



ESDU 06019

Issued February 2007
Supersedes ESDU 84036

Temperature measurement: resistance thermometry

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TEMPERATURE MEASUREMENT: resistance thermometry

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TEMPERATURE MEASUREMENT: resistance thermometry

1. PURPOSE AND SCOPE OF THIS DATA ITEM

This Data Item is one of a series concerned with the measurement of temperature. Companion Data Item ESDU 02006 (Reference 1) describes the principal techniques that are available for industrial and research applications. ESDU 06018 (Reference 2) details the operation and application of thermocouples for temperature measurement.

In this Data Item the various resistance techniques are described together with their main advantages and disadvantages. Section 2 is concerned with some fundamental aspects and in Section 3 a range of practical sensors is described together with methods of mounting and protection. Some of the problems that might arise when applying resistance thermometry are described in Section 4 while the various resistance measuring techniques appear in Section 5. A glossary of resistance thermometry terms is included in Section 7.

When using this Data Item it is suggested that Section 2 should be read first to provide background on the basis of resistance thermometry. Section 3 can then be consulted as to the suitability of the technique for particular applications and also the selection of the most appropriate type of sensor. Reference to Section 4 will provide some information on some of the practical problems that may arise and Section 5 indicates the most suitable methods for connecting the sensor to the output device and also some of the measurement systems available.

The Data Item is principally concerned with platinum resistance thermometry, as platinum is the best and probably the most commonly used material for resistance type sensors. Other resistance materials are used for particular applications and the information given in Sections 3, 4 and 5 will, in general terms, apply to sensors incorporating these other materials. Thermistors are a relatively specialised type of temperature sensor and Section 6 provides a short description of thermistors and their applications.

Appendix A summarises the standard resistance versus temperature relationships in use for industrial type thermometers. Finally in Appendix B some physical properties of the materials used in resistance thermometer construction are provided.

Although throughout the Data Item the techniques are discussed in terms of the measurement of temperature, many of the comments are applicable to resistance thermometers used as sensors in temperature control systems. In this regard, aspects such as time response, temperature equilibrium and stability may be important.

A temperature scale is necessary in order to enable comparisons between measurements. The International Temperature Scale of 1990 (referred to as the ITS-90) is intended to be a practical, internationally agreed, best approximation to the thermodynamic temperature scale. A brief summary of the ITS-90 can be found in ESDU 02006 (Reference 1) or from the original sources (References 3, 4 and 5).

1.1 Characteristics of Resistance Methods

Resistance methods have some particular attributes. Platinum resistance thermometry is probably the most accurate method of temperature measurement that is available; it represents a considerable improvement on thermocouple thermometry, for example. Between $-259.3467^{\circ}\text{C}$ and 961.78°C the platinum resistance thermometer, built to certain specifications, is used as the interpolation instrument for defining the ITS-90.

Using such instruments uncertainty of ± 2 mK at the lower end and ± 7 mK at the upper end of this scale is possible (Reference 6). Resistance thermometry is a well established method and there is a very considerable body of knowledge and experience in its design, manufacture and application requirements.

Table 1.1 shows advantages and disadvantages associated with resistance thermometry.

TABLE 1.1 Some Features Of Resistance Thermometry

<i>Advantages</i>	<i>Disadvantages</i>
High precision Good stability Reproducible Simple concept Well documented	Some devices are sensitive to shock Needs energising current Self-heating effects Expensive (for high accuracy)

It should be realised that while extremely high precision is possible with resistance techniques it is not necessarily readily achieved. Considerable expenditure of time and attention to detail may be required. The most precise sensors are expensive and fragile and not suited to everyday industrial usage. It is worth deciding critically what uncertainties in temperature determination are really acceptable. Is the process really sensitive to temperature measured in absolute terms, or is it the differences in temperature that are more important?

There is a considerable amount of information on resistance thermometry in the literature. The following references offer some useful background and detailed information. References 7, 8, 9 and 10 are text books with sections on resistance thermometry and related areas. References 11, 12, 13, 14 and 15 are edited collections of conference papers on all aspects of temperature measurement.

When contemplating resistance type temperature measurements it should also be remembered that the manufacturers and suppliers who specialise in these instruments have considerable knowledge and accumulated experience. Many provide useful literature on the subject.

2. HOW A PLATINUM RESISTANCE THERMOMETER WORKS

2.1 Electrical Resistance

The phenomenon of electrical conduction arises in a material as a result of the presence of an electric field modifying the normal random motion of electrons to produce a net flow in a given direction. This systematic flow is impeded by scattering arising from imperfections in the crystal lattice such as the presence of grain boundaries, impurities, lattice distortions, etc. Electrons are further scattered by thermally induced effects, e.g. lattice vibrations and phonon scattering.

Matthiessen's rule expresses how the overall resistivity of a "pure" metal is the sum of such effects.

$$\rho = \rho_t + \rho_i + \rho_d \quad (2.1)$$

where

- ρ = the overall resistivity,
- ρ_t = the component due to thermal effects,
- ρ_i = the component due to the presence of impurities,
- ρ_d = the component due to lattice deformation arising from the mechanical stress.

Clearly, when constructing a resistance thermometer, the temperature related effect ρ_t should be dominant and the unwanted resistivity changes ρ_i and ρ_d should be suppressed. Practically this means that the material for the sensor should be, and remain in, as pure and strain free condition as possible.

A number of metals can be used for resistance thermometry including gold, silver, platinum, nickel and copper. Some special alloys have also been developed and although some nickel, copper and alloy based resistance sensors are still produced for particular applications, there is a growing tendency for platinum to become universally used for resistance thermometry. While platinum is an expensive material, the amounts used in resistance thermometers, particularly with modern designs, are very small and the platinum content does not represent a highly significant part of the sensor cost.

2.2 Platinum for Thermometry

Platinum is a metallic element that is well suited to resistance thermometry applications. Some of its physical properties are given in Appendix B. Its particular advantages are that it is a relatively inert material, it can be produced in a very pure form (99.999% is quoted) and it has a satisfactory temperature coefficient of resistance. Platinum can also be drawn into very fine wires, a useful property for thermometer construction.

As discussed earlier, the principal requirements for a predictable performance from a platinum resistance thermometer are that the platinum material should be very pure and in a strain free condition. The criterion used to establish and specify the condition of platinum for resistance thermometry is the value of the mean temperature coefficient of resistance, α , between 0°C and 100°C, *i.e.*

$$\alpha = \frac{(R_{100} - R_0)}{100 R_0} \quad (2.2)$$

where

R_{100} = the resistance of the sensor at 100°C
 R_0 = the resistance of the sensor at 0°C.

The value of α increases with the reduction of both the amount of impurities and the amount of strain in the platinum material. For satisfactory resistance thermometry it should exceed 0.0038 K⁻¹. A value of 0.00385 K⁻¹ is typical for an industrial platinum resistance thermometer and 0.003927 K⁻¹ is typical for a standards platinum resistance thermometer.

Thus the main requirements for a good platinum resistance thermometer sensor are:

- (i) the use of very pure platinum material,
- (ii) the use of fully annealed platinum material,
- (iii) an arrangement of support for the platinum that will result in minimum strain arising in the platinum from thermal expansion movements or other effects,
- (iv) the protection of the platinum material from contamination.

2.3 The Resistance versus Temperature Relationship

The resistance versus temperature relationship of a platinum resistance thermometer is well represented by two simple equations from 0°C to 630°C by the Callendar equation,

$$R_t = R_0(1 + At' + Bt'^2) \quad (2.3)$$

and from -180°C to °C by the Callendar – van Dusen equation,

$$R_t = R_0[1 + At' + Bt'^2 + Ct'^3(t' - 100)] \quad (2.4)$$

where

t' = temperature in °C defined by Equations (2.3) and (2.4),

R_t' = resistance of the sensor at temperature t' ,

A, B and C = constants relating to the platinum material.

Equations (2.3) and (2.4) can be re-written in the form:

$$t' = \frac{1}{\alpha} \left(\frac{R_t}{R_0} - 1 \right) + \delta \left(\frac{t'}{100} - 1 \right) \frac{t'}{100} \quad (2.5)$$

$$t' = \frac{1}{\alpha} \left(\frac{R_t}{R_0} - 1 \right) + \delta \left(\frac{t'}{100} - 1 \right) \frac{t'}{100} + \beta \left(\frac{t'}{100} - 1 \right) \frac{t'^3}{100} \quad (2.6)$$

where

R_{100} = resistance of the sensor at the boiling point of water,

α, δ and β = constants determined during the calibration of the thermometer.

The various constants and coefficients are inter-related:

$$A = \alpha \left(\frac{1 + \delta}{100} \right), \quad (2.7)$$

$$B = -\frac{\alpha\delta}{10^4}, \quad (2.8)$$

$$C = \frac{\alpha\beta}{10^8}, \quad (2.9)$$

$$\alpha = A + 100B, \quad (2.10)$$

$$\delta = -\frac{10^4 B}{A + 100B}, \quad (2.11)$$

$$\beta = -\frac{10^8 C}{A + 100B}. \quad (2.12)$$

These expressions have formed the basis of resistance thermometer temperature calculations over the years and Equations (2.3) and (2.4) were, in fact, used to define part of the International Practical Temperature Scale of 1948 (IPTS-48). However it was recognised that temperatures obtained from these equations did not represent the thermodynamic temperatures precisely and when the IPTS-68 was formulated, (which has itself now been superseded by the ITS-90), the determinations of the various fixed point temperatures were incorporated together with revised interpolation techniques. For industrial PRTs specified by IEC-751-83¹⁶ (plus amendments A1:1986¹⁷ and A2:1995¹⁸), BS 60751:1996 and EN 60751:1996¹⁹ the reference function used takes the form given in Equation (2.4):

$$R_{t=0^{\circ}\text{C}} = 100 \, \Omega, A = 3.9083 \times 10^{-3} \, \text{K}^{-1}, B = -5.775 \times 10^{-7} \, \text{K}^{-2};$$

$$\text{for } t \geq 0^{\circ}\text{C}, C = 0.0 \text{ and for } t < 0^{\circ}\text{C}, C = -4.183 \times 10^{-12} \, \text{K}^{-4}.$$

The tolerance in degrees celsius for Class A devices is 0.15+0.2% and for Class B devices is 0.3+0.5%.

References tables for the resistance temperature characteristic from EN 60751¹⁹ are given in Appendix A.

3. PRACTICAL SYSTEMS

In this Section the components that comprise the temperature sensing parts of different types of resistance thermometers are described. There appear to be no standard designations for the various components, for example the term “resistance thermometer” can apply equally to a short length of platinum wire or the complete temperature measuring system including the output indicator.

Sketch 3.1 depicts a typical industrial resistance thermometer assembly with the designations used in this Data Item. Where applicable, some other commonly used designations are also included.

3.1 Sensors

It is important to select the most suitable type of sensor for each application. As a general rule, reductions in temperature determination uncertainties are achieved with more fragile and expensive sensors. Such sensors can be susceptible to structural damage and deterioration of the sensing material from the fully annealed condition as a result of mechanical shocks, vibration or sudden thermal changes.

The temperature ranges that can be covered by the various types are given in Sketch 3.2. With industrial type sensors operating at high temperatures appropriate connecting wire insulation materials and wire attachment methods will be required. The likely uncertainties for various types of sensor are given in Sketch 3.3. Industrial type sensors can be obtained that conform to either Class B or Class A tolerances (See Appendix A) while it is also possible to specify sensors with much closer tolerance but these would be at higher unit costs, *e.g.* the “Selected Industrial Type” line in Sketch 3.3. Industrial sensors are described in Section 3.1.3.

Higher accuracy can be achieved with the precision types of thermometer. These are intended for use in the laboratory as transfer standards and are described in Section 3.1.2. Finally, for the highest possible accuracy, standard type instruments can be employed where uncertainties may be as low as $\pm 0.001^{\circ}\text{C}$. The use of these instruments is confined to the standards laboratory where constant vigilance will be required to maintain their condition. Standard resistance thermometers are described in Section 3.1.1. The important characteristics of most types of resistance sensors are given in Table 3.1.

3.1.1 Standard platinum resistance thermometers.

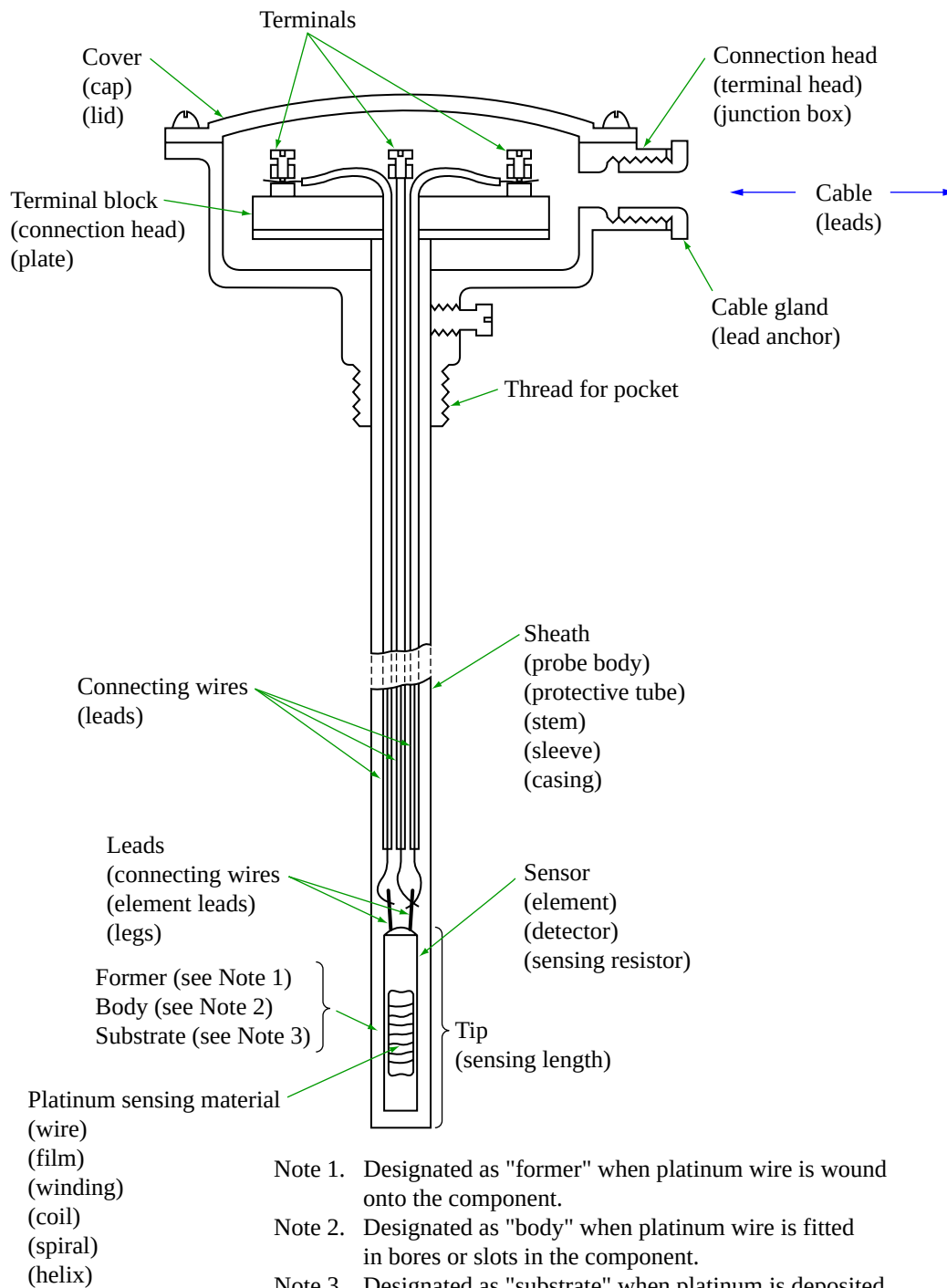
Standard platinum resistance thermometers represent the highest quality of resistance thermometer and are suitable for use as an instrument to realise the ITS-90 over the specified range. They are expensive fragile instruments intended for use in the laboratory as reference standards for calibrating other measuring instruments.

They divide into two or perhaps three types depending on their operating temperature ranges. From 13 K to 300 K special capsule types have been developed (References 8 and 20) In a typical design 0.07 mm diameter platinum wire is wound into a helical coil and fitted into two silica tubes twisted together in a long helix. This is somewhat similar to the arrangement in the long-stem type (Sketch 3.4). The assembly is

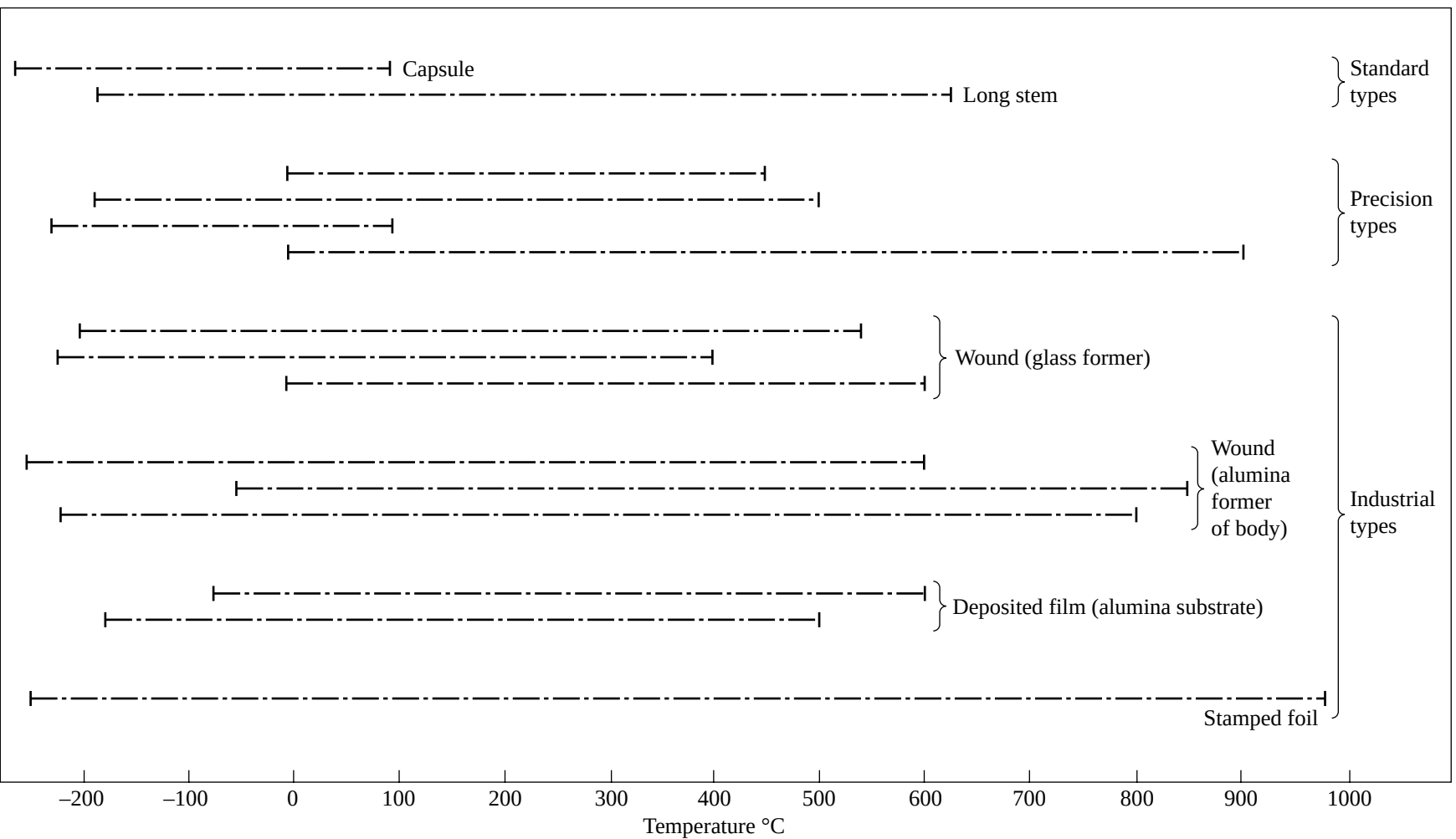
sealed in to a 5 mm O.D. helium filled platinum tube with four platinum wire leads passing through suitable glass to metal seals. There are other designs in use in different parts of the world. The important requirement is to provide support for the platinum wire that will impose minimum strains. The particular problem with these instruments at cryogenic temperatures is their low resistance which tends to make the effect of the connecting wire resistances more significant. There may also be problems arising from thermal conduction across the very steep temperature gradients that tend to be present in cryogenic applications.

TABLE 3.1 Some Properties of Platinum Resistance Thermometers

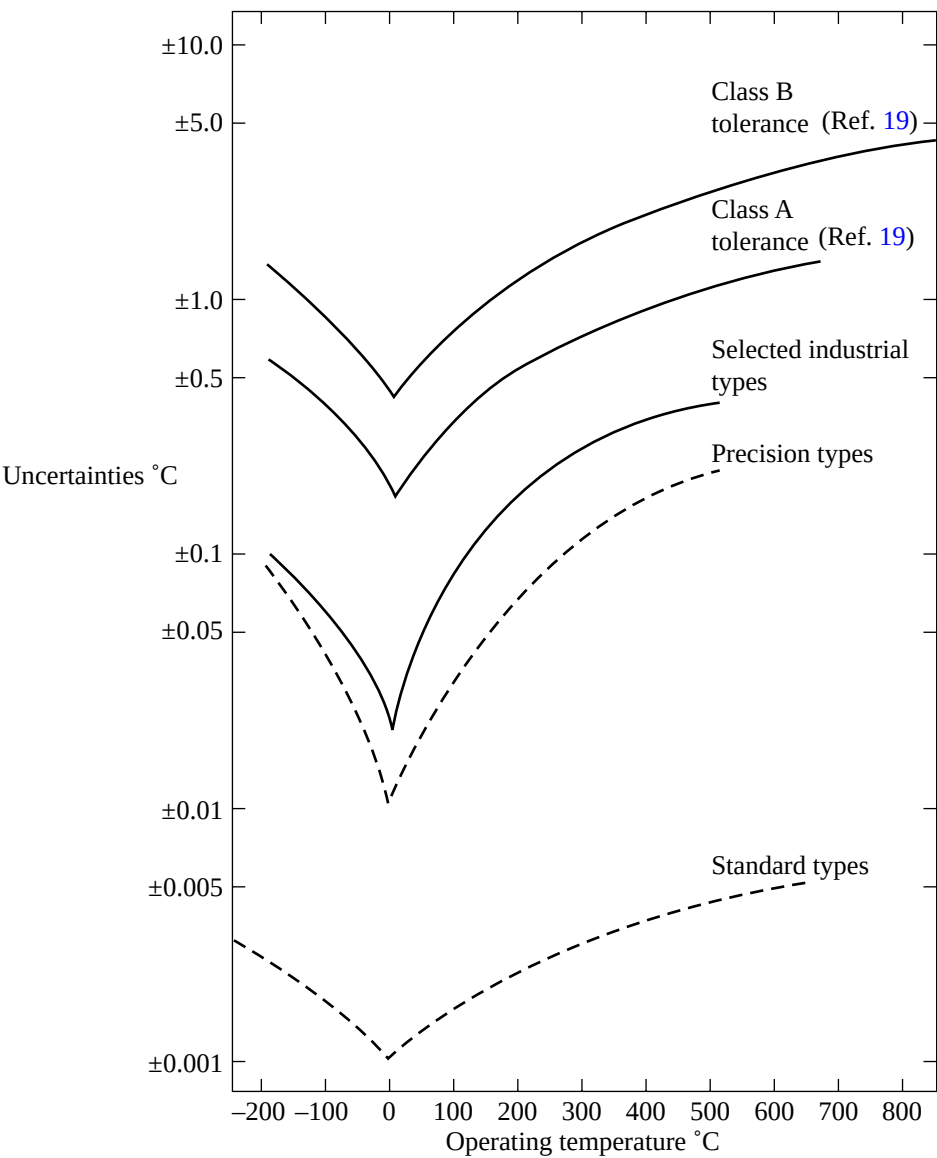
Type	Typical Dimensions (mm)			Temperature Range (°C)	Uncertainties (°C)	R_0 (ohm)	Self-heating effect (°C/mW)
	Length	Width or Diameter (D)	Thickness				
STANDARD TYPE							
low temperature	(Sheath) 50	5.0 (D)		−259 to 100	±0.003	25	0.08
medium temperature	(Sheath) 480	7.0 (D)		−183 to 630	±0.001 at 20 ±0.005 at 630	25	0.08
PRECISION TYPE	(Sheath) 457	4.0 (D)		−180 to 500	±0.01	100	0.3
" "	" 500	8.0 (D)		−220 to 100	±0.2 at 420	10	---
" "	" 500	8.0 (D)		0 to 900	±0.2 at 420	0.2	---
INDUSTRIAL TYPE (Sensors only)							
Wire-wound, glass cylinder	5.0 to 70	1.0 to 6.0 (D)		−220 to 550	supplied to Class A or Class B tolerances see Appendix A and Section 3.1.3	50, 100, 500, 1000	0.02 to 0.04
Wire-wound, alumina cylinder	5.0 to 50	0.75 to 5.0 (D)		−220 to 850		10, 20, 50, 100, 500	0.01 to 0.03
Wire-wound, alumina plate	4.0 to 25	4.0 to 20	0.75 to 2.5	−260 to 600		100	---
Wire-wound, alumina disc		5.0 to 10 (D)	1.5 to 3.0	−200 to 550		100	0.05
Deposited film, alumina cylinder	5.0 to 35	2.0 to 7.0 (D)		−180 to 600		100, 200, 500, 1000, 2000	0.01 to 0.06
Deposited film, alumina plate	2.0 to 10	2.0 to 4.0	0.3 to 2.0	−180 to 500		100, 200, 500, 1000	0.06 to 0.15
Deposited film, alumina disc		4.0 to 7.0 (D)	1.0 to 3.0	−50 to 600		100	---
Foils	4.0 to 12	2.0 to 12	0.005	−250 to 980	±4% (when attached)	50, 100, 250, 500	---
M.I. cable type probes	75 to 25 metres (cable length)	3.0 to 6.0 (D)		−200 to 540	±0.2%	100	0.01 to 0.03



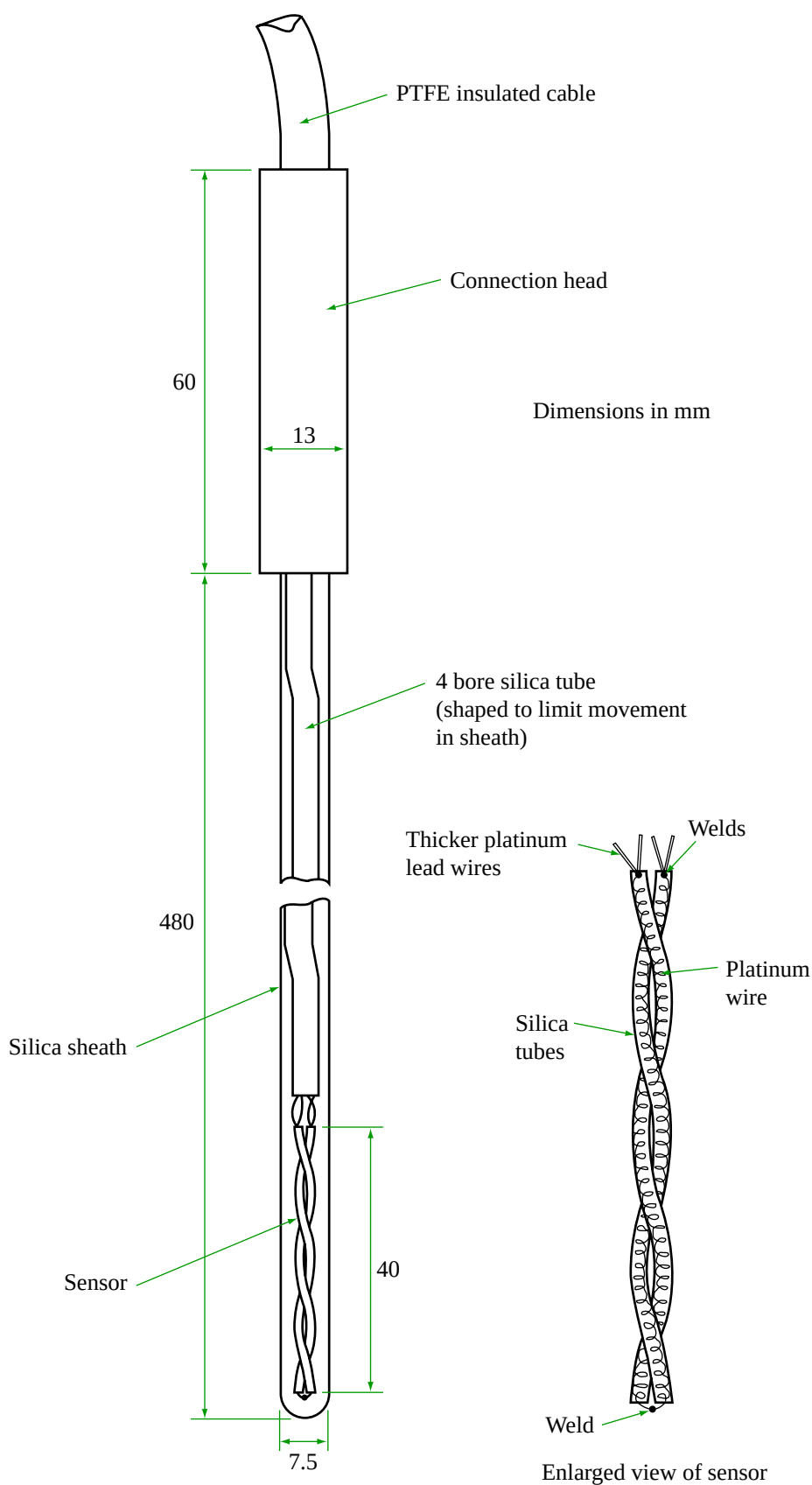
Sketch 3.1 Components of an industrial resistance thermometer



Sketch 3.2 Typical temperature ranges of platinum thermometers



Sketch 3.3 Typical uncertainties in temperature determinations for different types of resistance thermometer



Sketch 3.4 A long-stem type standard platinum resistance thermometer

The long stem type of standard platinum resistance thermometer is used over the temperature range -180°C to 630°C . A number of designs for long-stem thermometers have emerged over the years (References 8 and 9). The construction of a typical long-stem standard platinum resistance thermometer is shown in Sketch 3.4. Here the fine platinum sensing wire (0.075 mm diameter) having an α value in excess of $0.0039250^{\circ}\text{C}^{-1}$, is in the form of two helices, each contained in a fused silica tube. The tubes are formed into long spirals and intertwined. The platinum wire is thus supported by the combination of its own, though limited, stiffness and frictional contact with the wall of the silica tubes. While this method of mounting allows the platinum wire to be almost strain-free, the physical support it provides for the wire is very limited. R_0 values (the resistance of the sensor at 0°C) are usually nominally 25 ohms.

The two ends of the platinum sensing wire are welded to two pairs of heavier gauge platinum wires. These thicker wires are carried along the sheath in a multi-bore silica tube to a terminal head where connections are made to a four conductor flexible cable. Coaxial connecting cables can be used to connect to A.C. bridges. To reduce unwanted, guided radiation heat transmission, the silica sheath of the thermometer may be treated by abrading or coating. On completion of manufacture the sheath is filled with dry air and sealed.

Designs such as this offer the highest precision that is possible in platinum resistance thermometry realising room temperature values with uncertainties no greater than $\pm 0.001^{\circ}\text{C}$. They are, however, fragile, bulky, have poor heat transfer characteristics and thus a fairly slow thermal response time (see Table 4.2). Extreme care is needed during the transportation, use and storage of these instruments (see Reference 21). Any mechanical shock or vibration, for example inadvertently striking the edge of a pocket prior to insertion, can displace the wires slightly, causing local strain and thus give rise to a change in R_0 . It has been suggested that if any impact involving the thermometer is audible, a change in R_0 will ensure. It is also undesirable for the thermometer to be subjected to sudden changes of temperature. Rapid cooling from 500°C can introduce cold work into the resistance wires which must be removed by subsequent annealing to restore R_0 . Regular determinations of the thermometer R_0 value is a necessary requirement for maintaining measurement accuracy.

Some designs have been suggested for high temperature SPRTs (sometimes referred to as high temperature SPRTs or HTSPRTs) (e.g. References 22, 23 and 24). For operation at elevated temperature SPRTs must be designed to resist contamination. Although relatively stable, platinum does oxidize (References 25 and 26) and undergoes crystal growth (Reference 27). Oxidization ultimately limits the upper useful temperature and the long term stability and uncertainty for a particular thermometer. Mica cannot be used at sustained temperatures above approximately 600°C and high purity quartz is usually used as an alternative. Unfortunately the insulation properties of substances reduce with temperature and the quartz mandrel serves as a shunt resistance across the platinum windings introducing an uncertain error source.

The resistance measuring devices used for precision thermometry are described in Section 5.

3.1.2 Precision platinum resistance thermometers

The precision platinum resistance thermometer, while not exhibiting the ultimate precision of the standard platinum resistance thermometer, provides a useful compromise between accuracy and robustness. These instruments, frequently referred to as transfer standards or precision thermometers, take the same general form as the long-stem standard thermometers but the platinum sensing wires are more rigidly constrained and the whole assembly may be contained in a stainless steel outer sheath.

In some designs the platinum wire may be positively attached within a ceramic former with a small deposit of cement locating a part of some of the turns along the element helix, somewhat similar to the illustration shown in Sketch 3.5b. This provides a reasonable compromise between strain-free conditions and a satisfactory mechanical support, and R_0 values are usually 100 ohms.

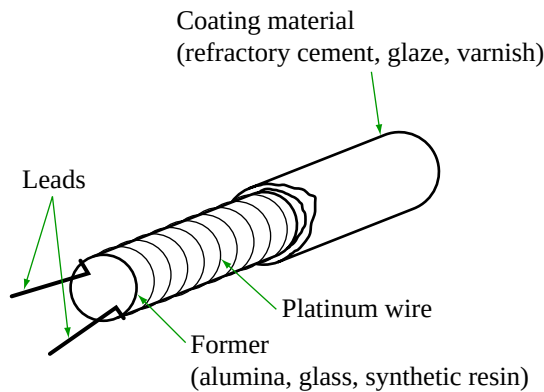
While such instruments are still not robust they can be used on a routine basis in a laboratory or similar environment. They are capable of operating at temperatures usually between -220°C and 600°C and might exhibit uncertainties at room temperature of the order $\pm 0.01^{\circ}\text{C}$. Some special versions are available with temperature ranges of -220°C to 100°C , 0°C to 630°C ($R_0 = 100 \text{ ohm}$) and 0°C to 900°C ($R_0 = 0.2 \text{ ohm}$)

3.1.3 Industrial platinum resistance thermometers

The description Industrial Platinum Resistance Thermometer may refer to any one of a wide variety of types that have been developed to suit the diverse requirements of science and industry. With these instruments, the extreme accuracy and stability of the standard and the precision types have been compromised in the interest of enhancing important alternative features such as robustness, smaller size, faster response time, more appropriate shape, ready availability and lower cost. Nevertheless, good examples of industrial thermometers can provide a highly accurate method of temperature measurement, (see Table 3.1). Reliability can also be very good and when failures do occur they frequently are the result of the connections becoming detached rather than the actual platinum materials being at fault. The diameters of the platinum wires used as the sensing material may range from 0.01 mm to 0.15 mm.

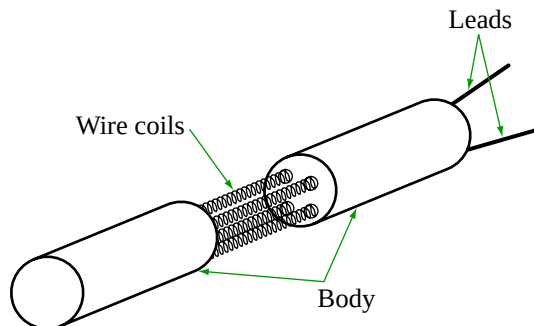
With the standard and precision types the design and performance requirements are such that the instruments are supplied as complete units which include the sensor, sheath, connecting head and flexible connecting cable (see Sketch 3.4). Industrial types, on the other hand, may be supplied in quite basic forms, comprising just a small cylinder, disc or strip of ceramic or glass supporting the platinum material, with short leads attached (see Sketch 3.5). These may be fitted in protecting sheaths to form assemblies with terminals. The assemblies may subsequently be fitted in pockets or thermowells depending upon the application (see Sketch 3.6). It is also possible to obtain platinum temperature sensors in the form of minute unsupported foils. Thermometer grade platinum wire is available for the manufacture of special sensors to meet particular measurement requirements.

The resistance versus temperature characteristics of industrial sensors are given in Appendix B for the temperature range of -200°C to $+850^{\circ}$. This represents the general practical temperature limits for these instruments although some suppliers will produce sensors that can function at temperatures as low as -260°C and as high as 1100°C .



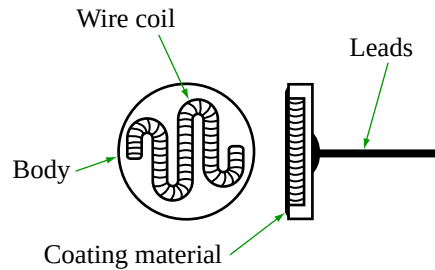
Note: In some designs the outer coating is on alumina sleeve. The annular gap is packed with alumina powder.

(a) Wire-wound on former sensor

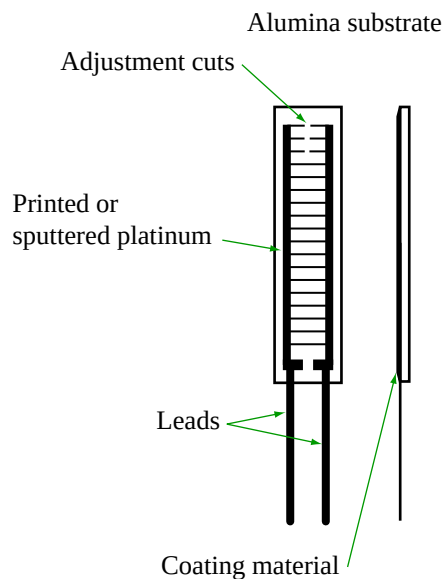


Note: The coils may have part of each turn attached to the bore wall or the boxes packed with powder in cement.

(b) Wire coils-in-bore sensor



(c) Pad type sensor



Note: This type of sensor is also fitted in a ceramic tube and packed with powder or cement to produce a cylindrically shaped sensor.

(d) Deposited film type sensor

Sketch 3.5 Some types of industrial platinum resistance sensor

The temperature of a platinum resistance thermometer constructed to conform to these standards can be obtained directly from the Tables, subject to one of two tolerance bands. For more accurate applications manufacturers can usually offer instruments with closer tolerances, or the thermometers may have to be calibrated individually against known standard instruments (see Section 4.7).