PART 2: TECHNIQUES AND THERMOMETERS TRACEABLE TO THE INTERNATIONAL TEMPERATURE SCALE OF 1990

In all temperature ranges there are thermometers that are widely used because of certain advantages such as low cost and ease of use (e.g. base metal thermocouples), yet they are insufficiently reproducible to be included with those of Part 1. Temperatures measured with them are of course traceable to the ITS-90 through proper calibration procedures. There are also thermometers of only modest quality that are nevertheless extremely useful for certain special measurements (e.g. measurements in the presence of high magnetic fields). In Part 2 there are discussed the more commonly used thermometers in these categories. For the cryogenic range there are included the carbon, carbon-glass, and platinum-0.5% cobalt resistance thermometers, and silicon and gallium arsenide diodes. For higher temperatures, thermistors, liquid-in-glass thermometers, IPRTs, and base-metal thermocouples are so widely used, largely because they can provide in appropriate circumstances adequate reproducibility or accuracy at very low cost, that discussion of them is mandatory. Additionally, Chapter 19 treats the behaviour in magnetic fields of several of the thermometers of both Parts 1 and 2.
11. Carbon Resistance Thermometers

Carbon resistors are widely used as secondary thermometers at low and very low temperatures. They are very sensitive, their readings depend little on magnetic field, and they are compact and easy to handle. They are stable enough for a 10 mK precision or even better with special care. In every case, one must be cautious of any overheating because the thermal conductance of the sensor is very low.

11.1 Fabrication and Use

Commercial carbon-composition resistors manufactured by Allen-Bradley were introduced as temperature sensors by Clement and Quinnell (1952). Since that time carbon resistance thermometers (CRTs) have been widely used for low temperature applications from about 100 K to below 1 K. Although they are less reproducible than the resistance thermometers described in Part 1, they are exceedingly inexpensive and their small size is advantageous. Since they are selected from mass-produced components for use in electronic circuits, it is not surprising that differences from batch to batch can occur. The carbon composition resistor is a small cylinder consisting of graphite with a binder encased in an outer phenolic shell. Embedded in the phenolic are two opposing copper leads which make ohmic contact with the graphite. The types used as thermometers are generally characterized by their room temperature resistance and their wattage [Rubin (1980)], and have come largely from the following manufacturers: Allen-Bradley, Airco Speer (usually referred to simply as Speer), Ohmite (prior to 1970, Ohmite supplied Allen-Bradley resistors under their own label. Both had the same characteristics. Thereafter the company distributed Speer resistors.), Matsushita, CryoCal, Physicotechnical and Radiotechnical Measurement Institute (PRMI).

CRTs can be mounted directly as received, but generally the outer epoxy coating is removed and lead contacts are resoldered. The resistor is then inserted inside a tube (a copper tube for example) with grease as a convenient bonding agent. Great care must be taken with these operations because they can have a great influence on the stability of the sensor (see below). Some general recommendations for the use of a CRT are: do not modify the electrical contacts once they are soldered; do not heat the resistor excessively during the connection of the leads; protect the resistor from high humidity and solvents; cool it slowly; if the resistor is to be used in vacuum, it should be calibrated in vacuum.
11.2 Resistance-Temperature Characteristics and Sensitivity

The resistance of a CRT increases roughly exponentially (Fig. 11.1) and the sensitivity increases smoothly (Fig. 11.2) with decreasing temperature. The resistance of a typical unit will be roughly 1 kΩ at 1 K. The nominal resistance value $R(300 \text{ K})$ determines the temperature range of use; the region where the slope of the R-T curve becomes very steep shifts towards higher temperatures for higher values of $R(300 \text{ K})$, and at any given temperature, the smaller the value of $R(300 \text{ K})$, the smaller the sensitivity $(dR/R)/(dT/T)$. This characteristic is independent of the size (wattage) of the unit provided that $R(300 \text{ K})$ is the same, although significant differences are often found between units that are nominally the same but come from different batches, even from the same manufacturer. Thus interchangeability of units is not possible, or otherwise, because the cost is small, it is recommended to purchase all resistors that will be needed for a given application at the same time [Anderson (1972), Ricketson (1975), Kopp and Ashworth (1972), Kobayasi et al. (1976)].

Baking a resistor for a short time (~1 h) at a relatively high temperature (~400 °C) modifies its R-T characteristic. For example, baking a 100 Ω Matsushita unit at 375 °C in argon for one hour reduces R by a factor of three [Steinback et al. (1978)]. The sensitivity and (mainly) $R(300 \text{ K})$ are reduced while the general behaviour remains unchanged. Thus, one can adjust the sensitivity of a thermometer by annealing. This can be advantageous since a lower slope at low temperatures means a wider useful range of temperature for a given sensor, without the resistance becoming prohibitively high [Anderson (1972), Johnson and Anderson (1971)]. On the other hand, any local heating of the thermometer, even for short periods, such as when soldering new electric contacts, will irreversibly alter its characteristic and necessitate recalibration.

Heating of the resistor can arise from [Oda et al. (1974), Hudson et al. (1975)] the measuring current (Joule effect), vibrations, spurious emfs, thermal conduction along the leads, residual gas in the cryostat, thermal radiation, and radio frequency pickup. In the latter case, heating of $10^{-10}$ W is easily introduced below 1 K by switching circuits, digital equipment, noise from power supplies enhanced by ground loops, etc. The problem becomes much more serious as the temperature is reduced. Shields and filters are effective in reducing the heat leak to $10^{-15}$ W but caution is needed to avoid interference with the resistance measurement if an ac technique is used.
Fig. 11.1: Resistance-temperature characteristic for several commercial resistors: (a) A, thermistor; B, 68 Ω Allen-Bradley; C, 220 Ω Speer (grade 1002); D, 51 Ω Speer (grade 1002); E, 10 Ω Speer (grade 1002) [Anderson (1972)]; (b) various nominal Matsushita carbon resistors of grade ERC-18SGJ [Saito and Sato (1975)].
Fig. 11.2: Relative sensitivity versus temperature for carbon (C), carbon-glass (CG), and germanium (Ge) thermometers [Swartz and Swartz (1974)].

11.3 Thermal Contact

Providing good thermal contact is one of the main problems that limits the usefulness of carbon resistors. The heat dissipated in the sensor must flow to the surroundings without causing a relative temperature rise greater than $\Delta T/T \approx 10^{-3}$. At 1 K, for a 220 $\Omega$ Speer resistor for example, the maximum power dissipated in the CRT must remain smaller than $10^{-7}$ W for a 1% accuracy in the measurement.

The thermal boundary resistance between the unit and the environment depends upon the mounting, but is roughly $10^{-2}$ K/W for an area of $10^{-4}$ m$^2$.

Different thermal grounding techniques have been proposed [Polturak et al. (1978), Johnson and Anderson (1971)]. Thermally grounding the resistor via its leads only is not recommended. It is important to bind the unit with a copper housing that is thermally anchored to the device to be studied, with grease, stycast, varnish or other equally good agent. The paint used for color coding the resistor should be removed because it may loosen after several thermal cycles.

11.4 Response Time

The thermal response time of a CRT is short; some typical values are given in Table 11.1. Longer time constants (up to tens of minutes) can be observed if the copper
leads are not thermally grounded. Grinding the resistor clearly shortens the thermal time constant. Also, to improve time response, attempts have been made to use carbon thin films deposited on different substrates. Time constants approaching 0.42 ms at 4.2 K have been achieved [Bloem (1984)].

11.5 Influence of External Factors

a. Pressure

CRTs are only slightly dependent upon pressure [Dean and Richards (1968) and Dean et al. (1969)]; a typical value for the pressure dependence is \( \Delta R/R \sim -2 \times 10^{-9} \text{ Pa}^{-1} \).

b. Radiation

CRTs are relatively insensitive to nuclear irradiations. After long exposure to gamma rays and fast neutrons, changes observed in resistance were less than 1 % at 20 K [NASA (1965)].

c. Humidity

CRTs are very sensitive to humidity. The nominal resistance value \( R(300 \text{ K}) \) increases by 5 to 10% after the resistor has been soaked for 240 h at 95% humidity [Ricketson (1975)]. Since \( \Delta R/R \) is about the same at 77 K and at 300 K, the indication is that the absorbed water introduces, a temperature dependent resistance, i.e. changes in calibration come from changes in the exponential coefficient. The process is not reversible, but the resistance can be reduced by heating the unit.

d. Magnetic Field

The effects of magnetic fields on CRTs is discussed in Chapter 19.
11.6 Stability and Reproducibility

It is difficult to determine the extent of the repeatability of CRTs. Reports on repeatability vary widely, from ± 1 mK up to 2% change in resistance at 4.2 K. By cycling resistors between room temperature and the temperature of use, it is possible to select units that are stable to within 10 mK. Nevertheless, one must be alert for changes in the R-T characteristic. Provided that they are not mistreated between runs, both Allen-Bradley and Speer units will retain their calibration within about 1% over a two year span and 30 or 40 thermal cyclings.

When the resistance is monitored at a fixed temperature, a drift with time is observed which is mostly towards higher resistance, giving an apparent reduced temperature. It occurs in all units tested [Ricketson (1975), Johnson and Anderson (1971), Forgan and Nedjat (1981)]. For example, at 77 K, drift rates have been as high as 50 mK/h just after immersion, decreasing to 25 mK/day after a two-day soak. The higher the temperature sensitivity of the unit, the greater the drift in terms of $\Delta T/T$. This means that the problem becomes more serious for a given thermometer as the temperature is reduced. Resistors of the same nominal value and brand exhibited the same drift rates to within about 15%. Therefore, the drift is intrinsic to the resistance material itself and is probably associated with a decrease in carrier concentration.

An increase in the resistance at liquid helium temperature is always observed after the first few thermal cycles (2% for a 1000 $\Omega$ Allen-Bradley unit). The phenomenon is associated with carbon granule rearrangement due to thermal shocks. Typically, maximum changes observed for an Allen-Bradley unit of 220 $\Omega$ are 13 mK at 4.2 K, 337 mK at 20 K and 2 K at 60 K [Ricketson (1975)]. After nearly twenty thermal cyclings between low temperature and 300 K during two years, the change in resistance of Matsushita units have remained within 1.5% [Kobayasi et al. (1976)]. The observed instabilities can be roughly explained by the thermal history of the unit, remembering the extreme sensitiveness to annealing and thermal heating of a CRT.

Broadly speaking, CRTs are less stable by more than an order of magnitude than germanium thermometers. Considerable improvement might be achieved if the low-cost CRTs were treated with as much care as encapsulated germanium sensors. Nevertheless, it is always wise to check that the resistance has not drifted nor undergone a step change during measurements. Whether a carbon resistance thermometer requires a new
calibration after each cool-down depends upon the accuracy desired. In practice the calibration may be no better than several parts in $10^3$, in terms of $\Delta T/T$, so to obtain a thermometer capable of better reproducibility and stability than this after an arbitrary history, one should choose a unit having lower temperature sensitivity and sacrifice resolution. When recalibration is needed, it may be sufficient to check only a few points and to derive the new calibration curve from the original one.

11.7 Calibration and Interpolation Formulae

The lack of a simple R-T characteristic has limited large scale use of CRTs. Their initial low price is partially offset by the need for individual calibration. One of the advantages of the CRT is its smooth R-T dependence, close to exponential, without any higher-derivative irregularities. Nevertheless, none of the existing interpolation equations are sufficiently exact to allow precise measurement to better than $10^{-3}$ T over a wide range that includes temperatures above 20 K. Many of the various equations that have been used (summarized by Anderson (1972)) relate $\ln R$ to $1/T$ in some non-linear fashion, with the number of coefficients to be determined by calibration ranging from two to five depending upon the temperature range, the accuracy required, and the type of CRT. For their original empirical equation, which is still widely used

$$\ln R + \frac{C}{\ln R} = A + B/T \quad (11.1)$$

Clement and Quinnell (1952) found an accuracy of ± 0.5% in the range 2 K to 20 K when applied to a group of Allen-Bradley resistors. Schulte (1966) found Eq. (11.1) accurate to within several percent for 270 $\Omega$ Allen-Bradley resistors over the much wider range from 4 K to about 200 K when the three coefficients were obtained from least-squares fits to four calibrations at the boiling points of helium, hydrogen, and nitrogen, and at room temperature. On the other hand, when applied to some specially constructed resistors, Eq. (11.1) failed by up to 0.25 T, although replacement of the term in $(\ln R)^{-1}$ by one in $(\ln R)^2$ provided an interpolation accuracy of 0.3% from 4 K to 20 K.

Oda et al. (1974) found that Eq. (11.1) also fitted Speer Grade 1002, 1/2 W, 220 and 100 $\Omega$ CRTs from 1 K to 0.1 K but below 0.1 K the deviations became large. The equation
\[ \ln R = a (\ln T)^2 + b \ln T + c \quad (11.2) \]

fitted the experimental data from 1 K to 30 mK. Similarly, Kobayasi et al. (1976) found that Eq. (11.1) fitted Matsushita ERC 18 SG 1/8 W CRTs from 0.4 K to 4 K, but that Eq. (11.2) provided a better fit over the range 15 mK to 1 K.

It may be more economical in time to proceed to a least-square analysis with a polynomial relationship of the type

\[ \frac{1}{T} = \sum_{i=0}^{n} a_i (\ln R)^i \quad (11.3) \]

It is sufficient for most practical applications to limit the regression to third degree. With 15 to 30 experimental points, Kopylov and Mezhov-Deglin (1974) were able to describe the R-T characteristic of an Allen-Bradley 1/8 W, 40 \( \Omega \) CRT in the range 1.2 K to 8 K with an error less than the random error of the measurement. For calibrations to higher temperatures, Groger and Strangler (1974) used Eq. (11.3) with index \( i \) running from -1 to 3 and calibration at five temperatures and found a maximum error in computed temperatures of \( \pm 1.5 \) mK at 4.2 K, \( \pm 20 \) mK at 20 K, \( \pm 80 \) mK at 77 K, and \( \pm 400 \) mK at 190 K.
12. Carbon-Glass Resistance Thermometers

Lawless (1972) suggested that carbon-glass thermometers be used instead of the classical carbon thermometer because of the latter's instability. Some thermometers also exist that use plastic instead of glass [Besley (1983)], but they are not commonly available and so are not discussed here.

12.1 Fabrication

A porous glass is prepared by removing the boron-rich phase from a borosilicate alkaline glass to leave a material having the appearance of silicate spheres of about 30 nm diameter, randomly distributed and separated by 3 to 4 nm pores. The spaces are then partially filled with high-purity carbon to form amorphous fibres. The resulting material is cut in pieces of about 5 x 2 x 1 mm on which are deposited electrodes of Nichrome-gold to which copper leads are attached. The pieces are heated at 100 °C for 24 h to desorb gases and water vapour and are then sealed in platinum capsules under an atmosphere of helium. The amorphous nature of the carbon gives the advantage that the specimens have no piezoresistance, so there is no problem of mounting without constraint as there is for a germanium resistor; this shortens the response time.

The thermal capacity of these elements [Lawless (1981)] varies with temperature much like that of the silica substrate but it is more important at very low temperatures. Between 2 and 30 K, the quantity CT^-3 (where C is the heat capacity) passes through a maximum near 10 K of 50 x 10^-4 J kg^-1 K^-4, for example, for a specimen having a resistivity of 9 Ωcm at 4.2 K.

The carbon also plays a small role in the thermal conductivity. For the same specimen as above, the order of magnitude is 5 x 10^-2 Wm^-1K^-1.

12.2 Resistance- Temperature Characteristics; Sensitivity; Calibration

The resistivity of these thermometers is small; those available commercially have a resistivity of 10 to 25 Ωcm at 4.2 K, decreasing to 0.7 Ωcm at 300 K.

The resistance of carbon-glass thermometers decreases exponentially and slowly with increasing temperature so that the useful range of a given specimen is easily 1.5 K to 350 K (Fig. 12.1). Typical values of resistance are 2100 Ω at 4.2 K, 34 Ω at 77 K, and 17 Ω at 300 K.
Few measurements have been made using alternating current but the thermometers seem to be perfectly ohmic.

The carbon-glass thermometer sensitivity is compared with that of germanium and carbon thermometers in Fig. 11.2.

The sensitivity is a monotonic function of temperature, which permits calibration of thermometers using a semi-empirical equation of the form \( R = k_1 T^{-3/2} e^{-k_2/T} + k_3 T^{-k_4} e^{-k_5/T} \), and so avoiding interpolation with polynomials of high degree. On the one hand this reduces the number of calibration points necessary, and on the other the same formula is valid over a large temperature range within the measurement precision. For example, between 4.2 K and 30 K, a calibration has been obtained [Swartz et al. (1976)] with a standard deviation of 0.43 mK with the following formula:

\[
R = k_1 T^{-3/2} e^{-k_2/T} + k_3 T^{-k_4} e^{-k_5/T} \tag{12.1}
\]

\( k_1 = 7231.956 \); \( k_2 = 10.76346 \); \( k_3 = 727.7906 \)
\( k_4 = 0.4644607 \); \( k_5 = 6672207 \)

The carbon-glass elements are not interchangeable but for specimens i and j coming from the same batch it is possible to relate the calibration of one to the other by using the relation: \( R_i = a R_j^b \), where a and b are temperature-independent constants and b is near unity. The accuracy of this procedure is not yet truly established; its use has led to a standard deviation with respect to a classical calibration of \( 4 \times 10^{-3} \) in \( \ln R \).

12.3 Stability

Carbon-glass is not as stable as germanium. The behaviour of carbon-glass thermometers when thermally cycled is not identical from one specimen to another. Between room temperature and 4.2 K, instabilities have ranged from tenths of millikelvins to many dozens of millikelvins [Besley (1979)]. This suggests that the instabilities have a variety of causes, such as structural defects and diffusion of impurities due to the passage of electrical current. There appears to be no improvement of stability through aging the specimens. The thermometer resistance does not suffer from drift or abrupt jumps. The reproducibility suffices for most applications; for the most part it is of the order of 0.5 mK at 4.2 K, 10 mK at 20 K, and 60 mK at 77 K.
Fig. 12.1: Resistance-temperature characteristic of typical carbon-glass thermometer (solid circles) compared with that of germanium (broken curve) and two Allen-Bradley carbon thermometers (BB: 1/8 W; EG: 1/2 W) [Lawless (1972)].

Although less stable than germanium, carbon-glass thermometers are also less sensitive to a magnetic field, although in magnetic fields higher than 5 to 8 teslas capacitive thermometers are preferable (see Chapter 19).
13. Platinum-Cobalt Resistance Thermometers

The platinum-cobalt thermometer having a cobalt content of 0.5 atomic percent has been developed since 1978 (Shiratori and Mitsui (1978), Shiratori et al. (1982)). This type of thermometer is available in a standard capsule and in an IPRT-like package (stainless-steel hermetic case). Results of testing and an assessment of stability are available at present only for the industrial type: Shiratori et al. (1982) reported changes of less than 10 mK after several hundreds of cycles between room temperature and 4 K, and Pavese and Cresto (1984) confirmed this behaviour. When the thermometers are cycled between 77 K and 500 K (total heating time ~ 200 h), changes of $R(0 \, ^\circ C)$ are smaller than the equivalent of 100 mK and changes of $R(77 \, K)$ smaller than the equivalent of 30 mK. Most of the change occurs after the first 50 h of heating. Specific testing for reproducibility between 2 and 20 K [Sakurai and Besley (1985)] has confirmed reproducibility within ± 10 mK when the thermometer is cycled to room temperature, and has shown that it may improve to a few millikelvins if the thermometer need never return above 100 K.

Shiratori and Mitsui (1978) studied the resistance/temperature characteristic of the standard type and proposed as a reference function the following equation that fits the experimental points between 3 K and 27 K to within 10 mK:

$$\frac{R(T')}{R(0 \, ^\circ C)} = A_0 + A_1 T' + A_2 T'^3 \left(1 + B_1 T' + B_2 T'^2\right)$$

(13.1)

where $T' = T - 11.732 \, K$; $A_0 = 7.7510 \times 10^{-2}$; $A_1 = 8.6680 \times 10^{-4}$; $A_2 = 2.8377 \times 10^{-6}$; $B_1 = 2.3167 \times 10^{-2}$; $B_2 = 1.4370 \times 10^{-5}$.

For the industrial type, the manufacturer supplies a reference table of resistance versus temperature which matches any particular thermometer within ± 0.5 K (4-30 K) or ± 0.4 K (above 30 K). With three calibration points at 0 °C, 77.3 K and 4.2 K, the accuracy is claimed to improve to ± 0.1 K above 16 K and to ± 0.2 K between 4.2 K and 16 K (Shiratori et al. (1982)]. Between 2 K and 29 K a simple sixth-degree polynomial was found to fit the experimental data with a maximum deviation of ± 1 mΩ (equivalent to ± 10 mK) at the sensitivity minimum near 13 K. The estimated accuracy of the experimental data was ± 5 mK (Pavese and Cresto (1984)].

The commercially-available, standard-type platinum-cobalt thermometer is probably less reproducible than the corresponding rhodium-iron thermometer; its stability on thermal cycling is likely to be in the range of a few millikelvins.
14. Diode Thermometers

Diodes can be used above room temperature (e.g. in clinical thermometry) but not with sufficiently-high accuracy to be considered in this monograph. There is an extensive literature on semiconducting diodes with possible application as cryogenic thermometers [e.g. Swartz and Swartz (1974), Lengerer (1974), and Rubin and Brandt (1982)] but only two types intended for use as thermometers are commercially available: GaAs and Si. The temperature-indicating parameter is the forward-biased junction voltage, which decreases approximately linearly with increasing temperature when the current is kept constant.

Because of their almost trivial cost, silicon diodes mass-produced for the electronics industry have been widely tested as thermometers. They would have particular appeal in large engineering projects requiring hundreds of sensors. It turns out, however, to be very costly to select the very small percentage that are adequate for thermometric use. The following discussion does not apply to these devices, but to diodes that are manufactured for specific use as thermometers. There are some specific drawbacks to diode thermometers:

a) The typical I-V characteristic is such as to make the internal impedance of the device very high (easily greater than 100 kΩ) at small currents; or else - using a larger current - one encounters unacceptably high power dissipation at low temperatures.

b) There is a transition region in the conduction mechanism around 20 K that makes fitting a V-T characteristic over the whole temperature range difficult for GaAs and impossible for Si (Figs. 14.1 and 14.2).

For GaAs the least-squares fitted equation [Pavese (1974)]

\[ V = \sum_{i=0}^{7} A_i (\ln T')^i \]  \hspace{1cm} (14.1)

(\text{where } T' = (T/T_1) + 1) fits to within about ± 0.1 K (~ ± 100 parts per million in voltage) from 4 K to 300 K. For higher accuracy, the range is subdivided into two sections with the junction near 90 K. An effective equation for the two-range fitting is [Swartz and Gaines (1972)]:

...
Fig. 14.1: Voltage and sensitivity of a gallium arsenide diode as a function of temperature and current (labels on curves) [after Pavese and Limbarinu (1972)].

Fig. 14.2: Forward biased voltage of a silicon diode as a function of temperature. The lower temperature region is shown to larger scale in the inset [Lanchester 1989]].
Equation (14.2) fits experimental data to better than ± 15 mK below 54 K and ± 25 mK above 90 K.

With silicon diode thermometers, the complete range must be fitted in two sections, omitting a small range around 20 K where the thermometer cannot be used because of the afore-mentioned sharp change in slope. On either side of this critical region the V versus T characteristic is smooth, allowing non-critical fitting with simple polynomials. The fitting equations require a dozen or more calibration points, suitably spaced in temperature, in each range. An accuracy within ± 0.05 K cannot be obtained from calibration at a smaller number of fixed points.

No general statement can be made regarding the stability of diode thermometers. Selected ones can be as stable as ± 0.01 K on thermal cycling but much larger instabilities can occur unpredictably.

In zero magnetic field and below 20 K, diodes show high sensitivity associated with a readily-measurable voltage (millivolts in 1-2 V).
15. Liquid-in-Glass Thermometry

Even though the liquid-in-glass thermometer is used much less frequently today than formerly, it is still a very commonly used device. Although it is normally an instrument of only moderate accuracy, the very best of them, when used with sufficient attention to detail, have millikelvin capability over a narrow temperature range. Amongst its advantages are easy portability, independence of auxiliary equipment, low cost, compatibility with most environments, moderate ruggedness, and wide range (it has been used to measure temperatures as low as 70 K and as high as 1000 °C, but its most frequent use is within the range -40 °C to 250 °C). Disadvantages include a large sensing element, impossibility for continuous or automatic readout, long time constant, awkward dimensions, secular changes, and hysteresis (except for special types).

The components of a typical liquid-in-glass thermometer are shown in Fig. 15.1. These include:

Bulb: The reservoir for containing most of the thermometric liquid.
Stem: The glass tube having a capillary bore along which the liquid moves with changes in temperature.
Auxiliary Scale: A narrow-temperature-range scale for reading a reference temperature (usually the ice point). It should be marked as for the main scale (below). If the main scale range includes the reference temperature no auxiliary scale is supplied.
Contraction Chamber: An enlargement of the capillary bore between the auxiliary and main scales, or between the reservoir and the main scale, to limit the length of the capillary (and hence the thermometer).
Immersion Line: A line marking the depth to which a partial-immersion thermometer should be immersed.
Main Scale: An engraved, etched, or otherwise permanently attached scale with well-defined, narrow graduation lines against which the height of the liquid in the capillary is measured. There may be a colored backing material for better visibility of the lines. The main scale is graduated in fractions or multiples of degrees Celsius. If its range incorporates the reference temperature, it is the only scale.
Fig. 15.1: Principal features of a solid-stem liquid-in-glass thermometer [after Wise (1976)].

Fig. 15.2: Illustrating the proper immersion techniques for the three types of liquid-in-glass thermometers. The arrow shows the location of the meniscus in each case.
Expansion Chamber: An enlargement at the top of the capillary into which the liquid can flow if the thermometer temperature exceeds the scale limit. It is undesirable for liquid to enter the expansion chamber, however, so it is much better to ensure that there is no overheating of the thermometer. The expansion chamber also prevents excessive gas pressure when the thermometer is used near the top of its range, especially in high-temperature pressurized thermometers.

The range of a liquid-in-glass thermometer is limited by the liquid, by the glass, and by the construction. The commonest and best liquid is mercury. The recommended range of use is from near the mercury freezing point (-38 °C) to about 350 °C with soda-lime glasses; higher temperatures require borosilicate or other special glasses. The capillary above the mercury is filled with a dry gas (frequently nitrogen) to prevent separation of the column and to inhibit distillation of the mercury; in the higher-temperature models, substantial gas pressures are required to raise the mercury boiling point above the range of the thermometer. Air is not a good filling gas because it may lead to oxidation of the mercury and consequent sticking of the latter in the capillary. A eutectic alloy of mercury containing 8.5 weight percent of thallium is used to extend the lower temperature limit to -56 °C; commonly the upper limit is at or a little above 0 °C to allow for ice-point reference checks. Organic liquids are used in thermometers for lower temperatures (alcohol, toluene, pentane, butane), in some cases down to -200 °C. These lower-temperature thermometers suffer from drainage problems associated with the low surface tension of the liquids and from vaporization; they are less reliable than mercury thermometers where the latter can be used.

Thermometers are designed and calibrated for vertical immersion of the bulb and stem to the top of the liquid column (total immersion), of the bulb and stem to the immersion line (partial immersion), or of the whole thermometer (complete immersion). These three types are illustrated in Fig. 15.2. The total-immersion type is the most accurate and is recommended wherever possible; the complete-immersion type is the least common.

For calibration, the ice (or other reference) point is always taken first, but not before the thermometer has been at least 72 h at room temperature. Suitable preparation of an ice bath is described in Supplementary Information. The thermometer must be allowed to attain thermal equilibrium with the ice and should be gently tapped with the fingernail or a pencil to ensure a non-sticking meniscus before reading.
For a thermometer graduated above 300 °C, a requisite quality check is to raise its
temperature to the highest point on the scale immediately after taking the ice point, then to
allow a rest period of three days at room temperature and to take a second ice point. If the
agreement between the first and second ice points is not within the stated accuracy limit of
the thermometer, the thermometer should be discarded. Following the ice-point checks, the
thermometer is calibrated from the lowest to the highest temperature against a laboratory
standard in a suitable bath. Readings may be taken with the bath temperature slowly
increasing to ensure that the meniscus is fully convex (less than one scale division per five
minutes is recommended to ensure that the exposed stem remains in thermal equilibrium) or
with the bath stabilized at the calibration temperature. In the latter case, bath-temperature
excursions should be smaller than the precision of reading and the thermometer should be
tapped before reading. After calibration at the highest temperature, the ice point should be
retaken after the thermometer has had time (in hours, approximately $t_{\text{max}}/100$) to relax back
to its static condition.

Calibration temperatures should be approximately equally spaced, their number
depending upon the thermometer range, the accuracy required and the scale graduation
interval. Calibration every 50 to 100 scale divisions should give an accuracy within one-half
of one division. For linear interpolation between calibration points on a plot of scale
correction versus temperature, the uncertainty is about one-half the largest discrepancy
found by extrapolating each linear segment to the next calibration point.

A thermometer calibration applies as long as the ice-point reading remains the same
as during calibration. Subsequent changes in the ice-point reading will result from small
changes in the glass of the thermometer bulb which affect its volume. Volume changes in
the capillary are minimal by comparison and, as a result, changes in the ice-point reading of
the thermometer (taken after not less than 3 days at room temperature) will be accompanied
by similar changes in readings at each point along the scale. The ice point should be taken
periodically, and scale corrections adjusted as necessary. If the ice point change is too large,
the thermometer must be recalibrated. How large a change is “too large” depends upon the
application and the type of thermometer.

Parallax errors of many tenths of a division may easily occur in reading a liquid-in-
glass thermometer. To avoid them one must view the thermometer from exactly the same
angle as was used for calibration, virtually always perpendicular to the liquid column. One of
the better ways of avoiding parallax and at the same time obtaining a precise reading is to
view the thermometer through a telescope which is aligned at the proper angle, or through a
magnifying lens attached to the thermometer. In the latter case, lack of parallax is indicated
by a straight (as opposed to curved) image of the graduation mark. In
the former case, a cross-hair can be centered by eye very accurately at the midpoint between the scale lines; if this is done, a good scale can be read to better than 1/20 division. For this reason it is recommended not to use too sensitive a thermometer; any attendant gain in sensitivity is outweighed by lack of stability, lack of linearity, increased fragility, and smaller temperature range of use. Similarly, it is recommended not to use a thermometer with graduations smaller than 1/10 °C, even if it is desired to measure temperatures to within a few hundredths oC.

With a partial-immersion thermometer, the average temperature \( t_c \) of the emergent stem (that part of the stem between the point of immersion and the top of the liquid column) during calibration should be stated. In subsequent use the average emergent-stem temperature \( t_s \) should be measured [Wise (1976)] and an additional correction \( \Delta t \) added to the reading, where \( \Delta t \) is given by

\[
\Delta t = k n (t_c - t_s) .
\]  

(15.1)

In Eq. (15.1) \( n \) is the equivalent number of degrees of the emergent stem and \( k \) is the differential coefficient of thermal expansion of the thermometer liquid relative to the thermometer glass. For mercury in pyrex for example, \( k = 1.6 \times 10^{-4}/°C \); for organic liquids \( k \approx 10^{-3}/°C \). Variations of coefficient of expansion among glasses are negligible in this connection.

A similar correction applies if a total-immersion thermometer is used at partial immersion, where now for \( t_c \) in Eq. (15.1) the temperature of the thermometer bulb is used.

The readings of a liquid-in-glass thermometer change with changes in both internal and external pressure: the former include change in bulb pressure resulting from the head of mercury in the capillary and from change of temperature of the gas above the mercury; the latter are usually due to variations in atmospheric pressure and in depths of immersion. Since there are approximately "6000 °C of mercury" contained in the bulb, obviously a small change in bulb volume can cause a large change in reading. The external pressure coefficient of a mercury-in-glass thermometer depends upon the internal and external bulb radii, and is usually about \( 1 \times 10^{-6} °C/Pa \). The internal pressure coefficient is about 10% larger.

Changes in bulb volume also occur because of both irreversible (secular) and reversible (temporary depression) structural changes in the glass that are influenced by time and heat treatment respectively. The secular change is almost always a slow contraction of the bulb, producing an increased thermometer reading. The rate of secular
rise decreases with time but increases with exposure of the thermometer to high temperatures. The maximum secular rise is unlikely to exceed 0.1 °C over several years in well-constructed thermometers provided the glass is not heated beyond its exposure limit. The reversible changes appear as a hysteresis on thermal cycling. The bulb expands on exposure to high temperatures and does not return to its original volume immediately on cooling, resulting in a depression of the ice-point reading (and all other readings). Recovery may not be complete for 24 to 72 hours or, if the thermometer is cooled very slowly, no depression may occur. It is to monitor and correct for these changes in bulb volume that ice points are taken before and after calibration, as described earlier. In a good thermometer the temporary depression is small.

For a variety of reasons the mercury in the capillary tube may become separated, leading to spurious readings until the separation is removed. Methods for doing this are described by Ween (1968); among these are centrifuging, shaking, rejoining in the contraction chamber or in the bulb, and (a very slow process) distillation. Ice-point checks are an easy way of detecting abnormal thermometer behaviour: a substantial increase in ice-point reading frequently indicates a separated column; a substantial decrease may mean that mercury is trapped in the expansion chamber or that the thermometer has been overheated. A small amount of mercury trapped in the expansion chamber can be detected by careful visual observation.

16. Industrial Platinum Resistance Thermometers

Industrial platinum resistance thermometers (IPRTs) are constructed from platinum of a lower quality than is used for SPRTs; typically, values of $W(H_2O \text{ b.p.)}$ range from 1.385 to 1.3925 and values of residual resistance from $10^{-3}$ to $2 \times 10^{-2}$. Since IPRT design must provide sufficient reproducibility in the presence of shocks, vibration, high pressure and other hostile environments such as are found in industrial applications, it does not comply with some requirements of the ITS-90, such as strain-free mounting of the wire. Therefore IPRTs are less reproducible than SPRTs. Nevertheless, it is possible to select IPRTs that are only an order of magnitude less reproducible than SPRTs and in a restricted temperature range this difference might be even smaller. In particular environments an IPRT can be even more reproducible than an SPRT where, of course, an SPRT would not be considered for use anyway. Although this chapter delineates many of the drawbacks of IPRTs, we must emphasize that they are among the most-commonly-used thermometers. It is possible to purchase IPRT elements of a selected design or configuration at relatively low cost, to assemble them into sheaths with a minimum of laboratory practice, to anneal them at 450 °C, and finally to calibrate them according to one of the proposed schemes and so obtain an approximation to the ITS-90 to within about ± 50 mK between -180 to 0 °C, and within about ± 10 mK between 0 and 420 °C [Actis and Crovini (1982), Bass and Connolly (1980), and Connolly (1982)].

16.1 Quality of Industrial Platinum Resistance Thermometers

IPRTs are manufactured in a great variety of models and the actual fabrication has a definite influence on their metrological quality. The accuracies discussed in Section 16.2 for IPRTs can be achieved only with thermometers that are suitably stable. This variability led to the specifications codes discussed in Section 16.3 which allow a minimum level of uniformity in the thermometer characteristics. The tolerances allowed are wide (~ 0.2 °C to 2 °C), however, so they are satisfactory only for the more common industrial uses.

A wide variety of techniques have been devised for winding the platinum wire (Fig. 16.1 a). Many thermometers are formed by winding a fine wire or coil on a glass support and imbedding the winding in glass. This can introduce strain into the wires and cause contamination of the wires at higher operating temperatures. The configuration so far introduced that offers the best stability [Actis and Crovini (1982)] and the lowest hysteresis [Curtis (1982)] is that in which a platinum coil is supported inside the
Fig. 16.1: (a) Fabrication of IPRTs: wire-wound;
Fig. 16.1: (b) Fabrication of IPRTs: thick film [Curtis (1982)].
capillaries of a twin- (or four-) bore, high-purity-alumina insulator. Either the use of a cement to clamp one side of the coil to the capillary wall or, preferably, the insertion of soft alumina powder prevents the platinum coil from vibrating freely and helps in achieving good reproducibility in industrial applications. IPRTs having the platinum wire fully embedded in cement or hard glass (as above) and thick-film IPRTs (as below) do not afford a comparable reproducibility. Advances in thick film technology led to the development of resistance thermometers having a deposited platinum ink as the detecting element, rather than a platinum wire. These films are deposited on ceramic wafers in a variety of forms (Fig. 16.1b), including the standard detector size of 3 mm diameter by 25 mm long. They also match the specifications of the national and international codes. One advantage of film sensors appears to be that they are less susceptible to mechanical shock and so are more rugged than conventional wire-wound detectors. However, they can suffer from strain due to differential thermal expansion.

16.1.1 Stability

A wire-wound thermometer is a delicate instrument since strain in the platinum wire causes a change in electrical resistance and so a shift of the W(T) versus T relationship. Also, change in impurity concentration (such as oxidation) affects the thermometric properties [Berry (1982a), (1982b)]. Therefore PRTs should be tested for stability with time on thermal cycling between extreme temperatures in the expected range of operation. For example, Mangum and Evans (1982) investigated the stability upon thermal cycling and handling of 60 IPRTs from 5 manufacturers. Most of them exhibited calibration drifts, instability caused by moisture, and hysteresis. After cycling to 235 °C, one-half of the thermometers showed changes in R(0 °C) larger than the equivalent of 15 mK and one-quarter larger than 50 mK. Comparable results were obtained in other experiments [Sinclair et al. (1972), Curtis (1982)]. Actis and Crovini (1982), Connolly (1982) and Bass and Connolly (1980), on the other hand, found rather better behaviour. Most of the national codes give tolerances for the permitted variation in resistance after a given number of thermal cycles.

IPRTs exhibit hysteresis on thermal cycling; this means that the IPRT may have different but reproducible R vs T relationships depending upon the thermal history of the thermometer and on whether a given temperature is being approached from lower or higher temperatures [Curtis (1982)]. A typical example is shown in Fig. 16.2. The span or width of the hysteresis loop can be correlated with W(H₂O b.p.) as shown in Fig. 16.3. For different thermometer constructions the hysteresis effect can be different. The user is
Fig. 16.2: A typical example of hysteresis in an IPRT [Curtis (1982)].

Fig. 16.3: Correlation between width of hysteresis loop and $R(\text{H}_2\text{O b.p.})/R(0 \, ^\circ\text{C})$ for industrial platinum resistance thermometers cycled between -200 °C and : 200 °C [after Curtis (1982)].
advised to choose the thermometer type that exhibits the smallest hysteresis span. Similar effects have been observed by Besley and Kemp (1983) and Chattle (1977) on cycling between 100 °C and -200 °C.

It follows then that a procedure should be developed to bring the IPRTs into a stable state that is needed for accurate measurements. Since the hysteresis behaviour is caused by reversible changes in resistance from annealed to strained conditions in the platinum (at least below the temperature range where hysteresis due to reversible oxidation of the platinum can also occur), this means that the IPRT must be strained for work below room temperature and annealed for work above room temperature and, subsequently, all thermal cycling must never exceed the limits of this stabilization thermal cycle. Consequently, since the thermometer is almost always stored at room temperature, this temperature must not be substantially crossed after stabilization at any temperature below 100 K (strained) or at 200 °C to 450 °C (annealed).

Another reason for hysteresis is connected with moisture inside the encapsulation (most of the IPRTs are not hermetically sealed) [Mangum (1984)] which acts as a shunting resistance on the platinum wire. Moisture was observed to produce changes as large as 35 mK on sensor cycling between 0 °C and 40 °C. Moisture (69% of the cases) rather than strain (19% of the cases) was believed to account for most of the drift in IPRTs as a result of tests on 94 IPRTs in the range 0°-100 °C (and with annealing up to 235 °C).

IPRTs are generally produced to match the (inter-) national codes but the production is not 100% reliable [Chattle (1975)]. Tests are therefore necessary to select thermometers that match within closer tolerances.

Many experiments have been done, especially below 650 °C, to evaluate the stability of IPRTs (the distinction between instability and hysteresis is slight, but the latter is considered to be reversible). These have involved, in total, about 250 thermometers in about 80 batches and models from most of the manufacturers. Most of the thermometers had R(0 °C) = 100 Ω, and most of the tests were in the range -50 °C to 250 °C. There was not much uniformity in the results. Some thermometers were stable to within 5 mK, many to within 10 mK, and most to within 50 mK. Increasing the test range to 420 °C did not affect the results much. Instability increases rapidly at higher temperatures; drifts in R(0 °C) equivalent to from 0.2 K to several kelvins can be expected. Figures 16.4-16.7 show examples of instability in tests of various batches of thermometers.

16.1.2 Self-heating

In measuring the electrical resistance of the thermometer it is impossible not to dissipate thermal energy by Joule heating. Consequently there exists a difference between
Fig. 16.4: Histogram showing the amount of the shift in $R(0 \, ^{\circ}C)$ after a single exposure to liquid oxygen following stabilization at 450 °C for a group of 18 industrial platinum resistance thermometers having $R(0 \, ^{\circ}C) = 100 \, \Omega$ [Actis and Crovini (1982)].

Fig. 16.5: Changes in $R(0 \, ^{\circ}C)$ for seven industrial platinum resistance thermometers after 10 cycles between 20 °C and -196 °C (with occasional measurement also of $R(100 \, ^{\circ}C)$: A, measurement of $R(0 \, ^{\circ}C)$; B, measurement of $R(100 \, ^{\circ}C)$; C, measurement of $R(0 \, ^{\circ}C)$; D, ten cycles between 293 K and 77 K; E, measurement of $R(0 \, ^{\circ}C)$; F, ten cycles between 293 K and 77 K; G, measurement of $R(0 \, ^{\circ}C)$; H, ten cycles between 293 K and 77 K; J, measurement of $R(0 \, ^{\circ}C)$; K, measurement of $R(100 \, ^{\circ}C)$; L, measurement of $R(0 \, ^{\circ}C)$; M, ten cycles between 293 K and 77 K; N, measurement of $R(0 \, ^{\circ}C)$; [after Besley and Kemp (1983)].
Fig. 16.6: Distribution of the rate of drift of R(0 °C) due to exposure to 260 °C for up to 100 hours for a group of 87 IPRTs [Connolly (1982)].

Fig. 16.7: Histogram of the maximum equivalent temperature change in R(0 °C) during ten 24 hour exposures to 235 °C for a group of 98 IPRTs [Mangum (1984)].
the temperature of the thermometer and that of the medium being measured. This difference is a function of the thermal characteristics of the thermometer and its coefficient of thermal exchange with the medium. It is proportional to the square of the thermometer current \(i\). Commonly, the PRT resistance is measured at 1 mA and \(\sqrt{2}\) mA, plotted as a function of \(i^2\), and extrapolated linearly to 0 mA. One can therefore evaluate the influence of the self-heating by measuring the variation of thermometer resistance with measuring current.

### 16.1.3 Response Time

Just as with self-heating, the response time of a thermometer depends upon both the characteristics of the thermometer and of the medium in which it is immersed. There are two methods to determine the response time. The first consists of immersing the thermometer in a fluid, measuring the response time under these conditions, and then by similarity deducing the response time in the medium to be used. The second method consists of studying, in situ, the response of the thermometer by using the thermometer resistance itself as a heating element. Then, by analyzing this response one can obtain the response time through the use of an algorithm [e.g. Kerlin et al. (1982)].

### 16.2 Interpolation Equations for Industrial Platinum Resistance Thermometers*

In principle, any of the approximations of Section 8.2 can also be used with IPRTs, although within some (generally unknown) broader limits of accuracy, but in practice few of them have been. Recall also that the techniques described here have been tested for sensors mounted by the experimenters in suitable glass or metal sheaths and not in the manufacturers' rugged sheaths meant for industrial applications. It is not known if the same accuracies apply in the latter case. No simple approximation for use above about 200 °C is yet available. The two most-used techniques are:

(a) Polynomials for \(W(t_{68})\) versus \(t_{68}\):

For secondary realizations extending above 0 °C it is possible to interpolate between fixed-point measurements with polynomials relating \(W(t_{68})\) to \(t_{68}\) similar to the defining equations of the IPTS-68. There are two distinctly different aspects that limit the accuracy of such realizations: one is the inherent irreproducibility of the IPRTs themselves, both repeatedly with one thermometer

* As in Section 8.2, these approximations were originally devised with reference to the IPTS-68, and so many of the equations in this section still carry an IPTS-68 designation. Generalization to the ITS-90 is straightforward.
and between different thermometers; the other is the indifferent agreement of the interpolating equation with the IPTS-68. There are not many data available on the accuracy that may be obtained. Actis and Crovini (1982) use the equations

\[ W(t') = 1 + At' + Bt'^2 \]  

(16.1)

\[ t = t' + \gamma \left( \frac{t}{100^\circ C} - 1 \right) \left( \frac{t}{t_2} - 1 \right) \frac{t}{630.74^\circ C} - 1 \]  

(16.2)

where \( t_1 \) and \( t_2 \) are the temperatures of the fixed points used to evaluate A and B, and \( \gamma \) is a constant determined by calibration at a third fixed point. They tested these equations with 20 IPRTs from 6 manufacturers over the temperature ranges 0 °C to 420 °C or 0 °C to 330 °C, depending upon the particular IPRT. They found rather close agreement between the calibration constants of all thermometers but one, although two had to be calibrated in a restricted range. For a subgroup of 15 IPRTs from 5 manufacturers, all having the same configuration (sensing element diameter between 2.5 and 3.5 mm, length between 15 and 30 mm, multi-bore alumina insulator containing a minimally constrained platinum coil, operation up to 500 °C) the agreement provided by Equations 16.1 and 16.2 was better. In the range from 0 °C to 420 °C, with A, B and \( \gamma \) determined from calibrations at the steam, zinc, and tin points respectively, the 15 thermometers showed a mean difference with respect to the IPTS-68 of \((3.6 \pm 2.7)\) mK at 327 °C and of \((-4.2 \pm 1.5)\) mK at 150 °C (one-standard-deviation estimates). The stability of R(0 °C) for these IPRTs upon repeated cycles between 0 °C and 450 °C and 0 °C and -190 °C was always inside \( \pm 5 \) mK, and for 13 of them better than \( \pm 2 \) mK. If Eq. (16.2) was omitted, the differences with respect to the IPTS-68 at 327 °C and 150 °C were \((45 \pm 5.9)\) mK and \((16 \pm 1.8)\) mK respectively. In this latter case, a maximum difference of about 50 mK was reached between 250 °C and 300 °C. Using both equations with different calibration points, provided they were reasonably spaced, produced equivalent results.

(b) Besley and Kemp (1983) investigated a group of 27 IPRTs having \( W(H_2O \ b.p.) \) in the range 1.3912 to 1.3923. They first stabilized the ice-point resistance of the thermometers by thermal cycling between 77 K and 273 K. They then used the ice point and the oxygen boiling point as the reference temperatures in a Z-function (Eq. 8.5) related to T by
\[ Z(T) = \sum_{i=0}^{8} a_i T^i \]  

(16.3)

and found an inaccuracy of ± 0.035 K from 70 K to 273 K.

(c) A simple polynomial fit of degree 2 to 4 for \( W(t) \) against \( t \) is frequently a good approximation depending upon the range and the number of calibration points. Calibrations accurate to within ± 20 mK can usually be obtained with a quadratic fit to 5 to 10 points in the range -50 °C to 200 °C. Connolly (1982) and Bass and Connolly (1980) found that a cubic equation

\[ W(t) = 1 + at + bt^2 + ct^3 \]  

(16.4)

fitted 87 wire-wound IPRTs (that came largely from one manufacturer) from 0 °C to 250 °C to within ± 10 mK. Selected thermometers were better than this. However, with thick film sensors the uncertainty was as high as ± 35 mK.

(d) Above 100 K the Callendar and Callendar-Van Dusen equations can be used with IPRTs with the coefficients determined from least-squares fits to calibrations at from 5 to 15 temperatures, depending upon the range. Such fits are typically uncertain to a few tens of millikelvins.

16.3 National and International Specifications for IPRTs*

Various organizations, including the International Electrotechnical Commission (IEC) and the International Organization of Legal Metrology (OIML), have promulgated specifications and manufacturing tolerances for IPRTs*. The relationship between \( R \) and \( t_{68} \) is generated from the Callendar and Callendar-Van Dusen equations

\[ \frac{R(t_{68})}{R(0 \, ^{\circ}C)} = 1 + At_{68} + Bt_{68}^2 \quad t_{68} \geq 0 \, ^{\circ}C \]  

(16.5)

and

\[ \frac{R(t_{68})}{R(0 \, ^{\circ}C)} = 1 + At_{68} + Bt_{68}^2 + Ct_{68}^3 \quad (t_{68}-100 \, ^{\circ}C) \quad t_{68} < 0 \, ^{\circ}C . \]  

(16.6)

Two sets of values of the coefficients \( A, B, C \) typical of IPRTs with \( W(H_2O \, b.p.) = 1.385 \) and 1.391 respectively are used (Tables 16.2, 16.3). The equation (or tables derived

* Since these international specifications and tolerances have not yet been reformulated to refer directly to the ITS-90, they are summarized here with their IPTS-68 designations.
therefrom) can then be used with any IPRT that has the specified \( R(0 \, ^{\circ}C) \) and \( W(H_2O \text{ b.p.}) \) to give temperatures accurate to within specified tolerances. These tolerances (the ones specified by IEC (1983) are shown in Fig. 16.8) vary with the temperature, having minimum values of a few tenths of a \(^{\circ}C\) at 0 \(^{\circ}C\), rising to about \( \pm 0.5 \, ^{\circ}C \) (Class A) and \( \pm 1.3 \, ^{\circ}C \) (Class B) at -200 \(^{\circ}C\) and to several \(^{\circ}C\) above 600 \(^{\circ}C\). These, naturally, are much larger than the uncertainty that results with a calibrated thermometer. The thermometer specifications currently and formerly issued by various standards organizations are summarized in Table 16.1. If one IPRT is interchanged for another nominally the same, temperature readings can differ by up to several degrees, depending upon the value of temperature. The tables issued by OIML (1985) for platinum with values of \( W(H_2O \text{ b.p.}) = 1.385 \) and 1.391 are reproduced here as Tables 16.2 (the same numerically as the equivalent table of IEC (1983)) and 16.3 respectively. The tables are in the form of \( R(t_{68})/R(0 \, ^{\circ}C) \) as a function of temperature.
Table 16.1: Summary of Current and Past IPTS Specifications

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<td>10, 46, 100</td>
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<td>± 0.06</td>
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<td>± 0.3</td>
<td>~ 0.03</td>
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<td>± 0.12</td>
<td>± 0.12</td>
<td>± 0.3</td>
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<tr>
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<td>α (°C⁻¹)</td>
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<td>3.85×10⁻³</td>
<td>3.85×10⁻³</td>
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<td>A (°C⁻¹)</td>
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<td>(Type I)</td>
<td>3.968 35×10⁻³</td>
<td>3.908 02×10⁻³</td>
<td>3.974 78×10⁻³</td>
<td>3.981 53×10⁻³</td>
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<td>B (°C⁻²)</td>
<td>-5.802 ×10⁻⁷</td>
<td>(Type I)</td>
<td>-5.8394 ×10⁻⁷</td>
<td>-5.801 95×10⁻⁷</td>
<td>-5.8775 ×10⁻⁷</td>
<td>-5.8531 ×10⁻⁷</td>
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<td>(Type I)</td>
<td>-4.3557 ×10⁻¹²</td>
<td>-4.2735 ×10⁻¹²</td>
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<td></td>
<td>(Type II)</td>
<td>3.968 47×10⁻³</td>
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<td>-5.847 ×10⁻⁷</td>
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<tr>
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<td>(Type II)</td>
<td></td>
<td>(Type II)</td>
<td>-4.3558 ×10⁻¹²</td>
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</tbody>
</table>

* BS = British Standard
DIN = Deutsches Institut für Normung
GOST = (All-Union State Standard, USSR)
IEC = International Electrotechnical Commission
OIML = International Organization for Legal Metrology
JEMIMA = Japanese Standard
SAHA = Scientific Apparatus Makers of America

** Type I refers to thermometers with α = 3.85×10⁻³ °C⁻¹ and Type II to thermometers with α = 3.91×10⁻³ °C⁻¹.
Class A and Class B refer to accuracy tolerances, A being the higher.
Table 16.2

RESISTANCE RATIOS FOR INDUSTRIAL PLATINUM RESISTANCE THERMOMETERS WITH \( R(100\, ^\circ C)/R(0\, ^\circ C) = 1.3850 \)

Interpolation equation for the temperature range from -200 to 0 °C: \( R(t_{\text{ref}})/R(0\, ^\circ C) = 1 + A t_{\text{ref}} + B t_{\text{ref}}^2 + C (t_{\text{seg}} - 100) t_{\text{ref}}^2 \)

Interpolation equation for the temperature range from 0 to 850 °C: \( R(t_{\text{ref}})/R(0\, ^\circ C) = 1 + A t_{\text{ref}} + B t_{\text{ref}}^2 \)

where

\[
\begin{align*}
A &= 3.90002 \times 10^{-3} \quad \text{°C}^{-1} \\
B &= -5.8220 \times 10^{-7} \quad \text{°C}^{-2} \\
C &= -4.274 \times 10^{-12} \quad \text{°C}^{-4}
\end{align*}
\]

| \( t_{\text{seg}} \) (°C) | 0    | -5   | -10  | -15  | -20  | -25  | -30  | -35  | -40  | -45  | -50  | -55  | -60  | -65  | -70  | -75  | -80  | -85  | -90  | -95  | -100 |
|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| -100              | 0.6025 | 0.5822 | 0.5619 | 0.5415 | 0.5211 | 0.5006 | 0.4800 | 0.4594 | 0.4387 | 0.4178 | 0.3971 | 0.3763 | 0.3553 | 0.3343 | 0.3132 | 0.2920 | 0.2708 | 0.2494 | 0.2280 | 0.2065 | 0.1849 |
| 0                 | 1.0000 | 0.9884 | 0.9609 | 0.9412 | 0.9215 | 0.9019 | 0.8822 | 0.8625 | 0.8427 | 0.8229 | 0.8031 | 0.7832 | 0.7633 | 0.7433 | 0.7233 | 0.7033 | 0.6833 | 0.6631 | 0.6430 | 0.6228 | 0.6025 |

<table>
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<tr>
<th>( t_{\text{seg}} ) (°C)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
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<td>0</td>
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<td>1.0195</td>
<td>1.0390</td>
<td>1.0585</td>
<td>1.0779</td>
<td>1.0973</td>
<td>1.1167</td>
<td>1.1361</td>
<td>1.1554</td>
<td>1.1747</td>
<td>1.1940</td>
<td>1.2132</td>
<td>1.2324</td>
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<tr>
<td>100</td>
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<td>1.4039</td>
<td>1.4229</td>
<td>1.4417</td>
<td>1.4606</td>
<td>1.4794</td>
<td>1.4982</td>
<td>1.5170</td>
<td>1.5358</td>
<td>1.5545</td>
<td>1.5731</td>
<td>1.5918</td>
<td>1.6104</td>
<td>1.6290</td>
<td>1.6476</td>
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<td>1.7768</td>
<td>1.7951</td>
<td>1.8134</td>
<td>1.8317</td>
<td>1.8498</td>
<td>1.8662</td>
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<td>1.9218</td>
<td>1.9407</td>
<td>1.9558</td>
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<td>2.1575</td>
<td>2.1736</td>
<td>2.1912</td>
<td>2.2088</td>
<td>2.2265</td>
<td>2.2441</td>
<td>2.2617</td>
<td>2.2792</td>
<td>2.2966</td>
<td>2.3142</td>
<td>2.3317</td>
<td>2.3491</td>
<td>2.3665</td>
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<tr>
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<td>2.4876</td>
<td>2.5048</td>
<td>2.5219</td>
<td>2.5390</td>
<td>2.5561</td>
<td>2.5732</td>
<td>2.5902</td>
<td>2.6072</td>
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<td>3.8292</td>
<td>3.8440</td>
<td>3.8587</td>
<td>3.8733</td>
<td>3.8880</td>
<td>3.9026</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Tables corresponding to various national specifications can be generated using the coefficients given in Table 16.1.
Table 16.3

RESISTANCE RATIOS FOR PLATINUM RESISTANCE THERMOMETERS WITH $R(100 \, ^\circ C)/R(0 \, ^\circ C) = 1.3910$

Interpolation equation for the temperature range from -200 to 0 °C: $R(t_{ref})/R(0 \, ^\circ C) = 1 + A + Bt_{ref} + Ct_{ref}^2$

from 0 to 850 °C: $R(t_{ref})/R(0 \, ^\circ C) = 1 + At_{ref} + Bt_{ref}^2$

where

- $A = 3.98868 \times 10^{-5} \, ^\circ C^{-1}$
- $B = -5.6677 \times 10^{-7} \, ^\circ C^{-2}$
- $C = -4.141 \times 10^{-11} \, ^\circ C^{-4}$

<table>
<thead>
<tr>
<th>$t_{ref}$ (°C)</th>
<th>-100</th>
<th>-90</th>
<th>-50</th>
<th>-45</th>
<th>-35</th>
<th>-30</th>
<th>-25</th>
<th>-20</th>
<th>-15</th>
<th>-10</th>
<th>0</th>
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</thead>
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<tr>
<td>10</td>
<td>0.5964</td>
<td>0.5758</td>
<td>0.5552</td>
<td>0.5345</td>
<td>0.5137</td>
<td>0.4929</td>
<td>0.4721</td>
<td>0.4511</td>
<td>0.4302</td>
<td>0.4091</td>
<td>0.3880</td>
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<td>0.9801</td>
<td>0.9603</td>
<td>0.9403</td>
<td>0.9204</td>
<td>0.9004</td>
<td>0.8804</td>
<td>0.8604</td>
<td>0.8403</td>
<td>0.8202</td>
<td>0.8000</td>
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</table>

<table>
<thead>
<tr>
<th>$t_{ref}$ (°C)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>40</th>
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<th>70</th>
<th>80</th>
<th>90</th>
<th>95</th>
<th>100</th>
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</thead>
<tbody>
<tr>
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<td>1.0000</td>
<td>1.0198</td>
<td>1.0396</td>
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<td>1.0791</td>
<td>1.0989</td>
<td>1.1185</td>
<td>1.1382</td>
<td>1.1578</td>
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<td>1.1970</td>
<td>1.2165</td>
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<td>1.4295</td>
<td>1.4486</td>
<td>1.4678</td>
<td>1.4870</td>
<td>1.5060</td>
<td>1.5251</td>
<td>1.5441</td>
<td>1.5631</td>
<td>1.5821</td>
<td>1.6010</td>
<td>1.6200</td>
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<tr>
<td>20</td>
<td>1.7703</td>
<td>1.7899</td>
<td>1.8075</td>
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<td>1.8447</td>
<td>1.8632</td>
<td>1.8818</td>
<td>1.9002</td>
<td>1.9187</td>
<td>1.9371</td>
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<td>3.9494</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Tables corresponding to various national specifications can be generated using the coefficients given in Table 16.1.
Fig. 16.8: Tolerances for industrial platinum resistance thermometers as specified by IEC (1983).
17. Thermistors

The term thermistor refers to semiconducting ceramic materials, generally oxides, acting as sensing elements of devices for measuring temperature. A very extensive literature is available on this subject: especially valuable is a book by Sachse (1975), and many papers in Temperature, Its Measurement and Control in Science and Industry, Vol. 4 (1972) and Vol. 5 (1982).

It is difficult to discuss thermistors within the framework of this document; their characteristics are much more device-dependent than those of other thermometers, so their properties must be related to specific commercial devices and a general description cannot be given in terms of materials, at least for a moderately high level of accuracy. On the other hand, the thermistor is very widely used and may show a stability comparable with that of an IPRT.

The range of use of each particular thermistor is narrow since the resistance/temperature relationship is exponential of the form

\[ R = R_0 \exp[-b((1/T) - (1/T_0))] \]  

where \( R_0 \) is the zero-power resistance (typically between 2 and 30 kΩ) of the thermistor at some reference temperature \( T_0 \) (kelvins), frequently 298 K (zero power resistance is the resistance when the current is low enough to produce negligibly small self-heating). The constant \( b \) is such that \( R \) changes about 4 percent per kelvin. Therefore a suitable type of thermistor must be chosen for each specific application.

Although thermistors can be used at very low temperatures (liquid helium [Schlosser and Munnings (1972)]) and at high temperatures (above 500 °C [Sachse (1975)]), the main area of application is between about -80 °C and 250 °C. They may be considered as secondary thermometers (accurate to within 50 mK to 5 mK) only in an even narrower range, between 0 °C and 100 °C. The following discussion is restricted to this latter range.

Both disk and bead types can have this quality when they are glass-coated to limit the deleterious effect of moisture. Apart from the effect of moisture on the thermistor itself, the probe where the thermistor is usually mounted can also be moisture-sensitive; for example, moisture can cause shunting between the connecting leads.

Interchangeability of thermistors can be within 50 mK, especially with disk types because the larger sensing element more easily allows constancy in the unit-to-unit distribution of materials in the mixture of oxides.
Stability on thermal cycling is the main guide to thermometer quality. Several studies [LaMers et al. (1982), Wood et al. (1978), Edwards (1983), Mangum (1986)] reveal a large variety of behaviours. As with germanium thermometers, it is difficult to express a general rule on stability or even on drift trends. In the most extensive of these studies, Wood et al. (1978) present a large number of figures that show the aging of a large variety of thermistors at various temperatures. The reader is referred to these figures for the details. Some types from two manufacturers appear to show a stability better than 10 mK/year.

Mangum (1986) found the bead-in-glass thermistors to be much more stable than the disk type. During about 4000 h aging at 100 °C, 11 of 12 bead-type thermistors were stable to within 5 mK but 10 of 11 disk-type thermistors changed several tenths of a degree. The bead-type sensors became much less stable if subjected to heating at 300 °C. When they were thermally cycled to 150 °C, about 30% of a sample of 20 changed by 50 to 250 mK. Mangum found no significant differences between the products of various manufacturers.

Moderately large calibration changes due to drift are reported [Code (1985)] to be retrievable by a single-point recalibration, since the whole characteristic shifts by the same amount in the whole temperature range.

Since the sensing element is generally mounted in a stem, the self-heating effect, dynamic response, and immersion error are determined essentially by the stem; therefore the magnitudes of these are common to those of other types of thermometers used in the same temperature range, such as IPRTs (see Section 16.3).

Interpolation equations of the exponential type, with two or more exponential terms, or the following inverse equation:

\[
T^{-1} = A + B \ln R + C (\ln R)^3
\]

(17.2)

can be used for approximation of the thermistor R-T characteristics within a few millikelvins over several tens of kelvins [Sapoff et al. (1982), Steinhart and Hart (1968)].
18. Base-Metal Thermocouples

18.1 General Remarks

By far the largest number of thermocouples used are composed of base metals and their alloys. They are produced in large quantities by many manufacturers to conform, within acceptable tolerances, with standard reference tables [IEC (1977) (1982), CMEA (1978), GOST (1977), ASTM (1987b)].*

Although base-metal thermocouples cannot be recommended for approximating the ITS-90 with accuracies comparable to that of, for example, IPRTs, they are nevertheless so widely used that some description of them is necessary here. These thermocouples are identified by letter designations originally assigned by the Instrument Society of America and now accepted internationally (Table 18.1) [IEC (1977)]. The use of base-metal thermocouples for temperature measurements of moderate precision requires careful consideration regarding design, specifications, and application (atmosphere, temperature range).

Table 18.1: Letter-designation for Thermocouples.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Copper(+)/Copper-nickel alloy(-)</td>
</tr>
<tr>
<td>J</td>
<td>Iron(+)/Copper-nickel alloy(-)</td>
</tr>
<tr>
<td>K</td>
<td>Nickel-chromium alloy(+)/Nickel-aluminium alloy(-)</td>
</tr>
<tr>
<td>E</td>
<td>Nickel-chromium alloy(+)/Copper-nickel alloy(-)</td>
</tr>
<tr>
<td>N</td>
<td>Nickel-chromium-silicon alloy(+)/Nickel-silicon alloy(-)</td>
</tr>
<tr>
<td>R</td>
<td>Platinum13%Rhodium(+)/Platinum(-)</td>
</tr>
<tr>
<td>S</td>
<td>Platinum10%Rhodium(+)/Platinum(-)</td>
</tr>
<tr>
<td>B</td>
<td>Platinum30%Rhodium(+)/Platinum6%Rhodium(-)</td>
</tr>
<tr>
<td></td>
<td>Tungsten5%Rhenium(+)/Tungsten20%Rhenium(-)</td>
</tr>
</tbody>
</table>

18.2 Types of Base-Metal Thermocouples

Brief descriptions of the most-commonly used thermocouples are given here. The most useful of these, having a wide temperature range coupled with good accuracy, is Type N. Considerably more detail may be found in ASTM (1981).

* ASTM: American Society for Testing and Materials (USA)
CMEA: Council for Mutual Economic Assistance (USSR)
GOST: Gosudarstvennyj Komitet Standartov (USSR)
IEC: International Electrotechnical Commission
18.2.1 Type T Thermocouple

Within its range (-200 to 350 °C) this thermocouple is the most accurate base-metal thermocouple, due in large part to the ready availability of high-purity, strain-free copper. Above 370 °C it is limited by oxidation of the copper. The accuracy usually attainable is 0.1 K, but with special calibration it may approach 0.01 K from 0 °C up to 200 °C. Because copper is universally used for electrical conductors, one may easily obtain thermal-free connections to the measuring instruments. On the other hand the high thermal conductivity of the copper thermoelement may be disadvantageous in some applications. The type T thermocouple can be used in a vacuum and in oxidizing, reducing, or inert atmospheres.

18.2.2 Type J Thermocouple

This thermocouple is most commonly used for industrial purposes in the temperature range from 0 to 760 °C in both oxidizing and reducing atmospheres. The accuracy attainable is fair to poor (0.1 to 0.5 K below 300 °C, 1 to 3 K above 300 °C); the stability is fair below 500 °C but poor above 500 °C because of the higher oxidation rate of the iron thermoelement.

18.2.3 Type K Thermocouple

This thermocouple has a wide temperature range (-200 to 1260 °C); in the range above 0 °C it is the most widely used thermocouple. It is recommended for continuous use in oxidizing or inert atmospheres. At high temperatures it and Type N are the most oxidation-resistant base-metal thermocouples. In reducing, sulfurous atmospheres or in a vacuum it is necessary to use suitable protection tubes. Atmospheres with reduced oxygen content promote the so-called "green-rot" corrosion of the positive thermoelement because of the preferential oxidation of chromium; this causes large negative errors in calibration. This is most serious in the temperature range from 800 to 1050 °C, for example when the thermocouple is exposed to carbon dioxide in this temperature range. Green-rot corrosion frequently occurs when thermocouples are used in long unventilated protecting tubes of small diameter. It can be minimized by increasing the oxygen supply with large-diameter protecting tubes or ventilated tubes. Both elements of the Type K thermocouple are subject to oxidation in air above about 850 °C, but this normally leads to only a very slow increase with time of the thermocouple emf for a given temperature. Type K can be used above 1200 °C for very short periods in air without serious decalibration. Changes of up to 10 K can occur in the positive thermoelement due to short-range ordering in the
nickel-chromium solid solutions, especially if the thermoelements are annealed or used near 400 °C [Fenton (1972)].

The accuracy attainable is 0.1 K below 300 °C and 1 K up to about 1000 °C. Stability is fair. The accuracy and stability of this thermocouple are limited by its susceptibility to inhomogeneities and mechanical strain (cold work) and to previous heat treatment.

18.2.4 Type E Thermocouple
This thermocouple is recommended for use up to 870 °C in oxidizing or inert atmospheres. In reducing atmospheres, marginally oxidizing atmospheres, and in vacuum it is subject to the same limitations as Type K thermocouples.

Type E thermocouples develop the highest emf per kelvin (80 µV/K at 700 °C) of all the commonly-used types and are often used primarily because of this feature. Their accuracy is better than 1 K below 300 °C and 1 to 3 K from 300 to 1000 °C.

18.2.5 Type N Thermocouple
The Type N thermocouple shows enhanced thermoelectric stability, particularly at high temperatures, compared to the other standard base-metal thermocouples (except Type T), obtained as a result of careful choice of composition of the two elements.

By suitable adjustment of composition [Burley (1972), Burley et al. (1978), Burley et al. (1982)], it has been possible to achieve higher oxidation resistance at temperatures above 1000 °C; reduce short-term cyclic variations in thermal emf due to structural phenomena (temperature range from 300 °C to 500 °C); and reduce time-independent perturbation in thermal emf due to magnetic transformations (temperature range from 50 °C to 230 °C). Furthermore, the Type N thermocouple can now be obtained in a mineral-insulated metal-sheathed construction (Section 18.3.4) with a Nicrosil sheath [Burley (1987)]. The result is an overall better long-term stability, higher reproducibility, and higher accuracy than for all other base-metal thermocouples (except Type T). Below about 500 °C, however, these advantages are not dramatic; for example, from 0 °C to 500 °C they may be more reproducible than Type K by a factor of about 2.

18.2.6 Tungsten-Rhenium Thermocouple
There are several tungsten-rhenium alloy thermocouples in use, but the only one standardized is tungsten 5% rhenium/tungsten 20% rhenium [CMEA (1978), GOST (1977)]. All have been used at 2500 °C to 2750 °C but general use is below about 2200 °C. These thermoelements are supplied as matched pairs guaranteed to meet an emf output of producer-developed tables within ± 1 percent or of standard reference tables
within ± 0.5 to 0.7 percent. Tungsten as the positive leg can pose problems because heating it to or above its recrystallization temperature (about 1200 °C) causes embrittlement, resulting in a loss of room-temperature ductility, an effect that does not occur with legs containing rhenium (3.5 percent). Use is only possible in a vacuum or in high-purity reducing (hydrogen) or inert atmospheres.

18.3 Construction

A complete thermocouple temperature-sensing assembly consists of: a sensing element assembly including, in its most basic form, two dissimilar wires supported by an electrical insulator and joined at one end to form a measuring junction; a protection tube (ceramic or metal), sometimes referred to as a thermowell, which protects the sensing element assembly from the deleterious effects of corrosive, oxidizing, or reducing atmospheres; and a connector for the wire terminations of the sensing element assembly. It is, of course, necessary to ensure that the sheath and protection tube do not themselves contaminate the thermocouple. The reader should consult ASTM (1981) for details.

18.3.1 Thermoelements

The positive and negative thermoelements for a given type of thermocouple, as supplied by anyone manufacturer, will conform to the calibration curve for that thermocouple within specified limits of error. However, because materials used for a given thermoelement by various manufacturers may differ slightly in thermal emf, larger errors may occur if positive and negative thermoelements from different sources are combined.

Recommended maximum-temperature limits according to the wire diameter of the thermoelements are given in Table 18.2. These limits apply to protected thermocouples; that is, to thermocouples in conventional closed-end protecting tubes. In actual operation, there may be instances where the temperature limits recommended can be exceeded. Likewise, there may be applications where satisfactory life will not be obtained at the recommended temperature limit.

18.3.2 Sheaths

A wide variety of materials are available for thermocouple sheaths. Up to about 100 °C the commonest include enamels and varnishes, cloth, plastics, and rubber. Most of these organic materials begin to decompose, or at least to conduct, at higher temperatures. Some silicone varnishes may be satisfactory up to about 300 °C, fibreglass up to 400 °C and with silicone as the binder up to 500 °C. The sheath has to ensure a sufficient electrical
### Table 18.2: Recommended Upper Temperature Limits for Protected Thermocouples [ASTM (1987b), ASTM (1981)].

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Diameter</th>
<th>J (JP)</th>
<th>E (IN, TN, EN)</th>
<th>T (TP)</th>
<th>K (KP, EP, KN), N</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 mm</td>
<td>1.6 mm</td>
<td>0.8 mm</td>
<td>0.51 mm</td>
<td>0.33 mm</td>
<td></td>
</tr>
<tr>
<td>J (JP)</td>
<td>760 °C</td>
<td>590 °C</td>
<td>480 °C</td>
<td>370 °C</td>
<td>370 °C</td>
</tr>
<tr>
<td>E (IN, TN, EN)</td>
<td>870 °C</td>
<td>650 °C</td>
<td>540 °C</td>
<td>430 °C</td>
<td>430 °C</td>
</tr>
<tr>
<td>T (TP)</td>
<td>--</td>
<td>370 °C</td>
<td>260 °C</td>
<td>200 °C</td>
<td>200 °C</td>
</tr>
<tr>
<td>K (KP, EP, KN), N</td>
<td>1260 °C</td>
<td>1090 °C</td>
<td>980 °C</td>
<td>870 °C</td>
<td>870 °C</td>
</tr>
</tbody>
</table>

### Table 18.3: Properties of Refractory Oxides [ASTM (1981)].

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Maximum use Temperature</th>
<th>Thermal stress Resistance</th>
<th>Thermocouple Commonly used with</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire crystal</td>
<td>99.9 Al₂O₃</td>
<td>1950 °C</td>
<td>very good</td>
<td>any</td>
</tr>
<tr>
<td>Sintered alumina</td>
<td>99.8 Al₂O₃</td>
<td>1900 °C</td>
<td>good</td>
<td>any</td>
</tr>
<tr>
<td>Sintered beryllia</td>
<td>99.8 BeO</td>
<td>1900 °C</td>
<td>excellent</td>
<td>high temperature</td>
</tr>
<tr>
<td>Sintered magnesia</td>
<td>99.8 MgO</td>
<td>1900 °C</td>
<td>fair-poor</td>
<td>any</td>
</tr>
<tr>
<td>Sintered mullite</td>
<td>72 Al₂O₃, 28 SiO₂</td>
<td>1750 °C</td>
<td>good</td>
<td>base-metals</td>
</tr>
<tr>
<td>Sintered stabilized zirconia</td>
<td>92 ZrO₂, 4 HfO₂, 4 CaO</td>
<td>2200 °C</td>
<td>fair-good</td>
<td>high temperature</td>
</tr>
<tr>
<td>Silica Glass</td>
<td>99.8 SiO₂</td>
<td>1100 °C</td>
<td>excellent</td>
<td>base-metal</td>
</tr>
<tr>
<td>Mullite porcelain</td>
<td>70 Al₂O₃, 27 SiO₂</td>
<td>1400 °C</td>
<td>good</td>
<td>base-metal</td>
</tr>
<tr>
<td>High alumina porcelain</td>
<td>90-95 Al₂O₃, 4-7 SiO₂</td>
<td>1500 °C</td>
<td>very good</td>
<td>base-metal, noble metal below 1100 °C for a variety of constructions</td>
</tr>
</tbody>
</table>
insulation even though it be affected adversely by moisture, abrasion, flexing, temperature extremes, chemical attack, or nuclear radiation. Hence an insulation should be selected only after considering possible exposure temperatures, the number of temperature cycles, mechanical movement, moisture, routing of the thermocouple wire, and chemical deterioration.

Above about 500 °C the various ceramics are the only materials with high enough resistivity and stability for sheaths. Fused-silica insulators are satisfactory to about 1000 °C and have excellent thermal-shock resistance. Low-purity aluminium oxide, such as porcelain or mullite, is also frequently used in this range, but above 1000 °C there is risk of contamination of the thermoelements and so its use is not recommended. Beyond 1000 °C the sheath is usually a high-purity ceramic oxide, mainly recrystallized alumina that has fair thermal-shock resistance and excellent chemical stability except in reducing atmospheres. Some properties of various refractory oxides used are given in Table 18.3.

18.3.3 Protection Tubes
A thermocouple protection tube is in principle simply a gas-tight closed-end tube containing a suitable atmosphere; it may be in the form of a well into which the thermocouple is inserted, or it may be an integral part of the thermocouple assembly. In choosing a material for the protection tube we must consider its stability, not only with respect to the thermocouple, but also with respect to the medium in which it is immersed. The choice of the proper protection tube is therefore governed by the conditions of use, such as gas tightness, thermal-shock resistance, or chemical compatibility with the medium. Metal protection tubes are adequate for base-metal thermocouples up to 700 °C (steel) or even up to 1150 °C (Ni-Cr alloys). Ceramic protection tubes are usually used at higher temperatures and sometimes also at lower temperatures in atmospheres harmful to metal tubes.

18.3.4 Thermocouple Construction
The classic construction has two wires sheathed in two single-bore or one twin-bore tube, the wire tips joined to form the hot junction, and the whole encased in a protection tube if necessary. Any of a number of methods is available for forming the hot junction (welding, brazing, hard-soldering, soft-soldering, clamping or twisting the wires). The junction must provide good electrical contact and should be as small as possible. Fluxes should be used sparingly or not at all, as the risk of contamination is great.
The compacted ceramic-insulated (also called mineral-insulated metal-sheathed) construction affords thermocouple protection together with flexibility and thermal-shock resistance. In this construction the wires are insulated by immersion in a pure, compacted, refractory-oxide powder which is contained in a thin metal sheath. Recommended sheath diameters for long-term service in air at various temperatures are given in Table 18.4. The advantages of this configuration are:

- isolation of the thermocouple wires from environment that may cause rapid deterioration;
- reduction of long-term calibration drift;
- the lessening of temperature versus wire-size problems; whereas in the classic construction small-diameter wires have shorter lifetimes at high temperatures than large-diameter wires for a variety of reasons, in this construction the wires are firmly held in the protective sheath so that small-diameter wires can be exposed to high temperatures for long periods of time without serious deterioration.
- excellent high-temperature insulation for the thermocouple wires;
- ease of use, in particular to form bent configurations or to weld the sheath without loss of insulation;
- availability in a wide variety of sizes and materials.

For most practical purposes the sheathed thermocouple material should have a minimum insulation resistance of 100 megohms at room temperature at 500 V dc for outside diameters larger than 1.5 mm. This is readily obtained by dry, uncontaminated, compacted ceramics. The addition of moisture by hygroscopic action and subsequent movement by capillary action through exposed ends will decrease the insulation resistance. Also, the insulation resistance of all ceramics decreases with increasing temperature (approximately a factor of ten for a 200 K temperature rise).

18.3.5 Circuit Construction

The thermal emfs that must be measured are always small, ranging from near zero to a maximum of about 100 mV. Precise absolute measurements may well require a detector sensitivity of better than 0.1 µV and an accuracy of about 1 µV for base-metal thermocouple thermometry, which are possible to realize with modern digital voltmeters or classically with dc potentiometers.

In the construction of such low-level thermocouple circuits the following points must be considered [Bedford et al. (1970)]:
Table 18.4: Recommended Sheath Diameters for Mineral-Insulated Metal-Sheathed Base Metal Thermocouples for Long Term Service in Air [ASTM (1981)].

<table>
<thead>
<tr>
<th>Sheath diameter (in mm)</th>
<th>1.0</th>
<th>1.5</th>
<th>3.0</th>
<th>4.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal wall (in mm)</td>
<td>0.18</td>
<td>0.25</td>
<td>0.5</td>
<td>0.62</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>temperatures</th>
<th>temperatures</th>
<th>temperatures</th>
<th>temperatures</th>
<th>temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>760 °C</td>
<td>870 °C</td>
<td>870 °C</td>
<td>870 °C</td>
<td>980 °C</td>
</tr>
<tr>
<td>J</td>
<td>540 °C</td>
<td>650 °C</td>
<td>760 °C</td>
<td>870 °C</td>
<td>870 °C</td>
</tr>
<tr>
<td>E</td>
<td>650 °C</td>
<td>760 °C</td>
<td>760 °C</td>
<td>870 °C</td>
<td>925 °C</td>
</tr>
</tbody>
</table>

Table 18.5: Thermoelectric Power at Room Temperature of Copper versus Various Metals in Thermocouple Measurement Circuits [Bedford et al. (1970)].

<table>
<thead>
<tr>
<th>Metal</th>
<th>Thermoelectric power in µV/K</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>group a</td>
<td></td>
<td>preferred materials</td>
</tr>
<tr>
<td>copper from a different spool of wire</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>low thermal solder</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>lead free-turning copper</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>group b</td>
<td></td>
<td>materials are likely to require some thermal uniformity</td>
</tr>
<tr>
<td>silver</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>gold</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>coin silver</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>group c</td>
<td></td>
<td>materials need very good thermal uniformity</td>
</tr>
<tr>
<td>carbon</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>platinum10%rhodium</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>beryllium copper</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>manganin</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>coin copper</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>yellow brass</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>phosphor bronze</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>lead50%tin solder</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>group d</td>
<td></td>
<td>materials likely to be unsuitable</td>
</tr>
<tr>
<td>steels</td>
<td>3.2 … -5.6</td>
<td></td>
</tr>
<tr>
<td>Chromel</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>constantan</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>
- temperature gradients and variations of temperature with time should be kept as small as possible. Only strain-free copper should be used in the regions of appreciable temperature gradients; all junctions should be in a zero-gradient region.
- all connections should be shielded from thermal radiation; this applies particularly when non-copper components are involved. A further improvement in accuracy is likely to result from the introduction of some heat capacity around the components, since this tends to reduce transient temperature fluctuations.
- conductor materials should be as thermoelectrically similar as possible; in practice this means that they should have thermoelectric powers near that of copper. The relative quality of various metals that can be used in thermocouple circuits is shown in Table 18.5.

Highest system accuracy can be obtained by running the thermocouple conductors directly to the reference junction, so avoiding the use of extension wires. If extension wires must be used, however, as in the case of metal-sheathed mineral-insulated thermocouples, the extension wires become an integral part of the temperature-sensing system. The user must be aware of the need to keep the temperature of the reference junction below 200 °C in the interest of overall accuracy. In any case, the termination should be designed in such a way as to guarantee that the temperature of the terminals is uniform.

18.4 Annealing of the Thermoelements

As with noble-metal thermocouples the base-metal thermoelements should be in a condition of thermodynamic equilibrium to ensure metallurgical stability over the temperature range of application. Accurate temperature measurements are generally impossible when this equilibrium condition does not exist. Annealing removes existing non-equilibrium states; for example, strains introduced by cold working. Inadequate annealing may result in errors varying in magnitude from a few tenths of a kelvin to several kelvins depending upon the temperature being measured and the temperature gradients along the thermoelements.

All base-metal thermocouple wires are usually delivered in an annealed state. The heat treatment given by the producer can be generally considered as sufficient, and seldom is it advisable to further anneal the thermoelements before testing. If an annealing should be necessary, however, the annealing temperature should be higher and the depth of immersion greater than will be encountered in service. A rough test for the adequacy of the annealing procedure is the reproducibility of the thermocouple emf at some fixed temperatures (such as fixed points) after consecutive annealing periods.
In the case of the Types K and E thermocouples and the negative legs of Types T and J thermocouples (all containing nickel or nickel-chromium), the thermodynamic equilibrium is limited by diffusion of constituents (temperature range from 300 °C to 500 °C) and magnetic-transformation processes (temperature range from 50 °C to 200 °C) so that a high accuracy (0.1 K) can be obtained only by special heat treatment, using specified calibration procedures, and in special application conditions [Burley et al. (1982)].

18.5 Guidelines for Proper Handling and Use -Installation and Sources of Errors

For accurate temperature measurements by means of base-metal thermocouples, in particular by metal-sheathed thermocouples, the following guidelines should be considered [ASTM (1981)]:
- be sure that the sheath or protection tube material will survive the environment.
- be sure that the thermocouple assembly is fully annealed for maximum life of sheath or protection tube and stability of the thermocouple calibration.
- remember that the life of the thermocouple will decrease with higher application temperatures and smaller thermoelement and sheath diameters and is limited by grain growth (Tables 18.2 and 18.4).
- in the case of metal-sheathed thermocouples, it must be possible to bend the sheath around a mandrel twice the sheath diameter without damage.
- in metal-sheathed thermocouples, the appearance of moisture in the assembly is indicated by a diminution in insulation resistance; this can cause an error in temperature measurement by electrical shunting. Moisture can be removed by heating and sealing the exposed ends of the thermocouple.
- metal-sheathed thermocouples should not be repeatedly bent at the same location as this work-hardens the sheath and may change the thermocouple calibration.

To evaluate the performance of a thermocouple circuit, the numerous possible sources of error should be considered: thermal shunting; electrical shunting; calibration; decalibration (from instability or drift); extension wires; reference junction.

A thermocouple, just as any other contacting temperature sensor, disturbs the temperature distribution of any object to which it is attached because it has a finite size and conducts heat away from (or to) the object. The thermocouple itself loses heat to (or gains heat from) its surroundings by conduction, convection, and radiation. This heat transfer can cause the thermocouple hot junction to be at a different temperature from that of the object.

These effects cause a thermal-shunting error, the magnitude of which depends
largely on the method of thermocouple installation. This error is avoided when the portion of
the thermocouple near the hot junction is isothermal and at the temperature of the object
whose temperature is to be measured. This error can be especially large when the heat
transfer from the measuring object to the thermocouple is poor and/or the heat transfer from
the thermocouple to the surroundings is large (such as in surface temperature
measurement).

At higher temperatures, where the electrical resistivity of the insulator will be lower,
an electrical shunting will occur and can cause temperature-measurement errors, especially
at temperatures above 1500 °C. This effect is greater in metal-sheathed thermocouples than
it is in the classic type of construction because of the larger area of electrical contact
between the insulator and the thermoelements.

Calibration errors depend upon the accuracy of the calibration standards and the
 calibration method applied (Sec. 18.6).

Decalibration errors or drift, i.e. a change of the emf-temperature relationship with
time, can occur even if the thermocouples are heat-treated, assembled, calibrated, and
installed with utmost care. In the literature (e.g. [Kinzie (1973)]) many results are reported
that show the same trends of decalibration but the magnitudes differ because of undetected
differences in experimental variables that control the drift rates.

Several factors cause a thermocouple to drift, such as: chemical reactions of the
thermoelements with the gaseous environment, with the electrical insulator, or with the
object whose temperature is to be measured (including impurities in the environment,
insulator, or object); metallurgical transformations (such as order-disorder transformations or
secondary recrystallization); loss of alloying elements by selective evaporation or oxidation
at higher temperatures; transmutation by nuclear radiation.

Drift rates generally increase rapidly with increasing temperature and are larger for
smaller-diameter thermoelements.

Extension-wire errors arise from the differences between the thermoelectric
properties of the thermoelements and of the corresponding extension wires. In high-
precision measurements the use of such wires should be avoided whenever possible. If
extension wires must be used due to installation conditions, any error can be reduced by
calibration of the complete thermocouple/extension-wire assembly and by ensuring a
uniform temperature at the junctions.

In thermocouple thermometry all emf measurements are referred to the temperature
of the reference junction. Any error in this temperature, therefore, is directly involved in the
error of the measured temperature. Reduction of this error is possible by ensuring that both
thermoelement reference junctions have the same temperature and that this
temperature is measured with the desired accuracy with another thermometer (mercury-in-glass thermometer or resistance thermometer) or by realization of a fixed-point temperature (ice point or water triple point, see Sec. 9.4).

18.6 Calibration of Base-Metal Thermocouples

The calibration of a thermocouple consists of the determination of its emf at a sufficient number of known temperatures, some of which can be fixed points, so that with some accepted means of interpolation its emf will be known over the entire temperature range in which it is to be used. In comparison to the situation with noble-metal thermocouples (Sec. 9.5), the number of calibration points necessary with base-metal thermocouples to reach their limit of accuracy will be greater because of the more complex emf-temperature relationships and because more factors can influence the deviation of the real thermocouple characteristics from the reference table or polynomial values. Because of this the methods of interpolating between the calibration points become of prime importance for interpolation accuracies approaching 0.1 K [ASTM (1981)]. For lower accuracies comparatively simple methods of calibration will usually suffice (comparison with a standard thermometer in an isothermal environment).

The errors in calibration are of two sorts: those influencing the observations at the calibration points and those arising from the interpolation between the calibration points. The influence of the first can be reduced by use of well-designed equipment and careful techniques. The recommended method to reduce the second error is to fit the differences between the observed calibration values and the values obtained from standard reference tables, i.e. the deviation of the real characteristics of the thermocouple from the nominal one. In order to determine the mean deviation curve the application of least-squares fitting is useful, but in several cases a graphical interpolation method will be sufficient (Sec. 9.5).

Typical accuracies to be expected with the various thermocouples if calibrated using fixed points are given in Table 18.6, and when calibrated by comparison techniques are given in Table 18.7. The interpolation formulae used to generate the standard reference tables are given in Appendix F. No such formulae have yet been internationally agreed upon for the tungsten-rhenium types.
Table 18.6: Accuracies Attainable with Thermocouples using Fixed Point Techniques [ASTM (1981)].

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature range (°C)</th>
<th>Calibration points</th>
<th>Calibration uncertainty at observed points (K)</th>
<th>total uncertainty of interpolated values (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S or R</td>
<td>0...1100</td>
<td>Zn, Sb, Ag, Au</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>S or R</td>
<td>0...1100</td>
<td>Sn, Zn, Al, Ag, Cu</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>B</td>
<td>600...1100</td>
<td>Al, Ag, Au</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>0...870</td>
<td>Sn, Zn, Al</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>J</td>
<td>0...760</td>
<td>Sn, Zn, Al</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>K</td>
<td>0...1100</td>
<td>Sn, Zn, Al, Ag, Cu</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>N</td>
<td>0...1100</td>
<td>Sn, Zn, Al, Ag, Cu</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>W/Re</td>
<td>1000...2000</td>
<td>Au, Ni, Pd, Pt, Rh</td>
<td>0.5...7.0</td>
<td>2.7...7.0</td>
</tr>
</tbody>
</table>

Table 18.7: Accuracies Attainable with Thermocouples using Comparison Techniques in Laboratory Furnaces [ASTM (1981)].

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature range (°C)</th>
<th>Calibration points</th>
<th>Calibration uncertainty at observed points (K)</th>
<th>total uncertainty of interpolated values (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S or R</td>
<td>0...1100</td>
<td>every 100 K</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>600...1100</td>
<td>&quot; &quot; &quot;</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>0...870</td>
<td>&quot; &quot; &quot;</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>J</td>
<td>0...760</td>
<td>&quot; &quot; &quot;</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>K</td>
<td>0...1100</td>
<td>&quot; &quot; &quot;</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>N</td>
<td>0...</td>
<td>&quot; &quot; &quot;</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
19. Thermometry in Magnetic Fields

Most thermometers change their calibration in the presence of a magnetic field. In this chapter we discuss by how much traceability to the original calibration can be affected and how accuracy can be preserved for the different types. The discussion will include types of thermometers from both Parts 1 and 2, as the problem of ensuring a traceable temperature value in the presence of a magnetic field is not restricted to industrial applications. It is very important in cryogenics and in thermophysical-property measurements at the highest possible accuracy. Some types of thermometer specifically developed for use in a magnetic field will also be briefly considered.

The general problem has two possible solutions: a) use of a thermometer insensitive, within the required accuracy, to magnetic fields up to the maximum strength likely to be encountered; b) accurate correction of the thermometer reading for the shift due to the magnetic field. The latter solution is made difficult by possible anisotropy of the magnetic-field sensitivity of the thermometer, or of the magnetic field itself, and, in addition, needs the local magnetic field strength to be known with sufficient accuracy. The first solution is almost mandatory for thermometers used in temperature regulation; otherwise, change of the magnetic field value would result in a change of the regulated temperature. In addition, for thermometers that exhibit a high magnetic-field shift, the sensitivity to temperature changes may be dramatically lower [Pavese and Cresto (1984)], resulting in a much worse regulation. Table 19.1 collects the data available on the magnetically-induced temperature errors of thermometers. It should be cross-checked with Table 1.1 which gives the quality of the thermometers with regard to general reproducibility.

All of the thermometers for use at cryogenic temperatures included in Part 1 exhibit substantial sensitivity to a magnetic field.

Although platinum resistance thermometer calibrations change considerably in magnetic fields [Brandt and Aubin (1988)], the magnetic error can be well corrected for because it is only slightly orientation dependent and varies little from thermometer to thermometer since the thermometers are well characterized by their values of \(W(H_20 \text{ t.p.})\). Below the liquid-nitrogen temperature range, however, the correction becomes too large to allow the best accuracy in fields larger than a few teslas. If lesser accuracy is acceptable the range of use of the correction may be extended to lower temperatures and higher fields, but the error then becomes dependent on the value of \(W(H_20 \text{ t.p.})\). The correction is lower for IPRTs with \(W(H_20 \text{ t.p.}) = 1.385\) and can be used to 30 K at 19 T, or to 20 K at 5 T. A correction must always be applied, even for uncertainties of the order of ± 0.1 K. It should
Table 19.1: Magnetic Field-Dependent Temperature Errors for Low Temperature Thermometers

<table>
<thead>
<tr>
<th>Type of Sensor</th>
<th>T(K)</th>
<th>Magnetic Flux Density, B</th>
<th>Notes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 T</td>
<td>2.5 T 8 T 14 T 19 T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon radio resistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allen-Bradley (2.7, 3.9, 5.6, 10 G)</td>
<td>0.5</td>
<td>2-4 5-13 7-20</td>
<td>a</td>
<td>Sample and Rubin (1977)</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2-4 6-15 9-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>1-5 6-18 10-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>1-5 5-20 10-35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allen-Bradley (47, 100, 220 Ω)</td>
<td>4.2</td>
<td>&lt;1 5 10</td>
<td>a</td>
<td>ibidem</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>&lt;1 3 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>&lt;1 1 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speer, Grade 1002 (100, 220, 470 C)</td>
<td>0.5</td>
<td>0-2 0-1 0-6</td>
<td>b</td>
<td>ibidem</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1-2 2-4 3-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>3-5 1-4 7-14</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>4-9 2-5 4-13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matsushita (68, 200, 510 C)</td>
<td>1.5</td>
<td>1-2 10-15</td>
<td>c</td>
<td>ibidem</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>1 10-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>2-3 4-8</td>
<td></td>
<td></td>
</tr>
<tr>
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(a) Sample and Rubin (1977)  
(b) Astrov et al. (1977)  
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(f) Sample and Rubin (1977)  
(g) ibidem; Neuringer et al. (1971); Rubin & Brandt (1986)  
(h) Astrov et al. (1977)  
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<td>s</td>
<td>Van Degrift et al. (1980)</td>
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Notes to Table 19.1

a) \( \Delta R/R_0 \) monotonic in B and T, and always positive. Higher nominal resistance units have smaller \( |\Delta T| \). Good agreement between similar units.

b) \( \Delta R/R_0 \) both positive and negative with complicated B and T dependence. Variations between similar units.

c) \( \Delta R/R_0 \) approximately independent of nominal resistance value. Higher resistance units have smaller \( |\Delta T| \).

d) Specifically developed for use as a thermometer.

e) Behavior similar to Allen-Bradley resistors. Negative \( \Delta R/R_0 \) below -20 K.

f) Very low magnetoresistance, but few types useful or available below 77 K.

g) Not recommended except at very low fields because of large, and strongly orientation dependent, \( |\Delta T| \).

h) Orientation dependent only above 20 K. Complicated behaviour below 10 K makes corrections difficult.

i) Some orientation dependence. Useful at all B only for \( T > 30 \) K. Magnetoresistance depends on \( W(H_20 \text{ t.p.}) \) value (a) 1.385 (b) 1.3914.

j) Little orientation dependence. Useful only at low fields.

k) Little orientation dependence. \( \Delta R \) negative below about 12 K and 2.5 T. Useful only below 3T, where it is the best high-stability thermometer.

l) Linear foil-type thermometer; magnetoresistance is negative and extremely high above 1 T.

m) Errors are negative for \( T \leq 140 \) K.

n) Maximum in capacitance versus temperature near 70 K, so that sensitivity is very low between about 60 K and 80 K.

o) Strongly orientation dependent; values are given for junction parallel to B.

p) Orientation dependent. Smaller values of \( |\Delta T|/T \) apply to diode junction parallel to B.

q) Gradients in the magnetic field crossed by the wires can cause higher errors.

r) Different % Fe gives rise to larger errors.

s) With use of non-magnetic bulb and connecting tube.
be noted that these lower temperature limits are approaching the overall low temperature limit for optimum advantage in using PRTs.

For temperatures below about 20 K, rhodium-iron resistance thermometers are in general preferred to PRTs. The sensitivity of their calibrations to magnetic fields is also much less marked than that of SPRTs below 30 K, but is comparable to it above. Anisotropy, correctability, and interchangeability of units are also comparable. The corrections become especially significant below 10 K, even for low fields (1 T). It is next to impossible to trace back to the zero-field calibration with high accuracy, but the correction must be applied even for low accuracy and low fields (1 T). At 4.2 K the change in resistance divided by the zero-field resistance is roughly proportional to the square of the magnetic flux density [Rusby (1972)]. The dependence of the calibration on temperature and magnetic flux density is shown in Fig. 19.1.

The platinum 0.5% cobalt resistance thermometer shows a much better behaviour in magnetic fields than does the rhodium-iron thermometer, while anisotropy, correctability, and interchangeability of units are comparable with those of SPRTs. The sensitivity to magnetic fields is smaller than for rhodium-iron, though it has a more complicated behaviour, as shown in Fig. 19.2; in fact, there is a change of sign of magnetoresistivity below about 14 K and 2.5 T. At 30 K the sensitivity to magnetic fields up to 6 T is less than one-third of that for PRTs. For low levels of accuracy, this thermometer can be used without corrections, within an uncertainty of ± 0.2 K, in the region above 8 K and below 3 T. Should the cobalt content of the alloy be reduced to about 0.3 atomic %, the low-temperature limit would become 4 K, with only a small change in the magnetic field limit (2.5 T) [Pavese and Cresto (1984)].

Germanium resistance thermometers have a high sensitivity to magnetic fields, even higher than that of PRTs above 10 K, and comparable with that of rhodium-iron below 10 K. Correctability is good, but the corrections can be made only in situ because they are strongly orientation-dependent (for best accuracy the sensing element of the thermometer should be parallel to the magnetic field). Consequently, the correction also applies only to a specific unit, with no interchangeability, even for low accuracy. Because of this, germanium thermometers are all but useless at all temperatures in the presence of a strong magnetic field. \( \Delta R/R \) increases more or less proportionally with \( B^2 \) and decreases monotonically as \( T \) increases (see Fig. 19.3). Table 19.1 gives values of the error that may be expected in various magnetic fields. Research has been undertaken in the USSR [Astrov et al. (1977), Zinov'eva et al. (1979)] and, more recently, in China [Fu Chiying et al. (1986)] to try to overcome the high magnetosensitivity of germanium thermometers. At present only the USSR type is available; it is a multiply-doped germanium resistor (type
Fig. 19.1: The change in calibration ($\Delta T$(mK)) of rhodium 0.5% iron as a function of temperature and magnetic flux density [Pavese and Cresto (1984)].

KG) which shows a much lower sensitivity to magnetic fields than any other of the above thermometers without its stability to thermal cycling being very much lower than that of regular germanium thermometers [Besley et al. (1986)]. The main problem is correctability, as the behaviour of the correction versus temperature is complicated; on the other hand, the thermometers are much less orientation-dependent than ordinary germanium thermometers below 20 K.

Among other semiconducting resistance thermometers, carbon resistors are known to have relatively small and reproducible magnetic field dependence [Sample and Rubin (1977), Sample and Neuringer (1974), Sample et al. (1974), Sanchez et al. (1977), Saito and Sato (1975), Neuringer and Rubin (1972), Alms et al. (1979)] (see Table 19.1 for the relative errors in temperature that may be expected). For temperatures below about 50 mK typical errors in temperature incurred by neglect of the magnetoresistance are shown in Fig. 19.4.
Fig. 19.2: The change in calibration (ΔT(mK)) of platinum 0.5% cobalt as a function of temperature and magnetic flux density [after Pavese and Cresto (1984)].

Fig. 19.3: Ratio of a CryoCal germanium thermometer resistance in a magnetic field to its resistance in the absence of a field when the thermometer current is perpendicular to the magnetic field [after Neuringer and Rubin (1972)].
Fig. 19.4: Error in the temperature for carbon thermometers when magnetoresistance effects are neglected at the magnetic flux densities (teslas) indicated [Sanchez et al. (1977)].

Fig. 19.5: Longitudinal magnetoresistance versus magnetic field for a typical carbon-glass thermometer [Sample et al. (1982)].
Carbon-glass thermometers (Chapter 12) were developed in an attempt to combine the low sensitivity of carbon resistance thermometers to magnetic fields with an improved stability. Carbon-glass shows good correctability (to within 10 mK [Sample et al. (1982)]) and little orientation dependence (equivalent temperature change less than 0.3% at 19 T from parallel to perpendicular position, between 4.2 K and 77 K). On the other hand, interchangeability is bad, as with germanium thermometers. The magnetoresistance of carbon-glass is much smaller (Fig. 19.5) than that of the previous types up to the highest field strengths but the same level of stability is never reached. In particular, carbon-glass thermometers have been reported to drift severely after a few years use in fields up to 12 T [Couach et al. (1982)].

Amongst the non-resistive thermometers used in cryogenics, none shows a reproducibility comparable with those of the resistance types. The magnetoresistance of diode thermometers (Chapter 14) is strongly orientation-dependent in magnetic fields. Correctability and interchangeability are poor. Some types of thermocouple have limited magnetic shift (see Table 19.1) but, apart from the intrinsic low accuracy, correction is almost impossible as the error develops along the whole length of the wire immersed in the magnetic field and stray emfs develop especially where field gradients are strong (there is no effect at all if the magnetic field region is isothermal). A capacitive thermometer is impervious to magnetic-field errors but the capacitance of the usual material (SrTiO$_3$) is known to be unstable on thermal cycling and dependent on charge effects and on the applied voltage. In addition, the capacitance versus temperature characteristic is not monotonic below 100 K. Some new ceramic materials may avoid these drawbacks [Chen Pufen and Li Jinwan (1986)].

At present none of these non-resistive thermometers should be considered as reliable storage for a traceable temperature scale, whether a magnetic field is involved or not. It is perhaps worth noting that two non-electric thermometers are best-suited as standards for approximating the temperature scales in the presence of a magnetic field: vapour pressure thermometers (except when using oxygen, which is paramagnetic) and gas thermometers. They are intrinsically immune to magnetic errors. They suffer the drawbacks, of course, of large size and complicated measurement requirements.
20. References


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Appendix A

Differences between the ITS-90 and the EPT-76, and between the ITS-90 and the IPTS-68.

\[(T_{90} - T_{76})/mK\]

<table>
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<tr>
<th>(T_{90}/K)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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\[(T_{90} - T_{68})/K\]

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\[(t_{90} - t_{68})/°C\]

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\[(t_{90} - t_{68})/°C\]

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\[(t_{90}/°C\]

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<th>200</th>
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<th>400</th>
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Fig. A.1: Differences between the ITS-90 and the IPTS-68.

The differences \( (t_{90} - t_{68}) \) in the temperature range -200 °C to 630 °C in the preceding table can be reproduced to within 1.5 mK below 0 °C and 1 mK above 0 °C by the following polynomial:

\[
(t_{90} - t_{68})/°C = \sum_{i=1}^{8} a_i \left( t/630 °C \right)
\]  
(A1)

The values of the coefficients \( a_i \) are:

\[
\begin{align*}
a_1 &= -0.148759 \\
a_2 &= -0.267408 \\
a_3 &= 1.080760 \\
a_4 &= 1.269056 \\
a_5 &= -4.089591 \\
a_6 &= -1.871251 \\
a_7 &= 7.438081 \\
a_8 &= -3.536296.
\end{align*}
\]
Appendix B

Addresses of National Standards Laboratories

Amt für Standardisierung
Messwesen und Warenprüfung
Fürstenwalder Damm 388
Postfach 1542
Berlin 1162, DDR
   Telex: 112630 ASMW DD

Bureau International des Poids et Mesures
Pavillon de Breteuil
92310 Sèvres, France
   Telex: 201067 BIPM F
   Fax: (33)(1) 45 342021

Institut National de Metrologie
C.N.A.M.
292, rue St. Martin
75141 Paris 03, France
   Telex: 240247 CNAM F
   Fax: (33) (1) 42 719329

Istituto di Metrologia "G. Colonnetti"
Strada delle Cacce 73
10135 Torino, Italy
   Telex: 212209 IMGCTO I
   Fax: (39)( 11) 346-761

Kamerlingh Onnes Laboratorium
Rijksuniversiteit te Leiden
Nieuwsteeg 18 - Postbus 9506
2300 RA Leiden
The Netherlands
   Telex: 39058 Astro NL
   Fax: (31) (71) 275819

National Institute of Standards and Technology
Center for Chemical Technology
Chemical Process Metrology Division
Gaithersburg, Maryland 20899, U.S.A.
   Telex: 0023-197674 NBS UT
   Fax: (301) 948-4087
National Institute of Metrology
P.O. Box 2112 Beijing
People’s Republic of China
Telex: 210028 NIM CN
Fax: (86) (1) 421-8703

National Measurement Laboratory
C.S.I.R.O.
Division of Applied Physics
P.O. Box 218
Lindfield NSW 2070, Australia
Telex: 26296 NATMEASURE SYDNEY
Fax: (61) (2) 467-1902

National Physical Laboratory
Quantum Metrology Division
Teddington, Middlesex
TW11 OLW, England
Telex: 262344
Fax: (44)(81) 943-2155

National Research Council of Canada
Laboratory for Basic Standards
Division of Physics
Ottawa, Ontario, K1A OR6, Canada
Telex: 053-4322
Fax: (613) 952-

National Research Laboratory of Metrology
1-4, 1-Chome, Umezono, Tsukuba
Ibaraki 305, Japan
Telex: 0072-3652570 AIST J
Fax: (81) (298) 54 4135

Nederlands Meetinstituut nv
Schoemakerstraat 97
2628 VJ Dekft, Postbus 654
2600 AR Delft
The Netherlands
Telex: 38373 IJKWZ NL
Fax: (31 )(15) 612 971

Physikalish- Technische Bundesanstalt
Bundesallee 100
3300 Braunschweig
Germany
Telex: 952822 PTB D
Fax: (49)(531) 592-7614
Physikalisch-Technische Bundesanstalt
Abbeistrasse 2-12
D-1000 Berlin 10
Federal Republic of Germany
Fax: (49)(30) 34 81 490

VNIIFTRI Mendeleev
Moscow Region 141 570
USSR
Telex: 411 038 KCSVSU

VNIIM
19, Moskovsky Prospekt
198005 Leningrad
USSR
Appendix C

Some Suppliers of Various Cryogenic Thermometers

**Germanium:**
- CryoCal, Inc.
  2303-2W Wycliff St.
  St. Paul, Minnesota 55114
  U.S.A.
- Lake Shore Cryotronics, Inc.
  64 East Walnut St.
  Westerville, Ohio 43081
  U.S.A.
- Scientific Instruments, Inc.
  1101 25th St.
  West Palm Beach, Florida 33407
  U.S.A.
- All-Union Research Institute for Physical, Technical, and Radio-Technical Measurement (VNIIFTRI)
  USSR State Committee for Standards
  9 Leninsky Prospekt
  117049 Moscow M-49
  USSR

**Rhodium-Iron:**
- All-Union Research institute for Physical, Technical, and Radio-Technical Measurement (VNIIFTRI)
  USSR State Committee for Standards
  (see entry for germanium)
- Cryogenic Consultants Ltd.
  The Metrostore Building
  231 The Vale
  London W3 70S
  U.K.
- H. Tinsley and Co. Ltd.
  Standards House
  61 Imperial Way
  Croydon CRO 4RR
  U.K.
- Oxford Instruments Ltd.
  Eynsham
  Oxford OX8 1 TL, U.K.
Carbon-Glass: Lake Shore Cryotronics, Inc.
(see entry for germanium)

Platinum-Cobalt: Chino Works, Ltd.
Sunshine 60, 19 Fl.
3-1-1 Higashi-ikebukuro, Toshina-ku
Tokyo 170
Japan.

Silicon Diodes: Institute of Cryogenics
University of Southampton
Southampton S09 SNH
U.K.
Appendix D

Calculations Relative to the Filling of a Vapour Pressure Thermometer

Notations

- $T_a$ - minimum temperature to be attained. At this temperature the bulb is completely filled with liquid.
- $T_b$ - maximum temperature to be attained. The bulb is empty of liquid except for a small quantity $v$ which remains for security and which can be neglected.
- $π_a, π_b$ - the corresponding saturated vapour pressures.
- $T_f$ - temperature used for condensation when filling.
- $π_f$ - corresponding saturated vapour pressure.
- $T_0$ - room temperature.
- $P_0$ - filling pressure at $T_0$.
- $T_m$ - average temperature along the capillary, equal to $\frac{T_0 + T_f}{2}$, $\frac{T_0 + T_a}{2}$, or $\frac{T_0 + T_b}{2}$ as the case may be.
- $V_b$ - the bulb volume partially filled with a volume $v_c$ of liquid.
- $V_c$ - volume of the capillary.
- $V_T$ - volume of the reservoir.
- $V_0$ - totality of volumes of connectors and manometer that remain at room temperature.
- $M$ - molar mass of the pure filling substance.
- $N$ - number of moles to be introduced.
- $n_1$ - number of moles of liquid = $\frac{V_b}{M} \cdot \rho$
- $n_2$ - number of moles of vapour in the bulb = $\frac{P(V_b - v_c)}{RT} (p, \text{ pressure in the bulb, } = p_a, p_b, p_M, \text{ or } p_0)$.
- $\rho_a, \rho_b$ - density of liquid at temperature $T_a, T_b$ respectively.
- $n_3$ - number of moles in the capillary = $\frac{PV_c}{RT_m}$
- $n_4$ - number of moles in the various volumes at room temperature = $\frac{PV_0}{RT_0}$
- $n_5$ - number of moles in the volume of the reservoir = $\frac{PV_T}{RT_0}$
- $N$ - total number of moles.

We assume that the vapour phase obeys the perfect gas law.

$V_T$ being generally much larger than the other volumes, we can make some approximations:
1. At the lowest temperature, $T_a$, we have $v_L \sim V_b$

\[ n_1 = \frac{V_b}{M} \rho_a \]

\[ n_2 = 0; \quad n_3 = \frac{2 \Pi_a V_c}{R(T_0 + T_a)}; \quad n_4 = \frac{\Pi_a V_0}{RT_0} \]

$V_T$ not connected; $n_5 = 0$

The total number of moles, $N$, must be

\[ N \leq \frac{\Pi_a}{RT_0} \left[ \frac{2V_c T_0}{T_0 + T_a} + V_0 \right] + \frac{V_b}{M} \cdot \rho_a \]  \hspace{1cm} (D1)

2. At the highest temperature, $T_b$, there is only a small volume $v$ of liquid in the bulb

$(v - 0)$.

\[ n_1 = \frac{v}{M} \rho_b \]

\[ n_2 = \frac{V_b - v}{RT_0} \Pi_b; \quad n_3 = \frac{2 \Pi_b V_c}{R(T_0 + T_b)}; \]

\[ n_4 = \frac{\Pi_b V_0}{RT_0}; \quad n_5 = 0. \]

The total number of moles, $N$, must be

\[ N \geq \frac{v \rho_b}{M} + \frac{\Pi_b}{RT_0} \left[ \frac{T_0}{T_b} (V_b - v) + V_0 + \frac{2V_c T_0}{T_0 + T_b} \right] \]  \hspace{1cm} (D2)

3. From relations (D1) and (D2), we obtain

\[ \rho_b \frac{v}{M} + \frac{\Pi_b}{RT_0} \left[ \frac{T_0}{T_b} (V_b - v) + V_0 + \frac{2V_c T_0}{T_0 + T_b} \right] \leq \frac{\Pi_a}{RT_0} \left[ \frac{2V_c T_0}{T_0 + T_a} + V_0 \right] + \frac{v \rho_a}{M} \]

or

\[ v \left[ \rho_a - \frac{\Pi_b}{RT_b} \right] \geq \frac{V_0}{RT_0} \left[ \Pi_b - \Pi_a \right] + v \left[ \rho_b - \frac{\Pi_b}{RT_b} \right] + \frac{2V_c}{R} \left[ \frac{\Pi_b}{T_0 + T_b} - \frac{\Pi_a}{T_0 + T_a} \right]. \]  \hspace{1cm} (D3)

This expression determines the volume $V_b$ of the bulb (to a first approximation, we can neglect the last two terms and overestimate the value).
4. The calculation of the number of moles to introduce:

Knowing \( V_b \), we can determine the number \( N = n_1 + n_2 + n_3 + n_4 \) of moles to introduce (staying within the limits where inequalities (D1) and (D2) are applicable).

At the time of filling, all of the moles are in the vapour and it is necessary to predict the reservoir volume \( V_T \). \( P_0 \) must be chosen so that at \( T_0 \) the pure substance is all gaseous.

At the condensation pressure, \( \Pi_f \) and just before isolating the thermometer, there remains in the reservoir \( n_5 \) moles, where \( n_5 = \frac{\Pi_f V_T}{RT_0} \).

Then \( N' = N + n_5 \) moles of pure substance must be introduced. At pressure \( P_0 \) and temperature \( T_0 \) these \( N' \) moles occupy a total volume \( V = V_b + V_c + V_0 + V_T = \frac{NRT_0}{P_0} \), from which the following equation allows the determination of the necessary volume \( V_T \), taking account of the chosen pressure \( P_0 \):

\[
V_T \left[ 1 - \frac{\Pi_f}{P_0} \right] = \frac{NRT_0}{P_0} - (V_b + V_c + V_0) \quad .
\]  \( \text{(D4)} \)
Appendix E

Calculation of the Aerostatic Pressure Correction for a Vapour Pressure Thermometer

The problem is to know the distribution of temperatures along the capillary. By neglecting the contribution by radiation and by conduction across the vapour, we can write:

\[ \Delta L_i = \frac{1}{\phi} \int_{T_{i-1}}^{T_i} k(T) \, dT \quad \text{with} \quad \phi = \frac{1}{L_n} \int_{T_T}^{T_e} k(T) \, dT \]

where

- \( \Delta L_i \) is a vertical section of the capillary at temperature \( T \) between \( T_i \) and \( T_{i-1} \),
- \( k(T) \) is the conductivity of the material of the capillary (stainless steel),
- \( L_n \) is the total length of the capillary,
- \( T_e \) and \( T_f \) are the temperatures of the hot and cold extremeties.

Knowing \( \Delta L_i \) and the corresponding \( T_i \), the pressure correction is

\[ \Delta P = g \sum_{i=1}^{n} \rho_i \Delta L_i , \]

where \( g \) is the acceleration of gravity,

and \( \rho_i \) is the density of vapour at temperature \( T_i \).

The temperature correction is calculated from the pressure correction and the sensitivity of the thermometer.
Appendix F

Interpolation Polynomials for Standard Thermocouple Reference Tables.*

All tables are for a reference temperature of 0 °C.

1. Interpolation polynomial for type T thermocouples

(E in mV, \( t_{68} \) in °C)

- temperature range from -270 °C to 0 °C:

\[
E = \sum_{i=0}^{14} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
d_0 &= 0; & d_9 &= 3.8648924201 \times 10^{-15}; \\
d_1 &= 3.8740773840 \times 10^{-2}; & d_{10} &= 2.8298678519 \times 10^{-17}; \\
d_2 &= 4.4123932482 \times 10^{-5}; & d_{11} &= 1.4281383349 \times 10^{-19}; \\
d_3 &= 1.1405238498 \times 10^{-7}; & d_{12} &= 2.8298678519 \times 10^{-22}; \\
d_4 &= 1.9974406568 \times 10^{-8}; & d_{13} &= 1.0803474683 \times 10^{-24}; \\
d_5 &= 9.0445401187 \times 10^{-10}; & d_{14} &= 1.3949291026 \times 10^{-27}; \\
d_6 &= 2.2766018504 \times 10^{-11};
\end{align*}
\]

- temperature range from 0 °C to 400 °C:

\[
E = \sum_{i=0}^{8} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
d_0 &= 0; & d_5 &= 1.1031900550 \times 10^{-11}; \\
d_1 &= 3.8740773840 \times 10^{-2}; & d_6 &= -3.0927581898 \times 10^{-14}; \\
d_2 &= 3.3190198092 \times 10^{-5}; & d_7 &= 4.5653337165 \times 10^{-17}; \\
d_3 &= 2.0714183645 \times 10^{-7}; & d_8 &= -2.7616878040 \times 10^{-20}; \\
d_4 &= -2.1945834823 \times 10^{-9};
\end{align*}
\]

* These polynomials relate to the IPTS-68. In due course they will be reformulated so as to relate to the ITS-90.
2. Interpolation polynomial for type J thermocouples
(E in mV, \( t_{68} \) in °C)

- temperature range from -200 °C to 760 °C:

\[
E = \sum_{i=0}^{7} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
d_0 &= 0; \quad d_4 = 1.3348825735 \times 10^{-10}; \\
d_1 &= 5.0372753027 \times 10^{-2}; \quad d_5 = -1.7022405966 \times 10^{-13}; \\
d_2 &= 3.0425491284 \times 10^{-5}; \quad d_6 = 1.9416091001 \times 10^{-16}; \\
d_3 &= -8.5669750464 \times 10^{-8}; \quad d_7 = -9.6391844859 \times 10^{-20};
\end{align*}
\]

- temperature range from 760 °C to 900 °C:

\[
E = \sum_{i=0}^{5} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
d_0 &= 2.9721751778 \times 10^{2}; \quad d_3 = -3.2210174230 \times 10^{-6}; \\
d_1 &= -1.5059632873 \times 10^{0}; \quad d_4 = 1.5949968788 \times 10^{9}; \\
d_2 &= 3.2051064215 \times 10^{-3}; \quad d_5 = -3.1239801752 \times 10^{-13}.
\end{align*}
\]

3. Interpolation polynomial for type E thermocouples (E in mV, \( t_{68} \) in °C)

- temperature range from -270 °C to 0 °C:

\[
E = \sum_{i=0}^{13} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
d_0 &= 0; \quad d_7 = -1.0930767375 \times 10^{-13}; \\
d_1 &= 5.8695857799 \times 10^{-2}; \quad d_8 = -9.1784535039 \times 10^{-16}; \\
d_2 &= 5.1667517705 \times 10^{-5}; \quad d_9 = -5.2575158521 \times 10^{-18}; \\
d_3 &= -4.4652683347 \times 10^{-7}; \quad d_{10} = -2.0169601996 \times 10^{-20}; \\
d_4 &= -1.7346270905 \times 10^{-8}; \quad d_{11} = -4.9502138782 \times 10^{-23}; \\
d_5 &= -4.8719368427 \times 10^{-10}; \quad d_{12} = -7.0177980633 \times 10^{-26}; \\
d_6 &= -8.8896550447 \times 10^{-12}; \quad d_{13} = -4.3671808488 \times 10^{-29};
\end{align*}
\]
- temperature range from 0 °C to 1000 °C:

\[
E = \sum_{i=0}^{9} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
    d_0 &= 0; \\
    d_1 &= 5.8695857799 \times 10^{-2}; \\
    d_2 &= 4.3110945462 \times 10^{-5}; \\
    d_3 &= 5.7220358202 \times 10^{-8}; \\
    d_4 &= -5.4020668025 \times 10^{-10}; \\
    d_5 &= 1.5425922111 \times 10^{-12}; \\
    d_6 &= -2.4850089136 \times 10^{-15}; \\
    d_7 &= 2.3389721459 \times 10^{-18}; \\
    d_8 &= -1.946296815 \times 10^{-21}; \\
    d_9 &= 2.5561127497 \times 10^{-25}.
\end{align*}
\]

4. Interpolation polynomial for type K thermocouples

(E in mV, 1G in °C)

- temperature range from -270 °C to 0 °C:

\[
E = \sum_{i=0}^{10} d_i \cdot t_{68}^i
\]

where:

\[
\begin{align*}
    d_0 &= 0; \\
    d_1 &= 3.9475433139 \times 10^{-2}; \\
    d_2 &= 2.7465251138 \times 10^{-5}; \\
    d_3 &= -1.6565406716 \times 10^{-7}; \\
    d_4 &= -1.5190912392 \times 10^{-9}; \\
    d_5 &= -1.8533063273 \times 10^{-2}; \\
    d_6 &= -2.4757917816 \times 10^{-13}; \\
    d_7 &= -3.5700231258 \times 10^{-13}; \\
    d_8 &= -3.5700231258 \times 10^{-13}; \\
    d_9 &= -1.5585276173 \times 10^{-15}; \\
    d_{10} &= -1.382797374 \times 10^{-23}; \\
    d_{11} &= -2.4581670924 \times 10^{-11};
\end{align*}
\]

- temperature range from 0 °C to 1372 °C:

\[
E = \sum_{i=0}^{8} d_i \cdot t_{68}^i + 0.125 \exp \left[ -\frac{1}{2} \left( \frac{t_{68} - 127}{65} \right)^2 \right]
\]

where:

\[
\begin{align*}
    d_0 &= -1.8533063273 \times 10^{-2}; \\
    d_1 &= 3.8918344612 \times 10^{-2}; \\
    d_2 &= 1.6645154356 \times 10^{-5}; \\
    d_3 &= -7.8702374448 \times 10^{-8}; \\
    d_4 &= 2.2835785557 \times 10^{-10}; \\
    d_5 &= -3.5700231258 \times 10^{-13}; \\
    d_6 &= 2.9932909136 \times 10^{-16}; \\
    d_7 &= -1.2849848798 \times 10^{-19}; \\
    d_8 &= 2.2239974336 \times 10^{-23}.
\end{align*}
\]
5. Interpolation polynomial for type S thermocouples

\( E \) in mV, \( t_{68} \) in °C

- temperature range from -50 °C to 630.74 °C:

\[ E = \sum_{i=0}^{6} a_i \cdot t_{68}^i \]

where:

- \( a_0 = 0 \);
- \( a_1 = 5.3995782346 \times 10^{-3} \);
- \( a_2 = 1.2519770000 \times 10^{-5} \);
- \( a_3 = -2.2448217997 \times 10^{-8} \);
- \( a_4 = 2.8452164949 \times 10^{-11} \);
- \( a_5 = -2.2440584544 \times 10^{-14} \);
- \( a_6 = 8.5054166936 \times 10^{-18} \);

- temperature range from 630.74 °C to 1064.43 °C:

\[ E = \sum_{i=0}^{2} g_i \cdot t_{68}^i \]

where:

- \( g_0 = -2.9824481615 \times 10^{-1} \);
- \( g_1 = 8.2375528221 \times 10^{-3} \);
- \( g_2 = 1.6453909942 \times 10^{-6} \);

- temperature range from 1064.43 °C to 1665 °C:

\[ E = \sum_{i=0}^{3} b_i \left( \frac{t_{68} - 1365}{300} \right)^i \]

where:

- \( b_0 = 1.3943438677 \times 10^1 \);
- \( b_1 = 3.6398686553 \);
- \( b_2 = -5.0281206140 \times 10^{-3} \);
- \( b_3 = -4.2450546418 \times 10^{-2} \).

6. Interpolation polynomial for type B thermocouples

\( E \) in mV, \( t_{68} \) in °C

- temperature range from 0 °C to 1820 °C:

\[ E = \sum_{i=0}^{8} d_i \cdot t_{68}^i \]
where:  
\(d_0 = 0;\)  
\(d_5 = -3.1757800720 \times 10^{-15};\)  
\(d_1 = -2.4674601620 \times 10^{-4};\)  
\(d_6 = 2.4010367459 \times 10^{-18};\)  
\(d_2 = 5.910211169 \times 10^{-6};\)  
\(d_7 = -9.0928148159 \times 10^{-22};\)  
\(d_3 = -1.4307123430 \times 10^{-9};\)  
\(d_8 = 1.3299505137 \times 10^{-25};\)  
\(d_4 = 2.1509149750 \times 10^{-12};\)  

7. Interpolation polynomial for type N thermocouples  
\((E \text{ in mV}, t_{68} \text{ in °C}, \text{wire diameter 1.6 mm})\)

- temperature range from 0 °C to 1300 °C:  
\[
E = \sum_{i=0}^{9} d_i \cdot t_{68}^i
\]

where:  
\(d_0 = 0;\)  
\(d_5 = 3.6526665920 \times 10^{-13};\)  
\(d_1 = 2.5897798582 \times 10^{-2};\)  
\(d_6 = -4.4390833504 \times 10^{-16};\)  
\(d_2 = 1.6656127713 \times 10^{-5};\)  
\(d_7 = 3.1553382729 \times 10^{-10};\)  
\(d_3 = 3.1234962101 \times 10^{-8};\)  
\(d_8 = -1.2150879468 \times 10^{-22};\)  
\(d_4 = -1.7248130773 \times 10^{-10};\)  
\(d_9 = 1.9557197559 \times 10^{-26}.\)

8. Interpolation polynomial for type R thermocouples  
\((E \text{ in mV}, t_{68} \text{ in °C})\)

- temperature range from -50 °C to 630.74 °C:  
\[
E = \sum_{i=0}^{7} a_i \cdot t_{68}^i
\]

where.  
\(a_0 = 0\)  
\(a_1 = 5.2891395059 \times 10^{-3}\)  
\(a_2 = 1.3911109947 \times 10^{-5}\)  
\(a_3 = -2.4005238430 \times 10^{-8}\)  
\(a_4 = 3.6201410595 \times 10^{-11}\)  
\(a_5 = -4.4645019036 \times 10^{-14}\)  
\(a_6 = 3.8497691865 \times 10^{-17}\)  
\(a_7 = -1.5372641559 \times 10^{-20}\)
- temperature range from 630.74 °C to 1064.43 °C:

\[ E = \sum_{i=0}^{3} g_i \cdot t_{68}^i \]

where:

- \( g_0 = -2.641\ 800\ 7025 \times 10^{-1} \)
- \( g_1 = 8.046\ 868\ 6747 \times 10^{-3} \)
- \( g_2 = 2.989\ 229\ 3723 \times 10^{-6} \)
- \( g_3 = -2.687\ 605\ 8617 \times 10^{-10} \)

- temperature range from 1064.43 °C to 1665 °C:

\[ E = \sum_{i=0}^{3} b_i \cdot t_{68}^i \]

where:

- \( b_0 = 1.490\ 170\ 2702 \times 10^{0} \)
- \( b_1 = 2.863\ 986\ 7552 \times 10^{-3} \)
- \( b_2 = 8.082\ 363\ 1189 \times 10^{-6} \)
- \( b_3 = -1.933\ 847\ 7638 \times 10^{-9} \)

- temperature range from 1665 °C to 1769 °C:

\[ E = \sum_{i=0}^{3} d_i \cdot t_{68}^i \]

where:

- \( d_0 = 9.544\ 555\ 9010 \times 10^{1} \)
- \( d_1 = -1.664\ 250\ 0359 \times 10^{-1} \)
- \( d_2 = 1.097\ 574\ 3239 \times 10^{-4} \)
- \( d_3 = -2.228\ 921\ 6980 \times 10^{-8} \).