

# 1

## Temperature Scales and Classification of Thermometers

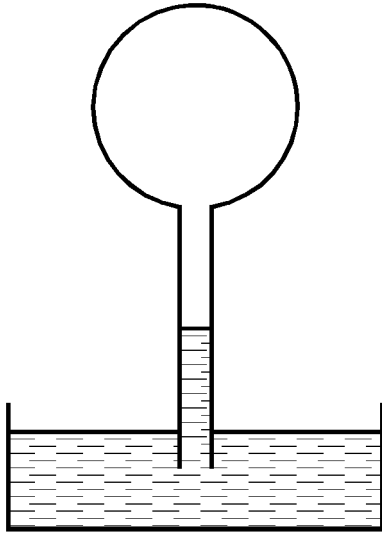
### 1.1 Temperature - Historical Background

The concept of temperature makes one think of physiological experiences whilst touching or approaching some solid. Some of them may be described as cold, cool or tepid, others as hot or warm. Warmer bodies transfer heat to other cooler bodies. Both bodies tend to equalise their temperatures, approaching a new common intermediate temperature. Thus the correctness of the definition, given to temperature by the Scotsman James Clerk Maxwell, may be seen. He stated that the *temperature of a body is its thermal state, regarded as a measure of its ability to transfer heat to other bodies*. At the present time, this definition compels the attribution of larger numerical values to those bodies which have a higher ability to transfer heat to other bodies. This definition forms the basis of all of the international temperature scales in use both presently and in the past. Science took a long, difficult and tortuous route, full of errors, to this contemporary definition of temperature.

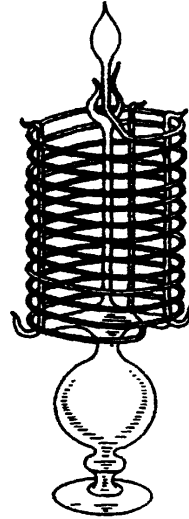
In ancient Rome, during the second century BC, the physician C. Galen introduced four degrees of coldness regarding the effects of different medicines upon human organisms. These medicines were supposed either to warm or to cool them. Galen also introduced a neutral temperature, attributing to it a value of zero degrees. He claimed that this neutral temperature depended upon geographical latitude.

The first device, which was used to measure the degree of warmth or coldness, seems to have been invented by Galileo Galilei some time between the years 1592 and 1603. This instrument, which is shown in Figure 1.1, consisted of a glass bulb connected to a long tube immersed in a coloured liquid. After a preliminary heating of the contained gas, its subsequent cooling caused a certain amount of the liquid to be sucked in. The liquid column rose or fell as a function of the ambient temperature. In the absence of any evidence that the instrument had any graduation, it is better to call it a *thermoscope*. As the indicated values were also a function of the atmospheric pressure its precision must have been quite poor. Subsequently, about the year 1650, the members of the Florentine Academy of Sciences made the first thermometer, which is represented in Figure 1.2. This consisted of a spiral shaped tube with a closed end and a graduation. However, no numbers were ascribed to the graduation marks (Lindsay, 1962).

In the course of time the need arose to define temperature fixed points, to standardise those thermometers which existed at that time. One of the first proposals came, in 1669,



**Figure 1.1** Galileo's air thermoscope (1592)



**Figure 1.2** Thermometer of the Florentine Academy of Sciences (1650)

from H. Fabri from Leida. His proposal was for two fixed points. The lower should be the temperature of snow and the higher the temperature of the hottest summer day. A later proposal, which was made by C. Rinaldi from Padua in 1693, suggested that the fixed points should be the temperatures corresponding to the melting point of ice and the boiling point of water. Between these two points, twelve divisions should be introduced. In the same year, and for the first time, the British scientist E. Halley applied mercury as a thermometric liquid.

Rømer, a thermometrist working in Copenhagen at the end of the 17th and beginning of the 18th century, developed a scale where zero degrees was associated with the coldest day, while the normal temperature of the human body was associated with  $24^\circ$ . This made the temperature of boiling water equivalent to  $\approx 50^\circ$ - $55^\circ$  on this unusual scale, which was influenced by the predominant use of thermometers for meteorological purposes at that time. Hence, if the freezing point of water had been taken as zero, the repeated use of negative values for winter temperatures would have occurred. Winter temperatures of  $-16^\circ\text{C}$  ( $\approx 0^\circ\text{F}$ ) are quite common in continental Europe.

A further notable milestone in thermometry is due to D. G. Fahrenheit from Danzig (now the city of Gdańsk in Poland), who visited Rømer's laboratory shortly after Rømer proposed his scale. To avoid the problems associated with Rømer's scale, it seemed obvious to Fahrenheit to use the lowest attainable temperature of those days as zero. As a result, Fahrenheit developed the specification and use of the mercury-in-glass thermometer in 1724. Evidently influenced by Rømer's scale, he proposed his own, very well known scale. This scale, called the Fahrenheit scale, which persists today, is essentially the same as that described by him to The Royal Society in 1724. Fahrenheit described the mercury-in-glass thermometer, introducing three *temperature fixed points*:

- A mixture of ice, water and ammonium chloride was taken as the zero point.
- A mixture of ice and water was taken as  $32^\circ$ .
- A human body temperature was taken as  $96^\circ$ .

Even yet there is no clear reason why Fahrenheit chose such a scale division based upon these assumed temperature fixed points. As Newton Friend (1937) indicated, the reasons for choosing such a scale division by Fahrenheit might have been that in the eighteenth century the majority of thermometers were intended for meteorological purposes. Taking the freezing point of water as zero would have involved the repeated use of negative values for winter temperatures. To avoid this, Fahrenheit proposed to use the lowest attainable temperature of those days as zero.

In the case of the upper fixed point, the temperature of boiling water was rejected as being unnecessarily high for meteorological purposes. In his decision to assume  $96^\circ$  for the temperature of the body, Fahrenheit was influenced by the already existing Rømer scale. He merely changed Rømer's 24 degrees for body temperature to 96. This change, which was equivalent to four subdivisions on each degree of the Rømer scale, was also probably made because 96 is divisible not only by 2 but also by multiples of 3 and hence 12. The decimal system was not in general use at that time.

Further development of the mercury-in-glass thermometer, in 1742, was due to the Swedish astronomer and physicist A. Celsius. He assigned  $0^\circ$  to the temperature of boiling water and  $100^\circ$  to the temperature of melting ice. The region between these two points was divided into 100 equal steps. Subsequently, after the death of Celsius in 1744, M. Strömer, friend and scientific collaborator of Celsius, reversed these values. Eventually, as science developed, a need to measure temperatures above the melting point of glass arose. Prinsep's air thermometer, which used a gold bulb to measure temperatures of  $1000^\circ\text{C}$  in 1828, was followed soon after, in 1836, by a platinum bulb in a similar thermometer by Pouillet.

A true Thermodynamic Temperature Scale (TTS), described below, had been the unconscious aim of all of the previous efforts. Such a scale was not possible until 1854 when its foundations were laid by the Belfast born William Thomson, who later became Professor of Natural Philosophy in the University of Glasgow, Scotland, and assumed the title Lord Kelvin of Largs. Of course, the aim of any scale of temperature, but especially the thermodynamic scale, is the representation of the hotness relations between objects and events in the real physical world by numbers.

## 1.2 Thermodynamic Temperature Scale (TTS)

The aim of any scale of temperature, but especially the thermodynamic scale, is the representation of hotness and hotness relations between objects and events in the real physical world by real numbers. As numerical values are correlated to some defined temperatures, *temperature fixed points* are required to characteristic certain values of temperature. Interpolation then allows the definition of temperature between these temperature fixed points.

To enable some defined interpolation between these temperature fixed points, a *thermometric working substance*, one of its *properties* and a *correlating function* must be assumed. The chosen function provides the means of associating the specific property of the working substance with a certain temperature. Because of the diversity of materials and

their properties there is an unlimited number of these temperature scales. Properties which may be relevant are, for example, the length of a rod, the pressure of saturated steam, the resistance of a wire and so on. In the given temperature range the property must be consistently repeatable and reproducible. In normal conditions, corresponding to 101.325 kPa, let the ice-point temperature be  $0^\circ$  and the temperature of boiling water be  $100^\circ$ . Assuming that the chosen property is linearly dependent upon the temperature it is apparent that any temperature scale based upon say the thermal expansion of a copper rod, will not coincide with a scale based upon the thermal expansion of another metal or on any change of its resistance with temperature.

The material, which most closely approximates this ideal thermometric working substance, is an ideal gas. Indeed it was the work of Robert Boyle and his co-workers in the middle of the 17th century which led to the conviction of many later scientists that there was such a thing as an *absolute zero* of temperature. These eminent individuals included G. Amontons, in Paris in 1699, J. H. Lambert, in 1770, and Gay-Lussac, in 1790. Gay-Lussac gave credit to J. A. C. Charles for that individual's previously unpublished research. All of their efforts resulted in what is now called the *ideal gas law*, also called the *Boyle-Mariotte law* which is written in the usual form:

$$pV = nkT \quad (1.1)$$

where  $p$  is the pressure,  $V$  is the volume,  $n$  is the number of moles of gas,  $k = 1.3807 \times 10^{-23}$  J/K is Boltzman's constant and  $T$  is the absolute temperature. When the temperature is held constant, equation (1.1) corresponds to *Boyle's law*. Similarly *Charles' law* is obtained from equation (1.1) when the pressure is held constant.

Since there are no direct methods for measuring temperature, as there are with say length measurement, difficulties are associated with temperature measurement. As only associative temperature measurements are possible, any temperature scale depends upon the chosen thermometric working substance and its chosen property. Although any working substance may be employed in principle, it will be restricted to some finite range determined by its thermal behaviour. For example, the application of mercury-in-glass thermometers is limited on the low-temperature side by the solidification of the mercury as it freezes and on the high-temperature side by the inability of the glass to expand indefinitely as well as its melting temperature. Melting of the glass was responsible for the development of the Prinsep and Pouillet thermometers.

An ideal solution to the problem of proposing a suitable temperature scale would be to find one valid in any temperature range and totally independent of the working substance. The thermodynamic Kelvin Scale, based upon the efficiency of the ideal reversible *Carnot cycle*, is such a scale (Herzfeld, 1962; McGee, 1988). A reversible Carnot cycle, which is impossible to realise in practice, consists of a reversible heat engine operating between two isotherms at the temperatures  $T_2$  and  $T_1$ , with  $T_2 > T_1$ , and of two adiabatic processes. A reversible heat engine absorbs the heat,  $Q_2$ , from the high-temperature source, at the temperature  $T_2$ , and discharges the heat  $Q_1$  to the low-temperature source, at the temperature  $T_1$ . The difference between the absorbed heat  $Q_2$  and the discharged heat  $Q_1$ , which is the external work,  $A$ , performed by the engine, may be written as:

$$A = Q_2 - Q_1 \quad (1.2)$$

Reversing the engine action, indicates that it may be driven by a second identical engine, working between the same two heat sources. The effect of such action might be the heat flow from the lower to the higher temperature source. Using the properties of reversible processes it may be proven that the ratio  $Q_2/Q_1$  is a function only of the two source temperatures, so that:

$$\frac{Q_2}{Q_1} = f(T_2, T_1) \quad (1.3)$$

Following Kelvin's proposal it may be assumed that the functional relation in equation(1.3) is:

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1} \quad (1.4)$$

Equation (1.3) is the basis of the TTS and thus the efficiency of a reversible heat engine is defined as:

$$\eta = \frac{Q_2 - Q_1}{Q_2} = \frac{T_2 - T_1}{T_2} = 1 - \frac{T_1}{T_2} \quad (1.5)$$

This efficiency and the definition of temperature, which is based upon it, may be shown to be independent of the working substance. As a result it may be used to define the TTS:

$$T_1 = T_2(1 - \eta) \quad (1.6)$$

By means of this scale any chosen thermal state such as the melting point of ice, may be assigned a certain value of thermodynamic temperature. The TTS may be founded upon a defined temperature difference between two temperature fixed points or on a defined value of one temperature fixed point.

In the course of the development of technology, the manner of defining the TTS has changed. Until 1954, it was assumed that  $100^\circ$  represented the difference between the boiling point of water and the melting point of ice. Since then, there has been a return to the original and older proposals of Kelvin, in 1848, Mendeleev, in 1874, and Giauque in 1939. Thus, since 1954, the TTS is based upon one temperature fixed point, which is the *triple point of water*. Triple points of physical materials are stable, repeatable temperatures where the solid, liquid and gaseous forms of the material exist in thermal equilibrium. The triple point of water occurs at that temperature where ice, water and water vapour exist in thermal equilibrium. A temperature of 273.16 has been assigned to this temperature fixed point.

In 1967 the Thirteenth General Conference on Weights and Measures (CGPM) introduced a new definition for the scale and a new symbol for the unit of thermodynamic temperature. This unit is called the *kelvin* denoted by the symbol K. In the *SI*, when units are called after people, the unit name always starts with a small letter to emphasise that it is the unit being referred to, not the person. It is defined as 1/273.16 part of the thermodynamic temperature of the triple point of water.

Even though the Carnot cycle cannot be realised in practice, it can be demonstrated using equation (1.1) that the thermodynamic scale may be reproduced by a gas thermometer with an ideal gas as the working substance. Here again, although the ideal gas is quite fictitious, it could be replaced by a noble gas at very low pressure. Either pressure difference at constant volume or volume difference at constant pressure can be chosen as the measure of temperature. When the readings of temperature at constant volume,  $T_v$ , and the similar readings at constant pressure,  $T_p$ , are extrapolated to zero they tend to the same value  $T_v = T_p = T$ , independently of the properties of the gas. Thus, the TTS may be reproduced using gas thermometers which have an application range up to about 1350 K.

Another simple method of reproducing the scale at thermodynamic temperatures above 1337 K is allowed by means of thermal radiation from heated bodies. When this radiation is in thermodynamic equilibrium with the radiating body, some properties of this radiation are directly linked to the temperature of the body (Herzfeld, 1962).

The concepts of black body radiation are essential for proper utilisation of the method. For thermal radiation to possess similar properties to that from black body radiators it should be emitted from an aperture which is sufficiently deep and narrow with a uniform temperature distribution in accordance with the principles given in Section 8.2. When these conditions are complied with, it may be shown that the radiation intensity and its spectral distribution only depend upon the temperature of the body and not upon its material. Take, as a reference system, a heated body, which is radiating heat with some radiation intensity and whose temperature,  $T_1$ , is within the measurement range of a gas thermometer. The radiant intensity of the body provides a means of extending the TTS to higher temperatures. A relation between the ratio of spectral radiant intensities of a black body at two different temperatures,  $T_1$  and  $T_2$ , at one wavelength,  $\lambda$ , exists. This relation is obtained from *Planck's law* (given later in equation (8.7)) which is:

$$\frac{W_{\lambda T_1}}{W_{\lambda T_2}} = \frac{e^{c_2/\lambda T_2} - 1}{e^{c_2/\lambda T_1} - 1} \quad (1.7)$$

where  $W_{\lambda T_1}$  and  $W_{\lambda T_2}$  are the spectral radiant intensities of a black body at the temperatures  $T_1$  and  $T_2$  respectively,  $c_2 = 0.014\,388$  m K is Planck's constant, and  $\lambda$  is the wavelength in metres.

Equation (1.7) presents the ratio of the spectral radiant intensities of a black body at two temperatures  $T_1$  and  $T_2$  at the same single wavelength,  $\lambda$ . The temperature  $T_2$  is to be determined, whereas  $T_1$  is the temperature of a fixed point measured by a gas thermometer.

## 1.3 International Temperature Scales

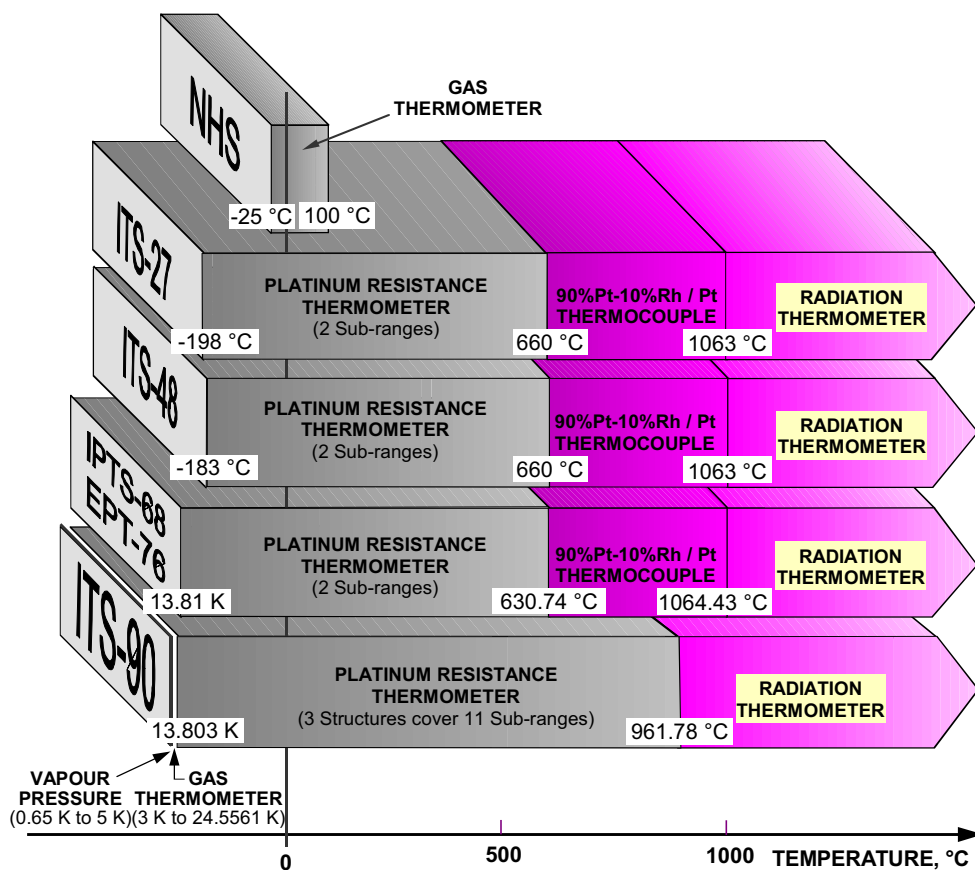
### 1.3.1 From the Normal Hydrogen Scale to EPT-76

A primary standard system for measuring temperature is the "Kelvin Thermodynamic Temperature Scale" referred to above. Because of the difficulties which are involved in

realising this primary standard system, widely accepted realisations are based upon *boiling points*, *freezing/melting points* and *triple points*. Boiling points correspond to characteristic temperatures where the liquid and gaseous states of a material exist in equilibrium. Freezing/melting points are temperatures where a material undergoes an equilibrium change in its physical state from liquid to solid or solid to liquid respectively. Freezing/melting points are preferred to boiling points as they are less sensitive to pressure changes. Triple points are temperatures where the solid liquid and gaseous forms of the material exist in equilibrium.

Practical realisations of temperature scales have been disseminated by previously adopted resolutions of the CGPM in 1889, 1927, 1948 (revised in 1960), 1968 (supplemented in 1976) and 1990. For comparative purposes all of these scales are summarised in Figure 1.3.

The Normal Hydrogen Scale, or NHS, which was based upon the work conducted by Chappuis (1888), a staff member of the International Bureau of Weights and Measures (BIPM), was proposed by the International Committee of Weights and Measures (CIPM) in 1887. Using hydrogen gas as the thermometric material, Chappuis built a gas thermometer



**Figure 1.3** Comparison of the various temperature measurement scales and the measuring ranges of their standard interpolating instruments or sensors

calibration facility covering the range  $-25^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$ . This early scale, which was used to calibrate mercury-in-glass thermometers, was a true centigrade scale as its fixed points were the ice-point, at  $0^{\circ}\text{C}$ , and the boiling point of water, at  $100^{\circ}\text{C}$ .

A gas thermometer is a complex piece of apparatus which is only appropriate for use as a primary standard in fundamental laboratory measurements. Since this severely limits its practical use, the gas thermometer needs to be replaced by some other, more practically convenient types. To this aim, in 1911, Germany, Great Britain and USA agreed to accept one common, practical temperature scale, but its completion was delayed by the outbreak of World War I. When it was defined in 1927 by the Seventh General Conference on Weights and Measures with the assignment of six defining or fixed points, it was called the *International Temperature Scale of 1927 (ITS-27)*. Development of thermometers using the noble metal platinum, giving rise to the *Platinum Resistance Thermometer*, or PRT, followed the pioneering groundwork of Siemens, in 1871, and Callendar, in 1887. By the end of World War I, PRTs were acknowledged as precision thermometers. This confidence provided the basis for their specification as one of the standard interpolating instruments of ITS-27. Over the range  $-190^{\circ}\text{C}$  to  $+660^{\circ}\text{C}$ , in the sub-ranges  $-190^{\circ}\text{C}$  to  $0^{\circ}\text{C}$  and  $0^{\circ}\text{C}$  to  $660^{\circ}\text{C}$ , the interpolating instrument was specified as the PRT made from platinum with defined properties, exhibiting resistances at three temperatures, expressed as ratios with respect to the resistance at  $0^{\circ}\text{C}$ . From  $660^{\circ}\text{C}$  to  $1063^{\circ}\text{C}$  the scale was to be interpolated using a platinum-10% rhodium / platinum (90%Pt-10%Rh/Pt) thermocouple made from materials with specified properties. The *Wien's law* defined temperatures above  $1063^{\circ}\text{C}$ . ITS-27 was a major step forward in the universality of thermometry as it removed previously observed ambiguities in the specification of temperature.

The tortuous path in the development of a temperature scale, which truly represented the thermodynamic scale, soon uncovered the inadequacies of ITS-27. Thus was born the *International Temperature Scale of 1948 (ITS-48)*, which possessed the same number of fixed points as ITS-27, but with the freezing point of silver now specified as  $960.8^{\circ}\text{C}$ , instead of  $960.5^{\circ}\text{C}$  as in ITS-27. The lower PRT interpolating limit was also raised to  $-183^{\circ}\text{C}$  to coincide with the oxygen boiling point of  $-182.970^{\circ}\text{C}$ . Otherwise the PRT standard interpolation sub-ranges remained the same, as well as that of the 90%Pt-10%Rh/Pt interpolating thermocouple. In the case of the interpolating thermocouple, a quadratic interpolating equation was introduced with new constraints placed upon the acceptable values and tolerances of the emf. Above  $1063^{\circ}\text{C}$ , *Wien's law* was replaced by *Planck's law* to improve the thermodynamic consistency of the temperatures in this range and also to allow the use of ITS-48 at higher temperatures than ITS-27. In 1960, a revision of ITS-48 became known as the *International Practical Temperature Scale of 1948(60)*, or IPTS-48(60), to avoid confusion with ITS-48. The changes, which specified the water triple point temperature as 273.16 K, creating the present Kelvin Thermodynamic Scale, also included its adoption as a fixed point of the scale in place of the ice-point temperature. The name of the unit of temperature was changed to degrees Celsius,  $^{\circ}\text{C}$ , in place of centigrade. ITS-47 was a true centigrade scale as it had 100 degrees as the fundamental interval between the ice-point and the water boiling point. As the freezing point of zinc, at  $419.505^{\circ}\text{C}$ , was more precisely realised, it was proposed as a replacement for the sulphur boiling point at  $444.60^{\circ}\text{C}$ . New restrictions were placed upon one of the PRT ratios and upon the standard thermocouple emf.

The *International Practical Temperature Scale of 1968*, or IPTS-68, which was based upon *boiling points, melting/freezing points and triple points*, arose from the need to extend



IPTS-48 to lower temperatures as well as from improved measurement methods. A total of thirteen fixed points were used to define the scale. Although the interpolating instruments were the same as for IPTS-48, the PRT range was extended to cover the lower temperature region down to 13.8 K, using four wire resistance connections in two different sensor structures. The scale was also more closely defined in terms of a reference function, with four different deviation functions defined to provide correction in the four different temperature sub-ranges for the particular PRT being calibrated. In the original statement of IPTS-68, the same 90%Pt-10%Rh/Pt thermocouple covered the same range as in IPTS-48(60) with the same quadratic form for the emf defining equation. The range of application of this thermocouple, subsequently adopted by the 15th CGPM in 1975, was changed to 630,74 °C to 1064,43 °C in IPTS-68(75) with a commensurate tightening of the emf specifications. Above 1064.43 °C, *Planck's law* defined the scale. An *Extended Practical Temperature Scale* of 1976, or EPT-76, which includes revisions to IPTS-68, allowed IPTS-68 to be extended at low temperatures with the addition of 11 fixed points in the cryogenic range from the super-conducting transition point of cadmium at 0.519 K to the boiling point of neon at 27.102 K.

### 1.3.2 The International Temperature Scale of 1990 (ITS-90)

IPTS-68 and EPT-76 have now been superseded by the *International Temperature Scale* of 1990, also called ITS-90 for brevity, which was adopted by the International Committee of Weights and Measures in September 1989. (NPL, 1989; Preston-Thomas, 1990; Rusby, 1987). The differences existing between values of ITS-90 and of ITS-68 are of no practical influence in industrial measurements.

The scale is established by correlating some temperature values with a number of well reproducible equilibrium states (*i.e.* the temperature fixed points), which define the primary standards to be used and gives the interpolating equations for calculating temperatures between the fixed points. More details about the PRT interpolating equations are given in Chapter 4. *Planck's law* is used to define ITS-90 above the freezing point of silver. Overall, ITS-90 represents Thermodynamic Temperature with an uncertainty of  $\pm 2$  mK from 1 K to 273 K increasing to  $\pm 7$  mK at 900 K. The unit of TTS is the *kelvin*, symbol K. One kelvin is defined as 1/273.16 of the thermodynamic temperature of the triple point of water.

Celsius temperature is expressed as:

$$t(^{\circ}\text{C}) = T(\text{K}) - 273.15 \quad (1.8)$$

The unit of Celsius temperature is degree Celsius, symbol °C, which equals one kelvin. The temperature difference is expressed either in kelvins or °C.

In ITS-90 a distinction exists between the International Kelvin Temperature,  $T_{90}$ , and the International Celsius Temperature,  $t_{90}$ , where

$$t_{90}(^{\circ}\text{C}) = T_{90}(\text{K}) - 273.15 \quad (1.9)$$

In this book the Celsius temperature will be indicated by  $\vartheta$  to avoid confusion with the unit of time, which is indicated by  $t$ .

*Interpolation* between the Defining Fixed points of ITS-90, listed in Table 1.1, are as follows.

1. *From 0.65 K to 5.0 K:*  $T_{90}$  is defined in terms of the vapour pressure temperature relations of  $^3\text{He}$  and  $^4\text{He}$ .
2. *From 3.0 K to 24.5561 K (the triple point of neon):* the constant volume type of  $^3\text{He}$  or  $^4\text{He}$  gas thermometer is used. It is calibrated at three experimentally realisable temperatures of defining fixed points using specified interpolation procedures.
3. *From 13.8033 K (the triple point of equilibrium hydrogen) to 961.78 °C (the freezing point of silver):* the standard instrument is a platinum resistance thermometer calibrated at specified sets of defining fixed points and using specified interpolation procedures. As indicated in Figure 1.3 and described by Nicholas and White (1994), Pt thermometers with 3 different structures are used in 11 different temperature sub-ranges. The temperatures are determined from the reduced thermometer *resistance ratio*, defined by the relation:

$$W(T_{90}) = \frac{R(T_{90})}{R(273.16 \text{ K})} \quad (1.10)$$

**Table 1.1** The temperature fixed points of ITS-90

Equilibrium state	Scale	
	$T_{90}$ K	$t_{90}$ °C
Vapour-pressure point of helium	3 to 5	-270.15 to -268.19
Triple point of equilibrium hydrogen	13.8033	-259.3467
Boiling point of hydrogen at a pressure 33 330.6 Pa	17	-256.15
Boiling point of equilibrium hydrogen	20.3	-252.85
Triple point of neon	24.5561	-248.5939
Triple point of oxygen	54.3584	-218.7916
Triple point of argon	83.8058	-189.3442
Triple point of mercury	234.3156	-38.8344
Triple point of water	273.16	0.01
Melting point of gallium	302.9146	29.7646
Freezing point of indium	429.7485	156.5985
Freezing point of tin	505.078	231.928
Freezing point of zinc	692.677	419.527
Freezing point of aluminium	933.473	660.323
Freezing point of silver	1234.93	961.78
Freezing point of gold	1337.33	1064.18
Freezing point of copper	1357.77	1084.62

The values of the temperature fixed points with the exception of the triple points are given at pressure,  $p_0 = 101\,325$  Pa.

where  $R(273.16 \text{ K})$  is the thermometer resistance at the triple point of water.

The platinum resistance sensor must be made from pure, strain free, annealed platinum, satisfying at least one of the following relations:

- at the gallium melting point,

$$W(29.764 \text{ }^\circ\text{C}) \geq 1.11807 \quad (1.11)$$

- at the triple point of mercury,

$$W(-38.834 \text{ }^\circ\text{C}) \geq 0.844235 \quad (1.12)$$

If used up to the freezing point of silver it must also satisfy the relation:

$$W(961.78 \text{ }^\circ\text{C}) \geq 4.2844 \quad (1.13)$$

In each of the resistance thermometer ranges,  $T_{90}$  is obtained from  $W_r(T_{90})$  as given by an appropriate *reference function* and the deviations  $W(T_{90}) - W_r(T_{90})$ . At the Defining Fixed Points this deviation is obtained directly from the calibration of the thermometer. At intermediate temperatures it is obtained by means of the appropriate deviation functions, as given in a Table attached to the text of ITS-90.

- 3a. *In the range from 13.8033 K (the triple point of equilibrium hydrogen) to 273.16 K (the triple point of water), the thermometer is calibrated at the triple points of equilibrium hydrogen (13.8033 K), neon (24.5561 K), oxygen (54.3584 K), argon (83.8058 K), mercury (234.3156 K) and water (273.16 K) and at two additional temperatures close to 17.0 K and 20.3 K, using a gas thermometer.*
- 3b. *In the range from 0 °C to 961.78 °C (the freezing point of silver) the thermometer is calibrated at the triple point of water (0.01 °C) and at the freezing points of tin (231.928 °C), zinc (419.527 °C), aluminium (660.323 °C) and silver (961.78 °C). In both of the ranges described above at 3(a) and 3(b), for sub-ranges with limited upper temperatures, fewer calibration points may be used, as precisely specified in ITS-90.*
4. *Above: 961.78 °C (the freezing point of silver) Planck's law is to be used. The temperature  $T_{90}$  is defined by the equation:*

$$\frac{L_\lambda(T_{90})}{L_\lambda[T_{90}(x)]} = \frac{e^{c_2/[\lambda T_{90}(x)]} - 1}{e^{c_2/(\lambda T_{90})} - 1} \quad (1.14)$$

where  $T_{90}(x)$  refers to any of the freezing points of silver, gold, or copper,  $L_\lambda(T_{90})$  and  $L_\lambda[T_{90}(x)]$  are the spectral concentrations of the radiance of a black body at wavelength,  $\lambda$ , at  $T_{90}$  and  $T_{90}(x)$  respectively, and  $c_2$  is a constant with a value of 0.014 388 m K.

Although the ITS-90 recommended scales are the Celsius and the Kelvin Scales, the Fahrenheit Scale, which is still permissible in ITS-90, is widely used in Anglo-Saxon countries. The relations for conversion between the temperature scales, specified in Table 1.2, are used to calculate the numerical conversions in Table I at the end of the book.

**Table 1.2** Conversion of temperature scales

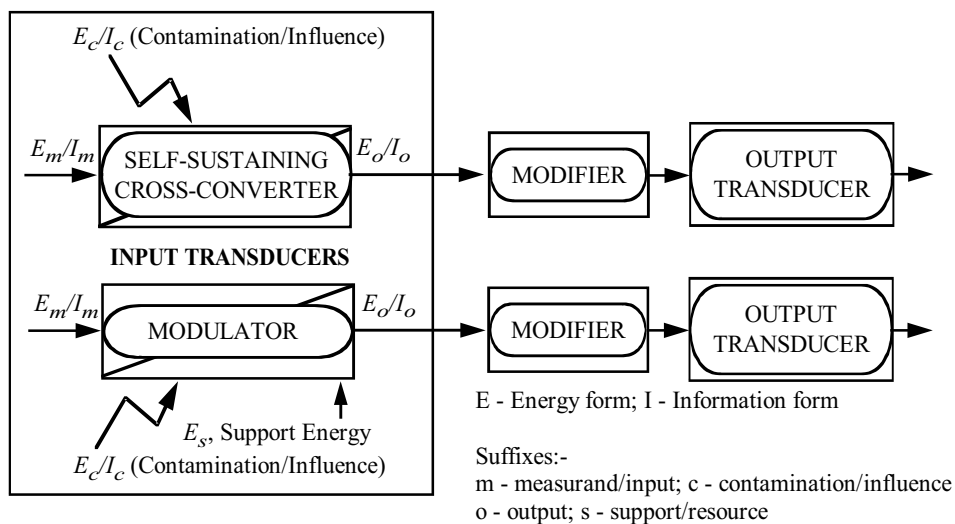
Scale	Given	To be determined	
		°C	°F
Celsius	X °C	X	1.8X + 32
Fahrenheit	X °F	0.5556×(X- 32)	X
Kelvin	X K	X-273.15	1.8×(X-273.15)+32

## 1.4 Classification of Thermometers

Temperature measuring instruments applied in industry and in laboratories will be described in this book. A systematic approach to grouping of the different types of thermometers will be given to obtain a summarising overview, which will help in the use of this book.

### 1.4.1 Temperature measuring chains

A temperature sensor is the initial part of a temperature measurement and instrumentation chain as shown in Figure 1.4. These sensors may be either *self-supporting cross-converters* or *modulators* in the terminology of McGhee *et al.* (1999). Self-sustaining cross-converter types of temperature sensors extract energy from the system under measurement during the conversion of an information bearing signal in the thermal energy domain into an information bearing signal in another, different, energy form. Modulating temperature sensors require the supply of an external power source to support the acquisition and flow of the temperature information, The sensor, which is also called an initial transducer, is the thermometer.

**Figure 1.4** A block diagram of temperature measuring chains

McGhee *et al.* (1999) have asserted that temperature sensors extend the human faculties to sense hotness relations between bodies or entities in the real world. Their main task, also described in Chapter 12, is the initial signal transformation of the information about the measured temperature into another physical quantity (Sydenham, 1983). In temperature sensors, which are the front end elements in temperature instrumentation, the main output is an information output. This quantity, known as the measuring signal, is subjected to further transformation in a *modifier*, such as a data converter, an amplifier, a filter or other kind of conditioner, into the desired output signal.

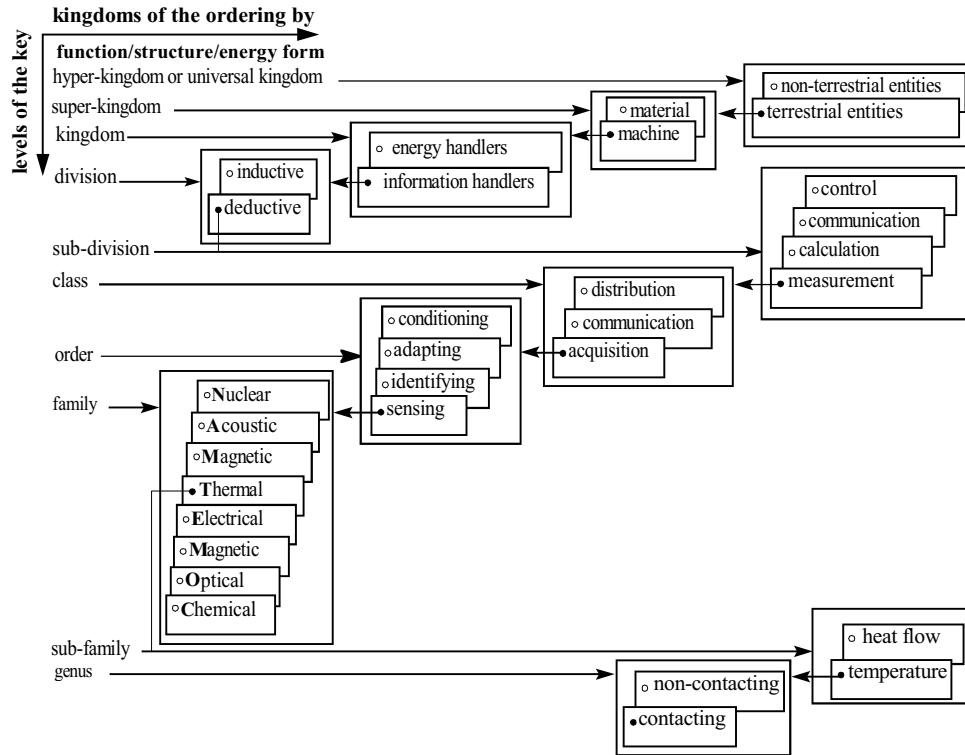
### 1.4.2 General principles for thermometer classification

A broad view of temperature measurement requires the application of the principles of classical taxonomy (Lion, 1969; Stein, 1969; McGhee and Henderson, 1993; McGhee *et al.*, 1999). The principal aim in temperature sensor classification is to introduce some kind of ordering so that similarities between each kind of sensor may be identified without in any way diminishing their important differences. This is achieved using the four techniques of classical taxonomy which are:

- Examine *generality* or *resemblance* of sensors using likeness relationships.
- Examine the *collectivity* or *composition* of sensors seeking structural details.
- Build a using relationships between the *heads* or *central members* of *groups of sensors* on the basis of *kinship* by *ascent*, *descent* and *collaterality*.
- Examine the *evolution* or *development* of different types of sensors.

There is a number of ways in which temperature sensors may be grouped (Behar, 1941; Hamidi and Swithenbank, 1987; Henderson and McGhee, 1993; McGee, 1988; McGhee *et al.*, 1996, 1999; Nicholas and White, 1994; Ptáček, 1993; Scholz and Ricolfi, 1990). The method to be employed here largely follows that presented in Henderson and McGhee (1993) and McGhee *et al.* (1996, 1999). Thus temperature sensors may be grouped by function, structure, energy form, conditioning circuits and so on. The *generality* and *resemblance* level of temperature sensor classes compares the human method of sensing hotness relations by looking at an object, by approaching it or by touching it. Neither looking at nor approaching an object require physical contact to sense its hotness. Touching an object to sense its hotness requires physical contact. Thus the contacting senses and sight or proximity sensing, with no contact, are the resembling forms of temperature sensing. Hence, temperature sensors are classified through their use of the heat transfer mechanism by contacting or non-contacting methods. Temperature sensing can be either *direct*, by measuring a variable characterising thermal energy flow or by *inferential methods* (McGhee *et al.*, 1999). The latter technique applies an external energy as an *interrogating* medium in the measuring scheme to capture information about the abilities of the body under measurement to store, dissipate, transmit or transform thermal energy.

Two forms of diagram are very useful in temperature sensor classification. The first, given in Figure 1.5, is called a key diagram which has the same structure as a card index file. It should be read in conjunction with Figures 1.6-1.8, which are called dendrographs or tree diagrams. The various levels in all key diagrams and dendrographs correspond to refinement of the classes as progress is made down through the levels.



**Figure 1.5** A key diagram for sensor classification with the location of temperature sensors in the ordering scheme

The classification of temperature instruments, in Figures 1.5-1.8, is based mainly on the physical quantity into which the temperature signal is transformed. Figure 1.5 shows the hierarchical context for temperature sensing within the physical experiences of humans. It can be seen that the universal kingdom, also called the hyper-kingdom, consists of the kingdoms of earth bound things and non-earth bound things. The levels descend from the universal or hyper-kingdom through the super-kingdom of earth bound things to the kingdoms of materials and machines. From the division of information machines, comes the sub-division of deductive types to the class of measurement machines. It is within this class of machine that the various families of sensors are placed. Note the classification of the family in Figure 1.5 by energy domain (Stein, 1969; McGhee *et al.*, 1998, 1999).

### 1.4.3 The non-electrical contacting temperature sensors

The various levels in the dendrographs, shown in Figures 1.5-1.8, correspond to refinement of the classification as progress is made down through the levels. It is based on the physical quantity into which the temperature signal is transformed. Although there is sometimes a close similarity in the construction of different types of thermometers, the order in which they are described in this book may not always be the same as in the classification given in Figures 1.5-1.8. The only reason for the difference is practical convenience. At each level in the tree diagrams, groups of central members of different types of temperature sensor are

related by *ascent* to other central members at higher levels in the key. An example of the relationship of *descent* can be seen between the *contacting genus* of temperature sensor and the various *self-sustaining cross-converters* sub-genus.

Contact sensors function through conductive and convective heat transfer. Further grouping by the energy form of the output signal, distinguishes non-electrical sensors from the electrical group. Non-electrical sensors are classified in Figure 1.6 on the basis of the thermal expansion of solids, liquids and gases. It should be noted that self-sustaining cross-converter types and modulating types of non-electrical sensors are grouped without distinction in the dendrograph of Figure 1.6 for the sake of brevity.

### 1.4.4 The electrical contacting temperature sensors

Electrical types of contacting thermometers, which may also be classified as either modulators or self-sustaining cross-converters, are grouped in Figure 1.7. Hence, modulating resistance thermometers may be based on (i) metallic electrical resistance or (ii) semiconducting electrical resistance. Other semiconducting modulating temperature sensors are classified using a standard method of semiconductor classification. Self-sustaining cross-converters operate upon the principle of either thermo-electric cross-conversion or upon noise thermometry.

### 1.4.5 The non-contacting group of temperature sensors

Figure 1.8 gives a fuller classification of non-contacting temperature sensors. It is based upon comparing the similarity between human sensing by sight or proximity and the radiation of thermal energy from heated bodies. It should be noted that a distinction is made between those non-contacting methods, which use *direct* sensing, and those which apply *interrogative* methods. In the direct sensing group of non-contacting temperature sensors,

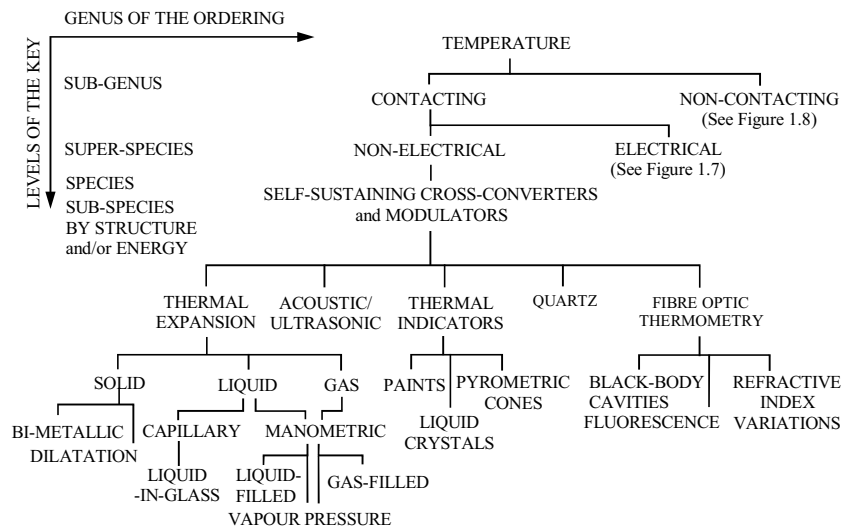


Figure 1.6 Classification of non-electrical contacting temperature sensors

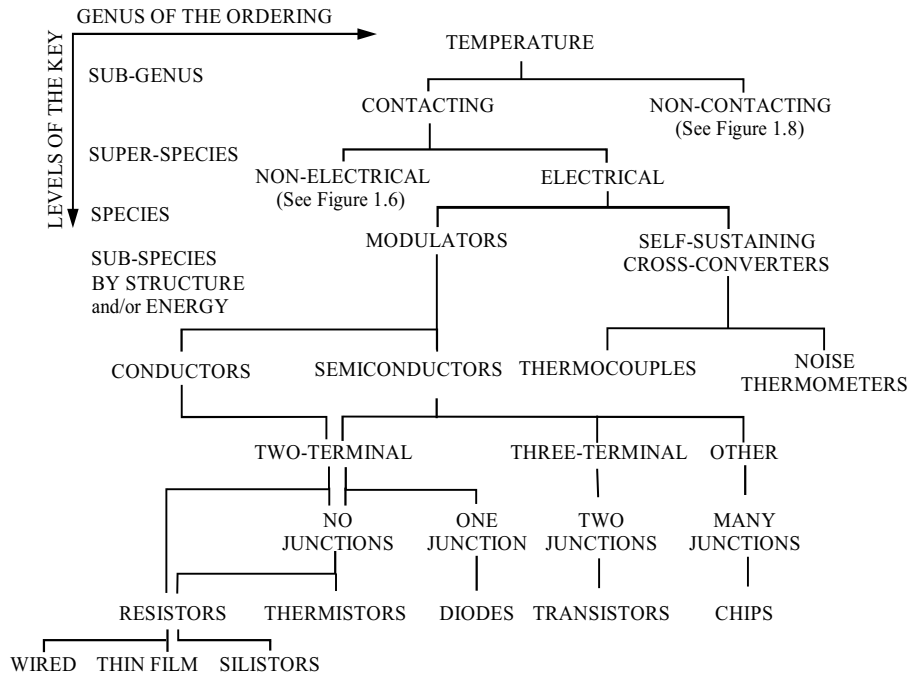


Figure 1.7 Classification of the electrical group of contacting temperature sensors

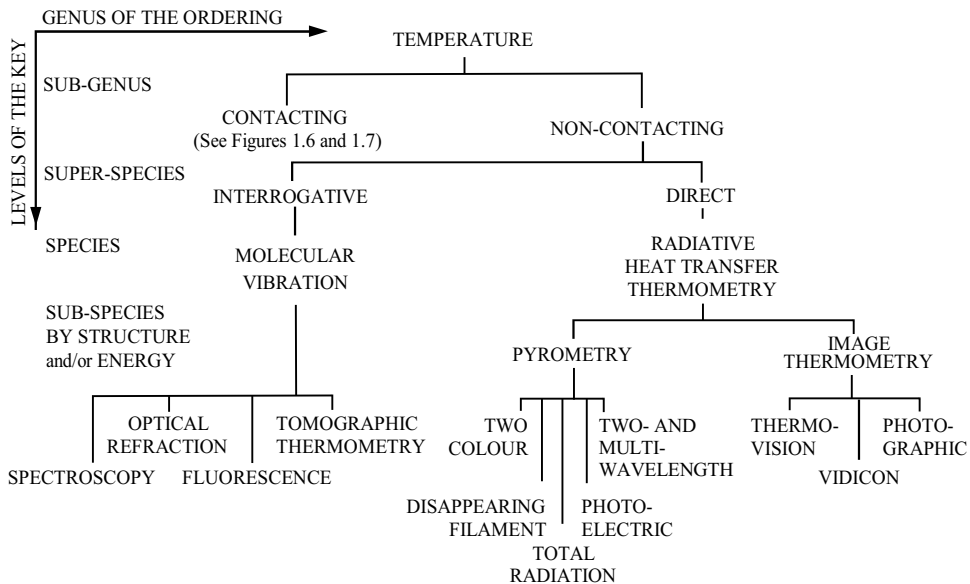


Figure 1.8 Classification of the non-contacting group of temperature sensors



the intensity of directly radiated energy is detected. This type of *direct* sensing may be further classified as either image forming or pyrometric (Nicholas and White, 1994; Ptáček, 1993). For the interrogating group, an excitation signal is used to interrogate the body or object whose temperature is to be sensed. Grouping for this kind of sensing is shown in Figure 1.8.

### 1.4.6 Temperature measuring ranges of temperature sensors

It is also possible to classify temperature sensors on the basis of the temperature range of application. Such a classification is given in Figure 1.9. An abbreviated form for the

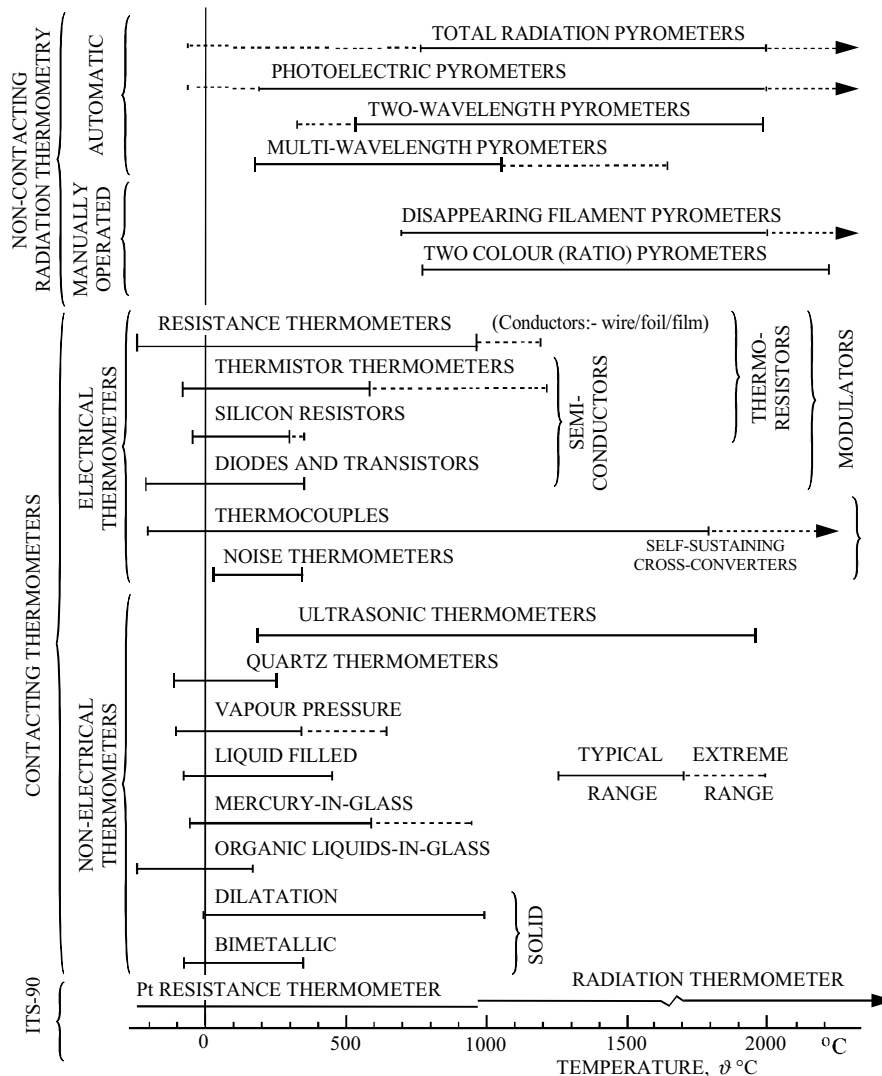


Figure 1.9 Classification of temperature measuring instruments/sensors by measuring range

temperature ranges of the standard thermometers of ITS-90, adapted from Figure 1.3, is also included in this diagram for the purposes of comparison. More detailed information is given in appropriate chapters.

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