

RESISTANCE THERMOMETER THEORY AND PRACTICE

1. BASIC THEORY

The electrical conductivity of a metal depends on the movement of electrons through its crystal lattice. Due to thermal excitation, the electrical resistance of a conductor varies according to its temperature and this forms the basic principals of resistance thermometry. The effect is most commonly exhibited as an increase in resistance with increasing temperature, a **positive temperature coefficient of resistance**.

When utilising this effect for temperature measurement, a large value of temperature coefficient (the greatest possible change of resistance with temperature) is deal; however, stability of the characteristic over the short and long term is vital if practical use is to made of the conductor in question. The relationship between the temperature and the electrical resistance is usually non-linear and described by a higher order polynomial:

$$R(t) = R_0(1 + A.t + B.t^2 + C.t^3 + \dots)$$

Where R_0 is the nominal resistance at a specified temperature. The number of higher order terms considered is a function of the required accuracy of measurement. The coefficients A, B and C etc. depend on the conductor material and basically define the temperature-resistance relationship.

Material most commonly utilised for resistance thermometers are Platinum, Copper and Nickel. However, Platinum is the most dominant material internationally.

Platinum Sensing Resistors

Platinum sensing resistors are available with alternative R_0 values, for example 10, 25 and 100 Ohms. A working form of resistance thermometer sensor is defined in IEC and DIN specifications and this forms the basis of most industrial and laboratory electrical thermometers. **The platinum sensing resistor, Pt100 to IEC 751** is dominant in Europe and in many other parts of the world. Its advantages include chemical stability, relative ease of manufacture, the availability of wire in a highly pure form and excellent reproducibility of its electrical characteristic. The result is a truly interchangeable sensing resistor which is widely commercially available at a reasonable cost.

This specification includes the standard variation of resistance with temperature, the nominal value with the corresponding reference temperature, and the permitted tolerances. The specified temperature range extends from -200 to 961.78°C . The series of reference values is split into two parts: -200°C to 0 and 0 to 961.78°C .

The first temperature range is covered by a third-order polynomial

$$R(t) = R_0(1 + A \cdot t + B \cdot t^2 + C \cdot [t - 100^{\circ}\text{C}] \cdot t^3)$$

For the range 0 to 850°C there is a second-order polynomial

$$R(t) = R_0(1 + A \cdot t + B \cdot t^2)$$

The coefficients are as follows:

$$A = 3.9083 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$$

$$B = -5.775 \times 10^{-7} \text{ }^{\circ}\text{C}^{-2}$$

$$C = -4.183 \times 10^{-12} \text{ }^{\circ}\text{C}^{-4}$$

The value R_0 is referred to as **nominal value** or **nominal resistance** and is the resistance at 0°C . According to IEC 751 the nominal value is defined as 100.00 Ohm , and this is referred to as a **Pt100 resistor**. Multiples of this value are also used; resistance sensors of 500 and 1000 Ohm are available to provide higher sensitivity, i.e. a larger change of resistance with temperature.

The resistance changes are approximately:

$$0.4 \text{ } \Omega / ^{\circ}\text{C} \text{ for the Pt100}$$

$$2.0 \text{ } \Omega / ^{\circ}\text{C} \text{ for the Pt100}$$

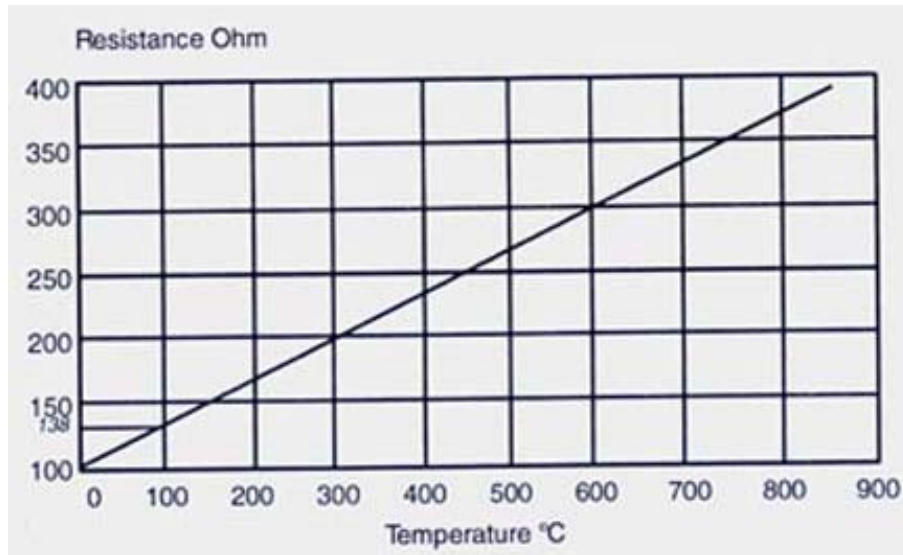
$$0.4 \text{ } \Omega / ^{\circ}\text{C} \text{ for the Pt100}$$

An additional parameter defined by the standard specification is the mean temperature coefficient between 0 and 100°C . It represents the mean resistance change referred to the nominal resistance at 0°C :

$$\alpha = \frac{R_{100} - R_0}{R_0 \times 100^{\circ}\text{C}} = 3.850 \times 10^{-3}$$

Note: For exact calculation use $= 0.00385055^{\circ}\text{C}^{-1}$

R_{100} is the resistance at 100°C , R_0 at 0°C . The resistance change over the range 0°C to 100°C is referred to as the **Fundamental Interval**.



Resistance/Temperature Characteristics of Pt100

The very high accuracy demanded of primary standard resistance thermometers requires the use of a more pure form of platinum for the sensing resistor. This results in different R_0 and alpha values. Conversely, the platinum used for Pt100 versions is “doped” to achieve the required R_0 and Alpha values.

2. ADOPTION OF Pt100 THERMOMETERS

The practical range of Pt100 based thermometers extends from -200°C to 650°C although special versions are available for up to 962°C . Their use has in part taken over from thermocouples in many applications for a variety of reasons:

- a) Installation is simplified since special cabling and cold junction considerations are not relevant. Similarly, instrumentation considerations are less complex in terms of input configuration and enhanced stability.
- b) Instrumentation developments have resulted in high accuracy, high resolution and high stability performance from lower cost indicators and controllers; such accuracy can be better exploited by the use of superior temperature sensors.
- c) The availability of a growing range of sensing resistor configurations include miniature, flat-film fast response versions in addition to the established wirewound types with alternative tolerance bands.

The usable maximum temperature of the sensing resistor is dependent on the type of sheath material used to provide protection. Those using stainless steel should not exceed 500°C because of contamination effects. Nickel and Quartz are alternative choices allowing higher operating temperatures.

3. RESISTANCE THERMOMETER PRACTICE

3.1 Terminating the Resistance Thermometer

Fundamentally, every sensing resistor is a two wire device. When terminating the resistor with extension wires, a decision must be made as to whether a 2, 3 or 4 wire arrangement is required for measurement purposes.

In the sensing resistor, the electrical resistance varies with temperature. Temperature is measured indirectly by reading the voltage drop across the sensing resistor in the presence of a constant current flowing through it using Ohm's Law:

$$V = R.I$$

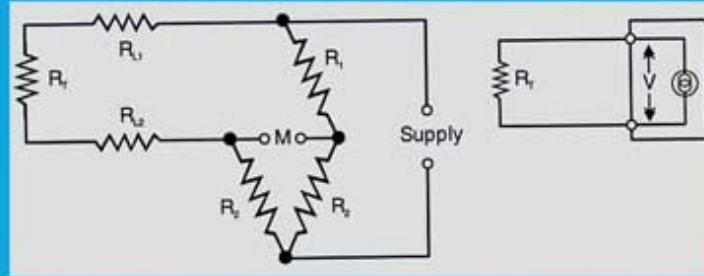
The measuring current should be as small as possible to minimise sensor self-heating; a maximum of around 1mA is regarded as acceptable for practical purposes. This would produce a 0.1V drop in a Pt100 sensing resistor at 0°C; the voltage dropped which varies with temperature is then measured by the associated circuitry. The interconnection between the Pt100 and the associated input circuit must be compatible with both and the use of 2, 3 or 4 wires must be specified accordingly. It is essential that in any resistance thermometer the resistance value of the external leadwire be taken into account, and if this value affects the required accuracy of the thermometer, its effect should be minimised.

This is usually accomplished by connecting the leadwires into the modified **WHEATSTONE BRIDGE** circuit in the measuring instrumentation. The leadwires can be 2, 3 or 4 in number, often dependant upon the requirements of the instrumentation and/or the overall accuracy required. Two leads are adequate for some industrial applications, three leads compensating for lead resistance improves accuracy, and for the highest accuracy four leads are required, in a current/voltage measuring mode. Typical bridge circuits for 2, 3 and 4 lead thermometers are shown below:

Practical Bridge Circuits for 2, 3 and 4 Wire Thermometers.

2 Wire Wheatstone Bridge

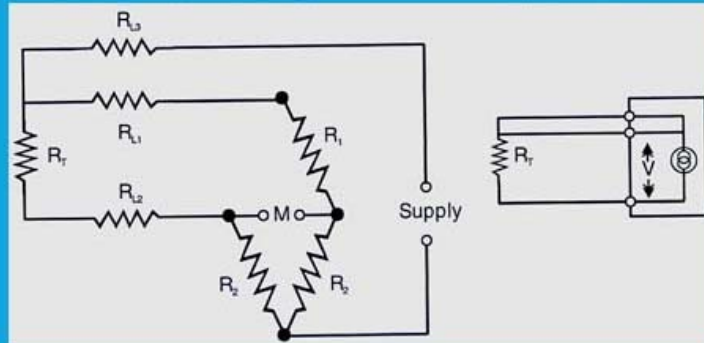
2 Wire Connections



The meter reads $R_T + (R_{L1} + R_{L2})$. R_{L1}, R_{L2} are lead resistances.

3 Wire Wheatstone Bridge

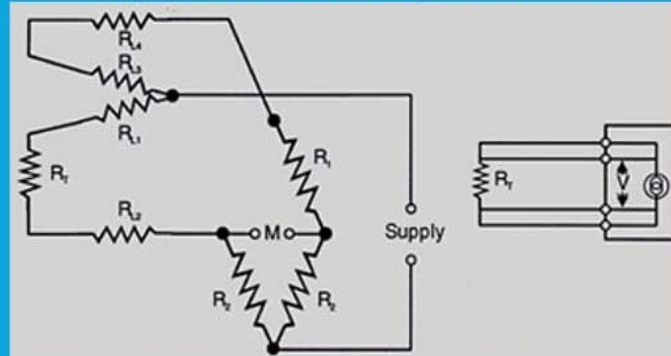
3 Wire Connections



One lead resistance is included in each of the two arms of the bridge. The errors reduce to $R_{L1} - R_{L2}$

4 Wire Compensated Wheatstone Bridge

4 Wire Connections



R_{L3}, R_{L4} appear in one arm of the bridge and R_{L1}, R_{L2} in the other. Errors are $R_{L1} + R_{L2} - R_{L3} - R_{L4}$.

The connection between the thermometer assembly and the instrumentation is made with standard electrical cable with copper conductors in 2, 3 or 4 core construction. The cabling introduces electrical resistance which is placed in series with the resistance thermometer. **The two resistances are therefore cumulative and could be interpreted as an increased temperature if the lead resistance is not allowed for.** The longer and/or the smaller the diameter of the cable, the greater the lead resistance will be and the measurement errors could be appreciable. In the case of a **2 wire connection**, little can be done about this problem and some measurement error will result according to the cabling and input circuit arrangement.

For this reason, **a 2 wire arrangement is not recommended.** If it is essential to use only 2 wires, ensure that the largest possible diameter of conductors is specified and that the length of cable is minimised to keep cable resistance to as low a values as possible.

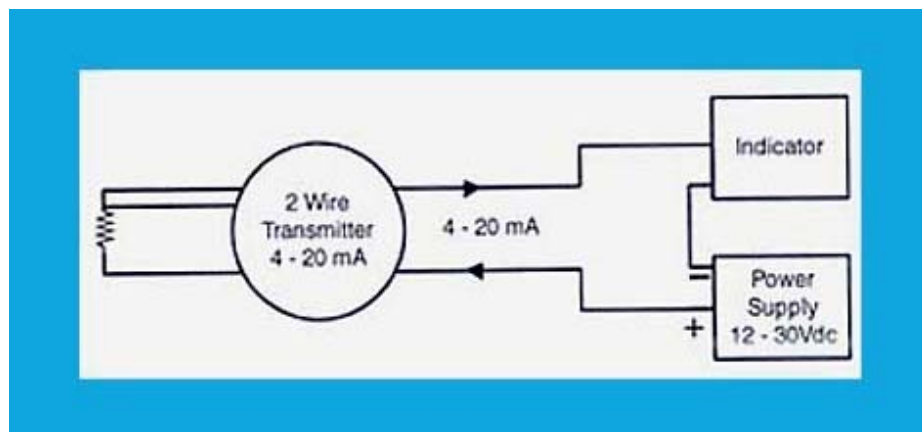
The use of 3 wires, when dictated either by probe construction or by the input termination of the measuring instrument, will allow for a good level of lead resistance compensation. **However the compensation technique is based on the assumption that the resistance of all three leads is identical** and that they all reside at the same ambient temperature; this is not always the case. Cable manufacturers often specify a tolerance of up to $\pm 15\%$ in conductor resistance for each core making accurate compensation impossible. Additional errors may result from contact resistance when terminating each of the 3 wires. A 3 wire system can not therefore be relied upon for high accuracy however carefully the sensor is installed or however accurate the host instrument may be.

Optimum accuracy is therefore achieved with a 4 wire configuration. The Pt100 measuring current is obtained through the supply. The voltage drop across the sensing resistor is picked off by the measurement wires. If the measurement circuit has a very high input impedance, lead resistance and connection contact resistances have negligible effect. The voltage drop thus obtained is independent of the connecting wire resistivity. In practice, the transition from the 2 wires of the Pt100 to the extension wires may not occur precisely at the element itself but may involve a short 2 wire extension for reasons of physical construction; such an arrangement can introduce some error but this is usually insignificant.

Note: The wiring configuration (2, 3 or 4 wire) of the thermometer must be compatible with the input to the associated instrument.

3.2 Transmitters

The problems of the 2 or 3 wire configuration as described can be resolved in large part by using a 4-20mA transmitter. If the transmitter is located close to the Pt100, often in the terminal head of the thermometer, then the amplified “temperature’ signal is transmitted to the remote instrumentation. Cable resistance effects are then no applicable other than those due to the relatively short leadwires between the sensor and transmitter.



Temperature Transmitter – 2 Wire Loop. Input Pt100, 3 Wire

Most transmitters use a 3 wire input connection and therefore provide compensation for lead resistance.

4. RESISTANCE THERMOMETER INSTALLATION AND APPLICATION

4.1 Sheathed Resistance Thermometers – Pt100 Sensing Resistors

A variety of sheath materials is used to house and protect the alternative types of sensing resistors; sheath materials are described in section 5.

The resistance element is produced in one of two forms, either wire-wound or metal film. Metal film resistors consist of a platinum layer on a ceramic substrate; the coil of a wire-wound version is fused into ceramic or glass.

a) Wire-wound resistors.

The construction of the wire-wound platinum detector uses a large proportion of manual labour, with a high degree of training and skill. The careful selection of all components is vital, as are good working conditions. Complete compatibility between metal, ceramic and glass when used, together with the connecting leads is essential, and most important, strain must be eliminated. Various methods of detector

construction are employed to meet the requirements of differing applications. The unsupported “bird cage” construction is used for temperature standards, and the partially supported construction is used where a compromise is acceptable between primary standards and use I industrial applications. Other constructional methods include the totally supported construction which can normally withstand vibration levels to 100g, and the coated wire construction where the wire is covered with an insulating medium such as varnish. The maximum operating range of the latter method is limited by the wire coating to usually around 250°C

Of the differing methods of construction described, the partially supported construction is the most suitable for industrial applications where high accuracy, reliability and long term stability are required. The wire is wound into a small spiral, and inserted into axial holes in a high purity alumina rod. A small quantity of glass adhesive is applied to these holes, which after firing secures a part of each loop into the alumina. Detectors have been produced by this method as thin as 0.9mm diameter and as short as 6mm with a resistance accuracy $\pm 0.01\%$. A host of other sizes and shapes are produced. The internal leads of a detector assembly should be constructed of materials dictated by the temperature the assembly will have to withstand. Up to 150°C and 300°C silver leads are preferred, from 300°C to 500°C nickel leads are considered best although the resistance tends to be high, and above 550°C noble metal leads prove most satisfactory.



Wire-Wound and Metal Film Pt100 Resistors

b) Metal Film Resistors

Metal film Pt resistors take the form of a thin (1 micron) film of platinum on a ceramic substrate. The film is laser trimmed to have a precise R_0 value and then encapsulated in glass for protection.

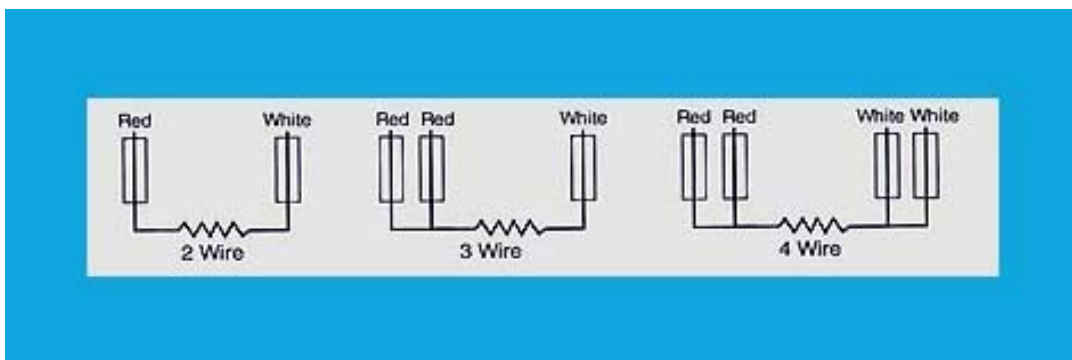
A wide range of styles and dimensions are produced to allow for different applications. Such sensors have fast thermal response and their small thermal mass minimises intrusion in the media being tested. Such sensors are known variously as flat film, thin film or chip sensors.

Thermoelements and resistance thermometer sensing resistors alike normally require protection from environmental conditions and, depending on the application would normally be housed in a suitable sheath material if immersion is required. Alternative housing are used for non-immersion use such as in surface or air sensing.

4.2 Connecting Resistance Thermometers to Instruments

Unlike thermocouples, resistance thermometers do not require special cable and standard electrical wires with copper conductors should be used. The heavier the gauge of the conductors, the less the impact is on errors due to lead resistance effects as described. Typically 7/0.2mm or 14/0.2mm conductors are specified with insulation chosen to suit a particular application.

Recommended Termination Colour Codes BS1904:1984



Installation Note:

- Always observe colour codes and terminal designations; the wiring configuration of the thermometer must match that of the instrument input arrangement.

- b) Avoid introducing “different” metals into the cabling; preferably use copper connecting blocks or colour coded (or other dedicated) connectors for greater accuracy, reliability and convenience of installation.
- c) Use screened or braided cable connected to ground in any installation where ac pick-up or relay contact interference is likely.
- d) For very long cable runs, ensure that cable resistance can be tolerated by the instrumentation without resulting in measurement errors. Modern electronic instruments usually accept up to 100 Ohms or so for 3 or 4 wire inputs. Refer to the relevant instrument specifications for full details.
- e) Cabling is usually available with many different types of insulation material and outer covering to suit different applications. Choose carefully in consideration of ambient temperature, the presence of moisture or water and the need for abrasion resistance.
- f) If errors occur, be sure to check the sensor, the cable, interconnections and the instrument. Many such problems are due to incorrect wiring or instrument calibration error rather than the sensor.

Interchangeability is facilitated by the use of plug and socket interconnections. Special connectors are available for this purpose.

4.3 Guide to Cable Insulation and Coverings

<i>Which Insulation material?</i>	<i>Usable Temperature Range</i>	<i>Application Notes</i>
<i>PVC</i>	-10°C to 105°C	Good general purpose insulation for “light” environments. Waterproof and very flexible.
<i>PTFE</i>	-75°C to $250/300^{\circ}\text{C}$	Resistant to oils, acids, other adverse agents and fluids. Good mechanical strength and flexibility.
<i>Glassfibre(vernished)</i>	-60°C to $350/400^{\circ}\text{C}$	Good temperature range but will not prevent ingress of fluids. Fairly flexible but does not provide good

		mechanical protection.
<i>High temperature glass fibre</i>	-60 ^o C to 700 ^o C	Will withstand temperature, up to 700 ^o C but will not prevent ingress of fluids. Fairly flexible, not good protection against physical disturbance.
<i>Ceramic Fibre</i>	0 to 1000 ^o C	Will withstand high temperature, up to 1000 ^o C. Will not protect against fluids or physical disturbance.
<i>Glassfibre (varnished) stainless steel overbraid</i>	-60 ^o C to 350/400 ^o C	Good resistance to physical disturbance and high temperature (up to 400 ^o C). Will not prevent ingress of fluids.

4.4 Performance Considerations When Using resistance Thermometers

There are various considerations appropriate to achieving good performance from resistance thermometer sensors:

- a) Length of cable runs and loop resistance – Refer to Installation Notes
- b) Interference and Isolation

With long cable runs, the cables may need to be screened and earthed at one end (at the instrument) to minimise noise pick-up (interference) on the measuring circuit.

Poor insulation is manifested as a reduction in the indicated temperature, often as a result of moisture ingress into the probe or wiring.

- c) Self-heating

In order to measure the voltage dropped across the sensing resistor, a current must be passed through it. The measuring current produces dissipation which generates heat in the sensor. This results in an increased temperature indication. There are many aspects to the effects of self-heating but generally it is necessary to minimise the current flow as much as possible; 1mA or less is usually acceptable. The choice of current value must take into account the **Ro value of the sensing resistor since**
dissipation = I²R

If the sensor is immersed in following liquid or glass, the effect is reduced because of more rapid heat removal. Conversely, in still gas for example, the effect may be significant. The self-heating coefficient E is expressed as:

$$E = \Delta t / (R - I^2)$$

Where Δt = (indicated temperature) – (temperature of the medium)

R = Pt resistance

I = measurement current

d) Stem conduction

This is the mechanism by which heat is conducted from or to the process medium by the probe itself; an apparent reduction or increase respectively in measured temperature results. The immersion depth (the length of that part of the probe which is directly in contact with the medium) must be such as to ensure that the “sensing” length is exceeded (double the sensing length is recommended). Small immersion depths result in a large temperature gradient between the sensor and the surroundings which results in a large heat flow.

The ideal immersion depth can be achieved in practice by moving the probe into or out of the process medium incrementally; with each adjustment, note any apparent change in indicated temperature. The correct depth will result in no change in indicated temperature.

For calibration purposes 150 to 300mm immersion is required depending on the probe construction.

The use of thermowells increases the thermal resistance to the actual sensor; heat also flows to the outside through the thermowell material. Direct measurements are preferable for good response and accuracy but may be mechanically undesirable.

Low flow rates or stationary media result in reduced heat transfer to the thermometer; maximum flow rate locations are necessary for more accurate measurement.

4.5 Surface Temperature Measurement

Resistance thermometers are mainly stem sensing devices with a finite sensing length and as such are best suited to immersion use. However, certain types of sensing resistors can be applied to surface sensing when suitable housed. Thin film devices and

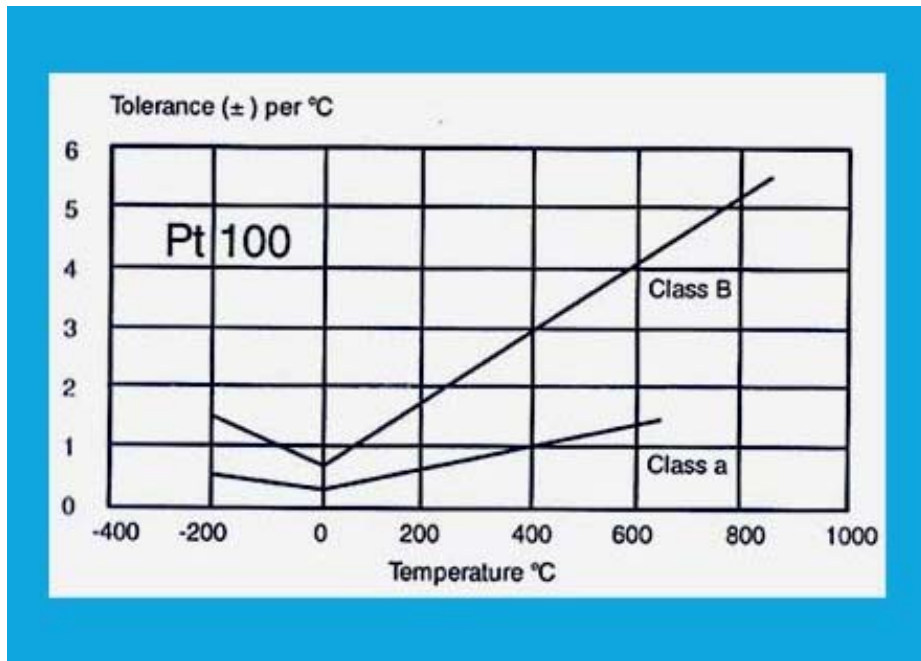
miniature wire-wound elements can be used in a surface contact assembly such as that shown below. In such cases, the sensing devices must be held in close contact with the surface whilst being thermally insulated from the surrounding medium. Rubber and PTFE bodies are often utilised for such assemblies. Locating the device on a surface can be achieved in various ways including the use of an adhesive patch and pipe clips. If it is possible to provide lagging (thermal insulation) around the sensor assembly, accuracy will be improved.



Self Adhesive Patch Pt100 Sensor for Surface Temperature Sensing

4.6 High Accuracy Measurement

Assuming a 3 or 4 wire connection, and the use of a class B sensing resistor, a standard thermometer assembly will provide an accuracy of around 0.5°C between 0°C and 100°C . Considerable improvement on this figure can be achieved by various means including the use of closer tolerance sensors. However, tolerance of 1/3, 1/5, and 1/10 of the Class B values are available with wire-wound and other resistors and these allow for higher precision of measurement. It is important to note that these tolerances are rarely achieved in practice due to stress and strain in handling and assembly, extension lead wire effects and thermal considerations. However, the closer tolerances do provide more precise basic accuracy platforms. Practice overall accuracy of around 0.15°C can be achieved between 0°C and 100°C if a 1/10 DIN sensor is used.



Pt100 Tolerances

System (probe and instrument) accuracy can be optimised by means of calibration and certification which identifies overall measurement errors; such calibrations are usually carried out to international standards.

High precision resistance thermometers are available for laboratory use and accuracies of a few millidegrees can be achieved using such devices. These may use different alpha values and must be calibrated at fixed points. Nominal 10, 25 and special 100 Ohm R_0 versions may be used.