there is limited radiant flux and the peak of the Planck curve is well into the

TABLE IV. Commonly used infrared detector materials.

Material	Wave band (μm)	Source
Al_2O_3	0.2–5	Michalski <i>et al.</i> (Ref. 43)
CaF_2	0.13–9.5	Hackforth (Ref. 129)
Ge	1–12	Michalski <i>et al.</i> (Ref. 43)
InAs	1–3.8	http://www.egginc.com
InSb	1–5.5	http://www.vigo.com
KBr	0.2–32	Hackforth (Ref. 129)
KCl	0.21–25	Hackforth (Ref. 129)
PbSe	2–5	http://www.rmtltd.ru
SiO_2	0.2–4	Michalski <i>et al.</i> (Ref. 43)
TiO_2	0.4–5.2	Hackforth (Ref. 129)
ZnS	8–12	http://www.mortoncvd.com

infrared. Thermal detectors offer wide spectral response by detecting the emitted radiation across the whole spectrum at the expense of sensitivity and response speed. For higher temperatures, devices with a narrower spectral bandwidth are more suitable.

Bolometers are thermal detectors in which the incident thermal radiation produces a change in temperature of a resistance temperature device, which may be a RTD or a thermistor. Bolometers can however be comparatively slow with time constants of 10–100 ms. An alternative to the use of a resistance temperature device in a thermal detector is to use a thermopile. A thermopile consists of a number of series-connected thermocouples arranged such that the local heat flux generates a temperature difference between each pair of thermocouple junctions. In an infrared thermal detector, the thermopile is arranged so that half of the junctions are maintained at a constant temperature by being in contact with a component with relatively large thermal inertia. The radiant energy heats the other junctions, generating a thermoelectric emf.

Pyroelectric detectors are manufactured using crystal wafers such as triglycerine sulfate or lithium tantalate, which produce surface electric charges when heated. The electrical signal corresponds to the removal of charge by conducting electrons deposited on the crystal. A change in the temperature of the crystal due to the absorption of radiation in a certain time period produces a change in the polarization charge. The detector produces an electrical signal proportional to the rate of change of charge and therefore cannot be used to measure a continuous heat flux. However, addition of a mechanical chopper system allows steady state flexibility with the chopper being used to interrupt the radiation from a target at a fixed frequency. Types include blackened and mirror choppers. Pyroelectric detectors have a wide spectral response similar to bolometers and thermopiles but have a faster response time. The accuracy of these devices is good, of the order of 0.2% over the temperature range.

Quantum, photon, or photoelectric detectors measure the direct excitation of electrons to conduction states by incident photons. Types of quantum detector include photoemissive, photoconductive, and photovoltaic. Photon detectors respond to individual photons by releasing or displacing electrical charge carriers by the photoelectric effect (vacuum photocells, photomultipliers), photoconductive effect, photovoltaic effect, or photoelectromagnetic effect. Photon detectors have

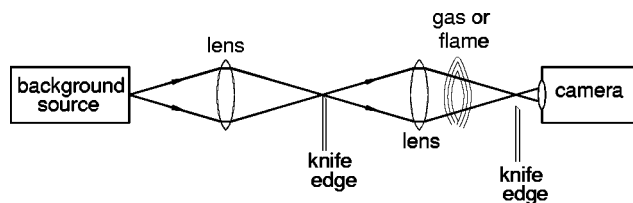


FIG. 10. Schlieren method for determining gas temperature.

much higher spectral detectivities than thermal detectors and have faster response. Quantum detectors are not perfect however because some of the incident photons are not absorbed or are lost and some excited electrons return to the ground state.

As listed in Table IV, there are infrared detectors that are sensitive across the range of the thermal radiation spectrum. The sensitivity of a detector decreases with the area that receives photons. In addition the sensitivity of photon detectors varies with wavelength. As indicated in Fig. 9, at a given temperature the majority of the radiation emitted from a body occurs across a finite band of wavelength. Depending on the temperature range to be observed the detector and the spectral characteristics of the optics can be chosen so that their sensitivity matches this. The required spectral range of a detector dictates the type of material to be used. Quantum detectors are more spectrally selective, more sensitive, and faster than thermal detectors.^{130–132}

Thermography or thermal imaging involves determining the spatial distribution of thermal energy emitted from the surface of an object. This technique allows mapping of the temperature distribution and can be used in conjunction with software analysis to provide quantitative information. Thermographic techniques are used in the detection of body temperatures, satellite imaging, and in automatic guidance systems. One commercial system (available from Infratech) has a range of -30 – 2000 °C with a sensitivity of 0.05 °C and an accuracy of $\pm 0.5\%$ of the full range, although the accuracy can be improved with detailed knowledge of the target and environment emissivities.

The principal criteria to be considered in the selection of an individual infrared temperature measurement system include the temperature range, atmospheric conditions, spectral sensitivity range, optical signal strength, desired signal level, maximum acceptable noise, cooling constraints, the spectral pass band, field of view, the resolution, speed of response, stability, the reference standard, geometry, and cost according to DeWitt and Nutter.¹³³

Noise or random fluctuations present in detectors place limitations on the lower limit of the temperature range and affect the overall precision. The noise can be considered to arise from two sources: detector noise originating in the detector itself and radiation noise due to the random variations in the rate at which a heated surface emits photons. The noise equivalent power gives an indication of the smallest amount of radiation that can be detected and is equal to the amount of incoming radiation required to produce a signal equal to the noise. The accuracy of a radiation thermometer depends on attenuation of the radiation between the target and the thermometer, background radiation reflected from the target

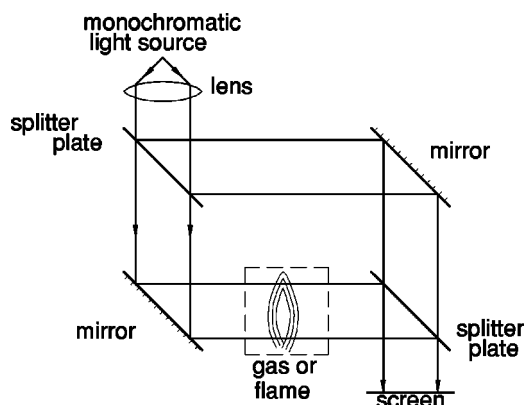


FIG. 11. Interferometry technique for gas temperature measurement.

and detected by the thermometer, uncertainty of the target emissivity, and errors caused by the thermometer itself. In order to reduce the effect of uncertainty in the emissivity on the temperature measurement, a narrow bandwidth is desirable.¹³⁴

B. Refractive index methods

In compressible flows the density varies with velocity sufficiently to give measurable results in the variation of the refractive index, and the temperature can be inferred from this. For incompressible flows, such as free convection, where the velocity is relatively low, the density and hence refractive index are directly related to temperature. Methods for observing this density variation include schlieren, shadowgraph, and interferometry techniques. In these methods, light and dark patterns are formed by the bending of light as it passes through a region of varying density.

A typical arrangement for schlieren photography is illustrated in Fig. 10. Here a light source such as an arc lamp is focused onto one edge of a wide slit and through the gas or flame normal to the plane of flow. A camera behind a second knife edge is focused onto the test object and can record deviation of the light due to changes in the refractive index.^{135,136} The range of measurement is approximately from 0 to 2000 °C, with a sensitivity of the order of 0.1 °C and an accuracy of 10% of the range. Tomographic or temperature mapping utilizing schlieren methods has been reported by Schwarz.¹³⁷ In the shadowgraph method, the linear displacement of a perturbed light beam is observed, rather than the angular deflection as in the schlieren method.¹³⁵ In the interferometry technique, Fig. 11, two parallel beams of light are split and one pair is passed through the region of interest. The other pair follows an equivalent path but avoids this test section. The splitter near the screen is used to project the beams onto it for optical recording. Light and dark patterns are formed as a result of phase shifts between the interference and measuring beams.

C. Absorption and emission spectroscopy

A useful technique for mapping the temperature distribution in flames or gases, described by Hall and Bonczyk¹³⁸ and Uchiyama *et al.*,¹³⁹ at high temperatures is absorption or emission spectroscopy. Atoms will emit electromagnetic ra-

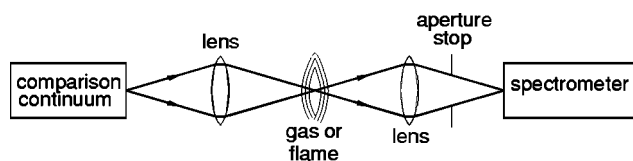


FIG. 12. Line reversal technique for gas temperature measurement.

radiation if an electron in an excited state makes a transition to a lower energy state. The band of wavelengths emitted from a particular species or substance is known as the emission spectrum. Emission spectroscopy involves measurements of this emission spectrum and can be achieved by utilizing an atom cell, a light detection system, a monochromator, and a photomultiplier detection system.¹⁴⁰ Conversely atoms with electrons in their ground state can absorb electromagnetic radiation at specific wavelengths; the corresponding wavelengths are known as the absorption spectrum. Absorption spectroscopy relies on measurements of the wavelength dependence of the absorption of a pump source such as a tunable laser due to one or more molecular transitions. In order to evaluate the temperature, it is necessary to fit the observed spectrum to a theoretical model, which normally involves prior knowledge of molecular parameters such as oscillator strength and pressure broadened linewidths. The temperature can then be calculated from the ratio of the heights of two spectral lines utilizing the Boltzmann distribution. The typical accuracy for these techniques is of the order of 15% of the absolute temperature.

D. Line reversal

The line reversal method, Fig. 12, can be used to measure the static temperature of a gas in the temperature range from approximately 1000 to 2800 K with an accuracy of approximately ± 15 K. Applications have included combustion chambers, flames, rocket exhausts, and shock waves. A comparison continuum of known brightness temperature is allowed to pass through the gas of interest and compared with the spectral line. If the temperature of the gas is less than the temperature of the brightness continuum, then the line will appear in absorption, that is, dark against the background. If the temperature of the test section is higher than the comparison brightness temperature, the spectral line will appear in emission or bright against the background.^{136,141} The temperature of the gas can be determined by adjusting the temperature of the brightness continuum until a reversal of brightness occurs.

E. Spontaneous Rayleigh and Raman scattering

An alternative technique for monitoring temperature in gases is the observation of spontaneous Rayleigh and Raman scattering. Scattering in this context is the absorption and re-emission of electromagnetic radiation by atoms and molecules. Rayleigh scattering is the elastic scattering of light by molecules or very small particles less than about $0.3 \mu\text{m}$ in size. Rayleigh scattering can be used to measure the density. If the pressure is constant, then the temperature can be derived from the ideal gas law or by resolving the Doppler

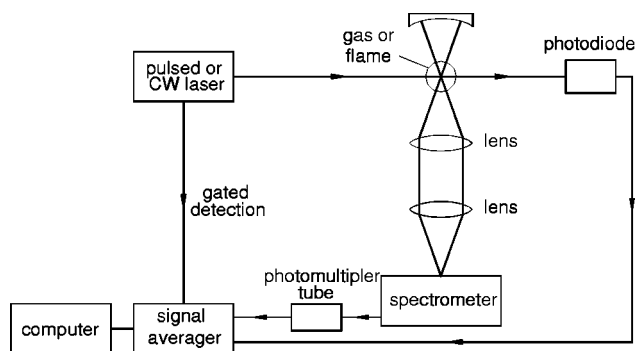


FIG. 13. Schematic of the usual experimental setup for the measurement of temperature by scattering methods (Ref. 154).

linewidth of the scattering.¹⁴² Rayleigh spectra can be obtained using continuous wave and pulsed lasers to excite the flow. In Rayleigh scattering, the collected signal will typically be a factor of 10^9 smaller than the pump signal from the laser, making it susceptible to corruption by other processes such as Mie scattering, optical effects, and background radiation. Also, in order to analyze the spectra, it is usually necessary to know the individual concentrations of the species in the flow. The range and accuracy for Rayleigh scattering are 20–2500 °C and 1% of the Celsius reading, respectively. Applications have included plasmas,¹⁴³ combustor flames,¹⁴⁴ sooting flames,¹⁴⁵ and supersonic flows.¹⁴⁶

If a molecule is promoted by incident radiation from the ground state to a higher unstable vibrational state, it can either return to the original state, which is classified as Rayleigh scattering as discussed above, or to a different vibrational state, which is classified as Raman scattering. This latter form of scattering gives rise to Stokes lines on the observed spectra.¹⁴⁷ Alternatively, if a molecule is in an excited state, it can be promoted to a higher unstable state and then subsequently return to the ground state. This process is also classified as Raman scattering and gives rise to an anti-Stokes line on the observed spectrum. Raman scattering involves the inelastic scattering of light from molecules. There are two basic methods for determining the temperature by Raman scattering: the Stokes Raman method and the Stokes to anti-Stokes ratio method. The Stokes Raman method is based on measurements of the density of the nonreactive species assuming uniform pressure and ideal gas conditions. The Stokes to anti-Stokes ratio method involves measurement of the scattering strengths of the Stokes to anti-Stokes signals of the same spectral line. The temperature can then be calculated utilizing the Boltzmann occupation factors for the lines in question.¹⁴⁸ This process is generally only suitable for high combustion temperatures due to the relative weakness of the anti-Stokes signal.¹⁴⁹ The uncertainties in temperature measurement utilizing Raman spectroscopy were discussed by Laplant *et al.*¹⁵⁰ Figure 13 illustrates the experimental setup for measuring temperature by scattering methods. The range and accuracy for Raman scattering are approximately 20–2230 °C and 7%, respectively. Applications have included reactive flows,¹⁵¹ flames,¹⁵² and atmospheric temperature observation.¹⁵³

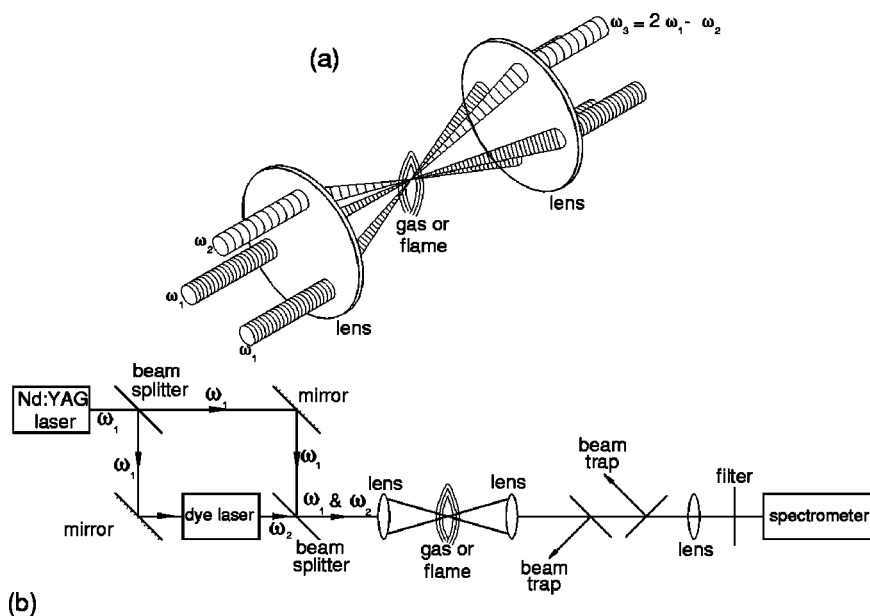


FIG. 14. Coherent anti-Stokes Raman scattering (a) after Ref. 164 and (b) after Ref. 154.

F. Coherent anti-Stokes Raman scattering

Coherent anti-Stokes Raman Scattering (CARS) involves irradiating a gas or flame with two collinear laser beams, a pump beam at frequency ω_1 and a probe beam at ω_2 . The temperature range of this method is from 20 to 2000 °C and the accuracy is approximately 5%. The pump and probe beam frequencies ω_1 and ω_2 are such that $\omega_1 - \omega_2$ is equal to the vibrational frequency of a Raman active transition of the irradiated molecules, so that a new source of light will be generated in the medium. This beam consists of monochromatic plane waves superposed onto the pump beams with a frequency of $2\omega_1 - \omega_2$. It is generated as the result of scattering of the probe laser beam by the gas molecules that are being driven synchronously and coherently by the pump beam. As the signal appears on the high frequency side of the pump, i.e., an anti-Stokes spectrum, and because it is observable only if the molecular vibrations are Raman active, this generation mechanism is called coherent anti-Stokes Raman scattering.¹⁵⁵ CARS permits noninvasive local temperature measurement in gases, flames, or plasmas.¹⁵⁶ Since temperature is related to the rotational state of the molecules, the anti-Stokes lines increase in intensity with increasing temperature. This is caused by photon-molecule collisions in which the incoming photon captures some rotational energy from the molecule and arrives at the detector with higher energy and hence higher frequency. A schematic diagram of a CARS system is shown in Fig. 14. It uses a Nd:YAG laser, which is split to provide a pump beam and also to pump a dye laser to generate the second tunable beam. More recent applications have utilized a XeCl excimer laser in place of the Nd:YAG laser because the former gives increased flexibility in the laser repetition rate, which can be moderated to match periodicity in the application, for example, engine speed. CARS is generally suitable to highly luminous or particulate laden systems. Applications have included flames,^{157,158} spark ignition engine combustion chambers¹⁵⁹ combustion and plasma diagnostics,¹⁶⁰ jet en-

gine exhausts,¹⁶¹ low pressure unsteady flows,¹⁶² and supersonic combustion.¹⁶³

G. Degenerative four wave mixing

Degenerative four wave mixing (DFWM) is similar to CARS but has three input beams. The difference is that all three, and hence the output signal as well, have the same frequency. Advantages over CARS are that phase matching conditions are satisfied, the process is Doppler free, beam aberrations are lower, and signal levels are greater. The use of this technique for measuring flame temperatures was reported by Herring *et al.*¹⁶⁵

H. Laser-induced fluorescence

Laser-induced fluorescence (LIF) is the optical emission from atoms or molecules that have been excited to higher energy levels by absorption of laser radiation.^{166,167} It is used to measure concentration and local temperature in flames by exciting molecules and atoms in specific species, for example, NO, SiO, OH, N₂, and O₂. The range of application of LIF is between 200 and 3000 K and the accuracy of the method is approximately $\pm 5\%$ at 2000 K. The excitation source for molecular LIF is typically a tunable dye laser in the visible spectral region (700–900 nm). Studies in the near ultraviolet (400–10 nm) and near infrared (700–1215 nm) are becoming more common as near-infrared lasers and frequency-doubling methods improve. LIF has been applied extensively to combustion measurements in flames¹⁶⁸ and the density in an engine cylinder at different locations was measured by Andresen *et al.*¹⁶⁹ to infer the temperature field from an analysis of the number and type of molecular collisions. LIF was used to analyze the liquid-phase temperature in diesel sprays by Megahed.¹⁷⁰ A semi-invasive LIF technique for the measurement of surface temperatures by embedding crystals of a temperature sensitive phosphor into the surface of a material was described by Goss *et al.*¹⁷¹

TABLE V. Guide to temperature measurement technique identification (N/A—not available).

Method	Minimum temperature (°C)	Maximum temperature (°C)	Response	Transient capability	Sensitivity	Accuracy	High signal	Stability/repeatability	Low thermal disturbance	Commercially available	Relative Cost
Gas thermometer	about -269	700	Slow	No	...	A standard	Yes	Yes	No	No	Very high
Liquid-in-glass thermometer	-200	600	Slow	Yes	1 °C	±0.02-±10 °C (ind) ±0.01 °C (lab)	Yes	Yes	No	Yes	Very low
Bimetallic strip	-73	540	Medium	Yes	...	±1 °C	Yes	Yes	Yes	Yes	Low
Thermocouple	-270	2300	Very fast	Yes	±10 μV/°C	±0.5-±2 °C	No	Yes	Yes	Yes	Very low
Suction pyrometer	-200	1900	Very fast	Yes	...	±5 °C of reading	Yes	Yes	No	Yes	Mid to high
Electrical resistance device	-260	1064	Fast	Yes	0.1 Ω/°C	The standard above 13 K	Yes	Yes	Yes	Yes	Mid to low
Thermistors	-100	700	Fast	Yes	10 mV/K	±0.01-±0.05 °C	Yes	Yes	Yes	Yes	Mid to low
Semiconductor devices	-272	300	Very fast	Yes	±1%	±0.1 °C	Yes	Yes	No	Yes	Low
Fiber optic probes	-200	2000	Fast	Yes	10 mV/°C	0.5 °C	Yes	Yes	Yes	Yes	Mid to high
Capacitance	-272	-170	Fast	Yes	Good	Poor	Yes	No	Yes	Yes	Mid
Noise	-273	1500	Fast	Yes	Good	Good	No	Yes	Yes	No	High
Chemical sampling	5	2100	Slow	No	...	±25 K	No	Yes	No	Yes	Mid
Thermochromic liquid crystals	-40	283	Medium	Yes	±0.1 °C	±1 °C	...	Yes	Yes	Yes	Low to Mid
Thermographic phosphors	-250	2000	Very fast	Yes	~0.05 °C	0.1%-5%	Yes	Yes	Yes	Yes	High
Heat sensitive paints	300	1300	Slow	No	...	±5 °C	Yes	Yes	Yes	Yes	Mid
Infrared thermometer	-40	2000	Very fast	Yes	~0.1 °C	±2 °C	Yes	Yes	Yes	Yes	Very high
Two color	150	2500	Very fast	Yes	1 °C/mV	±1%(±10 °C)	Yes	Yes	Yes	No	Very high
Line scanner	100	1300	Very fast	Yes	...	±2 °C	Yes	Yes	Yes	Yes	Very high
Schlieren	0	2000	Fast	Yes	N/A	N/A	Visual	Yes	Yes	Yes	Mid
Shadowgraph	0	2000	Fast	Yes	N/A	N/A	Visual	Yes	Yes	Yes	Mid
Interferometry	0	2000	Fast	Yes	N/A	N/A	Yes	Yes	Yes	Yes	High
Line reversal	727	2527	Very fast	No	Line of sight avg.	±10-15 K	Yes				Low
Absorption spectroscopy	20	2500	Very fast	No	Line of sight avg	15%	Yes	Yes	Yes	Yes	Low
Emission spectroscopy	20	2700	Very fast	Yes	Line of sight avg.	15%	Yes	Yes	Yes	Yes	Low
Rayleigh scattering	20	2500	Very fast	No	0.1 mm ³ in 100 °C	1%	Yes	Yes	Yes	No	Very high
Raman scattering	20	2227	Very fast	No	0.1 mm ³ in 100 °C	7%	Yes	Yes	Yes	No	Very high
CARS	20	2000	fast		1 mm ³ in 50 °C	5%	Yes	at atm	Yes	Yes	Very high
Degenerative four wave mixing	270	2600	Very fast	Yes	1 mm ³ in 50 °C	10%	Yes	at atm	Yes	No	Very very high
Luminescence	20	200	fast	Yes	1.5 nm in 200 °C	±5 °C	Yes	Yes	Yes	No	High
LIF	0	2700	Very fast	No	...	10%	Yes	Yes	Yes	No	Very high
Speckle methods	27	2100	Very fast	No	...	6%	Yes	Yes	Yes	No	Very high
Acoustic thermography	-269	2000	Very fast	Yes	...	4%	Yes	Yes	Yes	No	High

I. Speckle methods

Speckle photography has been used for gas temperature measurements and provides a line of sight average temperature gradient in any direction. Two sheared images of the object are superimposed to produce an interference pattern using a diffractive optical element as a shearing device. With such a device, it is possible to split light beams into different sets of subbeams. The range of application is from 20 to 2100 °C and the accuracy is approximately 6% of the Celsius reading. The speckle method was used by Farrell and Hofeldt¹⁷² to examine a cylindrical propane flame at gas temperatures up to 2000 °C.

Speckle shearing interferometry can be used to calculate the entire thermal field of a gaseous flame. This provides the line of sight average temperature gradient in the direction normal to a line connecting the two apertures of the imaging system. The contours seen are at a constant temperature gradient in one direction only. The temperature range of application is from 0 to 1200 °C and the accuracy level achieved

is ±0.15% of full scale. The use of this method was analyzed by Shakher and Nirala¹⁷³ for a flame up to 1200 °C. A thorough review of speckle photography and its application is given by Erf.¹⁷⁴

J. Acoustic thermography

Acoustic thermography¹⁷⁵⁻¹⁷⁷ can be used to measure the temperature of a fluid or solid surface. The technique has traditionally been used at low temperatures, 2.5-30 K, but can be used at up to 1000 °C. For gases, the method is based on the thermodynamic relationship between the speed of sound and the static temperature of a gas: $u = \sqrt{\gamma \mathcal{R} T}$. In principle gas temperatures can be determined by the measurement of the transit time of a sound signal between a pair of acoustic transducers at a known separation distance.

In general the two techniques used for measurement in the three media, gas, liquid, and solid, are introducing a sensor into the medium to be measured and using the medium

itself as the sensor. Acoustic thermometry has been used to detect changes in ocean temperature by receiving low-frequency sounds (below 100 Hz) transmitted across an ocean basin.¹⁷⁸ In liquids the speed of sound is related to the bulk modulus by $(K/\rho)^{1/2}$. The velocity of sound in different liquids was tabulated by Lynnworth and Carnevale.¹⁷⁹ In a solid, the speed of sound is related to the Young's modulus for the material by $(E/\rho)^{1/2}$. This technique can be used to monitor temperature in rapid thermal processing where an electric pulse across a transducer generates an acoustic wave guided by a quartz pin.¹⁸⁰ This results in the generation of Lamb waves (a type of ultrasonic wave propagation in which the wave is guided between two parallel surfaces of the test object), which propagate across the medium. Temperatures can be measured from 20 to 1000 °C (with a proposed use up to approximately 1800 °C) with an accuracy of ± 5 °C.¹⁸¹

V. SELECTION

Considerations in the selection of a method and of the associated equipment to suit a particular application include temperature range, likely maximum temperature, heating rate, response, accuracy, 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 brief descriptions and references given in Secs. II–IV are intended to serve this purpose. 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 measurements may be acceptable. Accuracy may or may not be worth the investment in equipment. The information given in Table V, which is based on a wide range of common selection criteria, can be used to assist in the initial choice of an appropriate technique.

For general references providing further information on temperature measurement the proceedings from the more recent symposium series on Temperature: Its Measurement and Control in Science and Industry are recommended,^{182–185} along with information provided by Quinn⁴² and by Bentley.¹⁸⁶ The related subject of heat flux measurement was reviewed by Childs *et al.*¹⁸⁷

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¹H. Preston-Thomas, "The International Temperature Scale of 1990 (ITS-90)," *Metrologia* **27**, 3–10 (1990).

²C. Webb, "Infrared: Faster, Smaller, Cheaper," *Control Instrumentation* **44** (1997).

³E. R. Cohen and B. N. Taylor, *J. Phys. Chem. Ref. Data* **2**, 663 (1973).

⁴E. R. Cohen and B. N. Taylor, "The 1986 Adjustment of the Fundamen-

tal Physical constants," *Rev. Mod. Phys.* **59**, 1121 (1987).

⁵L. A. Guildner and W. Thomas, "The Measurement of Thermodynamic Temperature," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982), Vol. 5, pp. 9–19.

⁶*AIP Handbook*, 3rd ed. edited by D. E. Gray (McGraw-Hill, New York, 1972), Sec. 4i.

⁷L. A. Guildner and R. E. Edsinger, "Deviation of International Practical Temperatures from Thermodynamic Temperatures in the Temperature Range from 273.16 K to 730 K," *J. Res. Natl. Bur. Stand., Sect. A* **80**, 703–738 (1976).

⁸R. A. Aziz, V. P. S. Nain, J. S. Carley, W. L. Taylor, and G. T. J. McConville, *Chem. Phys.* **70**, 4330–4342 (1979).

⁹K. H. Berry, NPL-75, "A Low Temperature Gas Thermometer Scale from 2.6 K to 27.1 K," *Metrologia* **15**, 89–115 (1979).

¹⁰R. C. Kemp, W. R. C. Kemp, and L. M. Besley, "A Determination of Thermodynamic Temperatures and Measurements of the Second Virial Coefficient of 4He Between 13.81 K and 287 K Using a Constant Volume Gas Thermometer," *Metrologia* **23**, 61–86 (1986).

¹¹F. C. Maticotta, G. T. McConville, P. P. M. Steur, and M. Durieux, "Measurements and Calculations of the 3He Second Virial Coefficient Between 1.5 K and 20.3 K," *Metrologia* **24**, 61–67 (1987).

¹²P. P. M. Steur, M. Durieux, and G. T. McConville, "Analytic expressions for the virial coefficients $B(T)$ and $C(T)$ of 4He between 2.6 K and 300 K," *Metrologia* **24**, 69–77 (1987).

¹³P. P. M. Steur and M. Durieux, "Constant Volume Gas Thermometry Between 4 K and 100 K," *Metrologia* **23**, 1–18 (1986).

¹⁴D. A. Astrov, L. B. Beliansky, Y. A. Dedikov, S. P. Polunin, and A. A. Zakharov, "Precision Gas Thermometry between 2.5 K and 308 K," *Metrologia* **26**, 151–166 (1989).

¹⁵R. E. Edsinger and J. F. Schooley, "Differences Between Thermodynamics Temperature and (IPTS-68) in the Range 230 °C to 660 °C," *Metrologia* **26**, 95–106 (1989).

¹⁶P. P. M. Steur, "The Interpolating Constant-Volume Gas Thermometer and Thermal Anchoring," *Metrologia* **36**, 33–39 (1999).

¹⁷F. Pavese and P. P. M. Steur, "3He Constant-Volume Gas Thermometry: Calculations for a temperature Scale Between 0.8 K and 25 K," *J. Low Temp. Phys.* **69**, 91–117 (1987).

¹⁸B. W. Mangum and G. T. Furukawa, "Guidelines for Realizing the ITS-90," NIST Tech. Note **1990**, 1265 (1990).

¹⁹G. T. McConville, "The Effect of Measuring Tube Surface on Thermomolecular Corrections in Vapor Pressure Thermometry," *Temperature. Its Measurement and Control in Science and Industry* (Instrument Society of America, Pittsburgh, 1972), Vol. 4, pp. 159–165.

²⁰S. Weber and G. Schmidt, "Experimentelle untersuchungen uber die thermomolekulare druckdifferenz in der nahe der grenzbedingung $p_1/p_2 = \sqrt{T_1/T_2}$ und vergleichung mit der theorie," *Communications from the Kammerlingh Onnes Laboratory of the University of Leiden*, Vol. 246c, 1–13 (1936).

²¹A. P. Gershanik, M. S. Glikman, and D. N. Astrov, *Session du Comité Consultatif de Thermométrie* (Bureau International des Poids et Mesures, Sèvres, France, 1978), Doc. 45.

²²A. Kent, *Experimental Low Temperature Physics* (Macmillan, New York, 1993).

²³G. K. White, *Experimental Techniques in Low Temperature Physics*, 3rd ed. (Oxford Science, New York, 1987).

²⁴C. A. Swenson, "From the IPTS-68 to the ITS-90," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 1–8.

²⁵BS 1041:Part 2: Sec. 2:1. Code for temperature measurement. Expansion thermometers. Guide to the selection and use of liquid-in-glass thermometers (1985).

²⁶ISO 386, Liquid in glass laboratory thermometers—Principles of design, construction and use (1977).

²⁷BS 1704, Specification for solid-stem general purpose thermometers (1985).

²⁸J. A. Wise, "Liquid in glass thermometry," NBS Monogr. 150 (1976).

²⁹J. V. Nicholas, "Liquid-in-Glass Thermometers," *The Measurement Instrumentation and Sensors Handbook*, edited by J. G. Webster (Chemical Rubber, Boca Raton, FL, 1999), Sec. 32.8.

³⁰S. G. Eskin and J. R. Fritze, "Thermostatic bimetal," *Trans. ASME* **62**, 433 (1940).

³¹R. J. Stephenson, A. M. Moulin, and M. E. Welland, "Bimaterials thermometers," *The Measurement Instrumentation and Sensors Handbook*,

- edited by J. R. Webster (Chemical Rubber, Boca Raton, FL, 1999).
- ³²R. V. Divita, "Bimetal thermometer selection," *Measurements Control* **167**, 93–95 (1994).
 - ³³A. R. Miedema, "The heat formation of alloys," *Philips Tech. Rev.* **36**, 217–231 (1976).
 - ³⁴D. D. Pollock, *Thermocouples: Theory and Properties* (Chemical Rubber, Boca Raton, FL, 1991).
 - ³⁵F. R. Caldwell, "Thermocouple materials," *Temperature. Its Measurement and Control in Science and Industry* (Reinhold, New York, 1962), Vol. 3, pp. 81–134.
 - ³⁶P. A. Kinzie, *Thermocouple Temperature Measurement* (Wiley, New York, 1973).
 - ³⁷T. W. Kerlin, *Practical Thermocouple Thermometry* (ISA, Research Triangle Park, NC, 1999).
 - ³⁸J. G. Hust, R. L. Powell, and L. L. Sparks, "Methods for Cryogenic Thermocouple Thermometry," *Temperature. Its Measurement and Control in Science and Industry* (Instrument Society of America, Pittsburgh, 1972), Vol. 4, pp. 1525–1535.
 - ³⁹N. A. Burley, "Nicrosil and Nilil, highly stable nickel base alloys for thermocouples," *Fifth Symposium on Temperature* (Paper T-4, Washington, DC, 1971), pp. 1677–1695.
 - ⁴⁰L. A. Guildner and G. W. Burns, "Accurate Thermocouple Thermometry," *High Temp.-High Press.* **11**, 173–192 (1979).
 - ⁴¹D. I. Finch, "General Principles of Thermoelectric Thermometry," *Temperature. Its Measurement and Control in Science and Industry* (Reinhold, New York, 1962), Vol. 3, pp. 3–32.
 - ⁴²T. J. Quinn, *Temperature*, 2nd ed. (Academic, New York, 1990).
 - ⁴³L. Michalski, K. Eckersdorf, and J. McGhee, *Temperature Measurement* (Wiley, New York, 1991).
 - ⁴⁴T. E. Duffey, M. I. Seegall, S. S. McElmury, J. C. Napier and W. A. Compton, "Research Analysis of Advanced Sensors for Turbine Inlet Gas Temperature," Final Report Naval Air Syst. Com. Contract No. N00019-69-C-0574, 1970.
 - ⁴⁵M. Villamayor, "Thermocouples for High Temperature Measurement," UKAEA Research Group Paper No. AERE-Trans-1095, 1967.
 - ⁴⁶BS 1041: Part 4, Temperature measurement. Guide to the selection and use of thermocouples (1992).
 - ⁴⁷EN 60584, Thermocouples. Part 1: Reference tables. Part 2: Tolerances (1996).
 - ⁴⁸ASTM E230-96e1, Standard specification and temperature-electromotive force (emf) tables for standardized thermocouples (1996).
 - ⁴⁹E. O. Doebelin, *Measurement Systems: Application and Design*, 4th ed. (McGraw-Hill, New York, 1990).
 - ⁵⁰TC Ltd., *TC Guide to Thermocouple and Resistance Thermometry*, Vol. 6 (TC Ltd., 1998).
 - ⁵¹R. P. Benedict and R. J. Russo, "A Note on Grounded Thermocouple Circuits," *J. Basic Eng.*, 337–380 (1972).
 - ⁵²T. J. Claggett, R. W. Worrall, and B. G. Liptak, "Thermocouples," *Instrument Engineers' Handbook Process Measurement and Analysis*, edited by B. G. Liptak (Chilton, 1991), 3rd ed.
 - ⁵³G. F. Strouse, B. W. Mangum, A. I. Pokhodun, and N. P. Moiseeva, "Investigation of High Temperature Platinum Resistance Thermometers at Temperatures up to 962 °C and in Some Cases 1064 °C," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 389–393.
 - ⁵⁴M. Arai and H. Sakurai, "Development of Industrial Platinum Resistance Sensors for Use Up to the Gold Point," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 439–442.
 - ⁵⁵R. M. Tennant, *Science Data Book* (Oliver and Boyd, Edinburgh, 1974).
 - ⁵⁶J. L. Riddle, G. T. Furukawa, and H. H. Plumb, *Platinum Resistance Thermometry* (National Bureau of Standards 1973).
 - ⁵⁷C. H. Meyers, "Coiled Filament Resistance Thermometers," *J. Res. Natl. Bur. Stand.* **9**, 807–813 (1932).
 - ⁵⁸H. M. Hashemian and K. M. Petersen, "Achievable Accuracy and Stability of Industrial RTDs," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 427–431.
 - ⁵⁹BS 1041: Part 3. Temperature measurement. Guide to the selection and use of industrial resistance thermometers (1989).
 - ⁶⁰ASTM E1137. Standard specification for industrial platinum resistance thermometers (1997).
 - ⁶¹BS EN 60751. Industrial platinum resistance thermometer sensors (1996).
 - ⁶²P. C. F. Wolfendale, J. D. Yewen, and C. I. Daykin, "A New Range of High Precision Resistance Bridges for Resistance Thermometry," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982), Vol. 5, pp. 729–732.
 - ⁶³J. Connolly, "Resistance Thermometer Measurement," *Handbook of Temperature Measurement, Vol. 2 Resistance and Liquid in Glass Thermometry*, edited by R. E. Bentley (Springer, New York, 1998), Chap. 3.
 - ⁶⁴J. Connolly, "Industrial Resistance Thermometers," *Handbook of Temperature Measurement, Vol. 2, Resistance and Liquid in Glass Thermometry*, edited by R. E. Bentley (Springer, New York, 1998), Chap. 2.
 - ⁶⁵C. Horrigan, "Calibration Enclosures," *Handbook of Temperature Measurement, Vol. 2, Resistance and Liquid in Glass Thermometry*, edited by R. E. Bentley (Springer, New York, 1998), Chap. 8.
 - ⁶⁶R. J. Berry, "Evaluation and Control of Platinum Oxidation Errors in Standard Platinum Resistance Thermometers," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982a), Vol. 5, pp. 743–752.
 - ⁶⁷R. J. Berry, "Oxidation, Stability and Insulation Characteristics of Rosemount Standard Platinum Resistance Thermometers," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982b), Vol. 5, pp. 753–762.
 - ⁶⁸H. L. Trietley, "Avoiding error sources in platinum resistance temperature measurement," *InTech* (ISA, 1981), pp. 57–60.
 - ⁶⁹R. L. Rusby, "The Rhodium-Iron Resistance Thermometer: Ten Years On," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982), Vol. 5, pp. 829–834.
 - ⁷⁰G. Schuster, "Temperature Measurement with Rhodium-Iron Resistors below 0.5 K," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 449–452.
 - ⁷¹J. R. Clement and E. H. Quinell, "The Low Temperature Characteristics of Carbon Composition Thermometers," *Rev. Sci. Instrum.* **23**, 213–216 (1952).
 - ⁷²L. G. Rubin, "Cryogenic Thermometry: A Review of Recent Progress," *Cryogenics* **10**, 14–20 (1970).
 - ⁷³L. G. Rubin, "Cryogenic Thermometry: A Review of Progress Since 1982," *Cryogenics* **37**, 341–356 (1997).
 - ⁷⁴L. M. Besley, "Stability Characteristics of Carbon Glass Resistance Thermometers," *Rev. Sci. Instrum.* **50**, 1626–1628 (1979).
 - ⁷⁵W. N. Lawless, "Thermometric Properties of Carbon Impregnated Porous Glass at Low Temperatures," *Rev. Sci. Instrum.* **43**, 1743–1747 (1972).
 - ⁷⁶W. N. Lawless, "Thermal Properties of Carbon-Impregnated Porous Glass at Low Temperatures," *Rev. Sci. Instrum.* **52**, 727–730 (1981).
 - ⁷⁷S. D. Wood, B. W. Mangum, J. J. Filliben, and S. B. Tillett, "An Investigation of the Stability of Thermistors," *J. Res. Natl. Bur. Stand.* **83**, 247–263 (1978).
 - ⁷⁸ASTM E879-93, Standard specification for thermistor sensors for clinical laboratory temperature measurements (1993).
 - ⁷⁹P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. (Cambridge University Press, New York, 1989).
 - ⁸⁰A. Szymrka-Grzebyk and L. Lipinski, "Linear Diode Thermometer in the 4–300 K Temperature Range," *Cryogenics* **35**, 281–284 (1995).
 - ⁸¹J. K. Krause and B. C. Dodrill, "Measurement System Induced Errors in Diode Thermometry," *Rev. Sci. Instrum.* **57**, 661–665 (1986).
 - ⁸²R. Morrison, *Grounding and Shielding Techniques*, 4th ed. (Wiley, New York, 1998).
 - ⁸³R. R. Dils, "High temperature optical fiber thermometer," *J. Appl. Phys.* **54**, 1198–1201 (1983).
 - ⁸⁴E. W. Saaski and J. C. Hartl, "Thin-film Fabry-Perot temperature sensors," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 731–734.
 - ⁸⁵T. D. McGee, *Principles and Methods of Temperature Measurement* (Wiley, New York, 1988).
 - ⁸⁶B. C. R. Ewan, "A Study of Two Optical Fibre Probe Designs for Use in High Temperature Combustion Gases," *Meas. Sci. Technol.* **9**, 1330–1335 (1998).
 - ⁸⁷K. T. V. Grattan and Z. Zhang, *Fibre Optic Fluorescence Thermometry* (Chapman and Hall, London, 1995).
 - ⁸⁸W. N. Lawless, C. F. Clark, and R. W. Arenz, "Method for Measuring Specific Heats in intense Magnetic Fields at Low Temperatures Using Capacitance Thermometry," *Rev. Sci. Instrum.* **53**, 1647–1652 (1982).

- ⁸⁹C. Bazan and S. Matyjasik, "Capacitors as Temperature Sensors," *Instrum. Exp. Tech.* **29**, 750–752 (1986).
- ⁹⁰W. N. Lawless, *Rev. Sci. Instrum.* **46**, 625 (1975).
- ⁹¹R. R. Li, G. P. Berg, and D. B. Mast, "Ceramic Chip Capacitors as Low-Temperature Thermometers," *Cryogenics* **32**, 44–46 (1992).
- ⁹²M. M. Maior, S. B. Molnar, Y. M. Vysochanskii, M. I. Gurzan, P. H. M. Vanloosdrecht, P. J. E. M. Vanderlinden, and H. Vankempen, "New dielectric material for low-temperature thermometry in high magnetic fields," *Appl. Phys. Lett.* **62**, 2646–2648 (1993).
- ⁹³F. C. Penning, M. M. Maior, P. Strehlow, S. A. J. Wieggers, H. Vankempen, and J. C. Maan, "Magnetic-Field Independent Capacitance Thermometers at Very-Low Temperatures," *Physica B* **211**, 363–365 (1995).
- ⁹⁴F. C. Penning, M. M. Maior, S. A. J. Wieggers, H. Vankempen, and J. C. Maan, "A sensitive capacitance thermometer at low temperature for use in magnetic fields up to 20 T," *Rev. Sci. Instrum.* **67**, 2602–2605 (1996).
- ⁹⁵P. Strehlow, "SOL-GEL derived glass capacitance sensors," *Physica B* **165**, 25 (1990).
- ⁹⁶P. Strehlow, "Low temperature glass capacitance sensors," *Proceedings of the 15th International Cryogenic Engineering Conference, 1994*, Vol. 34, pp. 421–424.
- ⁹⁷S. A. J. Wieggers, M. M. Maior, F. C. Penning, S. B. Molnar, H. Vankempen, Y. M. Vysochanskii, and J. C. Maan, "Reproducibility of Low Temperature Capacitance Thermometers Based on $(\text{Pb}_{0.45}\text{Sn}_{0.55})_2\text{P}_2\text{Se}_6$ Single Crystal," *Ferroelectrics* **192**, 349–352 (1997).
- ⁹⁸J. B. Johnson, "Thermal Agitation of Electricity in Conductors," *Phys. Rev.* **32**, 97–109 (1928).
- ⁹⁹H. Nyquist, "Thermal Agitation of Electric Charge in Conductors," *Phys. Rev.* **32**, 110–113 (1928).
- ¹⁰⁰D. S. Betts, *An Introduction to Millikelvin Technology* (Cambridge University Press, Cambridge, UK, 1989).
- ¹⁰¹R. A. Kamper, "Survey of noise thermometry," *Temperature. Its Measurement and Control in Science and Industry* (Institute Society of America, Pittsburgh, 1972), Vol. 4, pp. 349–354.
- ¹⁰²T. V. Blalock and R. L. Shepard, "A Decade of Progress in High Temperature Johnson Noise Thermometry," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982), Vol. 5, pp. 1219–1223.
- ¹⁰³D. R. White *et al.*, "The Status of Johnson Noise Thermometry," *Metrologia* **33**, 325–335 (1996).
- ¹⁰⁴R. J. Soulen, W. E. Fogle, and J. H. Colwell, "Measurements of absolute temperature below 0.75 K using a Josephson junction noise thermometer," *J. Low Temp. Phys.* **94**, 385–487 (1994).
- ¹⁰⁵S. Menkel, D. Drung, C. Assmann, and T. A. Schurig, "A Resistive dc SQUID Noise Thermometer," *Appl. Supercond.* **6**, 417–422 (1998).
- ¹⁰⁶J. Macfarlane, D. Peden, L. Hao, J. Gallop, and E. Romans, "Effect of junction noise in a resistive high T -c SQUID noise thermometer," *Appl. Supercond.* **1&2**, 723–726 (1997).
- ¹⁰⁷J. J. Suter, "Piezoelectric Properties of Quartz Crystal Resonators Below 10 K," *Cryogenics* **30**, 547–548 (1990).
- ¹⁰⁸K. Agatsuma, F. Uchiyama, S. Ishigami, and M. Satoh, "High-Resolution Cryogenic Quartz Thermometer and Application to Wireless Measurement," *Cryogenics* **34**, 405–408 (1994).
- ¹⁰⁹K. Agatsuma, F. Uchiyama, K. Tukamoto, S. Ishigami, M. Satoh, Y. Saitoh, and H. Sugimoto, "Wireless Cryogenic Quartz Thermometer and Application to Cryogenic Temperature Control Systems," *Adv. Cryog. Eng.* **39** **249**, 1035–1042 (1994).
- ¹¹⁰M. Durieux, H. van Dijk, H. ter Harmsel, and C. van Rijn, "Some Remarks on Magnetic Thermometry Between 1.5 and 23 K and on the Vapor Pressure–Temperature Relation of Liquid Hydrogen," *Temperature. Its Measurement and Control in Science and Industry* (Reinhold, New York, 1962), Vol. 3, pp. 383–390.
- ¹¹¹T. C. Cetas and C. A. Swenson, "A paramagnetic salt temperature scale, 0.9 to 18 K," *Metrologia* **8**, 46–64 (1972).
- ¹¹²R. L. Rusby and C. A. Swenson, "A New Determination of the Helium Vapor Pressure Scales Using a CMN Magnetic Thermometer and the NPL-75 Gas Thermometer Scale," *Metrologia* **16**, 73–87 (1980).
- ¹¹³D. S. Greywall and P. A. Busch, "Fast Cerium Magnesium Nitrate (CMN) Thermometer for the Low Millikelvin Temperature Range," *Rev. Sci. Instrum.* **60**, 471–473 (1989).
- ¹¹⁴D. S. Greywall and P. A. Busch, "A Fast CMN Thermometer With a Wide Temperature Range," *Physica B* **165**, 23–24 (1990).
- ¹¹⁵P. Mohandas, D. I. Head, and R. L. Rusby, "A Powdered CMN Thermometer for High Accuracy Measurements in the Range 0.01 to 1 K," *Czech. J. Phys.* **46**, 2867–2868 (1996).
- ¹¹⁶B. J. Klemme, M. J. Adriaans, P. K. Day, D. A. Sergatskov, T. L. Ase-lage, and R. V. Duncan, "PdMn and PdFe: New materials for temperature measurement near 2 K," *J. Low Temp. Phys.* **116**, 133–146 (1999).
- ¹¹⁷T. C. Cetas, "A Magnetic Temperature Scale from 1 to 83 K," *Metrologia* **12**, 27–40 (1976).
- ¹¹⁸C. Camci, "Liquid Crystal Thermography," *Temperature Measurements* (Von Karman Institute, Brussels, 1996), Chaps. 1–3.
- ¹¹⁹S. A. Hippensteele, L. M. Russell, and F. S. Stepka, "Evaluation of a Method for Heat Transfer Measurements and Thermal Visualisation Using a Composite of a Heater Element and Liquid Crystals," *J. Heat Transfer* **105**, 184–189 (1983).
- ¹²⁰J. W. Baughn, "Review—Liquid Crystal Methods for Studying Turbulent Heat Transfer," *Int. J. Heat Fluid Flow* **16**, 365–375 (1995).
- ¹²¹P. T. Ireland and T. V. Jones, "The Measurement of Local Heat Transfer Coefficients in Blade Cooling Geometries," *AGARD CP390, Heat Trans. and Cooling in Gas Turbs.* (1985), Chap. 28.
- ¹²²P. T. Ireland, A. J. Neely, R. H. Gillespie, and A. J. Robertson, "Turbulent Heat Transfer Measurements Using Liquid Crystals," *Int. J. Heat Fluid Flow* **20**, 355–367 (1999).
- ¹²³P. T. Ireland and T. V. Jones, "The Response Time of a Surface Thermometer Employing Encapsulated Thermochromic Liquid Crystals," *J. Phys. E* **20**, 1195–1199 (1987).
- ¹²⁴S. W. Allison and G. T. Gillies, "Remote Thermometry with Thermographic Phosphors: Instrumentation and Applications," *Rev. Sci. Instrum.* **68**, 2615–2650 (1997).
- ¹²⁵K. W. Tobin, S. W. Allison, M. R. Cates, G. J. Capps, D. L. Beshears, M. Cyr, and B. W. Noel, "High-Temperature Phosphor Thermometry of Rotating Turbine Blades," *AIAA J.* **28**, 1485–1490 (1990).
- ¹²⁶BS 1041, Part 7, Temperature measurement. Guide to the selection and use of temperature/time indicators (1988).
- ¹²⁷J. Gallery, M. Gouterman, J. Callis, G. Khalil, B. McLachlan, and J. Bell, "Luminescent Thermometry for Aerodynamic Measurements," *Rev. Sci. Instrum.* **65**, 712–720 (1994).
- ¹²⁸C. O. Fairchild and W. H. Hoover, "Disappearance of the Filament and Diffraction Effects in Improved Forms of an Optical Pyrometer," *J. Opt. Soc. Am.* **7**, 543–579 (1923).
- ¹²⁹H. L. Hackforth, *Infrared Radiation* (McGraw-Hill, New York, 1960).
- ¹³⁰BS 1041: Part 5, British Standard, Temperature measurement. Guide to selection and use of radiation pyrometers (1989).
- ¹³¹E639-78e1, Standard Test Method for Measuring Total-Radiance Temperature of Heated Surfaces Using a Radiation Pyrometer (1996).
- ¹³²M. Delfino and D. T. Hodul, "Wavelength Specific Pyrometry as a Temperature Measurement Tool," *IEEE Trans. Electron Devices* **39**, 89–95 (1992).
- ¹³³*Theory and Practice of Radiation Thermometry*, edited by D. P. DeWitt and G. D. Nutter (Wiley, New York, 1988).
- ¹³⁴R. R. Corwin and A. Rodenburgh, "Temperature Error in Radiation Thermometry Caused by Emissivity and Reflectance Measurement error," *Appl. Opt.* **33**, 1950–1957 (1994).
- ¹³⁵R. J. Goldstein, "Optical Measurement of Temperature," *Measurement Techniques in Heat Transfer*, edited by E. R. G. Eckert and R. J. Goldstein (AGARD, Slough, 1970), pp. 177–228.
- ¹³⁶A. G. Gaydon and H. G. Wolfhard, *Flames. Their Structure, Radiation and Temperature* (Chapman and Hall, London, 1979).
- ¹³⁷A. Schwarz, "Multi-tomographic Flame Analysis with a schlieren Apparatus," *Meas. Sci. Technol.* **7**, 406–413 (1996).
- ¹³⁸R. J. Hall and P. A. Bonczyk, "Sooting Flame Thermometry Using Emission/Absorption Tomography," *Appl. Opt.* **29**, 4590–4598 (1990).
- ¹³⁹H. Uchiyama, M. Nakajima, and S. Yuta, "Measurement of Flame Temperature Distribution by IR Emission Computed Tomography," *Appl. Opt.* **24**, 4111–4116 (1985).
- ¹⁴⁰E. Metcalfe, *Atomic Absorption and Emission Spectroscopy* (Wiley, New York, 1987).
- ¹⁴¹D. J. Carlson, "Static Temperature Measurements in Hot Gas Particle Flows," *Temperature. Its Measurement and Control in Science and Industry* (Reinhold, New York, 1962), Vol. 3, pp. 535–550.
- ¹⁴²H. D. Baker, E. A. Ryder, and N. H. Baker, *Temperature Measurement in Engineering* (Wiley, New York, 1961), Vol. 2.
- ¹⁴³A. B. Murphy and A. J. D. Farmer, "Temperature Measurement in Thermal Plasmas by Rayleigh Scattering," *J. Phys. D: Appl. Phys.* **25**, 634–643 (1992).
- ¹⁴⁴R. B. Barat, J. P. Longwell, A. F. Sarfim, S. P. Smith, and E. Bar-Ziv,

- "Laser Rayleigh Scattering for Flame Thermometry in a Toroidal Jet Stirred Combustor," *Appl. Opt.* **30**, 3003–3010 (1991).
- ¹⁴⁵D. Hoffman, K. U. Munch, and A. Leipertz, "Two Dimensional Temperature Determination in Sooting Flames by Filtered Rayleigh Scattering," *Opt. Lett.* **21**, 525–527 (1996).
- ¹⁴⁶R. Miles and W. Lempert, "Two Dimensional Measurement of Density, Velocity and Temperature in Turbulent High Speed Air Flows by UV Rayleigh Scattering," *Appl. Phys. B: Photophys. Laser Chem.* **B51**, 1–7 (1990).
- ¹⁴⁷C. Kittel, *Introduction to Solid State Physics*, 6th ed. (Wiley, New York, 1986).
- ¹⁴⁸G. J. Edwards, Review of the status, traceability and industrial application of gas temperature measurement techniques, NPL Report CBTM S1, (1997).
- ¹⁴⁹M. C. Drake, C. Asawaroengchai, D. L. Drapcho, K. D. Veirs, and G. M. Rosenblatt, "The Use of Rotational Raman Scattering for Measurement of Gas Temperature," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1982), Vol. 5, pp. 621–629.
- ¹⁵⁰F. Laplant, G. Laurence, and D. Ben-Amotz, "Theoretical and Experimental Uncertainty in Temperature Measurement of Materials by Raman Spectroscopy," *Appl. Spectrosc.* **50**, 1034–1038 (1996).
- ¹⁵¹R. W. Dibble, S. H. Starner, A. R. Masri, and R. S. Barlow, "An Improved Method of Data Reduction for Laser Raman-Rayleigh and Fluorescence Scattering from Multispecies," *Appl. Phys. B: Photophys. Laser Chem.* **B51**, 39–43 (1990).
- ¹⁵²E. J. Burlbaw and R. L. Armstrong, "Rotational Raman Interferometric Measurement of Flame Temperatures," *Appl. Opt.* **22**, 2860–2866 (1983).
- ¹⁵³G. Vaughan, D. P. Wareing, S. J. Pepler, L. Thomas, and V. Mitev, "Atmospheric temperature measurements made by rotational Raman scattering," *Appl. Opt.* **32**, 2758–2764 (1993).
- ¹⁵⁴*Laser Diagnostics and Modelling of Combustion*, edited by K. Iinuma, T. Asanuma, T. Ohsawa, and J. Doi (Springer, New York, 1987).
- ¹⁵⁵B. Attal-Tretout, P. Bouchardy, P. Magre, M. Pealat, and J. P. Taran, "CARS in Combustion: Prospects and Problems," *Appl. Phys. B: Photophys. Laser Chem.* **B51**, 17–24 (1990).
- ¹⁵⁶W. M. Tolles, J. W. Nibler, J. R. McDonald, and A. B. Harvey, "A Review of the Theory and Application of Coherent Anti-Stokes Raman Spectroscopy (CARS)," *Appl. Spectrosc.* **31**, 253–271 (1977).
- ¹⁵⁷R. L. Farrow, P. L. Mattern, and L. A. Rahn, "Comparison Between CARS and Corrected Thermocouple Temperature Measurements in a Diffusion Flame," *Appl. Opt.* **21**, 3119–3125 (1982).
- ¹⁵⁸F. M. Porter and D. A. Greenhalgh, *Applications of the Laser Optical Technique CARS to Heat Transfer and Combustion* (UK Atomic Energy Authority, Harwell, 1985).
- ¹⁵⁹G. C. Alessandretti and P. Violino, "Thermometry by CARS in an Automobile Engine," *J. Phys. D: Appl. Phys.* **16**, 1583–1594 (1983).
- ¹⁶⁰T. J. Anderson, G. M. Dobbs, and A. C. Eckbreth, "Mobile CARS Instrument for Combustion and Plasma Diagnostics," *Appl. Opt.* **25**, 4076–4085 (1986).
- ¹⁶¹A. C. Eckbreth, G. M. Dobbs, J. H. Stufflebeam, and P. A. Tellex, "CARS Temperature and Species Measurements in Augmented Jet Engine Exhausts," *Appl. Opt.* **23**, 1328–1339 (1984).
- ¹⁶²N. Herlin, M. Pealat, M. Lefebvre, P. Alnot, and J. Perrin, "Rotational Energy Transfer on a Hot Surface in a Low Pressure Flow Studied by CARS," *Surf. Sci.* **258**, 381–388 (1991).
- ¹⁶³R. R. Antcliff, M. W. Smith, O. Jarrett, G. B. Northam, A. D. Cutler, and D. J. Taylor, "A Hardened CARS System Utilized for Temperature Measurements in a Supersonic Combustor," 9th Aerospace Sciences Meeting, Reno, Nevada, Vol. 0457, pp. 1–7 (1991).
- ¹⁶⁴A. C. Eckbreth, *Laser Diagnostics for Combustion Temperature and Species* (Abacus, Turnbridge Wells, 1988).
- ¹⁶⁵G. C. Herring, W. L. Roberts, M. S. Brown, and P. A. DeBarber, "Temperature Measurement by Degenerate Four Wave Mixing with Strong Absorption of the Excitation Beams," *Appl. Opt.* **35**, 6544–6547 (1996).
- ¹⁶⁶L. J. Dowell, "Fluorescence Thermometry," *Appl. Mech. Rev.* **45**, 253–260 (1992).
- ¹⁶⁷K. T. V. Grattan and Z. Y. Zhang, *Fibre Optic Fluorescence Thermometry* (Chapman and Hall, London, 1995).
- ¹⁶⁸C. Chan and J. W. Daily, "Measurement of Temperature in Flames Using Laser Induced Fluorescence Spectroscopy of OH," *Appl. Opt.* **19**, 1963–1968 (1980).
- ¹⁶⁹P. Andresen, G. Meijer, H. Schlüter, H. Voges, A. Koch, W. Hentschel, W. Oppermann, and E. Rothe, "Fluorescence Imaging Inside an Internal Combustion Engine Using Tunable Excimer Lasers," *Appl. Opt.* **29**, 2392–2404 (1990).
- ¹⁷⁰M. Megahed, "Estimation of the Potential of a Fluorescence Thermometer for Diesel Spray Studies," *Appl. Opt.* **32**, 4790–4796 (1993).
- ¹⁷¹L. P. Goss, A. A. Smith, and M. E. Post, "Surface Thermometry by Laser-Induced Fluorescence," *Rev. Sci. Instrum.* **60**, 3702–3706 (1989).
- ¹⁷²P. V. Farrell and D. L. Hofeldt, "Temperature Measurement in Gases Using Speckle Photography," *Appl. Opt.* **23**, 1055–1059 (1984).
- ¹⁷³C. Shaker and A. K. Nirala, "Measurement of Temperature Using Speckle Shearing Interferometry," *Appl. Opt.* **33**, 2125–2127 (1994).
- ¹⁷⁴*Speckle Metrology*, edited by R. K. Erf. (Academic, New York, 1978).
- ¹⁷⁵A. R. Colclough, "Primary Acoustic Thermometry: Principles and Current Trends," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1992), Vol. 6, pp. 65–75.
- ¹⁷⁶S. F. Green, "Acoustic Temperature and Velocity Measurement in Combustion Gases," Proceedings of the International Heat Transfer Conference, 1986, Vol. 2, pp. 555–560.
- ¹⁷⁷G. Moore, "Acoustic Thermometry—A Sound Way to Measure Temperature," *Electron. Power* **9**, 675–677 (1984).
- ¹⁷⁸A. Forbes, "Acoustic Monitoring of Global Ocean Climate," *Sea Technol.* **35**, 65 (1994).
- ¹⁷⁹L. C. Lynnworth and E. H. Carnevale, "Ultrasonic thermometry using pulse techniques," *Temperature. Its Measurement and Control in Science and Industry* (American Institute of Physics, New York, 1972), Vol. 4, pp. 715–732.
- ¹⁸⁰Y. J. Lee, B. T. Khuriyakub, and K. C. Saraswat, "Temperature Measurement in Rapid Thermal Processing Using Acoustic Techniques," *Rev. Sci. Instrum.* **65**, 974–976 (1994).
- ¹⁸¹B. A. Auld, *Acoustic Fields and Waves in Solids*, 2nd ed. (Wiley, New York, 1990).
- ¹⁸²*Temperature. Its Measurement and Control in Science and Industry*, edited by C. H. Herzfeld (Reinhold, New York, 1962), Vol. 3.
- ¹⁸³*Temperature. Its Measurement and Control in Science and Industry*, edited by H. H. Plumb (Instrument Society of America, Pittsburgh, 1972), Vol. 4.
- ¹⁸⁴*Temperature. Its Measurement and Control in Science and Industry*, edited by J. F. Schooley (American Institute of Physics, New York, 1982), Vol. 5.
- ¹⁸⁵*Temperature. Its Measurement and Control in Science and Industry*, edited by J. F. Schooley (American Institute of Physics, New York, 1992), Vol. 6.
- ¹⁸⁶*Handbook of Temperature Measurement*, edited by R. E. Bentley (Springer, New York, 1998), Vols. 1–3.
- ¹⁸⁷P. R. N. Childs, J. R. Greenwood, and C. A. Long, "Heat Flux Measurement Techniques," *Proc. Inst. Mech. Eng., Part C: J. Mech. Eng. Sci.* **213**, 655–677 (1999).