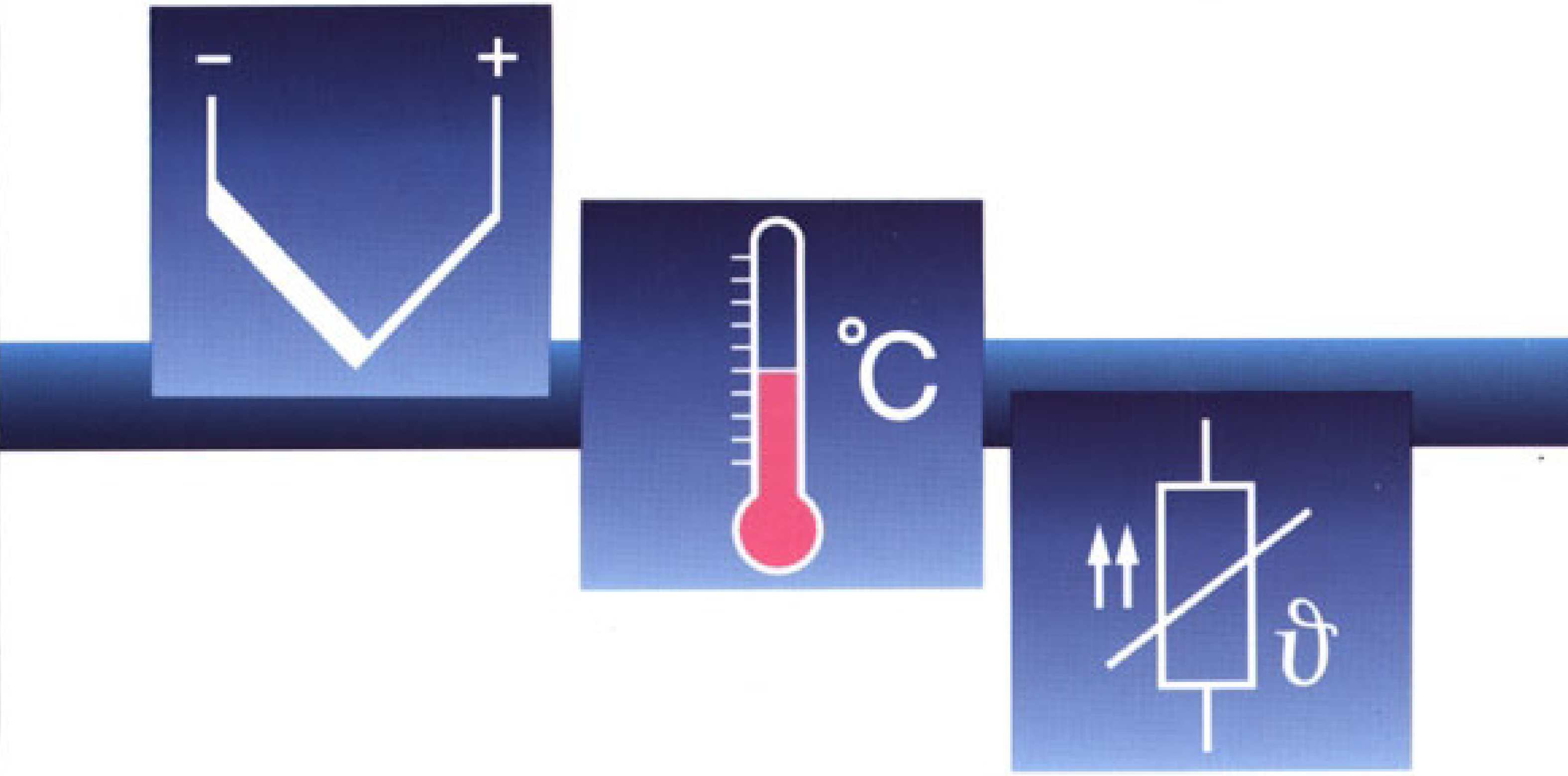
Electrical Temperature Measurement

with thermocouples
and resistance thermometers

Matthias Nau



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Dipl.-Phys. Matthias Nau

For decades, temperature has been one of the most important process variables in the automation, consumer goods and production industries. Electrical measurement of temperature, by using resistance thermometers and thermocouples, is in fact more than 100 years old, but the development of sensors and thermometers is by no means over. The continuous optimization of processes leads to ever higher demands on the thermometers, to measure temperature faster, more accurately, and with better repeatability over a longer time.

Since there is, regrettably, no single thermometer that is capable of handling all possible measurement tasks with sufficient accuracy, it is vitally important, especially for the user, to be first familiar with the fundamentals of electrical temperature measurement and then to understand the characteristics and sources of error involved. A precision thermometer by itself is no guarantee that the temperature will be properly measured. The temperature that is indicated is only the temperature of the sensor. The user must take steps to ensure that the temperature of the sensor is indeed the same as that of the medium being measured.

This book has been a favorite guide for interested users for many years. This version has been revised and updated to take account of altered standards and new developments. In particular, the new chapter “Measurement uncertainty” presents the basic concepts of the internationally recognized ISO guideline “Guide to the expression of uncertainty in measurement” (abbreviated to GUM) and illustrates methods of determining the measurement uncertainty of a temperature measurement system and the factors that affect it. The chapter on explosion-proof thermometers has also been extended to take account of the European Directive 94/9/EC, which comes into force on July 1st 2003.

In view of extended product liability, the data and material properties presented in this book can only be considered to be guidelines. They must be checked, and corrected, if necessary, for each individual application. This applies in particular where safety aspects are involved.

Fulda, August 2002

Matthias Nau

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The measurement of temperature is of special importance in numerous processes, with around 45% of all required measurement points being associated with temperature. Applications include smelting, chemical reactions, food processing, energy measurement and air conditioning. The applications mentioned are so very different, as are the service requirements imposed on the temperature sensors, their principle of operation and their technical construction.

In industrial processes, the measurement point is often a long way from the indication point; this may be demanded by the process conditions, with smelting and annealing furnaces, for example, or because central data acquisition is required. Often there is a requirement for further processing of the measurements in controllers or recorders. The direct-reading thermometers familiar to us all in our everyday life are unsuitable for these applications; devices are needed that convert temperature into another form, an electrical signal. Incidentally, these electrical transducers are still referred to as thermometers, although, strictly speaking, what is meant is the transducer, comprising the sensor element and its surrounding protection fitting.

In industrial electrical temperature measurement, pyrometers, resistance thermometers and thermocouples are in common use. There are other measurement systems, such as oscillating quartz sensors and fiber-optic systems that have not yet found a wide application in industry.

1.1 Contact temperature measurement

Thermocouples and resistance thermometers, in addition to other methods, are especially suitable where contact with the measured object is permitted. They are employed in large quantities, and are used, for example, for measurements in gases, liquids, molten metals, and for surface and internal measurements in solids. The sensors and protection fittings used are determined by the accuracy, response, temperature range and chemical properties required.

Resistance thermometers make use of the fact that the electrical resistance of an electrical conductor varies with temperature. A distinction is made between positive temperature coefficient (PTC) sensors, and negative temperature coefficient (NTC) sensors. With PTC sensors, the resistance increases with rising temperature, whereas with NTC sensors, the resistance decreases with rising temperature.

PTC sensors include the metallic conductors. The metals mainly used are platinum, nickel, iridium, copper and undoped silicon (spreading resistance), with the platinum resistance thermometer most widely used. Its advantages include the metal's chemical immunity, which reduces the risk of contamination due to oxidation and other chemical effects.

Platinum resistance thermometers are the most accurate sensors for industrial applications, and also have the best long-term stability. A representative value for the accuracy of a platinum resistance can be taken as ±0.5% of the measured temperature. There may be a shift of about ±0.05°C after one year, due to ageing. They can be used within a temperature range up to around 800°C, and their application spectrum ranges from air conditioning to chemical processing.

NTC sensors are made from certain metal oxides, whose resistance decreases with rising temperature. They are sometimes referred to as "hot conductors", because they only exhibit good electrical conductivity at elevated temperatures. Because the temperature/resistance graph has a falling characteristic, they are also referred to as NTC (negative temperature coefficient) resistors.

Because of the nature of the underlying process, the number of conducting electrons increases exponentially with rising temperature, giving a graph with a sharply rising characteristic.

This strong non-linearity is a major disadvantage of NTC resistors, and limits the measurable temperature span to about 50°C. Although they can be linearized by connecting them in series with a pure resistance of about ten times the resistance value, their accuracy and linearity over wider measurement spans are inadequate for most requirements. Furthermore, the drift under alternating temperatures is higher than with the other methods shown [7]. Because of their characteristic, they are sensitive to self-heating due to excessive measurement currents. Their area of use lies in simple monitoring and indication applications, where temperatures do not exceed 200 °C, and accuracies of a few degrees Celsius are acceptable. Because of their lower price and the comparatively simple electronics required, they are actually preferred to the more expensive thermocouples and (metal) resistance thermometers for such simple applications. In addition, they can be manufactured in very small versions, with a fast response and low thermal mass. They will not be discussed in detail in this publication.

Thermocouples are based on the effect that when a temperature gradient exists along a wire, a charge displacement dependent on the electrical conductivity of the material occurs in the wire. If two conductors with different conductivities are brought into contact at one point, a thermoelectric emf can be measured by the different charge displacements, dependent on the magnitude of the temperature gradient.

In comparison with resistance thermometers, thermocouples have the clear advantage of a higher upper temperature limit of up to several thousand degrees Celsius. Against this, their long-term stability is not as good, and their accuracy somewhat less.

They are frequently used in ovens and furnaces, for measurements in molten metals, plastics machinery, and in other areas with temperatures above 250 °C.

1.2 Non-contact temperature measurement

This category covers moving objects and objects which are not accessible for measurement. Examples of these include rotary ovens, paper or foil machines, rolling mills, flowing molten metal etc. The category also covers objects with a low thermal capacity and conductivity, and the measurement of an object inside a furnace or over a longer distance. These conditions preclude the use of contact measurement, and the thermal radiation from the measured object is used as the measured value.

The basic design of such non-contact temperature instruments, called pyrometers, corresponds to a thermocouple which measures the thermal radiation from a hot body through an optical system. If it can be ensured that the same (total) field of view of the pyrometer is taken up by the measured object, this simple measuring principle can be utilized for temperature measurement.

Other types work slightly differently. They filter out a specific wavelength from the radiation received, and determine the proportion of this radiation component in the total radiation. The higher the temperature of a body, the higher the proportion of shorter wavelengths; the light radiated by the body appears increasingly bluish. As is well known, the color of a glowing body gradually changes from the initial red to white heat, due to the higher blue component. Pyrometers are sensitive to infrared radiation and do not generally operate in the visible region, as the object temperatures corresponding to the measured radiation are too low to radiate visible wavelengths in measurable quantities.

After passing through the spectral filter, the radiation reaches a thermopile, a number of thermocouples mounted on a semiconductor chip and connected in series. The thermoelectric emf produced here is amplified, and is then available as an output signal. A typical signal range here would be 0 — 20 mA for temperatures within the measuring range. The signal is available in linearized form and hence can be analyzed directly by a measuring instrument. Handheld instruments have an integral display. The different types available are as follows [16]:

1.2.1 Total radiation pyrometer

A pyrometer whose spectral sensitivity within the thermal radiation spectrum is almost independent of wavelength. If the measured object is a black body, the signal of the radiation receiver approximately follows the **Stefan-Boltzmann** radiation law.

1.2.2 Spectral pyrometer

A pyrometer that is only sensitive to a narrow band of the thermal radiation spectrum. If the measured object is a black body, the signal of the radiation receiver approximately follows **Planck's** radiation law.

1.2.3 Band radiation pyrometer

A pyrometer sensitive to a a wide band of the thermal radiation spectrum. The signal of the radiation receiver does not follow either the Stefan-Boltzmann or Planck's radiation laws to any acceptable approximation.

1.2.4 Radiation density pyrometer

A pyrometer with which the temperature is determined from the radiation density, either directly, or by comparison with a standard radiator of known radiation density.

1.2.5 Distribution pyrometer

A pyrometer with which the temperature is determined by matching the color impression of a mixed color made up of two spectral ranges of the thermal radiation of the measured object, and the mixed color of a standard radiator of known radiation density distribution.

1.2.6 Ratio pyrometer

A pyrometer with which the temperature is determined by the ratio of the radiation densities in at least two different bands of the thermal radiation spectrum of the measured object.

The non-contact measuring principle of the pyrometer enables the temperature of moving objects to be measured easily and quickly. However, the emission capacity of the measured object can be difficult to determine. The ability of a body to radiate heat depends on the nature of its surface, or more precisely, on its color. When black bodies are heated, they radiate more heat or light waves than colored or white bodies. The emissivity of the object must be known and must be set on the pyrometer. Standard values are quoted for various materials such as black sheet metal, paper, etc.

Unfortunately, the temperature indicated by the pyrometer cannot normally be checked using another measurement method, which means that it is difficult to obtain absolute values. However, if all conditions remain the same, particularly those affecting the surface of the object, comparative measurements within the accuracy limits stated for the instrument can be obtained.

When installing the pyrometer, which outwardly is not dissimilar to a telescope, it must be ensured that only the object to be measured is actually in the instrument's field of view. Incorrect measurements are highly likely with reflective surfaces due to external radiation. Dust deposits on the lens distort the measurement result; installing a compressed air nozzle can help where sensors are installed in inaccessible positions. The compressed air jet is used to remove deposits of suspended particles from the lens at regular intervals. Infrared rays penetrate fog (water vapor) much better than visible light does, but they are noticeably absorbed by it, just as they are absorbed by carbon dioxide. For this reason, it makes good sense to choose the spectral sensitivity range such that it lies outside the absorption band, so that water vapor and carbon dioxide have no effect on the measurement result. Nevertheless, high dust concentrations, as found in cement works, for example, will adversely affect the measurement. The range of application of pyrometric measurement covers temperatures ranging from 0°C to 3000°C.

2 The concept of temperature

In a physical sense, heat is a measure of the amount of intrinsic energy possessed by a body due to the random movement of its molecules or atoms. Just as the energy possessed by a tennis ball increases with increasing speed, so the internal energy of a body or gas increases with rising temperature. Temperature is a variable of state, which, together with other variables such as mass, specific heat etc., describes the energy content of a body. The primary standard of temperature is the kelvin. At 0 K(elvin), the molecules of all bodies are at rest and they no longer posses any thermal energy. This also means that there can never be a negative temperature, as a lower energy state cannot exist. The measurement of the internal kinetic energy of a body is not directly accessible. Instead use is made of the effect of heat on certain physical properties such as the linear expansion of metals or liquids, the electrical resistance, the thermoelectric emf, the oscillation frequency of a quartz crystal, and the like. To achieve objective and accurate temperature measurements, it is essential that the effect is both stable and reproducible.

2.1 The historical temperature scale

Fig. 1: Galileo

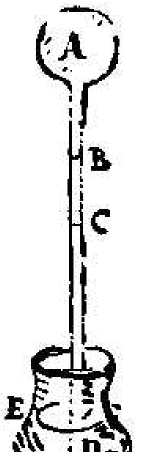


Fig. 2: Thermoscope

Because man's sensory feel for heat is not very reliable for temperature determination, as early as 1596, Galileo (Fig. 1) was looking for an objective method of temperature determination. For this he made use of the expansion of gases and liquids when heated. The thermoscope (Fig. 2), as it was known, comprised a glass bulb A filled with air, to which was attached a glass tube C. The open end of this tube dipped into a storage vessel E filled with colored water D.

As the air in the glass bulb heats up, it expands and forces the column of water in the tube down.

The height of the water level B was referred to for the temperature indication. One disadvantage of this design was the fact that barometric pressure fluctuations affected the height of the column. A reproducible temperature measurement could only by obtained by correcting for the barometric pressure.

In the middle of the 17th century, the Academy in Florence was designing and building thermometers. In contrast to the Galileo thermometer, these thermometers were sealed, so that the temperature measurement was unaffected by barometric pressure. Alcohol was used as the thermometric liquid.
The temperature scale was defined by the minimum winter and the maximum summer temperatures. It is quite obvious here that a new scale is created whenever a thermometer is newly set up or recalibrated, as the same maximum and minimum temperatures do not occur in subsequent years. There was still no universally applicable temperature scale that could be referred to at any time for thermometer calibration.

Around 1715, David **Fahrenheit**, a glass blower from Danzig (now Gdansk), was building mercury thermometers with consistent indications, which represented a major advance at that time. He also adopted a temperature scale, which was later named after him, and which is still used even today in America and England. As the zero for his scale, he chose the lowest temperature of the harsh winter of 1709, which he could reproduce later using a specific mixture of ice, solid ammonium chloride and water. By choosing this zero, Fahrenheit hoped to be able to avoid negative temperatures. For the second fixed point of his scale, Fahrenheit is said to have chosen his own body temperature, to which he arbitrarily assigned the value 100.

In 1742, the Swedish astronomer Anders **Celsius** proposed that the scale introduced by Fahrenheit should be replaced by one that was easier to use (which was finally named after him). He chose two fixed points that could be accurately reproduced anywhere in the world:

- the melting temperature of ice was to be 0 °C
- the boiling point of water was to be 100 °C

The difference between the two marks on a thermometer is referred to as the fundamental interval. It is divided into 100 equal parts, with the interval between the graduations representing a temperature difference of 1 °C.

This enabled any thermometer to be calibrated at any time, and ensured a reproducible temperature measurement. If the thermometric liquid is changed, the thermometer must be readjusted at the two fixed points, as the temperature-dependent material properties vary quantitatively, leading to incorrect readings after the change of liquid.

A clear physical definition of temperature was only made possible in the 19th century through the basic laws of thermodynamics, in which, for the first time, no material properties were used to define the temperature. In principle, this thermodynamic temperature can be determined by any measurement method that can be derived from the second law of thermodynamics.

The **Boyle-Mariotte** law states that the pressure at constant temperature is inversely proportional to the volume ($p \sim 1/V$). The **Gay-Lussac** law states that the pressure at constant volume is directly proportional to the absolute temperature ($p \sim V$). From this the general gas equation for one mole of a gas can be derived:

Formula 1:

$$p \cdot V_m = R_m \cdot T$$

where V_m is the molar volume and R_m the gas constant. It shows a direct relationship between the pressure p, the volume V and the temperature T of an ideal gas. The temperature is therefore referenced to the measurement of the pressure of a known volume of gas. Using this method, no material-dependent auxiliary variables and conversion factors such as coefficients of expansion, definitions of length, etc. are required, as is the case, for example, with the mercury thermometer.

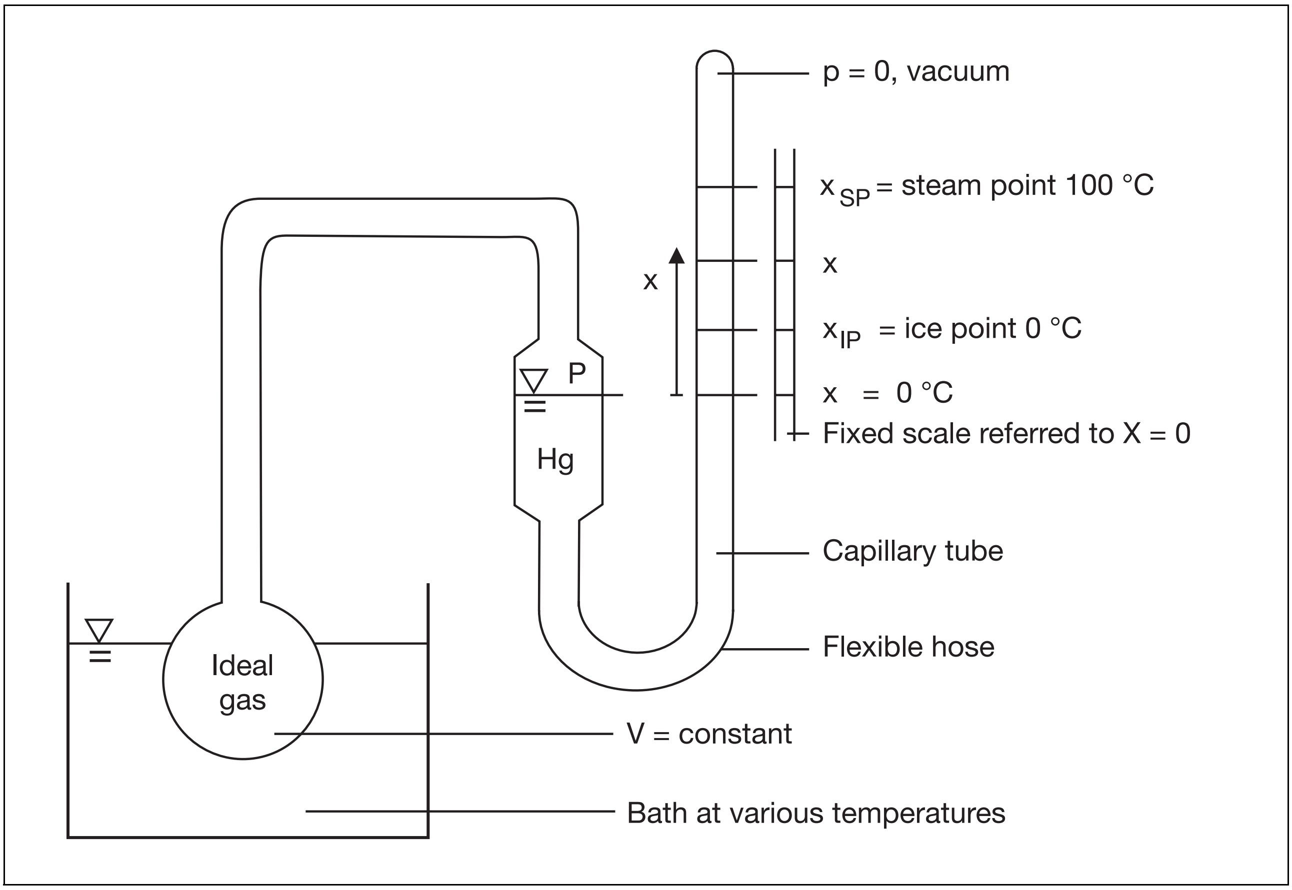


Fig. 3: Gas thermometer

In principle, a pressure measurement takes place with the gas thermometer. The measured quantity is the hydrostatic pressure or the hydrostatic liquid column x.

Formula 2:

$$p = \rho \cdot g \cdot x$$

The volume V of the enclosed gas is always maintained constant by raising or lowering the capillary (index mark at x = 0).

Formula 3:

$$V_{gas} + V_{Hg} = \text{constant}$$

Then the fixed points (x_{IP} = ice point; x_{SP} = steam point) are established. With the Celsius scale, the length x_{SP} - x_{IP} is defined as 100 °C.

Formula 4:

$$t = \frac{x - x_{IP}}{x_{SP} - x_{IP}} \cdot 100\ °C$$

and

Formula 5:

$$t = \frac{1}{\alpha} \cdot \frac{x - x_{IP}}{x_{IP}} \cdot 100\ °C$$

with

Formula 6:

$$\alpha = \frac{x_{SP} - x_B}{x_B \cdot 100\ °C}$$

Measurements with different “ideal” gases and different filling capacities always result in:

Formula 7:

$$\alpha = \frac{1}{273.15\ °C}$$

Formula 8:

$$t = \frac{x - x_B}{x_B} \cdot 273.15\ °C$$

for x = 0, it follows that t = -273.15°C or 0K; the absolute zero. The concept of absolute zero is attributed to William **Thomson,** who introduced the concept in 1851. Thomson, who later became Lord **Kelvin**, introduced a reproducible temperature scale in 1852, the thermodynamic temperature scale. The scale is independent of the temperature level and material properties, and is based purely on the second law of thermodynamics. Yet another fixed point was required to define this temperature scale. In 1954, at the 10th General Conference of Weights and Measures, this was defined as the triple point of water. It corresponds to a temperature of 273.16 K or 0.01°C. The unit of thermodynamic temperature is defined as follows:

1 kelvin is the fraction 1/ 273.16
of the thermodynamic temperature of the triple point of water.

In metrological establishments, the thermodynamic temperature is determined mainly with this type of gas thermometer. However, because the method is extremely expensive and difficult, as early as 1927, agreement was reached on the creation of a practical temperature scale that mirrored the thermodynamic temperature scale as closely as possible.

The practical temperature scale generally refers to a specific measuring instrument or an observable material property. The advantage of a definition of this type is the high reproducibility possible for comparatively low technical expenditure.

2.2 The fixed temperature points

Substances have different physical states; they are liquid, solid or gaseous. Which of these states (referred to as phases) the material assumes depends on the temperature. At certain temperatures, two or three states coexist, ice cubes in water at 0°C, for example. Furthermore, with water, there is a temperature at which solid, liquid and vapor phases coexist. With water, this triple point temperature, as it is called, is 0.01 °C. With most other substances only two phases occur simultaneously.

Other fixed points are the solidification points of pure metals. As a molten metal cools down, the liquid starts to solidify at a certain temperature. The change from the liquid to solid state does not occur suddenly here, and the temperature remains constant until all the metal has solidified. This temperature is called the solidification temperature. Its value depends on the degree of purity of the metal, so that highly accurate temperatures can be simply reproduced using this method.

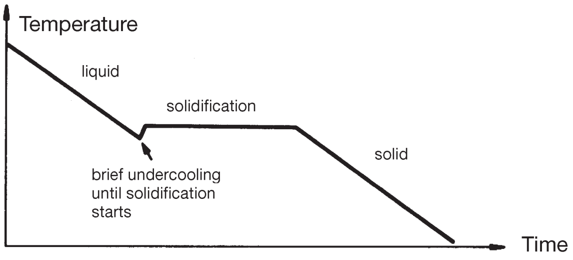


Fig. 4: Simplified solidification curve of a metal

2.3 The temperature scale according to ITS-90

The temperatures corresponding to the fixed points are determined using gas thermometers or other instruments with which thermodynamic temperatures can be measured. The values are then established by statute, based on a large number of comparative measurements carried out in official establishments like the Physikalisch-Technische Bundesanstalt (PTB). This type of expensive apparatus is not suitable for industrial measurement, and so, following international agreement, certain fixed points were specified as primary values. For the intermediate values, the temperature scale was defined using interpolating instruments. These are instruments which permit measurement not only at a single temperature, such as the solidification point and triple point mentioned earlier, but also at all intermediate values. The simplest example of an interpolating instrument is the mercury thermometer, but a gas thermometer can also be used.

Up to the end of 1989, the valid scale was the International Practical Temperature Scale of 1968, the IPTS-68. From 1990 a new scale has been in force, the ITS-90 International Temperature Scale. The new scale was needed because a large number of measurements in various laboratories around the world demonstrated inaccuracies in the previous determination of the temperature fixed points. The defined fixed points of the ITS-90 and their deviation from the IPTS-68 are given in Table 1 below.

Fixed point °C	Substance	Deviation (in K) from the ITPS-68
-218.7916	Oxygen	-0.0026
-189.3442	Argon	0.0078
- 38.8344	Mercury	0.0016
0.01	Water	0.0000
29.7646	Gallium	0.0054
156.5985	Indium	0.0355
231.928	Tin	0.0401
419.527	Zinc	0.0530
660.323	Aluminum	0.1370
961.78	Silver	0.1500

Table 1: Fixed points of the ITS-90 and their deviation from the IPTS-68

The platinum resistance thermometer is approved as an interpolating thermometer in the range from -259 to 961.78°C. To ensure that the characteristic of this thermometer reproduces the thermodynamic temperatures as closely a possible, the ITS-90 sets requirements with regard to material purity. In addition, the thermometer must be calibrated at specified fixed points. On the basis of the measurements at the fixed points, an individual error function of the thermometer is decided on as a reference function, with the aid of which any temperature can then be measured. Temperatures are expressed as ratios of the resistance $R(T_{90})$ and the resistance at the triple point of water R(273.16K). The ratio $W(T_{90})$ is then defined as:

Formula 9:

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

To fulfil the requirements of the ITS-90, a thermometer must be manufactured using spectrally pure, strain-free suspended platinum wire that at least fulfils the following conditions:

- W(29.7646°C) $\geq$ 1.11807,
- W(-38.8344°C) $\geq$ 0.844235.

If the thermometer is to be used up to the silver solidification point, the following condition also applies:

- W(961.78°C) $\geq$ 4.2844°C.

For a specific temperature range, a specific function $W_r(T_{90})$ is applicable, called the reference function. For the temperature range from 0 to 961.78°C, the following reference function is applicable:

Formula 10:

$$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \cdot \left[\frac{T_{90}/K - 754.15}{481}\right]^{-1}$$

For the individual thermometer, the parameters a, b, c and d of the deviation function $W(T_{90})$ - $W_r(T_{90})$ are then worked out from the calibration results at the specified fixed points. If the thermometer is to be used from 0 °C up to the silver solidification point (961.78 °C), for example, it must be calibrated at the fixed points corresponding to the triple point of water (0.01 °C) and the solidification points of tin (231.928 °C), zinc (419.527 °C), aluminum (660.323 °C) and silver (961.78 °C). The deviation function is then expressed as follows:

Formula 11:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c[W(T_{90}) - 1]^3 + d[W(T_{90}) - W(660.323\ °C)]^2$$

(Further details on the implementation of the ITS-90 are contained in “Supplementary Information for the ITS-90” (BIPM-1990).)

3.1 The thermoelectric effect

The thermocouple is based on the effect first described by **Seebeck** in 1821 where a small current flows when two metallic conductors made of dissimilar materials A and B are in contact and when there is a temperature difference along the two conductors. The two conductors connected to one another are called a thermocouple (Fig. 5).

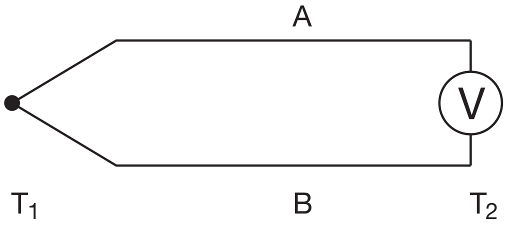


Fig. 5: Thermoelectric effect

The voltage itself depends on the two materials and the temperature difference. To be able to understand the Seebeck effect, the make-up of metals and their atomic structure must be looked at closely. A metallic conductor is distinguished by its free conducting electrons that are responsible for the current. When a metallic conductor is exposed to the same temperature along its length, the electrons move within the crystal lattice as a result of their thermal energy. Outwardly, the conductor shows no charge concentration; it is neutral (Fig. 6).

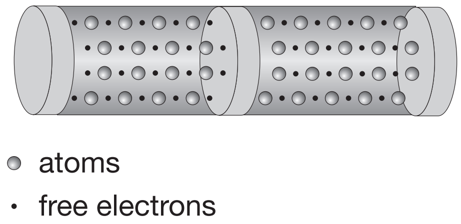


Fig. 6: Structure of a metallic conductor

If one end of the conductor is now heated, thermal energy is supplied to the free electrons, and their mean speed increases compared with those at the cold end of the conductor. The electrons diffuse from the heated end to the cold end, giving up their energy as they do so; they become slower moving (Fig. 7).

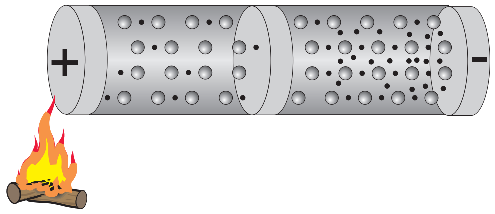


Fig. 7: Charge displacement in a metallic conductor when it is heated

This is also the reason for heat conduction in a metal. As the electrons move due to the supply of heat at one end, a negative charge concentration develops at the cold end. Against this, an electric field is established between the positive charge concentration at the hot end and the negative charge concentration at the cold end. The strength of this field drives the electrons back to the hot end again. The electric field builds up until there is a dynamic equilibrium between the electrons that are being driven to the cold end due to the temperature gradient and the repelling force of the electric field. In the state of equilibrium, an equal number of electrons is moving in each direction through a specific cross-sectional area. Here, the speed of the electrons from the hot end is higher than the speed of the opposing electrons from the cold end. This speed difference is responsible for the heat conduction in the conductor without an actual transport of charge, apart from that which occurs until the point at which the dynamic equilibrium described above is attained.

If the voltage difference between the hot and cold ends is now to be measured, the hot end of the conductor, for example, must be connected to an electrical conductor. This conductor is also exposed to the same temperature gradient, and also builds up the same dynamic equilibrium. If the second conductor is made from the same material, there is a symmetrical arrangement with the same charge concentrations at the two open ends. No voltage difference can be measured between the two charge concentrations. If the second conductor is made from a different material with a different electrical conductivity, a different dynamic equilibrium is established in the wire. The result of this is that different charge concentrations, which can be measured with a voltmeter, build up at the two ends of the conductor (Fig. 8).

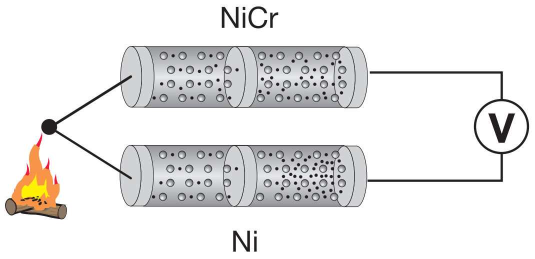


Fig. 8: The thermoelectric effect

A problem can arise when the voltmeter used to measure the voltage has terminals made of different metals, as two additional thermocouples are created. If the connecting cable to the instrument is made from Material C, a thermoelectric emf develops at the two junctions A - C and B - C (Fig. 9).

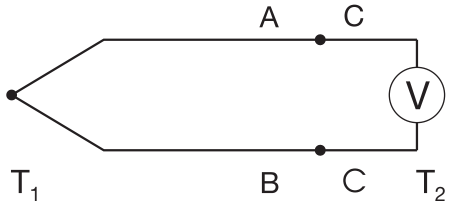


Fig. 9: Thermocouple connected via an additional material

There are two possible solutions to the problem of compensating for the additional thermoelectric emf:

- a reference point of known temperature,
- correction for the thermocouples formed at the connections to the instrument.

Fig. 10 shows the thermocouple with the reference junction held at a constant, known temperature.

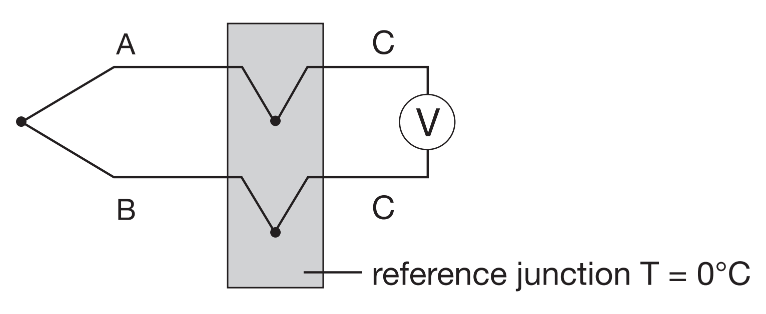


Fig. 10: Thermocouple with reference junction

The voltage of the material combination A-C plus the voltage of the combination C-B is the same as the voltage of the combination A-B. As long as all the junctions are at the same temperature, material C does not produce any additional effect. As a result of this a correction can be made by measuring the temperature at junctions A-C and B-C and then subtracting the voltage expected for the combination A-B at the measured temperature (reference junction compensation). The reference junction (or cold junction) is normally maintained at 0 °C (e.g. ice bath) so that the measured voltage can be used directly for the temperature determination in accordance with the tables of standard values.

Each junction that is exposed to the measured temperature is classed as a measurement point. The reference junction is the junction where there is a known temperature. The name thermocouple is always used to refer to the complete arrangement required to produce the thermoelectric emf; a thermocouple pair comprises two dissimilar conductors connected together; the individual conductors are referred to as the (positive or negative) legs [16].

The voltage caused by the thermoelectric effect is very small and is only of the order of a few microvolts per kelvin. Thermocouples are generally not used for measurements in the range -30 to +50 °C, because the temperature difference relative to the reference junction temperature is too small here to obtain an interference-free measurement signal. Although applications where the reference point is maintained at a significantly higher or lower temperature are feasible, by immersion in liquid nitrogen, for example, they are rarely used in practice.

Incidentally, it is not possible to specify an “absolute” thermoelectric emf but only the difference between the two emfs assigned to the two temperatures. A “thermoelectric emf at 200 °C” (or indeed at any other temperature) quoted in the standard tables always means “... relative to the emf at 0 °C”, and is made up as follows:

Formula 12:

$$V(200\ ^\circ\mathrm{C}) = V_{th}^{A}(200\ ^\circ\mathrm{C}) - V_{th}^{B}(200\ ^\circ\mathrm{C})$$

The actual emfs in the individual conductors of materials A and B are thus considerably higher, but they are not accessible for a direct measurement.

A thermocouple is always formed where two dissimilar metals are connected to one another. This is also the case where the metal of the thermocouple is connected to a copper cable to provide remote indication of the thermoelectric emf.

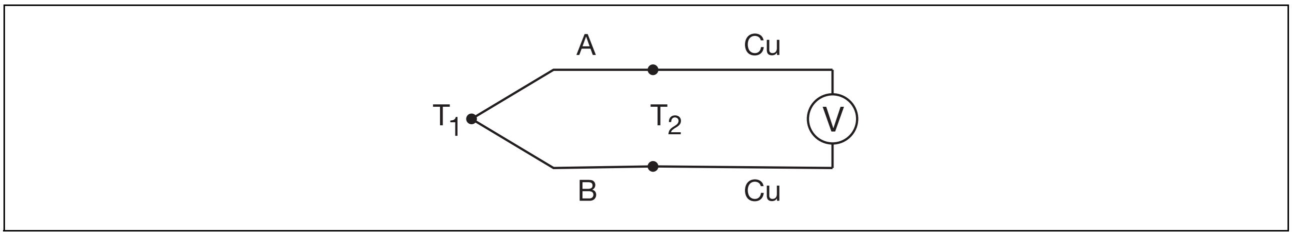


Fig. 11: Thermocouple with reference junction at temperature T_2

As the signs of the thermoelectric emfs produced are reversed here (transition from material A-copper/material B), only the difference in the emfs between material B and material A is significant. In other words, the material of the connecting cable has no effect on the thermoelectric emf present in the circuit. The second junction can be taken as being located at the connection point. By contrast, the prevailing temperature at the connection point to the copper cables (or to connecting cables made from a different material) is important. In this context, this is also referred to as the terminal temperature, as the thermocouple and the connecting cable are connected together here via terminals.

If the terminal temperature is known, the measured temperature at the thermocouple reference junction can be inferred directly from the measured emf: the emf generated by terminal temperature is added to the measured voltage and hence corresponds to the thermoelectric emf against a reference of 0°C.

Example: the temperature at the measurement point is 200°C, the terminal temperature 20°C, measured emf is 9mV. This corresponds to a temperature difference of 180°C. However, as the temperature is normally referred to 0°C, a positive correction of 20°C must be applied.

The following hypothetical exercise should help to clarify this: if the temperature of the reference junction - in this case the terminals - were to be actually reduced to 0°C, the total voltage would increase by an amount corresponding to a temperature difference of 20°C. Hence, the thermoelectric emf referred to 0°C is:

Formula 13:

V	=	V(t)	+	V(20°C)
thermoelectric emf referred to 0°C		measured voltage		thermoelectric emf of the terminal temperature

3.2 Thermocouples

An industrial thermocouple consists only of a single thermocouple junction that is used for the measurement. The terminal temperature is always used as the reference. Measurement errors will occur if this terminal temperature varies as a result of the connection point - in the terminal head of the thermocouple, for example - being exposed to fluctuating ambient temperatures. The following measures can be taken to prevent these errors:

The terminal temperature is either measured or maintained at a known temperature. Its value can be determined by a temperature sensor fitted in the probe head, for example, and then used as an external reference junction temperature for correction. As an alternative to this, the thermocouple material and the connecting cable are connected in a reference junction thermostat which is electrically heated to maintain a constant internal temperature (usually 50 °C). This temperature is used as the reference junction temperature. However, this type of reference junction thermostat is rarely used, and is only worthwhile when the signals from a number of thermocouples at one location have to be transmitted over a long distance. They are then wired to the reference junction thermostat using compensating cable (see Fig. 12), with the remainder of the transmission route via conventional copper cable.

There is no copper connecting cable in the terminal head. Instead, connections are made using a material with the same thermoelectric properties as the thermocouple itself. This compensating cable is either made of the same material, or, for reasons of cost, made of a different material but with the same thermoelectric properties. Because of this, no thermoelectric emf occurs at the thermocouple connection point. This only occurs at the point where the compensating cable once again connects to normal copper cable, at the instrument terminals, for example. A temperature probe, located at this point, measures and compensates for this internal reference junction. This is the most widely used method.

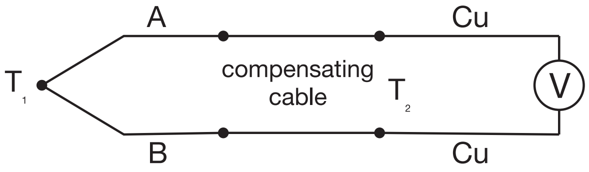


Fig. 12: Thermocouple measuring circuit with compensating cable

Only compensating cables made of the same material as the thermocouple itself (or with the same thermoelectric properties) should ever be used, as otherwise a new thermocouple is formed at the connection point. The reference junction is formed at the point where the compensating cable is connected to a different material; an extension using copper cable or a different type of compensating cable is not possible.

3.3 Polarity of the thermoelectric emf

A metal whose valency electrons are less strongly bound, will give up these electrons more easily than a metal with a tighter bond. Hence, it is thermoelectrically negative in comparison to it. As well as this, the direction of current flow is also affected by the temperature of the two junctions. This can easily be seen by visualizing the thermocouple circuit as two batteries, where the one with the higher temperature is currently generating the highest voltage. The direction of current flow thus depends on which end of the circuit has the highest voltage. With thermocouples, the polarity specification always assumes that the measuring point temperature is higher than that of the reference junction (terminal or reference junction temperature).

3.4 Action on break and short circuit

A thermocouple does not generate a voltage when the measured temperature is the same as the reference junction temperature. This means that the resting position of a connected indicator must be at the reference junction temperature rather than at 0 °C. If a thermocouple is disconnected, the indication - in the absence of any special broken-sensor message - does not go back to zero, but to the reference point temperature as set on the instrument.

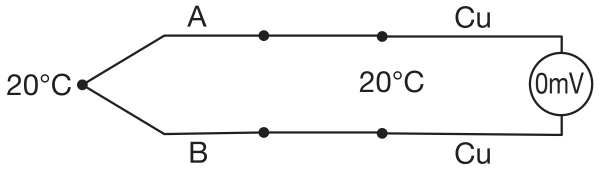


Fig. 13: Thermocouple at the same temperature as the reference junction

If a thermocouple or compensating cable is short-circuited, a new measurement point is created at the point of the short circuit. If a short circuit of this type occurs in the terminal head, for example, the temperature indicated is no longer that of the actual measurement point but that of the terminal head. If this is close to the actual measured temperature, it is quite likely that the fault will not be noticed at first.
This type of short circuit can be caused by the individual strands of the connecting cable not being correctly gripped by the terminal, and forming a link to the second terminal.

At high temperatures, thermocouples become increasingly brittle over time, as the grain size in the metal increases due to recrystallization. Most electrical instruments for connection to thermocouples incorporate input circuits that record and report a thermocouple break. As explained above, sensor short circuits are not as easily detected, but they are also much less frequent.

3.5 Standardized thermocouples

Among the large number of possible metal combinations, certain ones have been selected and their characteristics incorporated in standard specifications, particularly the voltage tables and the permissible deviation limits. The thermocouples listed below are covered by both international (IEC) and European standard specifications with regard to thermoelectric emf and its tolerance.

IEC 584-1, EN 60 584-1	**Type Designation**
iron - constantan (Fe-Con or Fe-CuNi)	J
copper - constantan (Cu-Con or Cu-CuNi)	T
nickel chromium - nickel (NiCr-Ni)	K
nickel chromium - constantan (NiCr-Con or NiCr-CuNi)	E
nicrosil - nisil (NiCrSi-NiSi)	N
platinum rhodium - platinum (Pt10Rh-Pt)	S
platinum rhodium - platinum (Pt13Rh-Pt)	R
platinum rhodium - platinum (Pt30Rh-Pt6Rh)	B

DIN 43710 (no longer valid)	
iron - constantan (Fe-Con)	L
copper - constantan (Cu-Con)	U

The materials concerned are technically pure iron and a CuNi alloy with 45 - 60 percent by weight of copper, as well as alloys of pure platinum and rhodium in the specified compositions; the other alloys have not yet been fully specified. The abbreviation NiCr-NiAl and the name “chromel-alumel” are often used for the nickel/chromium-nickel thermocouple, as aluminum is added to the nickel leg so that the nickel is protected by a layer of Al_2O_3. In addition to this thermocouple, there is also the nicrosil-nisil thermocouple (NiCrSi-NiSi), Designation N. It differs from the nickel/chromium-nickel thermocouple by virtue of having a higher chromium content in the positive leg (14.2 % instead of 10 %), and a proportion of silicon in both legs. This leads to the formation of a silicon dioxide layer on its surface which protects the thermocouple. Its thermoelectric emf is around 10 % less than that of Type E, and is defined up to 1300 degrees.

At this point, it should be noted that two Fe-Con type thermocouples (Types L and J) and two Cu-Con types (Types U and T) are listed in the standards, for historical reasons. However, the “old” Type U and L thermocouples have since faded into the background in comparison with the Type J and T thermocouples to EN 60 584. The particular thermocouples are not compatible because of their different alloy compositions; if a Type L Fe-Con thermocouple is connected to a linearization circuit intended for a Type J characteristic, errors of several degrees can be introduced, due to the different characteristics. The same applies to Type U and T thermocouples.

3 Thermocouples

Color codes are laid down for thermocouples and compensating cables. It should be noted that despite the existence of international standard color codes, nationally defined color codes are repeatedly encountered, which can easily lead to confusion.

Country		Internat.	USA		England	Germany	Japan	France
Type	**Standard**	**IEC 584**	**ANSI MC96.1 (thermo-couple)**	**ANSI MC96.1 (comp. cable)**	**BS1843**	**DIN 43714**	**JIS C1610-1981**	**NF C42-323**
J						Type L		
	Sheath	black	brown	black	black	blue	yellow	black
	Positive	black	white	white	yellow	red	red	yellow
	Negative	white	red	red	blue	blue	white	black
K	Sheath	green	brown	yellow	red	green	blue	yellow
	Positive	green	yellow	yellow	brown	red	red	yellow
	Negative	white	red	red	blue	brown	white	purple
E	Sheath	violet	brown	purple	brown	black	purple	
	Positive	violet	purple	purple	brown	red	red	
	Negative	white	red	red	blue	black	white	
T						Type U		
	Sheath	brown	brown	green	blue	brown	brown	blue
	Positive	brown	blue	black	white	red	red	yellow
	Negative	white	red	red	blue	brown	white	blue
R	Sheath	orange		green	green		black	
	Positive	orange		black	white		red	
	Negative	white		red	blue		white	
S	Sheath	orange		green	green	white	black	green
	Positive	orange		black	white	red	red	yellow
	Negative	white		red	blue	white	white	green
B	Sheath	gray		gray		gray	gray	
	Positive	gray		gray		red	red	
	Negative	white		red		gray	white	
N	Sheath	pink	brown	orange				
	Positive	pink	orange	orange				
	Negative	white	red	red				

Table 2: Color codes for thermocouples and compensating cables

If the thermocouple wires are not color-coded, the following distinguishing features may be useful:

Fe-Con:	positive leg is magnetic
Cu-Con:	positive leg is copper-colored
NiCr-Ni:	negative leg is magnetic
PtRh-Pt:	negative leg is softer

The limiting temperatures are also laid down in the standard. A distinction is made between:

- the maximum temperature,
- the definition temperature.

The maximum temperature here means the value up to which a deviation limit is laid down (see Chapter 3.5.2). The value given under “defined up to” is the temperature up to which standard values are available for the thermoelectric emf (see Table 2).

Standard	Thermocouple		Maximum temperature	defined up to
EN 60 584	Fe-Con	J	750°C	1200°C
	Cu-Con	T	350°C	400°C
	NiCr-Ni	K	1200°C	1370°C
	NiCr-Con	E	900°C	1000°C
	NiCrSi-NiSi	N	1200°C	1300°C
	Pt10Rh-Pt	S	1600°C	1540°C
	Pt13Rh-Pt	R	1600°C	1760°C
	Pt30Rh-Pt6Rh	B	1700°C	1820°C

Table 3: Thermocouples to EN 60 584

3.5.1 Voltage tables

As a general statement, the thermoelectric emf increases with increasing difference between the metals of the two legs. Of all the thermocouples mentioned, the NiCr-Con thermocouple has the highest electromotive force (emf). In contrast, the platinum thermocouple, where the legs differ only in the rhodium alloy component, has the lowest emf. This, together with the higher cost, is a disadvantage of the noble metal thermocouple.

The standardized voltage tables are calculated from 2-term to 4-term polynomials which are quoted in the Appendix of EN 60 584, Part 1. They are all based on a reference temperature of 0°C. However, the actual reference junction temperature is usually different. The voltage corresponding to the measured temperature must therefore be corrected by this amount:

Example:
Thermocouple Fe-Con, Type J,
measured temperature 300°C,
reference junction temperature 20°C

thermoelectric emf at 300°C:	16.325 mV
thermoelectric emf at 20°C:	1.019 mV
resultant thermoelectric emf:	15.305 mV

Because of the non-linearity of the voltage, it is incorrect to work out the temperature by first of all determining the temperature corresponding to the measured emf and then deducting the reference junction temperature from this value. In all cases, the emf corresponding to the reference junction must first be subtracted from the measured emf. In general, the correction for the emf generated at the reference junction is carried out automatically by suitable electronic circuitry in the connected instrument.

3.5.2 Deviation limits

Three tolerance classes are defined for thermocouples to EN 60 584. They apply to thermocouple wires with diameters from 0.25 to 3mm and refer to the as-supplied condition. They cannot provide any information on possible subsequent ageing, as this very much depends on the conditions of use. The temperature limits laid down for the tolerance classes are not necessarily the recommended limits for actual use; the voltage tables cover thermoelectric emfs for considerably wider temperature ranges. However, no deviation limits are defined outside these temperature limits (see Table 2).

Fe-Con (J)	Class 1	- 40 to + 750°C	±0.004 · t	or	±1.5°C
	Class 2	- 40 to + 750°C	±0.0075 · t	or	±2.5°C
	Class 3				
Cu-Con (T)	Class 1	0 to + 350°C	±0.004 · t	or	±0.5°C
	Class 2	- 40 to + 350°C	±0.0075 · t	or	±1.0°C
	Class 3	-200 to + 40 °C	±0.015 · t	or	±1.0°C
NiCr-Ni (K) and NiCrSi-NiSi (N)	Class 1	- 40 to +1000°C	±0.004 · t	or	±1.5°C
	Class 2	- 40 to +1200°C	±0.0075 · t	or	±2.5°C
	Class 3	-200 to + 40°C	±0.015 · t	or	±2.5°C
NiCr-Con (E)	Class 1	- 40 to + 900°C	±0.004 · t	or	±1.5°C
	Class 2	- 40 to + 900°C	±0.0075 · t	or	±2.5°C
	Class 3	-200 to + 40°C	±0.015 · t	or	±2.5°C
Pt10Rh-Pt (S) and Pt13Rh-Pt (R)	Class 1	0 to +1600°C	±[1 + 0.003 · (t-1100°C)]	or	±1.0°C
	Class 2	0 to +1600°C	±0.0025 · t	or	±1.5°C
	Class 3				
Pt30Rh-Pt6Rh (B)	Class 1	+600 to +1700°C	±0.0025 · t	or	±1.5°C
	Class 2	+600 to +1700°C	±0.005 · t	or	±4.0°C
	Class 3				

Table 4: Deviation limits for thermocouples to EN 60 584

Cu-Con (U)	0 to + 600°C	±0.0075 · t	or	±3.0°C
Fe-Con (L)	0 to + 900°C	±0.0075 · t	or	±3.0°C

Table 5: Deviation limits for thermocouples to DIN 43 710

NiCr-Con (E)	standard	0 to + 900°C	±0.005 · t	or	±1.7°C
	special	0 to + 900°C	±0.004 · t	or	±1.0°C
Fe-Con (J)	standard	0 to + 750°C	±0.0075 · t	or	±2.2°C
	special	0 to + 750°C	±0.004 · t	or	±1.1°C
NiCr-Ni (K)	standard	0 to +1250°C	±0.0075 · t	or	±2.2°C
	special	0 to +1250°C	±0.004 · t	or	±1.1°C
Cu-Con (T)	standard	0 to + 350°C	±0.0075 · t	or	±1.0°C
	special	0 to + 350°C	±0.004 · t	or	±0.5°C
Pt10Rh-Pt (S) and Pt13Rh-Pt (R)	standard	0 to +1450°C	±0.0025 · t	or	±1.7°C
	special	0 to +1450°C	±0.001 · t	or	±0.6°C

Table 6: Deviation limits for thermocouples to ANSI MC96.1 1982

Here, the largest respective value always applies.

Example:
Thermocouple Fe-Con Type J, measured temperature 200 °C, reference junction temperature 0 °C, tolerance to EN 60 584: 2.5 °C or 0.0075 · t = 2.5 °C or 0.0075 · 200 °C = 2.5 °C or 1.5 °C.

Hence an uncertainty in the measurement of ±2.5 °C must be assumed. Of course, this is the maximum permissible tolerance; in most cases the actual deviation will be less.

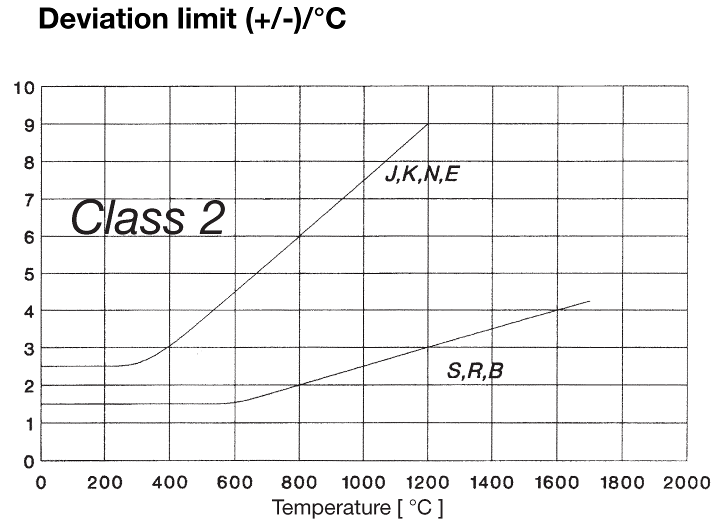


Fig. 14: Class 2 deviation limits to EN 60 584

A tolerance such as this means: if a thermocouple of this type generates a voltage that corresponds to a temperature difference of 200 °C between the measurement and reference junctions, the actual temperature difference can lie between 197.5 and 202.5 °C.

3.5.3 Linearity

The voltage generated by a thermocouple does not vary linearly with temperature, and must therefore be linearized in special input circuits in the subsequent electronics. Linearization tables are programmed in digital instruments, or the basic data must be entered by the user. Analog instruments often have non-linear scale divisions. The characteristics of standardized thermocouples are specified by the voltage tables in such a way that there is full interchangeability. This means, for example, that a Type K iron-constantan thermocouple can be replaced by any other thermocouple of this type, irrespective of the manufacturer, without the need for recalibration of the instrument connected to it.

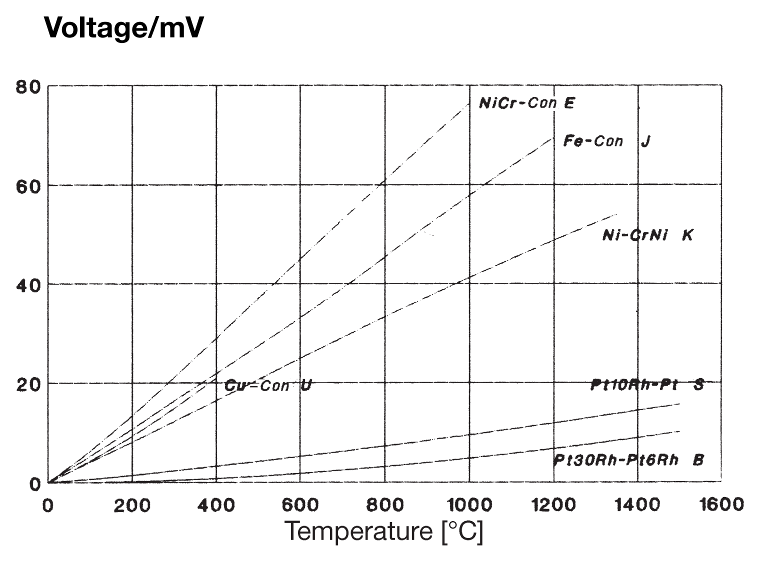


Fig. 15: Characteristics of thermocouples to EN 60 584

3.5.4 Long-term behavior

The maximum operating temperature of the materials is largely determined by their oxidizability and ageing at elevated temperatures. In addition to the low-price thermocouples made from copper, nickel and iron, for ranges above about 800 °C, noble metal thermocouples containing platinum are available, with a maximum temperature of up to 1800 °C.

The positive leg of Type K or E thermocouples, and the negative leg of Types J, T or E, exhibit a reversible crystal structure change in the range from 250 °C to 650 °C that gives rise to an indication error of about 5 °C.

There are also various other metal combinations, including those with metal carbides that are mainly intended for extremely high or low temperature ranges. Their characteristics are not standardized.

However, the resistance of thermocouples to oxidizing and reducing atmospheres is normally of only minor importance, as they are almost invariably fitted in gas-tight protection tubes and then hermetically sealed by potting.

Unprotected thermocouples in which the thermocouple wires are freely suspended in the furnace chamber, are actually only used above 1000 °C, because the insulation resistance of even ceramic materials becomes too low here. However, when this type of unprotected thermocouple is used (which must always be one of the platinum versions), numerous other factors must be considered that can sometimes lead to premature ageing within the space of just a few hours.

Silicon in particular, which is often contained in the heating elements or their insulation, is released to a greater extent, especially on initial commissioning. It readily diffuses into the thermocouple wires and contaminates them. Hydrogen causes embrittlement and hence thermocouples without protection tubes can only be used in oxidizing atmospheres. (For instance, tungsten-rhenium thermocouples are used in reducing atmospheres above 1000 °C, but cannot tolerate any oxygen.) Ceramics that can withstand temperatures up to 1800 °C are now available, so the use of unprotected thermocouples should be avoided wherever possible, and gas-tight protection tubes used at all times.

Another particular high-temperature thermocouple is the molybdenum-rhenium type. It has higher mechanic stability than the tungsten-rhenium thermocouple and, like this type, can only be used in reducing atmospheres or in a high vacuum. The maximum temperature is around 2000 °C, but this is generally limited by the insulation material used. There is no compensating cable for this thermocouple. The terminal head is therefore cooled and its temperature used for the reference junction temperature. Where this thermocouple is not freely suspended, but instead is mounted in a protection fitting, this fitting must be evacuated of gas or purged with protective gas, because of the thermocouple’s sensitivity to oxygen.

The ageing of the materials is of major importance for a thermocouple’s temperature stability. As the temperature approaches the melting point, the diffusion rate of the atoms in a metal increases. Foreign atoms then migrate readily into the thermocouple from the protection tube material, for example. Because both thermocouple legs here are alloyed with the same foreign atoms, their thermoelectric properties come closer together and the thermoelectric emf decreases. So only platinum thermocouples should be used for temperature measurements above 800 °C, where a long-term stability of a few degrees is required.

Pure platinum exhibits a strong affinity for the absorption of foreign atoms. Because of this, the long-term stability of the platinum-rhodium thermocouple increases with increasing rhodium content. The long-term stability of the Pt13Rh-Pt thermocouple is around twice that of the Pt10Rh-Pt thermocouple [1]. Furthermore, it also supplies a higher thermoelectric emf. The Pt30Rh-R6Rh thermocouple has even better long-term stability, but has only about half the thermoelectric force.

When selecting and using a thermocouple, it is important to consider the ageing phenomenon in the high-temperature region. A practical example shows that in a heat-treatment furnace at a temperature of approx. 950 °C, Type K thermocouples fitted in heat-resistant metal tubes exhibited a drift of -25 °C after two years use. Regular checking of installed thermocouples is always advisable. As an example, a thermocouple of the same type as the one installed can be held back and then used for regular checks on the installed thermocouple. For this, the thermocouple to be tested (thermocouple complete with protection sleeve and terminal head) is replaced by the reference thermocouple, and the indicated temperature compared with that of the one under test, to obtain information about the ageing of the thermocouple under test.

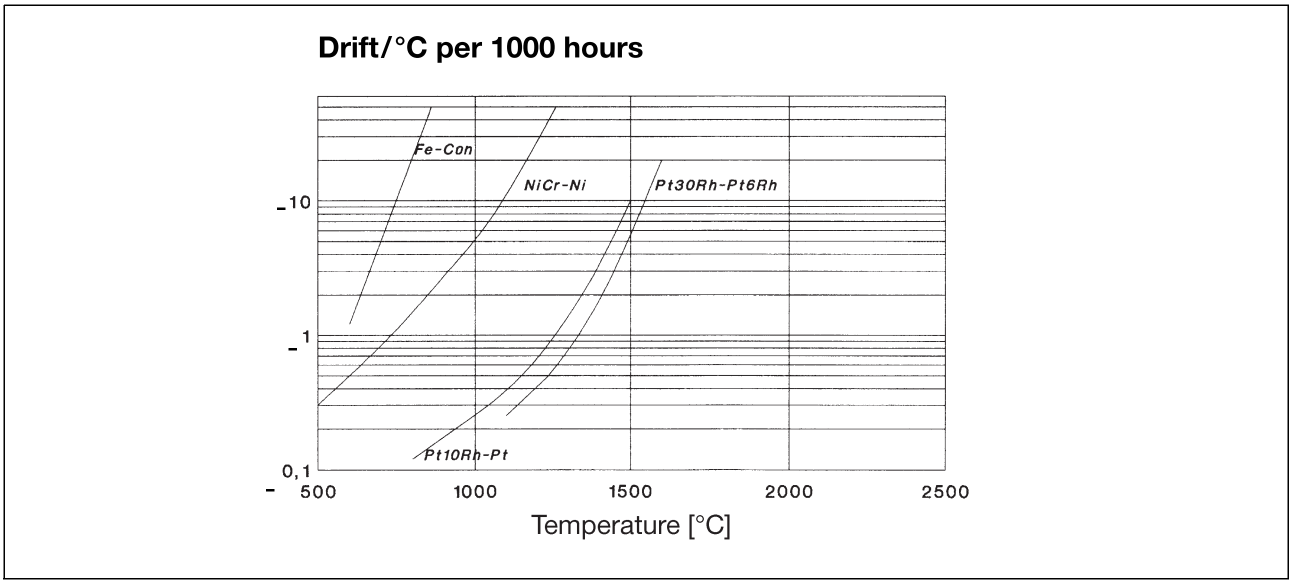


Fig. 16: Ageing of thermocouples (from [1])

The calibration thermocouple is then once again replaced by the one under test. Spare tubes next to the actual thermocouples allow the reference thermocouples to be inserted without the need for removal of the thermocouples under test. The provision of spare tubes should therefore be considered at the design stage. Thermometers with ceramic protection sleeves should only be gradually subjected to a temperature change, and so care should be taken when inserting them into and withdrawing them from the protection tube. Otherwise there is a possibility of microscopic cracks developing in the ceramic material, through which contaminants can reach the thermocouple and change its characteristic.

3.6 Selection criteria

The selection of the type of thermocouple depends primarily on the operating temperature. Furthermore, a thermocouple with a high thermoelectric emf should be selected to obtain a measurement signal with the highest possible interference immunity.

Table 8 below lists the various thermocouples together with a brief characterization. The recommended maximum temperatures should only be taken as a general guide, as they are heavily dependent on the operating conditions. They are based on a wire diameter of 3 mm for base metal and 0.5 mm for noble metal thermocouples.

Cu-Con	350 °C[1]	not widely used
Fe-Con	700 °C[1]	widely used, low-cost, prone to corrosion
NiCr-Con	700 °C[1]	not widely used, high thermoelectric emf
Ni-CrNi	1000 °C	often used in range 800 - 1000 °C, but also suitable for lower temperature range.
NiCrSi-NiSi	1300 °C	(still) little used can replace noble thermocouples to some extent
Pt10Rh-Pt	1500 °C (1300 °C[1])	expensive, very good long-term constancy, close tolerances
Pt30Rh-Pt6Rh	1700 °C	expensive, lowest thermoelectric emf, high maximum temperature

1. to DIN 43 710 (1977) when used in clean air

Table 8: Thermocouple properties

3.6.1 Type T (Cu-Con)

The limit of 400°C given in DIN 43 710 for the Cu-Con thermocouple has been reduced to 350°C, as the tolerance of this type of thermocouple to IEC 584 is only defined up to this temperature; in clean air, oxidation already occurs above 200°C. Above 350°C the copper leg oxidizes very quickly and changes the standard thermoelectric emf value. Furthermore, thermal conduction errors can easily be introduced due to the good conductive properties of the copper leg. The thermocouple is often used for low-temperature measurement down to -270°C. This thermocouple is not widely used. Where corrosion resistance is a priority, it is preferable to revert to the more widely-used NiCr-Ni thermocouple.

3.6.2 Type J (Fe-Con)

The Fe-Con thermocouple is the most widely used of all. Apart from traditional reasons, this is because of its low price and high thermoelectric emf. It is used in the lower and middle temperature range, unless the NiCr-Ni thermocouple is a more appropriate choice on corrosion resistance grounds. The tables of standard voltages in EN 60 584 actually give values up to 1200°C. However, because the oxidation rate increases above 750°C, the thermocouple should not be operated at temperatures above this. At 769°C, the iron leg undergoes a magnetic change, and at 910°C a crystal structure change. Both effects cause a permanent change in the output signal. If the thermocouple is used in a damp environment (there is a risk of condensation), the unprotected iron leg rusts. Embrittlement of the iron can easily occur in the presence of sulfurous gases above 500°C. The Fe-Con thermocouple is also very widely used in the mineral-insulated form.

3.6.3 Type E (NiCr-Con)

The NiCr-Con thermocouple differs from the others by virtue of its comparatively high thermoelectric emf, which is why it is used primarily in the lower temperature range. It is widely used in the United States, but hardly ever in Europe. Because of the high voltage sensitivity, this thermocouple is also used for low-temperature measurement. It is also used in radiation pyrometers because of the low thermal conductivity of the leg, although other more suitable thermocouples with even higher thermoelectric emfs are available for such applications [2].

3.6.4 Type K (Ni-CrNi)

The Ni-CrNi (Cr-Al) thermocouple shows a higher resistance to oxidation than Types E and J, and so it is used for temperature measurement above 500°C. They should not be used at temperatures above 750°C without protection, as the oxidation rate rises sharply. This applies equally to temperature measurement in sulfurous, oxidizing or reducing atmospheres. When used in a vacuum or at high temperatures, the vacuum sensitivity must be taken into account, as the chromium slowly diffuses out of the positive leg. The presence of oxygen or water vapor can lead to green rot. Between 800°C and 1050°C, the chromium is oxidized, but not the nickel. The measurement error can amount to several hundred °C. The positive leg undergoes a reversible structural change in the range from 400°C to 600°C, amounting to a change in the output signal of up to 5°C.

3.6.5 Type N (NiCrSi-NiSi)

With NiCrSi-NiSi thermocouples, the upper temperature is raised to 1300°C compared with the NiCrNi thermocouple. The alloyed silicon oxidizes on the surface of the thermocouple wires and forms a protective layer against corrosion. The silicon also suppresses the reversible “K state” of the Type K thermocouple. So it can be used to some extent as a replacement for the considerably more expensive platinum thermocouples. Mineral-insulated versions are also available where the sheath material is very similar to the thermocouple material. This is intended to prevent contamination of the thermocouple material.

3.6.6 Types R, S and B

In general, the service life of the noble metal thermocouple is limited by the grain growth in the thermocouple wires. The mechanical strength is reduced and the material embrittles. Furthermore, lighter contaminants can diffuse inwards along the grain borders, causing a change in the thermoelectric emf.

Because of their high cost and low emf, noble metal thermocouples are only used at temperatures above 800°C. As well as the significantly reduced drift due to ageing, they also have the advantage of a lower basic tolerance, as shown in Table 9 below:

Thermocouples	**Deviation limit (Class 2/Class 1)**		
	600 °C	**800 °C**	**1000 °C**
Fe-Con J	±4.5/2.4°C	±6.0/3.2°C	-
Ni-CrNi K	±4.5/2.4°C	±6.0/3.2°C	±7.5/4.0°C
Pt10Rh-Pt S	±1.5/1.0°C	±2.0/1.0°C	±2.5/1.0°C

Table 9: Basic tolerances of noble metal thermocouples

The disadvantages are the high cost and the low thermoelectric emf. The Pt13Rh-Pt thermocouple (Type R) is distributed mainly in the English-speaking countries. The question of whether to use a Type S or Type R thermocouple often depends on the linearization circuit available in the instrument. Type B thermocouples are only used at temperatures above 1300°C, because of their low thermoelectric emf. The maximum temperature can be raised to 1800°C by using a gas-tight protection tube.

3.7 Standard compensating cables

The electrical and mechanical properties of compensating cables for standard thermocouples are laid down in the IEC 584-3 standard. They are either made from the same material as the thermocouple itself (thermocables, extension cables) or from special materials that have the same thermoelectric properties over limited temperature ranges (compensating cables). They are made up of twisted cores and are identified by a color code and code letters derived as follows:

First letter:	Code letter for the standard thermocouple type
Second letter:	X: same material as the thermocouple C: special material
Third letter:	Where there are several types of compensating cable they are distinguished by a third letter.

Example:
KX: compensating cable for a NiCr-Ni thermocouple Type K made of thermocouple material
RCA: compensating cable for a PtRh-Pt thermocouple Type R made of special material, Type A

Two tolerance classes are defined for compensating cables, Class A and Class B. Class B has closer tolerances and can only be met by compensating cables made from the same material as the thermocouple, i.e. Type X. Class B compensating cables are supplied as standard.

Table 10 specifies the deviation limits of the various classes of compensating cables:

Thermocouple type and wire grade	Deviation limit class		Operating temperature range [°C]	Measurement temperature [°C]
	1	2		
JX	± 85µV / ±1.5°C	±140µV / ±2.5°C	-25 to + 200	500
TX	± 30µV / ±0.5°C	± 60µV / ±1.0°C	-25 to + 100	300
EX	±120µV / ±1.5°C	±200µV / ±2.5°C	-25 to + 200	500
KX	± 60µV / ±1.5°C	±100µV / ±2.5°C	-25 to + 200	900
NX	± 60µV / ±1.5°C	±100µV / ±2.5°C	-25 to + 200	900
KCA	-	±100µV / ±2.5°C	0 to 150	900
KCB	-	±100µV / ±2.5°C	0 to 100	900
NC	-	±100µV / ±2.5°C	0 to 150	900
RCA	-	± 30µV / ±2.5°C	0 to 100	1000
RCB	-	± 60µV / ±5.0°C	0 to 200	1000
SCA	-	± 30µV / ±2.5°C	0 to 100	1000
SCB	-	± 60µV / ±5.0°C	0 to 200	1000

Table 10: Deviation limits of compensating cables

The operating temperature range designates the temperature to which the complete cable including the thermocouple termination point may be exposed, without exceeding the stated tolerances.

In addition, this temperature can also be limited by the insulation material of the cable. Because of the non-linearity of the thermoelectric emfs, the deviation limits quoted in µV or °C are only valid at a measurement temperature that is specified in the right-hand column. In practical terms, this means for example:

A Type J thermocouple is connected to a Type JX, Class 2 compensating cable. If the measured temperature remains constant at 500°C and the terminal temperature and/or the temperature of the compensating cable varies from -25°C to 200°C, then the indicated temperature here varies by not more than ±2.5°C.

In general, there is no need to differentiate between compensating cables for Cu-Con and Fe-Con thermocouples to EN 60 584 or DIN 43 713 standards; the same compensating cables can be used for both these types of thermocouple. However, it should be noted that this type of thermocouple is sometimes manufactured in a form where the compensating cable cores themselves are linked together to form a measuring junction and then provided with a protection fitting. Naturally, a careful distinction must then be made between the thermocouples of the two standards. It should also be noted that the thermoelectric emfs for thermocables and compensating cables are only identical with the corresponding thermocouple voltage up to a measurement temperature of 200°C. Probes manufactured in this way can only be used up to this temperature.

The characteristic of the Type B platinum-rhodium thermocouple is so flat at the beginning that conventional copper cables can be used as compensating cable, providing that the terminal temperature is not too high: a termination point temperature of 100°C would cause the measured value to be displaced by 0.032mV. At a measured temperature of 1500 °C, this corresponds to an error of 0.3% or -4.5°C.

3.7.1 Color codes of compensating cables

The following rule applies for thermocouples to EN 60 584:
The positive leg has the same color as the sheath, the negative leg is white.

However different color codes are applicable for the “old” Type U and L thermocouples according to DIN 43 713.

Thermocouple	Type	Sheath	Positive	Negative
Cu-Con	T	brown	brown	white
Fe-Con	J	black	black	white
NiCr-Ni	K	green	green	white
NiCrSi-NiSi	N	pink	pink	orange
NiCr-Con	E	violet	violet	white
Pt10Rh-Pt	S	orange	orange	white
Pt13Rh-Pt	R	orange	orange	white

Table 11: Thermocouples to IEC 584-1

Fe-Con	L	blue	red	blue
Cu-Con	U	brown	red	brown

Table 12: Thermocouples to DIN 43 713 (new)

In addition to these color codes for compensating cables, there are also those according to DIN 43 714 (1979). They differ from those quoted above as follows:

NiCr-Ni	K	green	red	green
Pt10Rh-Pt	S	white	red	white
Pt13Rh-Pt	R	white	red	white

Table 13: Color coding to 1979 DIN standard

The only exceptions are cables for intrinsically safe circuits with explosion-proof apparatus. If these cables are colored, the sheath of all compensating cables is light blue, whilst the cores have the color code as specified. (The blue color coding for the Cu-Con thermocouple to DIN 43 713 is actually a dark blue shade)

To comply with DIN 43 714, the cable cores are twisted together for electromagnetic shielding. In addition a foil or braid screen can be provided. The core to core and core to shield insulation resistance must be not less 10 MΩ/meter at the maximum temperature, and the breakdown voltage must exceed 500V AC.

3.8 Connection of thermocouples

Particularly with the Fe-Con thermocouple, it is important to remember that the positive leg consists of pure iron, which can lead to increased corrosion at clamp and plug connections. In particular, the iron-copper transition that occurs, for example, at the connection to a copper connecting cable, produces a galvanic cell. In the presence of moisture this leads to the formation of a local cell with increased corrosion. The resulting parasitic voltages can significantly distort the measurement result. Tinned terminals and cables with tinned conductors are therefore always preferable to bare copper. Although tin is much higher than iron on the electrochemical scale, its reactivity is reduced by surface passivation.

A frequently asked question is whether thermocouple wires can be connected to the compensating cable or extended using standard copper or brass terminals. Apart from the corrosion aspect at the point of contact of two dissimilar metals, this is definitely possible. Interposing one or two terminals in one or both legs of a thermocouple or of the compensating cable is quite acceptable, as long as the temperature at both sides of the terminal is the same.

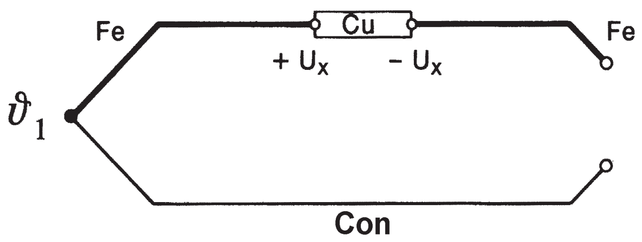


Fig. 17: Inserting a copper terminal in the thermocouple circuit

The thermoelectric emfs produced at the Fe/Cu and Cu/Fe transitions cancel each other out at the same temperature due to the opposite polarity, irrespective of both the temperature level at this connection point and the actual material of the junction. Of course, it is important to remember that this only applies if the temperatures at both ends are the same.

Where there are individual terminals for each core of the compensating cable, it is quite possible that they are at different temperatures; the one important thing is that the temperature at both sides of each terminal is the same. Problems can be encountered with enclosure entries where there is a big difference between the internal and external temperatures. The additional thermoelectric emfs generated as a result of this temperature difference distort the measurement. So there are special connectors, free from thermoelectric emf, that avoid the phenomenon described here.

With longer cable lengths, the connecting cable (compensating cable or copper cable) should be screened and grounded at one end. Screened compensating cables are available for this purpose; in certain cases the use of a reference junction thermostat and conventional screened copper cable is appropriate. With mineral-insulated thermocouples (see Chapter 3.10), using the cable sheath as a screen can raise problems: in some versions the measuring point is welded to the sheath to reduce the response time. The screen is then directly connected to the sensor input of the connected instrument and is thus ineffective. Special precautions with regard to interference should always be taken with thermocouples where the measuring point is welded to the protection tube, as the sheath tube can act as an aerial here.

Even if the measuring point is not welded to the protection tube, the sheath of a mineral-insulated thermocouple should not be used as a screen. As the sheath is made of bare metal, in electrically heated furnaces, equalizing currents can flow between the furnace material and the earthing point. These can distort the measurement result and, if the equalizing currents are high enough, destroy the probe tube.

Generally speaking: thermocouples that are electrically connected to the protection tube can easily give rise to interference and external voltages caused by coupling of voltages to the connected instrument.

Additionally, two such inputs form a current loop through which the two inputs are connected together. As current loops like this have a large effective cross-sectional area, they form an ideal point of entry for interference.

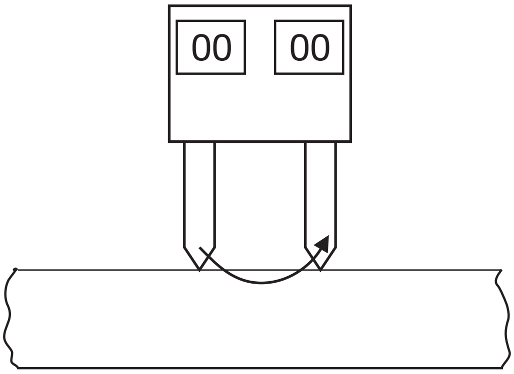


Fig. 18: Formation of a conductor loop

Under such conditions, thermocouples should always be electrically isolated, i.e. there must be no internal connection between the amplifier circuits and the rest of the electronics. Most instruments intended for connection to thermocouples already incorporate this feature.

Ceramic materials of the type used to insulate the thermocouple in the protection tube suffer a marked loss of insulation resistance above 800 to 1000°C. As a result, the phenomena described above occur in the high-temperature range even with thermocouples where the measuring point is not welded to the protection tube. Here too, electrical isolation is strongly advised.

With electrically heated furnaces in the high-temperature range, it should also be noted that the increasing conductivity of the ceramic insulation material can lead to the supply voltage being coupled into the thermocouple circuit. Here again, an electrical isolation against the supply and earth potential is absolutely essential. The insulating voltage must exceed the peak value of the supply voltage (heater voltage).

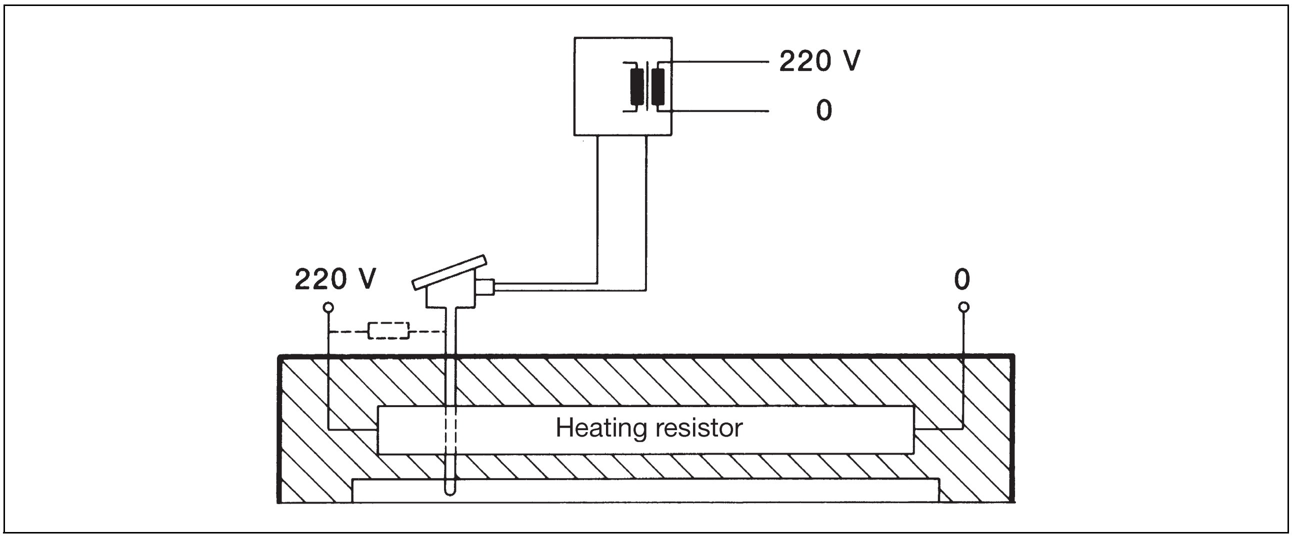


Fig. 19: Coupling of supply voltages

The electrical isolation of the inputs takes on special importance when electrically heated furnaces are fitted with several thermocouples that are linked to one or more instruments. As an example, two thermocouples each of which is linked to a separate controller. The controllers themselves are linked via a second input for external setpoint selection.

In this case, the thermocouple inputs must be isolated in two respects: firstly, with respect to the supply voltage, and secondly, with respect to the external setpoint inputs. Isolation with respect to the supply voltage is straightforward; on instruments with a built-in power supply the isolation is considerably higher than the supply voltage. However, the isolation between inputs is not normally as high. With an unfavorable installation, this can then lead to the following problems:

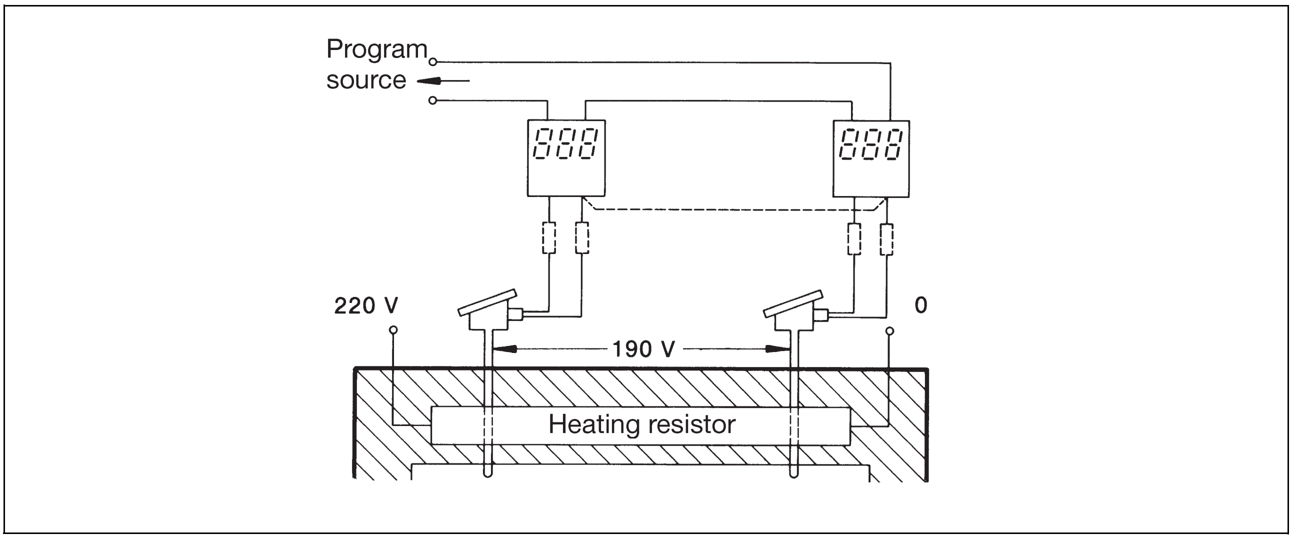


Fig. 20: Distortion of the measured value due to inadequate electrical isolation

If the thermocouples are mounted close to the heater windings, but at a large distance from each other, a potential difference appears between them that is picked up across the insulation resistance. This potential difference can easily be of the same order as the heater voltage, and it is possible that the insulation is no longer adequate. This can be remedied by connecting the thermocouples together at the positive or negative leg, so that these are at the same potential. For simplicity this connection is normally made at the instrument terminals. However, this can raise problems with longer compensating cables:

Assuming a voltage of 190V and an insulation resistance of 1MΩ, a current of 0.19mA flows. This current, which flows through the compensating cable, causes a volt drop of 1.9mV across their resistance, assuming a resistance value here of 10Ω. The thermoelectric emf is increased by this amount, and incorrect measurements are obtained as a consequence.

For this reason, it is preferable to provide equipotential bonding as close as possible to the thermocouple. This can be achieved by connecting their protection fittings together electrically and possibly earthing them. As a result, no equalizing currents flow, and the additional voltages that would otherwise occur are eliminated.

3.9 Construction of thermocouples

Base metal thermocouples are made from wires with diameters ranging from 1 to 3mm, noble metal ones from 0.5 or 0.35mm diameter wires. The different diameters are selected mainly on grounds of cost. In principle, thicker thermocouple wires have a longer service life.

The thermocouple wires are welded or soldered at one end. Strictly speaking, the type of connection here is of minor importance. They can be twisted, welded, soldered etc. Twisting can lead to poor contact due to scaling of the materials. In addition, galvanic cells can be formed due to the ingress of moisture into the boundary layer between the metals. The measuring effect is distorted as a result.

3.10 Mineral-insulated thermocouples

These represent a special form of thermocouple. They are manufactured by taking stainless steel tubes about 1m long and a few centimeters internal diameter; two rods made of the thermocouple materials are then positioned in the tube, and the interior space filled with magnesium or aluminum oxide that is then compacted. The tubes prepared in this way are sealed at both ends and then drawn to form wires from 15 to 0.5mm thick. During this process the geometry inside the tube is unchanged. Consequently, a 1mm diameter mineral-insulated thermocouple has the same ratio of wall thickness to diameter, thickness of the aluminum oxide insulation, thermocouple wire diameters, etc. as the much larger initial piece. Mineral-insulated thermocouples made in this way are supplied in continuous lengths and are assembled later, so that virtually any length can be supplied. During fabrication they are first cut to length, and the thermocouple wires welded at one end. The sheath is laser welded at the same end. At the other end, a short length of the sheath is removed and the thermocouple wires are either exposed as connection tails or fitted with a plug or a stranded copper connecting cable. This end of the cable is also sealed with an epoxy resin to prevent moisture ingress and the consequent reduction in insulation resistance. Thermocouples made in this way have numerous advantages: thin flexible versions with outside diameters down to 0.5mm can be produced, they are highly resistant to shock and vibration, and have a fast response (because of their small size). Compensating cables are not required as the mineral-insulated thermocouple itself is used as the (high-temperature!) compensating cable. They are only made from base metal thermocouple materials, as the noble metal materials are not sufficiently ductile and would break during the drawing process. The characteristics of the mineral-insulated thermocouples correspond to the applicable standards.

Because of the small distance between the thermocouple wires and the probe tube however, it is important to remember that the insulation resistance decreases rapidly at higher temperatures. The maximum operating temperature depends on the diameter of the mineral-insulated thermocouple; here again, thicker cables have higher temperature limits. Fig. 21 shows this relationship for the continuous operating temperatures of two types of thermocouple (figures taken from manufacturer's data).

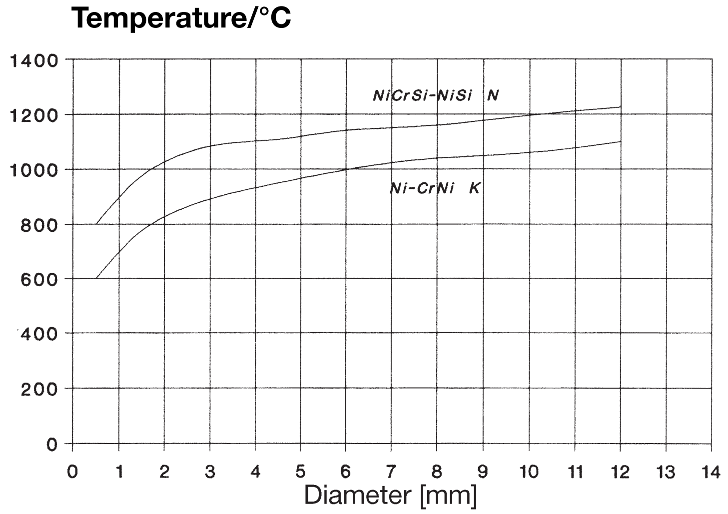


Fig. 21: Maximum temperatures for mineral-insulated thermocouples

Of particular importance with mineral-insulated thermocouples is the fact that because the sheath and the thermocouple wires are rigidly coupled, they are subjected to higher mechanical stresses due to differences in expansion coefficients. This leads to an increased drift.

Furthermore, because the thermocouple wires and the sheath material are so close together, the thermocouple can easily be contaminated by the sheath material. **Körtvelessy** [1] showed that the presence in the fill material of oxygen in the form of air, water or carbon dioxide was responsible for this effect; the oxygen provides a transport medium for an equalization of the sulfur and carbon concentrations in the sheath and thermocouple materials, and thus changes the composition of the materials.

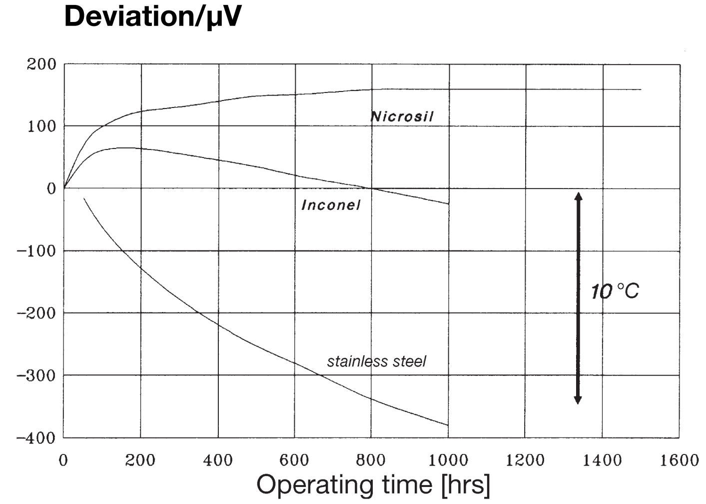


Fig. 22: Drift in relation to sheath material (according to [18])

The extent to which the drift of a mineral-insulated thermocouple is dependent on the materials used is shown, for example, by the results of a test [18] on a Type N thermocouple with a diameter of 3 mm, sheathed with different materials.

Efforts are therefore made to select the sheath material so that its properties are as similar as possible to the thermocouple material. For Type N thermocouples, for example, the manufacturer recommends a nicrosil sheath, a material with a composition that matches the positive leg of the thermocouple.

This type of thermocouple is best installed and secured using compression glands which permit free installation of the probe tube. As an alternative to this, they can be mounted directly on the measurement object or secured with clips. As they cannot be shortened, any surplus length is coiled up.

Mineral-insulated thermocouples are also used in conventional measurement inserts to DIN standard, and are assembled with a protection tube and terminal head to form a complete thermocouple. The manufacturing process involved is often more economical than the use of conventional thermocouples.

3.11 Troubleshooting

Listed here are a number of possible mistakes that can be made when installing a thermocouple, and their effects. Of course, the malfunctions described may be due to other causes. One of the most common mistakes is forgetting about or selecting the wrong compensating cable, a point that is worth mentioning again here.

A thermocouple can be checked for continuity with a simple continuity tester or ohmmeter. The thermocouple resistance should only be a few milliohms. However, the resistance of the compensating cable can easily reach several ohms, especially with thermocouples containing constantan (Fe-Con, Cu-Con, NiCr-Con), because constantan is a poor conductor that is also used for the manufacture of wire-wound resistors. So a loop resistance of several ohms, measured at the terminals of the indicating instrument or the controller, does not always indicate an unusually high contact resistance. Table 14 below gives the resistance of the outgoing and return lines for various compensating or thermocouple cables:

Compensating cable	**Cross-section** (mm^2)	**Resistance** (ohms/meter)
Fe-Con	2x 0.25 2x 0.75	2.5 0.9
NiCr-Ni	2x 0.25 2x 0.75	4.0 1.5
PtRh-Pt	2x 0.25 2x 0.75	0.4 0.15
Copper cable	2x 0.25 2x 0.75	0.14 0.05

Table 14: Resistances of compensating cables and thermocouple cables

The easiest way to simulate a thermocouple is with a millivolt calibration unit connected directly to the indicating instrument. The values given in the standard voltage tables (see Chapter 3.5.1) are set and the indicated values checked against the corresponding temperatures. This is the quickest way to establish whether the right linearization setting and range have been selected. As a quick test, the insulation can be stripped off a short length of compensating cable, the cores twisted together at one end, and the other end connected to the indicating instrument. The twisted cores form a thermocouple that can then be used to check the basic operation of the instrument by warming the junction.

3.11.1 Possible connection errors and their effects:

- *Indicating instrument shows room temperature:*
  thermocouple or cable open-circuit.
- *Indicated value is correct but has negative sign:*
  reversed polarity at the indicating instrument.
- *Indicated temperature clearly too high; indicated value drifts:*
  a) reversed polarity of the compensating cable in the terminal head (when the cable is crossed, two additional thermocouples are formed).
  b) wrong compensating cable (see below).
- *Indicated value clearly too high or too low:*
  a) wrong linearization in the indicating instrument.
  b) wrong compensating cable used or connected reverse polarity (see below).
- *Indicated value too high or too low by a fixed amount:*
  incorrect reference junction temperature.
- *Indicated value correct, but drifts slowly:*
  reference junction temperature not constant or not measured.
- *Indicated value wrong by about 20 to 25°C:*
  Type L thermocouple linearized as a Type J or vice versa.
- *A value is still indicated when one leg of the thermocouple is disconnected:*
  a) electromagnetic interference is being coupled into the input line.
  b) parasitic voltages are being introduced due to the furnace insulation, for example, because of the absence of electrical isolation or defective insulation.
- *A high value is indicated even when both thermocouple legs are disconnected:*
  a) electromagnetic interference is being coupled into the input line.
  b) parasitic galvanic voltages, due, for example, to damp insulation in the compensating cable.

Thermocouple	Compensating cable	Polarity	Error °C	Measured temperature °C
Fe-Con	Fe-Con	correct	-	600
		wrong	- 173 to -163	
	NiCr-Ni	correct	- 41 to - 36	
		wrong	- 155 to -163	
	PtRh-Pt	correct	- 88 to - 78	
		wrong	- 107 to - 97	
NiCr-Ni	Fe-Con	correct	- 2 to + 14	1000
		wrong	- 218 to -202	
	NiCr-Ni	correct	- 7.5 to - 7.5	
		wrong	- 191 to -175	
	PtRh-Pt	correct	- 98 to - 82	
		wrong	- 125 to -104	
PtRh-Pt	Fe-Con	correct	+ 300 to +314	1200
		wrong	- 440 to -462	
	NiCr-Ni	correct	+ 214 to +228	
		wrong	- 347 to -333	
	PtRh-Pt	correct	-	
		wrong	- 105 to - 91	

according to [24]

Table 15: Indication errors when the wrong compensating cables are used

4.1 The variation of resistance with temperature

The electrical conductivity of a metal depends on the mobility of the conduction electrons or electron gas. If a voltage is applied to the ends of a metal, the electrons move to the positive pole. Imperfections in the metal's crystal structure interfere with this movement. These imperfections include foreign or missing lattice atoms, grain boundaries and atoms in the interstices. Because these dislocations are not temperature-dependent, they produce a constant resistance. As the temperature rises, the oscillation of the atoms of the metal lattice about their rest position increases, which restricts the movement of the conducting electrons. As the oscillation increases linearly with temperature, then, as a first approximation, the resulting increase in resistance is directly proportional to temperature. This is referred to as a positive temperature coefficient, a PTC resistor.

To be able to use this effect for temperature measurement, a high temperature coefficient, i.e. the greatest possible change in resistance with temperature, is the ideal. On the other hand, if at all possible, the characteristic properties must not change much over a long period of time. Furthermore, the temperature coefficient must be as independent of temperature and pressure as possible, and not be influenced by chemical effects.

In general, the relationship between the temperature and the electrical resistance is not directly proportional, but is described by a higher-order polynomial:

Formula 14:

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

The resistance R_0 represents the nominal resistance and is determined at a temperature still to be decided. The higher-order terms (T^2, T^3, etc.) are taken into account depending on the accuracy of the measurement. The coefficients A, B, etc. depend on the resistance material, and clearly define the temperature/resistance relationship.

4.2 Platinum resistors

Platinum is now widely used as a resistance material in industrial measurement. Its advantages include the high chemical resistance, comparatively easy workability (particularly for wire manufacture), its availability in highly refined form, and the good reproducibility of the electrical properties. These properties are fully specified in the European standard EN 60 751, so that the platinum resistance sensor is universally interchangeable to an extent unmatched by hardly any other temperature sensor.

These specifications include the variation of resistance with temperature, which is laid down in a reference table of standard values, and the nominal value along with the associated reference temperature and permissible deviation limits. The temperature range is also specified in the standard, extending from -200 to 850°C. Two distinct temperature ranges are covered in the tables of standard values:

-200°C to 0°C
0°C to 850°C

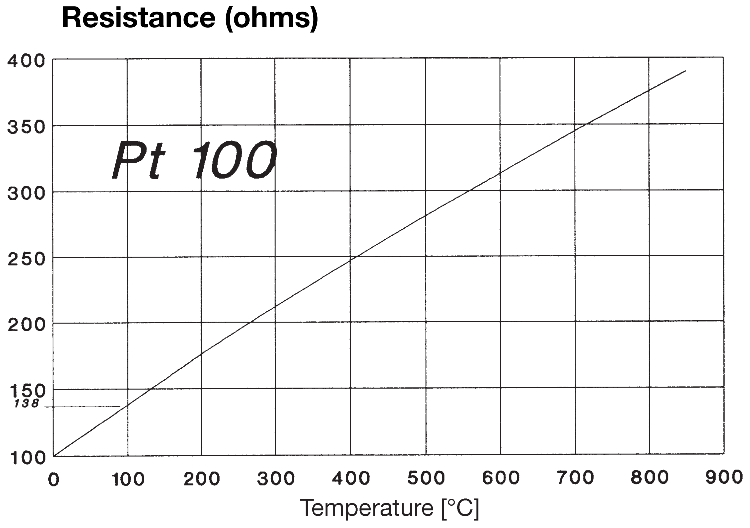


Fig. 23: Characteristic of a Pt 100 temperature sensor

A third-order polynomial covers the temperature range -200 to 0°C:

Formula 15:

$$R(T) = R_0 (1 + A \cdot T + B \cdot T^2 + C \cdot [T - 100°C] \cdot T^3)$$

The temperature range 0 to 850°C is covered by a second-order polynomial:

Formula 16:

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

The coefficients have the following values:

$A = 3.90802 \cdot 10^{-3} \cdot °C^{-1}$

$B = - 5.775 \cdot 10^{-7} \cdot °C^{-2}$

$C = - 4.2735 \cdot 10^{-12} \cdot °C^{-4}$

The value R_0 is designated the nominal value or nominal resistance and is the resistance at 0°C. EN 60 751 defines the nominal value as 100 Ω, and so we talk about the Pt 100 resistor. Multiples of this value are also permissible, and so 500 Ω and 1000 Ω resistance sensors are also available. Their advantage is higher sensitivity, i.e. a greater change in resistance with temperature (Pt 100: approx. 0.4 Ω/°C; Pt 500: approx. 2.0 Ω/°C; Pt 1000: 4.0 Ω/°C).

The standard also defines a Pt 10 resistor that is rarely used, however, because of its low sensitivity. The operating temperature range of the Pt 10 is above 600°C. Smaller nominal values (for example: 25 Ω, 10 Ω, 5 Ω, or 0.25 Ω) are found mainly in precision thermometers, which must then fulfil the requirements of ITS 90 and which must be used where measurements demand a very low measurement uncertainty. These thermometers cannot be used in industry because of the fineness of the wire used, and their delicate construction.

The standard also defines an additional parameter, a mean temperature coefficient between 0°C and 100°C. This specifies the mean resistance change referred to the nominal value at 0°C:

Formula 17:

$$\alpha = \frac{R_{100} - R_0}{R_0 \cdot 100}$$

where R_0 = resistance at 0°C, R_{100} = resistance at 100°C and 100 = temperature difference of 100°C.

The value of α for spectroscopically pure platinum is $3.925 \cdot 10^{-3}$ per °C. Consequently, with platinum resistance sensors to EN 60 751, the temperature coefficient deviates from this value. The platinum used here is deliberately contaminated with foreign materials. The purpose of this is to ensure that the platinum absorbs less contaminants from its surroundings both during manufacture and subsequent use above 400°C, in order to maintain higher long-term stability.

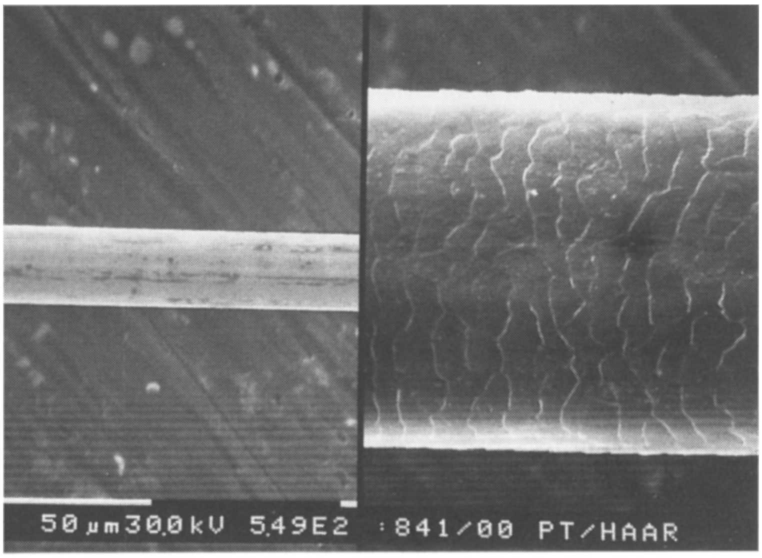


Fig. 24: A platinum wire (left) compared with a human hair (right)

This long-term stability is more than adequate for industrial applications. However, even small diffusion effects can become vitally important with precision thermometers, whose stability is of the order of less than 0.001°C. Because of this, relatively thick wires up to 0.25mm diameter are used with precision thermometers. To keep the size of the temperature sensor down, nominal values of 25 or 10Ω are used for such precision instruments in the range above 600°C. Wires with a diameter of less than 30 µm are used in sensors manufactured using normal industrial techniques. (In comparison, the thickness of a human hair is approx. 100 µm).

4.2.1 Calculating the temperature from the resistance

When used as a thermometer, the sensor resistance is used to determine the corresponding temperature. However, the formulae above only indicate the variation of resistance with temperature, not the determination of the temperature from the measured resistance. For temperatures above 0°C, the temperature can be calculated from the resistance using an explicit formula to describe the characteristic according to EN 60 751.

Formula 18:

$$t = \frac{-R_0 \cdot A + \sqrt{(R \cdot A)^2 - 4 \cdot B \cdot (R_0 - R)}}{2 \cdot R_0 \cdot B}$$

R = measured resistance in ohms
t = calculated temperature in °C
R_0, A, B = parameters according to IEC 60 751

It is not possible to derive an explicit formula for the fixed inverse function for temperatures below 0°C. A numerical approximation method is required to obtain the temperature that corresponds to a measured resistance. **Newton's** approximation method is adequate with regard to the required accuracy. Beginning with a random start value t_0, the subsequent iteration values are calculated in accordance with the following formula:

Formula 19:

$$t_{i+1} = t_i - \frac{R(t_i) - R}{R'(t_i)} = t_i - \frac{R_0 \cdot (1 + A \cdot t + B \cdot t^2 + C \cdot (t - 100\ °C) \cdot t^3) - R}{R_0 \cdot (A + 2 \cdot B \cdot t + C \cdot (3 \cdot t^2 \cdot (t - 100\ °C) + t^3))}$$

The iteration is terminated when two consecutive iteration results change by not more than the required accuracy.

Example:
measured value R = 87.648 Ω
start value t_0 = -5°C.

Iteration step	**T_i (°C)**	**R(t) (Ω)**	**R'(t) (Ω/°C)**	**t_{i+1} (°C)**	**Termination criterion (°C)**
0	-5.00	98.045	0.391	-82.66	
1	-82.66	67.257	0.402	-81.69	0.9728
2	-81.69	67.648	0.402	-81.69	0.0002
3	-81.69	67.648	0.402	-81.69	0.0000

Table 16: Example showing completion of the iteration method

The example shows that the temperature is already determined to within 0.01°C after the first iteration step.

Of course, the temperature can also be determined from the table of standard values. Intermediate values not given in the table are calculated by linear interpolation: to calculate the temperature t corresponding to a resistance R, two adjacent pairs of temperature-resistance values above and below the required value are considered:

Formula 20:

$$t = t_1 + \frac{t_2 - t_1}{R_2 - R_1} \cdot (R - R_1)$$

Example:
The temperature corresponding to a resistance of 129.53 Ω is to be calculated.

Interval from the reference tables: $R_1 = 129.37\,\Omega$ $t_1 = 76\,°C$
$R_2 = 129.75\,\Omega$ $t_2 = 77\,°C$

Formula 21:

$$t = 76\ °C + \frac{1\ °C}{129.75\ \Omega - 1239.37\ \Omega} \cdot (129.53 - 129.37) = 76.42\ °C$$

4.2.2 Deviation limits

EN 60 751 defines two different tolerance classes:
Class A: $\Delta t = \pm(0.15 + 0.002 \cdot t)$
Class B: $\Delta t = \pm(0.30 + 0.005 \cdot t)$
t = temperature in °C (without sign)

Class A applies to temperatures ranging from -200 °C to +650 °C, and only for thermometers using a 3-wire or 4-wire circuit. Class B applies to the entire definition range from -200 °C to +850 °C.

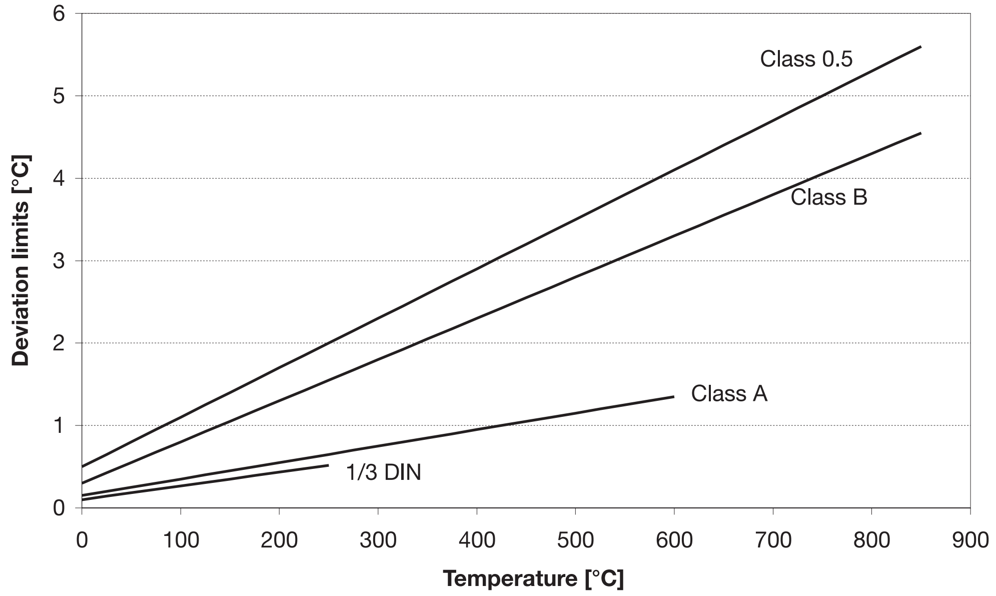


Fig. 25: Deviation limits for the Pt 100

Example:
The measurement tolerance at a temperature of 200 °C is required for a Pt 100 Class B resistance sensor:

$t = \pm(0.30 + 0.005 \cdot 200)\,°C,$
$= \pm(0.30 + 1)\,°C,$
$= \pm 1.3\,°C.$

4.2.3 Extended tolerance classes

The tolerance classes specified in the standard are frequently inadequate, since the demands for measurement accuracy are also steadily increasing because of increased requirements for production quality. As a result, an agreement between customers and sensor manufacturers created a new tolerance class with closer tolerances compared to Class B. Quite the opposite applies in some cases, where the extended tolerance classes are adequate for the user, and are attractive for many applications on cost grounds. It should be emphasized here that even sensors with increased tolerances lose none of the excellent properties of the platinum resistance sensor. The long-term stability and reproducibility of the characteristic, and the interchangeability of the sensors are fully maintained. As well as the two standard tolerance classes, JUMO has defined additional tolerance classes, and can now offer the user a choice of sensors with lower or higher accuracy, to be matched to the particular application.

Tolerance class	Applicable range	Tolerance in °C	Tolerance	
			at t = 0°C	at t = 100°C
1/3 Class B	- 70 to +250°C	±(0.10°C + 0.0017 x ltl)	±0.10°C	±0.27°C
Class A	-200 to +600°C	±(0.15°C + 0.0020 x ltl)	±0.15°C	±0.35°C
Class B	-200 to +850°C	±(0.30°C + 0.0050 x ltl)	±0.30°C	±0.80°C
Class 0.5	-200 to +850°C	±(0.50°C + 0.0060 x ltl)	±0.50°C	±1.10°C

Table 17: Resistance thermometer tolerance classes

The restricted tolerance class 1/3 Class B is based on the Class B standard, with the limits divided by three. It should be noted that the applicable range for this tolerance class is generally specified as from -70°C to +250°C. This restriction is necessary because both the nominal value and the line of the characteristic of sensors are subject to fluctuations caused by the manufacturing process. To classify the sensors into the individual classes, the required measurements are made over a temperature range from 0°C to 100°C. Because only two measurement points are generally used, the variation of the second order function cannot be calculated. In addition, the measurement uncertainty of the measurement increases due to the extrapolation of the temperature range, so that the applicable range is restricted when using the 1/3 Class B. It should be noted here that the functional temperature range of a sensor or a temperature probe assembly is not affected by this; it merely means that the restricted tolerances are not valid above the applicable range, and no guarantee can be given that the tolerances will be maintained if the limits are infringed.

4.3 Nickel resistors

As well as platinum, nickel is also used as a resistance material, but to a much lesser extent. Compared to platinum, nickel has a significant price advantage, and its temperature coefficient is almost double ($6.18 \cdot 10^{-3}$ per °C). However, the measuring range only extends from -60°C to +250°C, as a phase transformation takes place above 350°C. The nickel resistance sensor is much less widespread than the platinum sensor. Its characteristics are laid down in DIN 43 760 (no longer valid); the relationship between resistance and temperature is given by:

Formula 22:

$$R(t) = R_0(1 + A \cdot t + B \cdot t^2 + C \cdot t^4 + D \cdot t^6)$$

The coefficient values are:

$A = 0.5485 \cdot 10^{-2} \cdot °C^{-1}$

$B = 0.665 \cdot 10^{-5} \cdot °C^{-2}$

The nominal value at 0°C is 100Ω.

$C = 2.805 \cdot 10^{-11} \cdot °C^{-4}$

$D = 2.111 \cdot 10^{-17} \cdot °C^{-6}$

As well as the characteristic according to DIN 43 760, there are also other manufacturer-specific characteristics on the market.

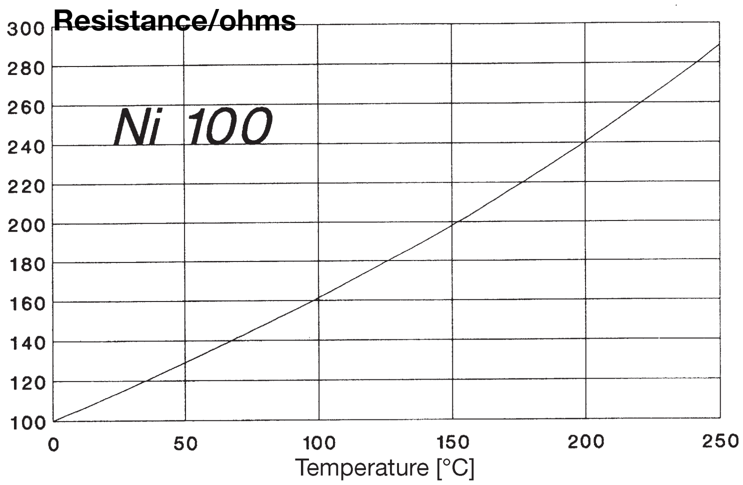


Fig. 26: Characteristic of the Ni 100 according to DIN 43 760

4.3.1 Deviation limits

The deviation limits for the nickel resistance are defined as follows:

$\Delta t = \pm(0.4 + 0.007 \cdot t)$ for 0°C to 250°C,
$\Delta t = \pm(0.4 + 0.028 \cdot t)$ for -60°C to 0°C,
t = temperature in °C (without sign).

Establishing these tolerance classes offers the same advantages as with the Pt 100 sensor: a sensor can be replaced by another at any time, without the need for recalibration. The Ni 100 sensors are frequently used in the HVAC field.

4.4 Connection of resistance thermometers

With resistance thermometers, the electrical resistance varies with temperature. The output signal is obtained by passing a constant measurement current through the resistance and measuring the voltage drop across it. This voltage drop is given by Ohm's law:

Formula 23:

$$V = R \cdot I$$

The smallest possible measurement current should be selected (see also Chapter 4.7.3), to avoid heating of the sensor. A measurement current of 1 mA can be assumed to have no significant effect. This current produces a voltage drop of 0.1 V with a Pt 100 resistance at 0 °C. The signal voltage must now be transmitted via the connecting cable to the indication or evaluation point with as small an error as possible. There are four different connection methods here:

4.4.1 2-wire arrangement

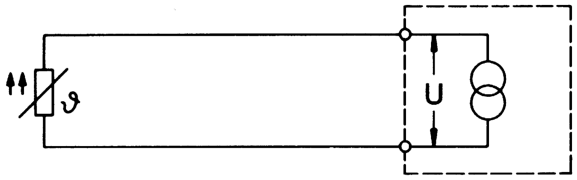


Fig. 27: 2-wire circuit

The connection between the thermometer and the evaluation electronics is made with a 2-core cable. Like any other electrical conductor, this also has a resistance, which is connected in series with the resistance thermometer. As a result, the two resistances add together, so that the system indicates a higher temperature. With longer distances, the cable resistance can amount to several ohms, and may introduce significant errors into the measured value.

Example:

Conductor cross-section:	0.5 mm^2,
Conductor material:	copper,
Resistivity:	0.17 Ω mm^2 per m,
Cable length:	100 m, conductor length is twice the cable length (loop), e.g. 200 m.

Formula 24:

$$R = 0.17\ \Omega\ mm^2 m^{-1} \cdot \frac{2 \cdot 100\ m}{0.5\ mm^2} = 0.68\ \Omega$$

With a Pt 100, 6.8 ohms corresponds to a temperature increase of 1.7 °C. To avoid this error, the lead resistance is compensated electrically: the input circuit of this type of instrument always assumes a lead resistance of 10 ohms. When the resistance thermometer is connected, a compensating resistance is inserted in one of the measuring leads and the sensor is initially replaced by a 100.00 ohms resistor. The compensating resistance is then altered until the instrument indicates 0 °C. The compensating resistance combined with the lead resistance is then 10 ohms. Because of this comparatively expensive compensating operation, and the fact that the effect of temperature on the measuring lead is not detected, the 2-wire circuit is being used less and less.

The following table lists the resistance of a 10m long copper connecting cable (outgoing and return leads).

Conductor cross-section (mm^2)	0.14	0.22	0.5	0.75	1.5
R_{Cond} (Ω)	2.55	1.62	0.71	0.48	0.24

Table 18: Resistance of a 10m long copper connecting cable relative to the conductor cross-section

4.4.2 3-wire arrangement

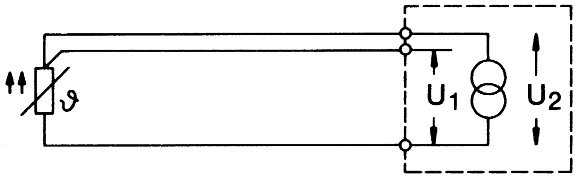


Fig. 28: 3-wire circuit

To minimize the effects of the lead resistances and their fluctuations with temperature, a 3-wire circuit is normally used instead of the 2-wire circuit described above, whereby an additional lead is run to one terminal of the resistance thermometer. As a result, two measuring circuits are formed, one of which is used as a reference. With the 3-wire circuit, it is possible to compensate for both the value of lead resistance and its variation with temperature. However. an essential requirement is that all three conductors have identical properties, and are exposed to the same temperature. Because these requirements are usually satisfied to an adequate level of accuracy, the 3-wire circuit is the most widely used method today. No adjustable lead compensation is required.

4.4.3 4-wire arrangement

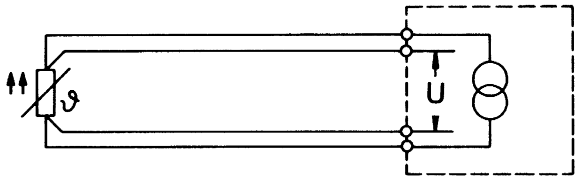


Fig. 29: 4-wire circuit

The 4-wire circuit is the optimal connection method for resistance thermometers. The measurement result is not affected by either the lead resistances or their variation with temperature. No lead compensation is required.

The measuring current is fed to the thermometer via the supply leads. The voltage drop at the resistance sensor is picked up via the measuring leads. If the input impedance of the connected electronics is many times higher than the lead resistance, the lead resistance can be neglected. The voltage drop determined in this way is thus independent of the properties of the connecting leads.

It should be noted that with both the 3-wire and 4-wire circuits, the circuit is not always run all the way to the sensing element. The connection from the sensor to the terminal head in the fitting, referred to as the internal connection, is often run as a 2-wire circuit. As a result, the same problems are encountered with this connection - although to a much lesser degree - as those described for the 2-wire circuit. The total resistance, given by the sum of the resistance of the internal connection and the resistance sensor, is then designated as the thermometer resistance, in accordance with DIN 16 160.

4.4.4 2-wire transmitter

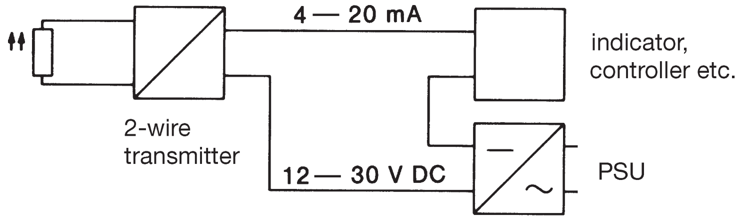


Fig. 30: 2-wire transmitter

2-wire transmitters are used to get round the problems described for the 2-wire arrangement and, at the same time, avoid the need for multicore cables. The transmitter converts the sensor signal to a normalized 4 — 20 mA current signal, directly proportional to temperature. The transmitter is also supplied via the two connections, and the quiescent current here is 4 mA. Because of the elevated zero, this arrangement is also referred to as “live” zero. Another advantage of the 2-wire transmitter is that, since the signal is amplified, the circuit is much less sensitive to interference. There are two arrangements for positioning the transmitter. Because the circuit carrying the unamplified signal must be kept as short as possible, to reduce the susceptibility of the signal to interference, the transmitter can be mounted directly in the terminal head of the thermometer. Although this is the optimal solution, it may not always be possible because of design constraints, or the fact that in some cases the transmitter might be difficult to access in the event of a fault. In such cases, a DIN-rail mounting transmitter is used, installed in the control cabinet. However, the advantage of improved access here is achieved at a cost, as the circuit carrying the unamplified signal must cover a longer distance.

2-wire transmitters are made for both resistance thermometers and thermocouples.

4.5 Construction

The construction of platinum sensors varies according to the area of use; basically there is a distinction between wire-wound and thin-film resistors. Whereas thin-film resistors invariably consist of a layer of platinum on a ceramic substrate, with wire-wound resistors the wire coil can either be fused into glass or embedded in powder. Unprotected, self-supporting coils are also possible, but they are only used in precision instruments for laboratory applications, because of their susceptibility to mechanical damage.

4.5.1 Ceramic resistance sensors

Here a platinum coil is fitted into two bores of a ceramic rod. The bores are filled with aluminum oxide powder to secure the winding and to improve heat transfer. A glass bead at each end seals the bores and secures the connecting wires. The diameter of these resistance sensors varies from 0.9 to 4.5 mm, with lengths from 7 to 30 mm. Ceramic resistors are used in the temperature range from -200 °C to +800 °C.

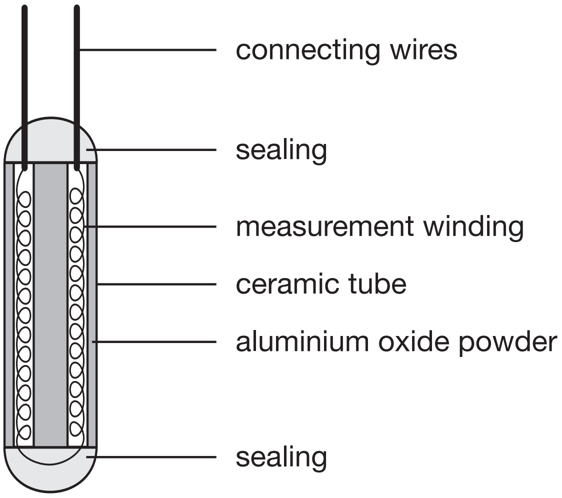


Fig. 31: Simplified construction of a Pt 100 wire-wound ceramic sensor

The type of internal construction chosen ensures that there is no firm contact between the Al_2O_3 powder and the platinum wire. So the platinum coil can expand freely during temperature changes, and is only lightly loaded. As a result, the sensor has a very high long-term stability. Tests on mineral-insulated resistance thermometers with this type of wire-wound resistance sensor show a stability value of better than 0.01 °C over a temperature range from 0 °C to 200°C, and better than 0.025 °C when used in temperatures up to 400 °C. It should be mentioned here that when this type of thermometer is used, they must be recalibrated at least once a year [17].

4.5.2 Glass resistance sensors

In this construction, two platinum wires are double-wound on a glass rod, fused into the glass and fitted with connecting wires. After the wire winding has been adjusted to the nominal value, an outer sleeve is forced over the glass rod and the two components fused together. This provides a hermetic seal for the platinum wire. Because the wire is completely surrounded by glass, these sensors are extremely resistant to shock and vibration. The wire used has a diameter between 17 µm and 30 µm. The length of the resistance sensor is between 7 and 55 mm, with diameters ranging from 0.9 to 4.8 mm.

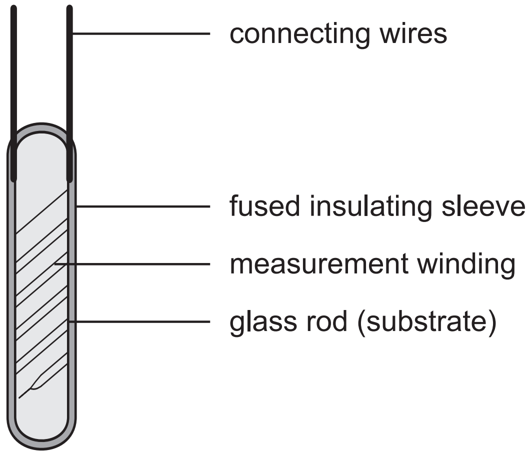


Fig. 32: Simplified construction of a Pt 100 wire-wound glass sensor

Glass resistors are used in a temperature range from -200°C to 400°C. The advantage of this construction is that the sensor can be inserted directly in the measuring medium and does not necessarily need an external protection tube. As a result, the thermometer has short response times. The shock resistance of the glass resistor is higher than that of a ceramic resistor.

Special versions of these sensors are made with a glass extension, resulting in a thermometer with a high chemical resistance, a type preferred for chemistry applications (laboratory). The sensor can also be directly inserted in aggressive media without the use of a pocket that would impair heat transfer. Excellent response times are achieved.

As well as the simple glass resistor, there is another type, the twin Pt 100, which is double-wound with two adjacent windings. This type of sensor is used where two separate measuring circuits measure the temperature at the same point. Another application is to build redundancy into a system, where the second winding can simply be used in the event of a fault, without having to replace the sensor.

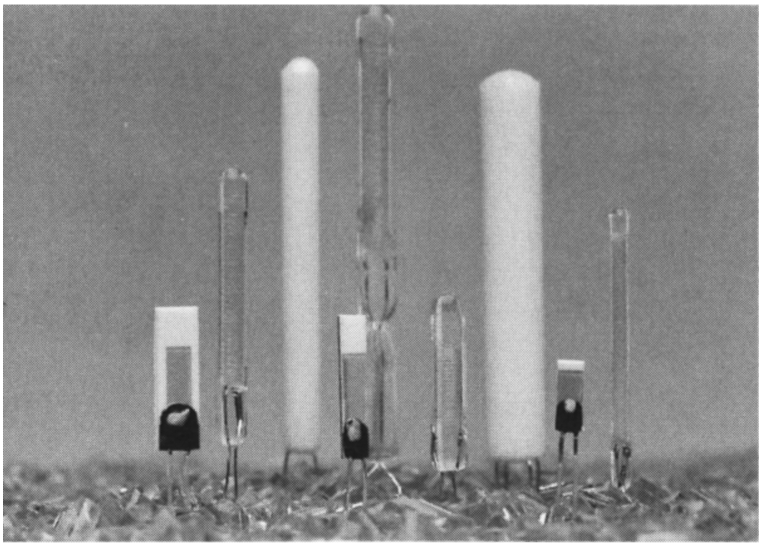


Fig. 33: Glass, ceramic and chip resistance sensors

4.5.3 Foil sensors

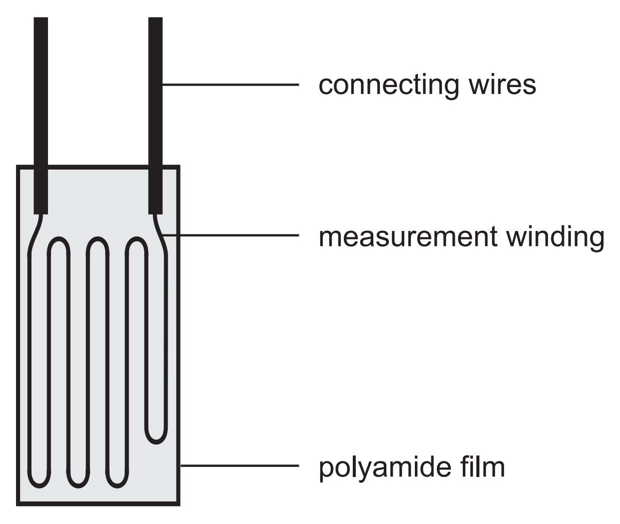


Fig. 34: Simplified construction of a Pt 100 wire-wound foil sensor

A platinum resistance wire about 30 µm diameter is embedded in an adhesive compound between two polyamide films. Because of the sensor's flat construction - it is only about 0.17 mm thick - and high flexibility, it is used for surface measurements on pipes, and is also embedded in transformer windings. The temperature range extends from -80 °C to 230 °C.

4.5.4 Thin-film sensors

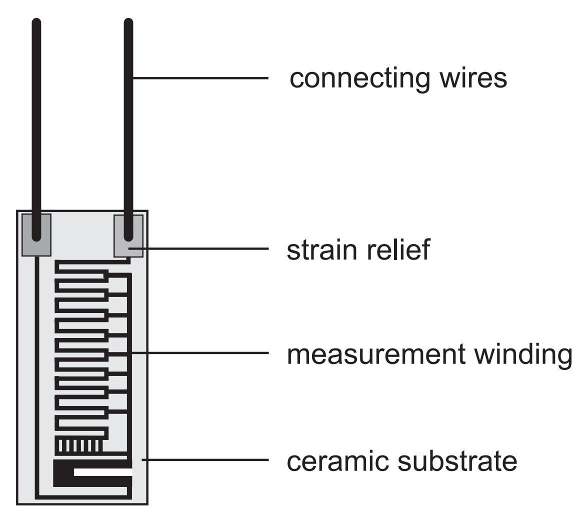


Fig. 35: Simplified construction of a Pt 100 thin-film sensor

Thin-film sensors are produced using methods originally developed in the semiconductor industry. A platinum film about 0.5 to 1 µm thick is either sputtered or evaporated onto an aluminum oxide substrate. The platinum film is then structured to form a serpentine resistance track, using either a lithographic process or a laser beam, and calibrated by means of a laser. A glass layer about 10 to 15 mm thick is then applied to protect the platinum. Connecting wires are welded on, to establish the electrical connection to the resistance track, and also secured by a glass bead. Depending on the type of construction, operating temperatures are between -50 °C and +400(600) °C.

A wide range of styles is available on the market, from which the user can select a suitable sensor. The standard forms are shown in Fig. 36:

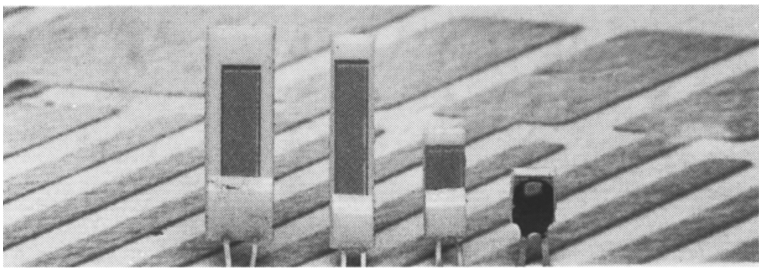


Fig. 36: Various forms of chip resistance sensors

The compact style in 2.5 and 5mm lengths is produced as Pt 100 and also as Pt 500 and Pt 1000 thin-film resistance sensors.

Features shared by all thin-film sensors are the fast response (less than 1 sec in water) and low thermal mass, as a result of which they have a negligible effect on the environment being measured.

The thin-film resistance sensor combines the positive properties of a platinum resistance sensor, such as interchangeability, long-term stability, reproducibility and wide temperature range, with the advantages of large-scale production.

On the other hand, production of the various types of wire-wound sensors described above always involves considerable manual labour, and this is reflected in the price. These higher costs of the platinum sensor are the main reason why, despite its clear advantages, it is not widely used in the automotive industry, air conditioning or domestic appliance fields.

4.6 Long-term behavior of resistance thermometers

One very important consideration when using temperature probes concerns their long-term stability. The accuracy of a probe must be maintained during the whole of its service life, to ensure that the desired indication accuracy is achieved at all times.

Conditions of use and constructional aspects greatly affect the stability. Sweeping statements such as approx. 0.05% per year are not very informative if no information about environmental conditions (stress) is provided. If a probe is subjected to a cyclic temperature stress between the upper and lower temperature limits, the probe components are affected much more than when they are subjected to a continuous stress. Ceramic sensors, in which the wire winding is embedded in a powder leading to only a weak mechanical coupling, have a very high long-term stability even when subjected to temperature change stresses. The resistance wire can expand freely relative to the other materials. Mechanical stresses that would generate a change in the crystal structure and hence in the electrical resistance are eliminated. Stability tests on wire-wound ceramic sensors over a temperature range from -196°C to +600°C show stability values of around 0.1°C [17].

Over the same period, stress tests were carried out on versions designed for applications above 600°C, over a range from -196°C to +900°C. These tests showed a stability value of 0.2°C, as much as double the nominal value.

With glass sensors, the platinum wire is enclosed in glass. The wire is more highly stressed because of the rigid mechanical coupling and the different expansion coefficients of glass and platinum. During manufacture of the sensor, care must be taken to ensure that the thermal expansion coefficients of the glass used match those of the platinum, as closely as possible. In spite of this, mechanical stresses that cause a long-term drift are still introduced at the manufacturing stage. The sensor is therefore stabilized by means of an artificial ageing process.

Another effect that is heavily dependent on the stress limits of the sensor is the hysteresis. This is defined as the reversible change in value of the nominal resistance R_0, which depends on whether the previous stress occurred in the positive or negative temperature range. A test with Pt 100 glass sensors showed a hysteresis of 0.1°C, when the applied temperature varied between -196°C and +300°C.

As is the case with glass sensors, in thin-film sensors too there is a close mechanical coupling between the temperature-sensitive platinum film and the underlying ceramic substrate. If the expansion coefficients of the two materials are not fully matched to each other, the ceramic forces its movement on to the platinum film (approx. 1mm thick). This results in changes of the crystal structure and changes in resistance linked to this. Because the expansion coefficient itself is temperature-dependent, it is very difficult to achieve synchronized movement of substrate and platinum film over the whole temperature range of the sensor. Today, as a result of intensive research and development, thin-film sensors have very good long-term stability. Specific applications up to 150°C have shown that the nominal value changed by 0.15 to 0.20°C after five years use.

This is an appropriate point to note that a thermometer's long-term stability does not depend solely on the quality of the temperature sensor used, but also on the other components such as insulation material, jointing techniques, connecting lead materials etc.

4.7 Errors in resistance thermometers

4.7.1 Effect of the cable

In measurements with resistance thermometers, incorrect measurement results may be obtained because of the effects of system design or the actual method of measurement. The most important effects that can lead to incorrect measurements are explained below:

As described earlier, the lead resistance appears in the measuring circuit as a resistance in series with the sensor. The lead resistance can be of the same order as the resistance sensor, particularly in larger installations involving long cable routes. Compensation of the lead resistance is therefore absolutely essential, and usually consists of shifting the zero of the connected instrument. This type of compensation, however, does not take account of changes in lead resistance caused by temperature. If the connecting cable is subjected to changing temperatures, this results in measurement errors that may or may not be significant. However, this effect only really comes to light with higher lead resistances, i.e. long runs of cables with small cross-sections.

Copper has almost the same temperature coefficient as platinum. Because of this, the measurement error incurred in a 2-wire measuring circuit due to the effect of temperature can be easily estimated.
It corresponds to the percentage proportion of the resistance of the sensor multiplied by the temperature fluctuations that the probe cable is exposed to.

Example: What is the measurement error caused by temperature for a Pt 100 in a 2-wire circuit with a copper cable 20m long, if the cable is exposed to temperature fluctuations from -20°C to +60°C?

The lead resistance is 8.12 Ω. This corresponds to 6.8% of the resistance of the Pt 100 at 50°C. The measuring cable is exposed to a temperature difference of 80°C; the measurement error caused by this is approx. 0.068 x 80°C = 5.46°C. For simplicity, this assumes that the temperature coefficients of platinum and copper are the same, and is based on the resistance of the Pt 100 at 50°C. However, the errors caused by these assumptions are so small that this simple method is ideally suited for estimating the expected measurement error with a 2-wire arrangement.

4.7.2 Inadequate insulation resistance

Further measurement errors can occur with poor insulation material due to a finite insulation resistance in the cables, or in the insulation material in which the sensor and its connecting wires are embedded. The temperature indicated is then too low. Based on a Pt 100 thermometer, an insulation resistance of 100kΩ causes an indication error of 0.25°C, or 1°C per 25kΩ. Because the insulation resistance is temperature-dependent, the error it causes can vary with the measuring conditions. Particularly with ceramic insulation materials, the resistance drops as the temperature rises. As the maximum temperature is limited to approx. 600°C, the effect is scarcely noticeable with platinum resistance sensors. Moisture ingress into the insulation material has a considerably greater effect, and can lead to significant measurement errors. Special attention must always be paid to moisture in the sensor and also in the insulation material between the cores of the connecting cable; so the sensors are usually hermetically sealed by glazed coatings or some other sealing methods. The measuring insert itself is sealed in the same way, to prevent moisture ingress into the probe tube. Measuring inserts can be safely exchanged, as they form a sealed unit. On the other hand, when repairing probes without measuring inserts, it is absolutely essential to ensure a reliable seal after the repair.

4.7.3 Self-heating

To measure the output signal of a resistance thermometer, a current must be passed through the sensor. This measuring current generates a power loss and thus produces heat in the sensor. As a result, the indicated temperature is higher than it should be. This self-heating depends on a number of factors, one of which is the extent to which the power loss generated can be conducted away by the medium being measured. Because of the formula for electrical power, $P = R \cdot I^2$ the effect also depends on the basic value of the resistance sensor: with the same measurement current, the heat produced in a Pt 1000 resistance is ten times as large as in a Pt 100. As well as this, the measurement error caused by self-heating is also determined by design features together with the thermal conductivity, thermal capacity and physical size of the thermometer. The thermal capacity and the flow rate of the medium being measured also have an important influence on the effect. Thermometer manufacturers often quote a self-heat coefficient that is a measure of the temperature rise in the sensor due to a defined power loss. Calorimetric measurements like this are carried out under specified conditions (in water with a flow rate of 0.5m/sec, or in air with a flow rate of 2.0m/sec). However, these figures are of a rather theoretical nature, and are used as comparison values for different design variants.

In most cases, a measurement current of 1mA is specified by the instrument manufacturers, as this value has proved useful in practice. For a Pt 100 resistance sensor, this corresponds to a power loss of 0.1mW. As an example, if a Pt 100 resistance sensor is enclosed in a sealed, fully-insulated container containing 10cm^3 of air, then, with the specified measurement current of 1mA flowing, this will heat up the air by 39°C after one hour. With flowing gases or liquids, the effect is much less significant, because the amount of heat conducted away is many times greater.

So this small power loss can lead to errors in long-term measurements in dilute, motionless gases. In such cases, the self-heating must be measured on site under the actual operating conditions. To do this, the temperature is measured with various values of current I, with the pre-condition that the temperature of the medium being measured remains constant. The self-heat coefficient E is given by the following:

Formula 25:

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

where t = (indicated temperature) - (temperature of the medium)
R = resistance of the thermometer
I = measurement current

The self-heat coefficient can then be used again to determine the maximum measurement current if a measurement error t is permissible.

Formula 26:

$$I = (t/E \cdot R)^{1/2}$$

4.7.4 Parasitic thermoelectric emfs

The effect of thermoelectric emfs also occurs in temperature measurements with resistance thermometers, although in this case as a highly undesirable side effect. As described in Chapter 3.1, a thermoelectric emf is generated at the junction of two dissimilar metals. This type of transition between metals occurs at the connections in resistance thermometers, as the sensor often has silver connecting wires that are extended as an internal connection, for example, using copper or nickel.

Normally it can be assumed that both contact points are at the same temperature, and hence the resulting emfs cancel each other out. In fact, different temperatures may be present because of different rates of external heat dissipation; the evaluation electronics interprets the emf arising from this temperature difference as a voltage drop caused by a change in resistance, and arrives at an incorrect value. The value can be too high or too low depending on the sign of the emf that arises. The size of error this causes depends very much on the evaluation electronics, in particular on how a voltage is evaluated as a temperature. If a Pt 100 sensor is operated with a measurement current of 1 mA, a parasitic thermoelectric emf of 1 µV corresponds to 1 mΩ. In fact, with 20 µV an error of 20 mΩ is introduced, corresponding to a temperature value of approx. 0.05 °C, half the permissible tolerance of DIN Class 1/3 at 0 °C.

A simple method of diagnosing the measurement error caused by this type of parasitic thermoelectric emf is to take two measurements, with the measurement current flowing in opposite directions. The greater the difference between the two measured values, the greater is the emf generated in the measurement circuit.

If a temperature probe at temperature T_0 is introduced into a medium to be measured at temperature T_1, heat flows from the higher temperature region to the lower temperature region as a result of the temperature gradient. The driving force for the heat flow is the temperature difference itself. As the temperature alignment continues, the temperature difference and the resulting heat flow reduce. As a result, the temperature alignment rate also slows down. Because of the thermal resistance in the probe and its masses, the temperature indication will never react immediately to a step change in temperature or to continuous temperature changes - the reaction is always delayed. The measurement error caused by this as a result of the time lag of the measured value compared to the measured temperature is referred to as the dynamic error [16].

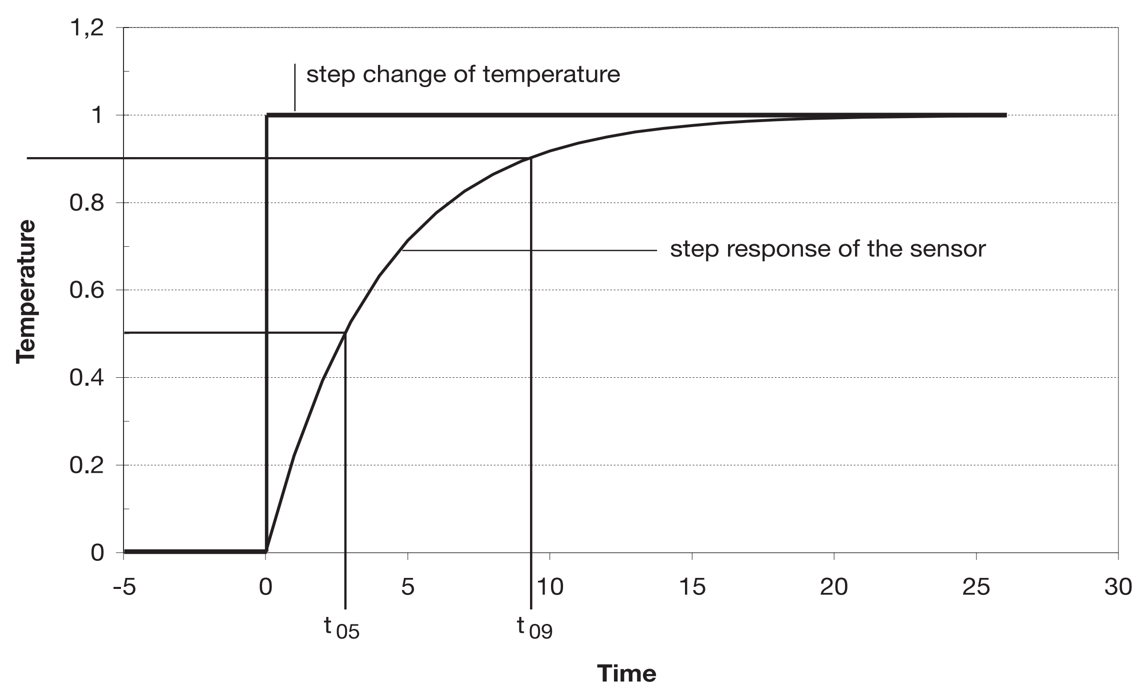


Fig. 37: The transfer function after a step change in temperature

As a simplification, the probe can be thought of as being made up of resistances and energy stores. Any insulation layers present constitute resistances, masses constitute energy stores. The components of the probe often have both properties at the same time:

In the case of a glass resistance sensor, for example, the glass body is both an energy store and a thermal resistance at the same time.

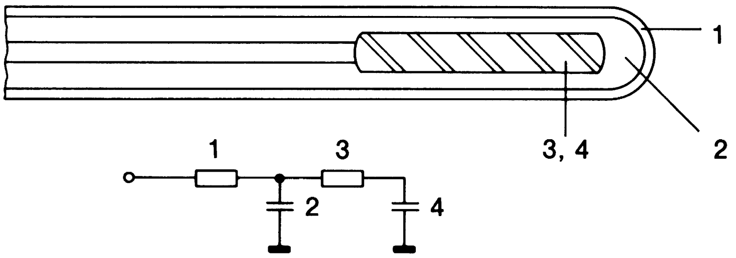


Fig. 38: Thermal resistances in a probe

The speed with which the probe responds depends primarily on the ratio of the thermal resistance to the thermal storage capacity of the probe. The larger the thermal resistance, the slower the probe heats up. If the probe only has a small heat capacity, it can only absorb a small quantity of heat, and so it reaches the final temperature quickly. The thermal resistance depends on the type and thickness of the material. The heat capacity is made up of the specific heat capacity and the mass of the probe.

For a simple cylinder with a radius R_I, surrounded by a protection layer with negligible thermal capacity and with an external radius R_A, the cylinder temperature T is given by:

Formula 27:

$$T = T_M - [T_M - T(t = 0)] \cdot e^{\frac{t}{\tau}}$$

$$\tau = \frac{c \cdot \rho \cdot R_I^2}{2 \cdot \lambda} \cdot \ln \frac{R_A}{R_I}$$

The constants here are:

- c specific heat capacity,
- ρ density,
- λ thermal conductivity of the protection layer.

Since a real probe assembly does not just consist of one single material, the heat capacities and thermal conductivities of the various components must be taken into account. This results in the following formula:

Formula 28:

$$T = T_M - [T_M - T(t = 0)] \cdot \left[\sum_{i=1}^{N} a_i \cdot e^{-\frac{t}{\tau_i}} \right]$$

Therefore, to achieve short response times, the smallest possible sensors should always be used, with thin materials that are good conductors of heat. Air gaps between the measurement insert and the protection tube have a particularly bad effect, as all gases are very bad conductors of heat. This can be remedied by embedding the measurement insert in heat conducting paste or metal powder.

Because of their lower thermal mass, thermocouples have fundamentally shorter response times than resistance thermometers. This applies particularly to thin mineral-insulated thermocouples. However, in most cases, the difference is completely swamped by the comparatively high heat capacity of the protection tube (Table 19). Generally, the response time increases with increasing diameter of the protection tube. Because of this, fittings with the thinnest possible walls should be used, provided that the mechanical conditions allow this. The thermal conductivity of the protection tube material is also highly significant. Copper and iron are relatively good conductors of heat, whereas stainless steel and ceramics are not.

The transfer function, i.e. the variation of the measured value following a step change in temperature at the probe, provides information on this effect. The transfer function U(t) after a step change in temperature is given by:

Formula 29:

$$U(t) = \frac{T(t) - T(0)}{T_M - T(0)}$$

Because the transfer function cannot generally be calculated sufficiently accurately, the transfer function resulting from a step change in temperature is recorded to characterize the dynamic response of temperature probes. For this, the temperature probe is subjected to a step change in temperature by immersing it quickly in moving water or air with a known flow rate and temperature. EN 60 751 and VDI 3522 standards recommend the following measurement conditions for comparison of thermometers:

Water: (0.4 ± 0.05) m/sec,

Air: (3.0 ± 0.30) m/sec.

Two times (response times) characterize the transfer function:

- the half-value time t_{05} the time to reach 50 % of the step change in temperature,
- the 90 percent time t_{09} the time to reach 90 % of the step change in temperature.

A time t required to reach 63.2 % of the final value, is not specified, to avoid any possible confusion with the time constant of an exponential function. The heat transfer function of practically every thermometer deviates clearly from such a function.

If the response time in a different medium is required, the transfer time for the new medium can be calculated from a knowledge of the heat transfer coefficient from the measured medium to the protection tube material of the probe, and the response times in air and water [25].

The ratio of the 90 percent time to the half-value time is approximately 3 : 1 and depends very much on the design of the probe. Manufacturers often specify both the 90 percent time and the half-value time, as this allows conclusions to be drawn on the shape of the transfer function of a thermometer. The ratio of t_{09} to t_{05} is always 3.01 for an exponential function. A smaller value for t_{05} for the same value of t_{09} means a steeper gradient over the first part of the curve. Specifying both times enables a qualitative determination of the extent to which the transfer function of a thermometer deviates from an exponential function. However, this is only of secondary importance for the user, as the absolute values for t_{05} or t_{09} are more important when estimating the time delay that the particular thermometer used causes in obtaining the measurement.

Thermometer type	**Diameter**	**Air 1.0 m/sec**		**Water 0.4 m/sec**	
		$t_{0.5}$ (sec)	**$t_{0.9}$ (sec)**	**$t_{0.5}$ (sec)**	**$t_{0.9}$ (sec)**
Measurement insert with thermocouple to DIN 43735	6 mm	40 - 60	150 - 180	0.3 - 0.8	1.0 - 1.5
	8 mm	45 - 70	160 - 200	0.4 - 1.0	2.0 - 5.0
in the protection tube to DIN 43772 Form 2	9 mm	80 - 100	280 - 350	6 - 8	25 - 40
Form 3	11 mm	100 - 120	320 - 400	7 - 9	30 - 50
Form 4	24 mm	320 - 400	900 - 1200	10 - 20	60 - 120
with ceramic protection tube to DIN 43724	11 mm	100 - 150	320 - 500		
	15 mm	180 - 300	500 - 800		
M.I. thermocouple insulated measurement point	3 mm	20 - 25	70 - 90	0.4 - 0.6	1.0 - 1.2
M.I. thermocouple insulated measurement point	1.5 mm	8 - 12	28 - 40	0.11 - 0.18	0.35 - 0.5

Table 19: Comparison of response times for various versions of thermometer

A thermometer is rarely used just in the ambient temperature range. If the measured temperature is higher or lower than the ambient temperature, a temperature gradient is established at the thermometer between the measurement location and the surroundings. This results in an incorrect temperature indication: the heat flows from a warmer to a cooler place through the protection tube or via the internal structure of the thermometer. In addition, the sensor is attached to the connecting leads, which form a direct metallic connection between the sensor and the surroundings. This connection acts as a thermal bridge, again resulting in incorrect temperature indication. Good electrical conductors always have a low thermal resistance too; so the requirement for a low resistance in the connecting leads always conflicts with the fact that they cause a large heat conduction error. The design of the thermometer also determines the heat conduction error: the sensor must have a good thermal connection to the protection tube, and at the same time be thermally decoupled from the connecting leads. The installation length of the selected thermometer should not be too short, as otherwise too much heat can be carried away. The immersion depth (the length of the part of the thermometer that is subjected to the medium being measured) also depends on the type of medium to be measured and the amount of heat that the medium transfers per unit time: for example, a fast-flowing liquid transfers more heat, and can therefore compensate for the heat conduction of the thermometer better than stationary air. With measurements in liquids, it is generally sufficient to have half the installation length compared to that required in gases.

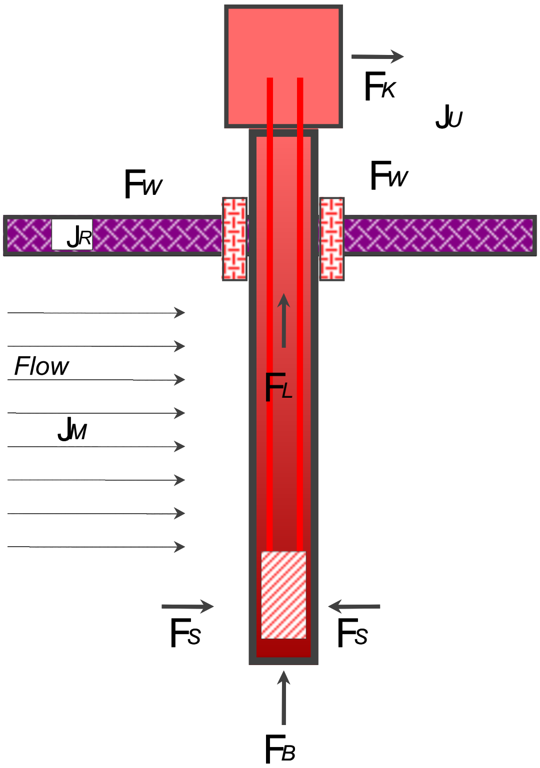


Fig. 39: Origin of the heat conduction error

6 Heat conduction error

The effect of the design on the heat conduction error is shown by the following example:

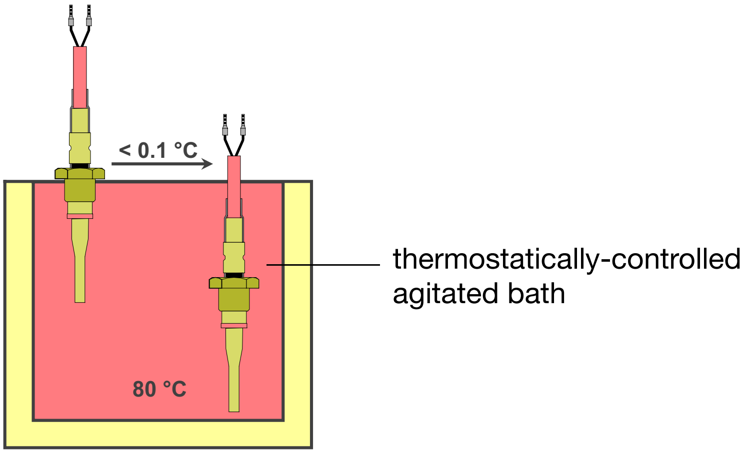


Fig. 40: Measuring arrangement to determine the heat conduction error

Temperature probes that are used as part of heat meters in heating systems must not exceed a specific heat conduction error at the specified minimum immersion depth. To determine the minimum immersion depth, the temperature probe is immersed up to the minimum immersion depth in fast-moving water (0.15 m/sec) at a temperature of 60 °C above ambient. When the probe is immersed further, the indicated value of the temperature probe must not increase by more than 0.1 °C (see Fig. 40).

Particularly with short temperature probes with installation lengths less than 50 mm, problems can be encountered in meeting the limit of 0.1 °C, and these problems have to be solved through the design. The connecting cable is taken right up to the sensor and is made of copper. The thermal interface between sensor and protection tube is normally provided by heat conducting paste. Without special measures for thermal decoupling, an error of approx. 0.3 °C occurs. Reducing the protection tube diameter in the region of the sensor gives an improvement of around 50 percent (see Fig. 41).

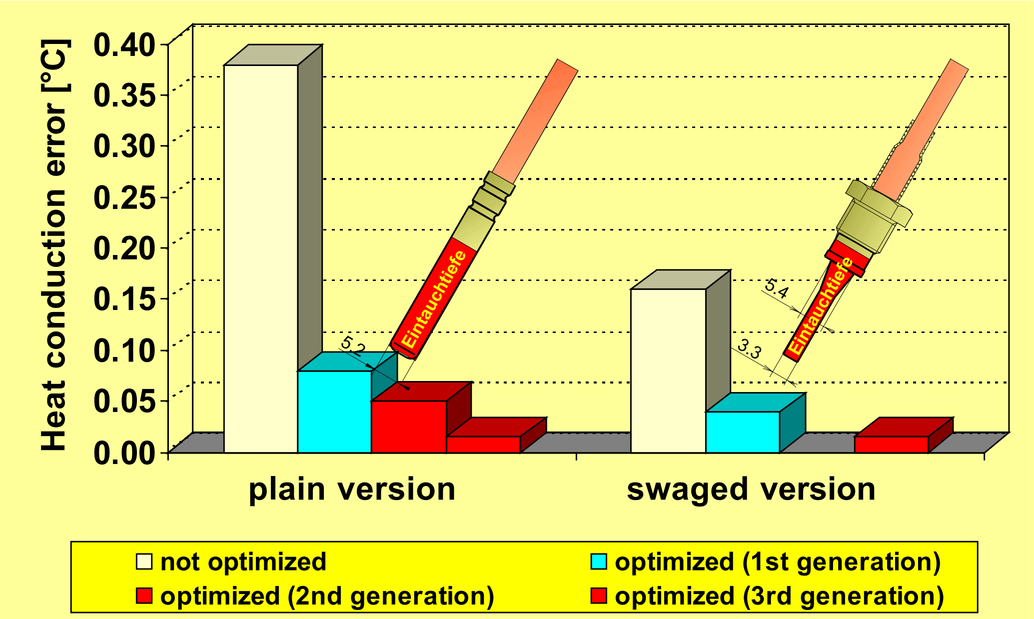


Fig. 41: Optimizing the heat conduction error by design improvements

However, with an error of 0.15°C, this variant of the probe still does not meet the test criteria. Only the provision of thermal decoupling of the connecting cable and sensor reduces the conduction error to 0.03°C, which represents a tenfold improvement compared with the original variant. Fig. 41 shows the reduction in heat conduction error in relation to the continuous development stages, with the specified minimum immersion depth of 27.5mm for the typical standard style of this application.

6.1 Measures to reduce the heat conduction error

It is not always possible to achieve such an optimum probe design for every application that the result is unaffected by the heat conduction error. The most important selection criteria for a probe with regard to the heat conduction error are summarized below.

The use of additional thermowells or pockets increases the thermal resistance to the actual sensor. In addition, heat flows to the outside through the pocket. A direct measurement is therefore preferable.

When pockets are used, dust can build up between the inner wall of the pocket and the thermometer stem, or the metal surfaces can oxidize. Once again this results in poorer heat transfer and an increase in the heat conduction error.

With small immersion depths, there is a higher temperature gradient between sensor and surroundings, resulting in a large flow of heat. The largest possible immersion depth should therefore be selected.

With low flow velocities or stationary media, only minimal heat transfer to the thermometer takes place. Because of this, a measurement location with a higher flow rate should always be chosen.

The external parts of a thermometer, such as the terminal head or the gland, exchange heat with the surroundings. These external parts should therefore be provided with thermal insulation to avoid heat loss. In addition, a strong airflow over the external parts of the thermometer promotes the exchange of heat with the surroundings. They should not be installed in locations where there is considerable movement of the ambient air. If necessary, the thermometer can be screened by a plate or some similar shield mounted upwind of it.

The exchange of heat with the surroundings is promoted by good thermal conductivity of the probe and by a large surface area of the external parts. For this reason, a thermometer with external parts (protection tube, terminal head) that have the smallest possible surface area should be used. The thermal conductivity of the protection tube in an axial direction can be reduced by interposing plastic washers. This significantly reduces the conduction heat loss, but has no adverse effect on the dynamic response of the thermometer.

7.1 Calibration

During the service life of a thermometer, its characteristic undergoes changes compared with the as-delivered condition. These changes are the result of chemical and mechanical effects, as well as ageing phenomena such as recrystallization and diffusion. The characteristic can also drift because of slight differences in the expansion coefficients of the support and resistance materials. The amount of change depends very much on the nature of the stresses imposed and on the design itself. The thermometer must be calibrated at regular intervals to take account of drift and to be able to compensate for it. This type of calibration means checking the indicated temperature values and, if necessary, establishing the amounts by which they deviate from the actual measured temperature. (By comparison, the concept of adjustment frequently used in this context means taking the necessary measures to keep the amount of measurement deviation small, at least less than the permissible error limits [16].)

A calibration is identical with testing and measuring the accuracy for each individual thermometer. However, the manufacturer cannot provide any guarantee for the long-term stability of these values, as he cannot foresee the future areas and frequency of use for the thermometer, or the related stresses imposed on it. No validity period for the calibration is specified, nor is a regular check by an accredited calibration service. Initially, a thermometer should be calibrated annually, and the results compared with the previous data. In the course of time, a history of the thermometer is built up, showing the stability of the thermometer. Where the reproducibility of the data is adequate for the specific application, a decision can then be made on whether the time period between calibrations should be shorter or longer.

The question of the procedure and accuracy of a calibration cannot be answered in general terms. This is always covered by an agreement between the user and the calibration service, in which the temperature range and measurement points are laid down. The accuracy is determined by the type of measurement and the instrument under test.

For the calibration, the thermometer to be tested is brought up to a known temperature, then the value (resistance, thermoelectric emf, etc.) produced by it is measured and then compared with the expected values. Depending on the temperature range, liquid-filled thermostatic baths, furnaces or fixed point cells are used for temperature-controlled heating. The temperature here is measured with a standard thermometer. During the comparison measurement it must be ensured that there is no temperature difference between the instrument under test and the standard thermometer. With a fixed point cell, the precisely known temperature of the change of state is set, and the comparison with a standard thermometer is not required. Fixed point cells offer higher accuracy; at the triple point of water, a measurement uncertainty of less than 0.005 °C is achieved.

Very often, in the course of a calibration, the insulation resistance is also measured at both room temperature and at maximum temperature, and also after the thermometer has been exposed to the temperature for a continuous period. For example, the thermometers are exposed to the maximum temperature for 20 hours. The change from the nominal value provides a first estimation of the stability. Thermocouples, resistance thermometers, and, in addition, all devices for temperature measurement can be calibrated. In fact, thermocouples can theoretically be calibrated within the same tolerance band as resistance thermometers, but there is little point in quoting this measurement uncertainty because of their higher drift. Within a short period of time, both the validity of the calibration and the corresponding ability to maintain measured values within these tight tolerance bands must be doubted. For this reason, the calibration certificate often contains recommendations concerning the anticipated drift and the related validity period and restrictions of the calibrated values, together with the reference conditions, i.e. the operating conditions for which the test results apply.

Account must be taken of the fact that the measurement uncertainty quoted in the calibration certificate may not always be the smallest measurement uncertainty that the particular calibration laboratory can quote. When determining the overall measurement uncertainty, the quality of the calibration object, and an estimate of the stability and reproducibility of the instrument under test are also included.

7.2 Calibration services

The globalization of the market through quality standards such as ISO 9000 and stricter product liability legislation impose increasing demands on the documentation of processes and monitoring of measuring equipment. In addition, customers are increasingly demanding high quality standards for the products they purchase.

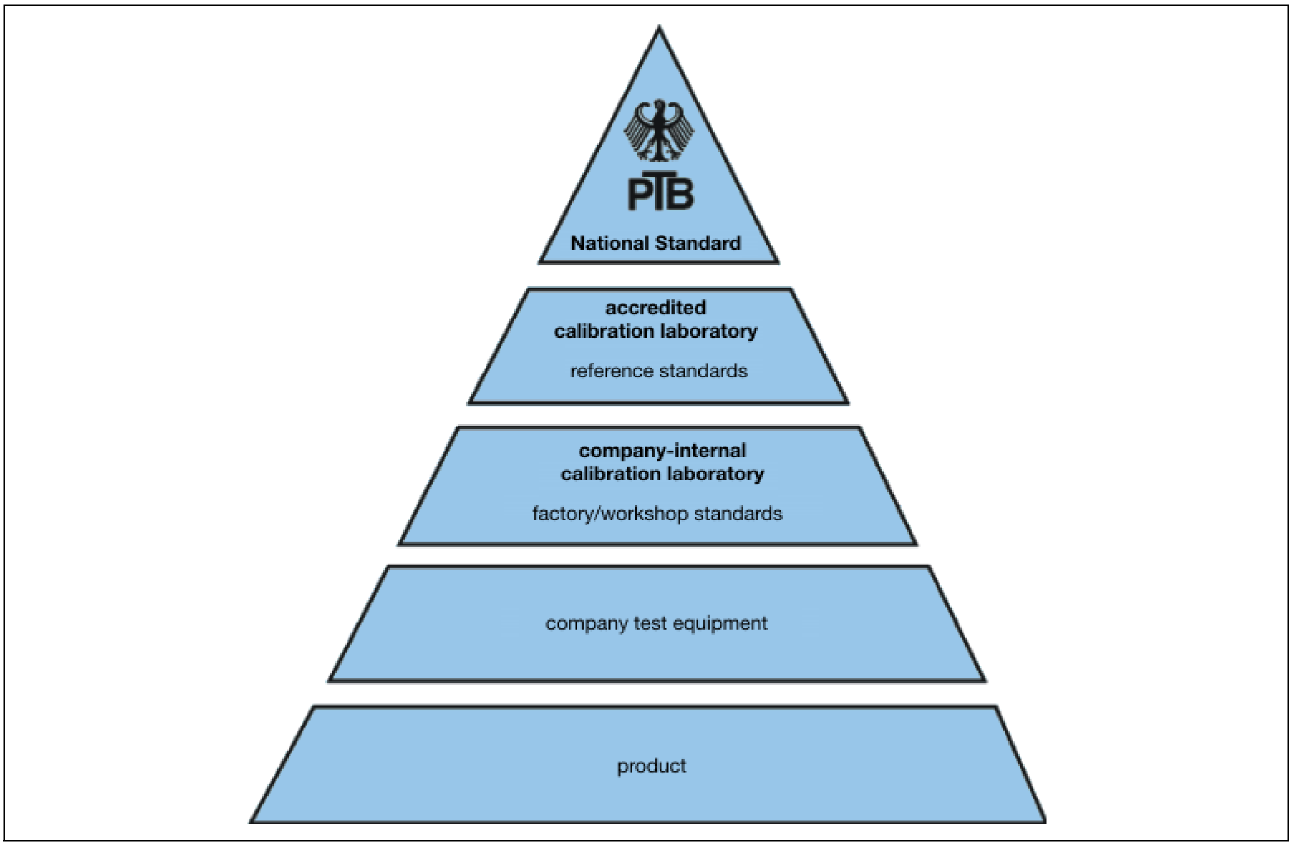


Fig. 42: The traceability chain

Particularly stringent demands stem from the ISO 9000 standard, which describes the global concept of a quality assurance system. If an organization is certified to this standard, all test equipment used in the production process must be traceable to the nationally recognized standards. Traceability to national standards means that when an item of test equipment is checked, the actual measurements can be traced back to official standards via a documented route. In Germany, the Physikalisch-Technische Bundesanstalt (PTB) lays down the national standards and compares them with the test results of other organizations, so that important parameters such as temperature can be uniformly represented by physical means throughout the world.

Because of the high demand for instruments calibrated in this way, there are insufficient government establishments, and industry has established and also supports calibration laboratories. In Germany these laboratories are affiliated with the German Calibration Service (DKD) and are subordinate to the national PTB laboratory for measurement aspects. This ensures that the measuring equipment used in a DKD laboratory is clearly traceable to national standards, and therefore also to the thermometers used there.

In the course of an official calibration, the thermometer is checked at different temperatures, as described above. The measured data are then used to determine the parameters of the characteristic and a certificate covering the measurements taken is issued. It is important here that the thermometer is certifiable in the opinion of the calibration service. This includes, in particular, a test of the stability of the nominal value after exposure to the maximum permissible operating temperature, as well as the stability of the insulation resistance. If a thermometer does not meet these requirements, it is not accepted for calibration.

The thermometer shown in Fig. 43 was specially developed from the point of view of high stability, so that it can be used in harsh industrial environments. With precision thermometers in particular, there are many versions on the market in which the resistance coil is freely suspended to minimize its exposure to the chemical and mechanical effects of a support material. However, the coil easily fractures when subjected to shock or vibration. In fact, these thermometers exhibit a very high stability of the order of better than 0.001 °C, but their low mechanical stability precludes their use in industrial applications.

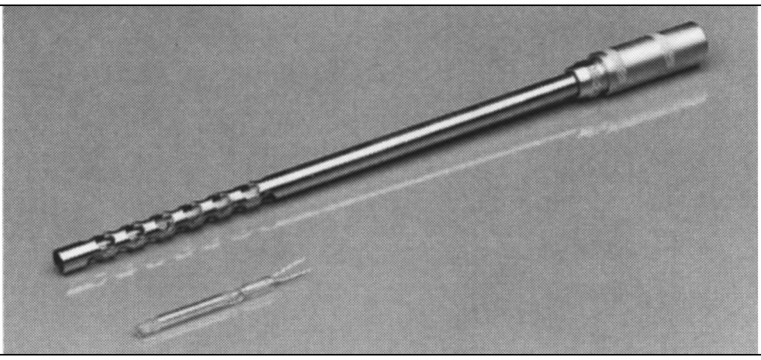


Fig. 43: A certifiable thermometer

The basic construction of the temperature sensor of this type of thermometer, which includes the one shown above, is similar to that of a wire-wound ceramic resistor in a mineral-insulated resistance thermometer. The temperature sensor is directly connected in a 4-wire circuit. The manufacturing process is followed by an ageing process during which the change in resistance at the triple point of water is monitored. Thermometers that do not exceed a certain value during the ageing process can also be calibrated in a temperature range up to 400°C. The following illustrations show the result of a test on several thermometers that are exposed to an ageing at 450°C. The change in resistance at the triple point of water was determined after various time intervals. Analysis shows that the resistance increases slightly within a band of ±0.005°C (Fig. 44). The same probe construction was then used for daily monitoring of a measuring system at temperatures up to a maximum of 150°C. Similarly, the resistance value at the triple point of water was determined, this time once a week (Fig. 45). At the reduced temperature loading there was no drift in resistance. The measurement uncertainty is within the range of the smallest measurement uncertainty (0.005°C) that can be quoted.

7.3 Certification

Certification can only be performed by appointed officials. It consists of a test and an official stamp. The types of thermometer that are subject to certification are regulated by law. In contrast to the calibration, the certification of a thermometer involves a test of the indicating mechanism within stipulated certification error limits. The limits are specified in regulations, and the thermometer must comply with these limits at the time of the test. During the specified validity period of the certification, the thermometer must not exceed the permissible service error limits, which are double the certification error limits. Certified thermometers are used in industrial applications, for example in heat meters. However, they are also used as clinical thermometers and as indicators in commercial freezers. The certification itself is performed by the appropriate authorities (weights and measures offices, trading standards offices etc.). Where large numbers of instruments are involved, however, an organization can perform the measurement itself, as an appointed test center. This process is defined as accreditation. The test centers, for their part, are subject to an annual audit by the appropriate certification authority.

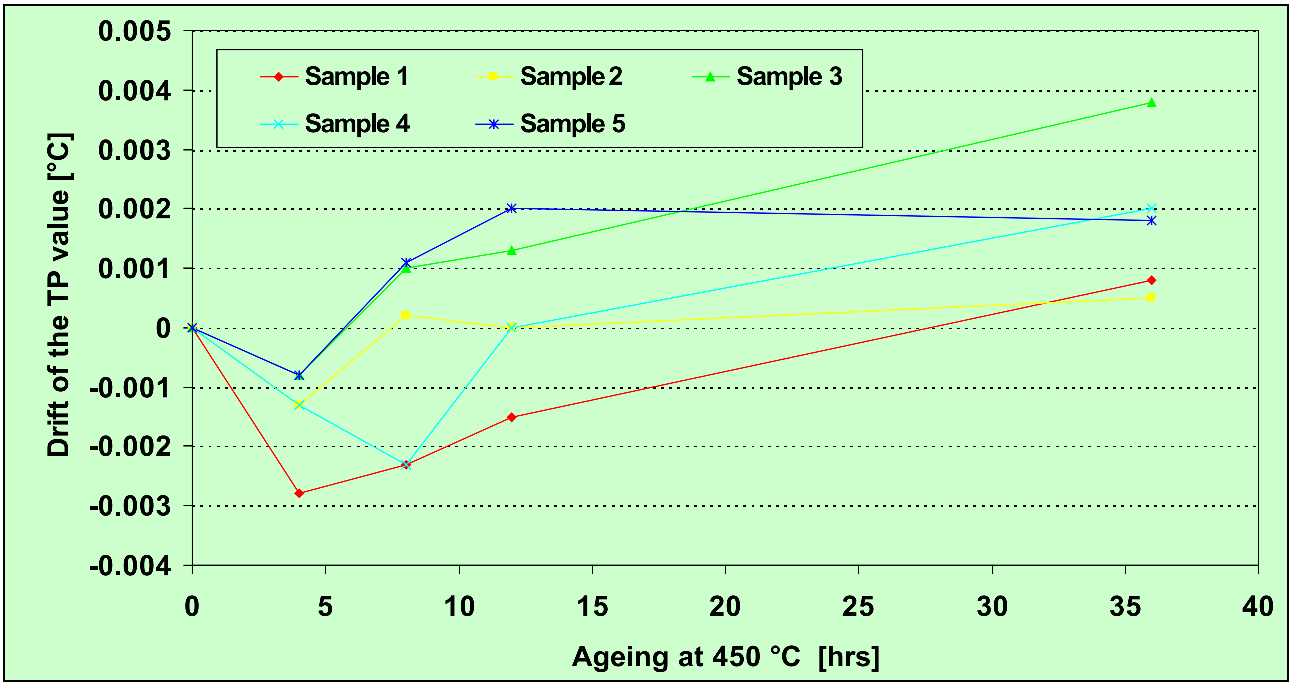


Fig. 44: Ageing of industrial precision thermometers at their upper operating temperature

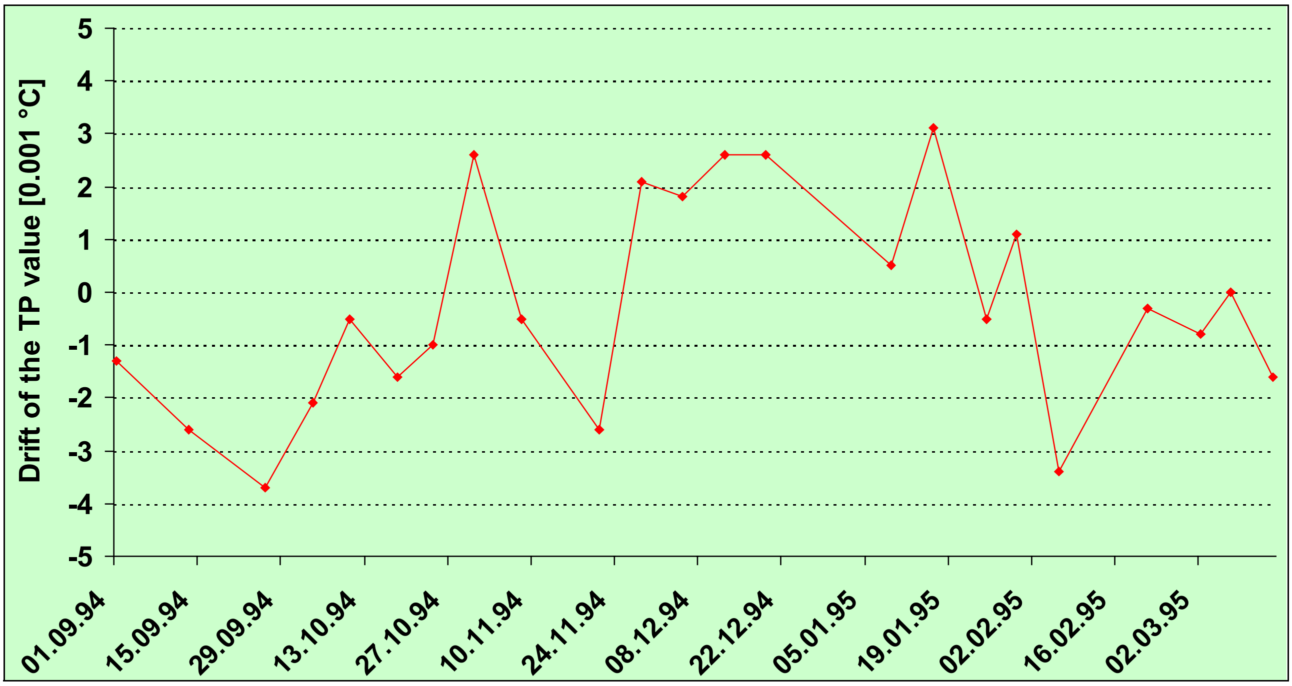


Fig. 45: Reproducibility of an industrial precision thermometer with daily use at 150°C

8.1 Construction of electrical thermometers

As well as an almost endless range of special versions suitable for extremely diverse applications and their associated measurement duties, there are some thermometers whose components are fully described by standard specifications. This type of thermometer - which always means the complete unit including the measuring element itself - has a modular construction: it is made up of the resistance sensor or thermocouple, the protection tube, the terminal head and the terminal block located inside it, as well as a process connection that could be, for example, a thread, flange, weld-in socket, compression gland or movable socket. The temperature detector or sensor denotes only the part of the thermometer that is directly affected by the measured variable, and contains the temperature-sensitive part of the thermometer [16].

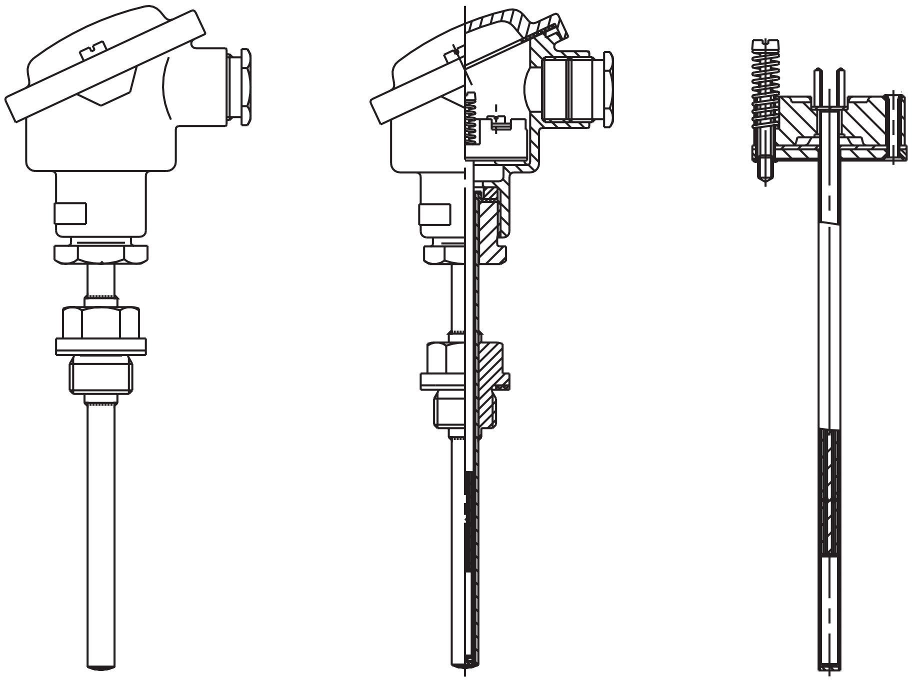


Fig. 46: Section through an electrical thermometer

Measuring inserts are pre-assembled units comprising the sensor and the terminal block, where the resistance sensor is housed in a 6mm or 8mm diameter stainless steel insert tube. The insert tube is then inserted in the actual protection tube, such that the tip of the insertion tube fits flush with the bottom of the protection tube, to ensure good heat transfer. With this arrangement, the measuring insert can be easily replaced at a later stage. The fixing screws are spring-loaded to ensure that flush-face contact is maintained even if the measuring insert and the protection tube expand by different amounts longitudinally. The units are produced as single or dual probes, and their dimensions are laid down by DIN 43 762. Measuring inserts with an integral 2-wire transmitter are also produced.

In the case of measuring inserts for thermocouples, the sheath of a mineral-insulated thermocouple acts as the insertion tube at the same time. Again, the dimensions are based on DIN 43 762.

If no measuring insert is used, the thermocouple or resistance sensor is mounted direct in the protection tube, embedded in aluminum oxide, heat conducting medium or some other embedding compound suitable for the temperature range. After the sensor is inserted, the terminal block is fitted in the terminal head and the sensor connections soldered to it. The sensor cannot then be replaced at a later stage; the complete thermometer must be replaced in this case.

Thermowells or pockets are often used to avoid this. These are a type of protection tube permanently attached to the machine or equipment; the thermometer is inserted into the pocket and secured with either a clamping screw or a wedge. Other versions have a G½ female pipe thread, so that a thermometer can be screwed in. The thermometer here may just consist of a measuring insert, but may also have its own protection tube. In the latter case, though, the response is then noticeably worse. The thermowell itself is either permanently welded to the machine (this is not possible with protection tubes, because of their thin-wall construction) or has a male thread, normally a pipe thread. Thermowells like this are very useful and they are indeed widely used. For example, when a pocket is used, a thermometer can be removed without having to de-pressurize or drain a system. In contrast to thermometers with measuring inserts, where this is also possible in theory, there is no need to open the terminal head in this case.

Of course, the connecting cable must also be disconnected when replacing the thermometer. However, because of space limitations, it is often easier to remove the thermometer from the machine before disconnecting the cable, and the use of a thermowell is clearly expedient here. As the thermowell comes into direct contact with the medium, it must meet the same requirements with regard to chemical and mechanical resistance as the protection tube would otherwise have to meet. Because of the materials available, pockets are mainly used in medium temperature applications, such as boiler plant and the like.

8.1.1 Terminal heads to DIN 43 729

DIN 43 729 defines two versions of terminal head; they differ in size and also slightly in shape.

The materials used can be cast iron, aluminum or plastic. The standard expressly indicates that the external shape and all features that do not affect the universal usability, as well as the method of fixing the cover, are left to the designer. So it is only necessary to comply with the specified dimensions to the extent that the universal usability is maintained. The dimensions specified for the overall size of the terminal block should be regarded as minimum values, those for the total overall height as maximum values. Because of this, there are also a number of different versions suitable for special requirements. Neither does the standard specify the degree of protection, although IP54 (splashproof) is normal. But user requirements dictate that versions with IP65 protection, or plastic or stainless steel versions are also needed.

For the two types of terminal head, the nominal size of the diameter of the bore to accept the protection tube is as follows:
Form A : 22, 24 or 32mm,
Form B: 15mm or M24 x 1.5 thread.

The smaller terminal head, Form B, is the most widely used; the 2-wire transmitter is designed for use with this version.

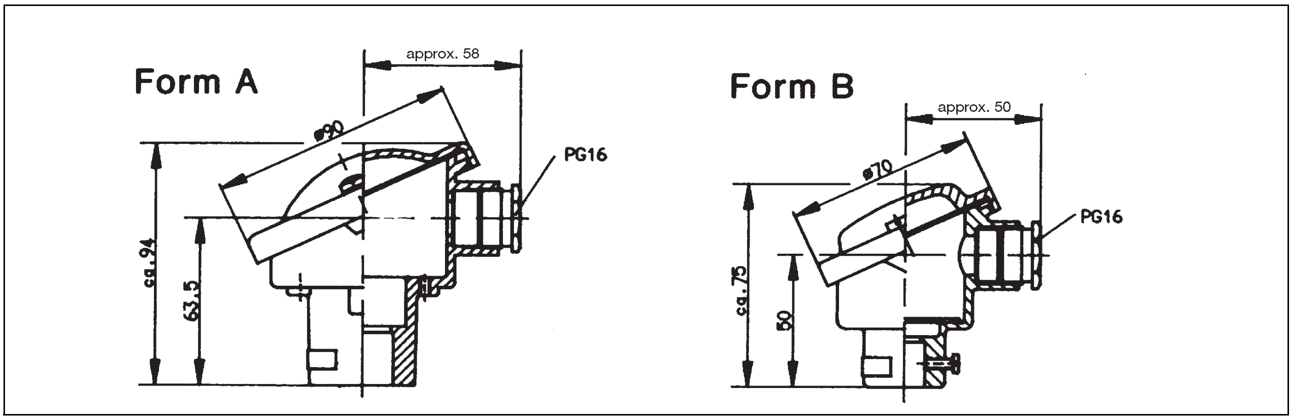


Fig. 47: Various terminal heads

8.2 DIN standard thermometers and protection tubes

DIN standards 43 764 to 43 769 lay down various styles for different duties. They are all equipped with a measuring insert and a Form B terminal head. The diameter and length of the protection tubes are also specified, so these are not dealt with here. Full details can be obtained from manufacturers' publications or from the appropriate standard.

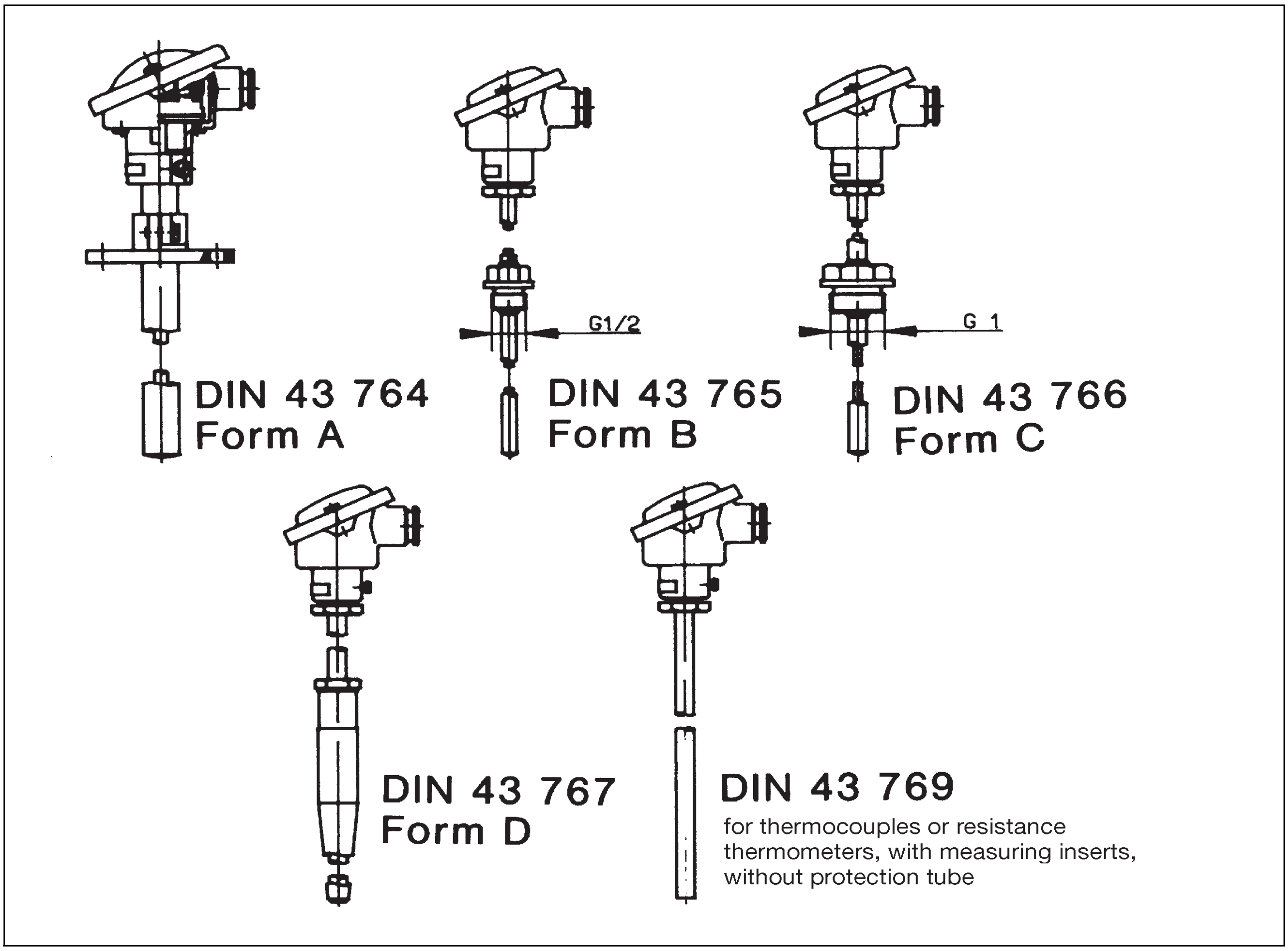


Fig. 48: Thermometers to DIN 43 770

8 Fittings and protection tubes

The various forms of protection tube of these thermometers (with flange, tapered etc.) are designated by code numbers as laid down in DIN 43 772. This standard has superseded DIN 43 763, where the forms of protection tubes were designated by code letters. In addition, DIN 43 772 also covers the protection tubes for engine glass thermometers and dial thermometers to DIN 16 179.

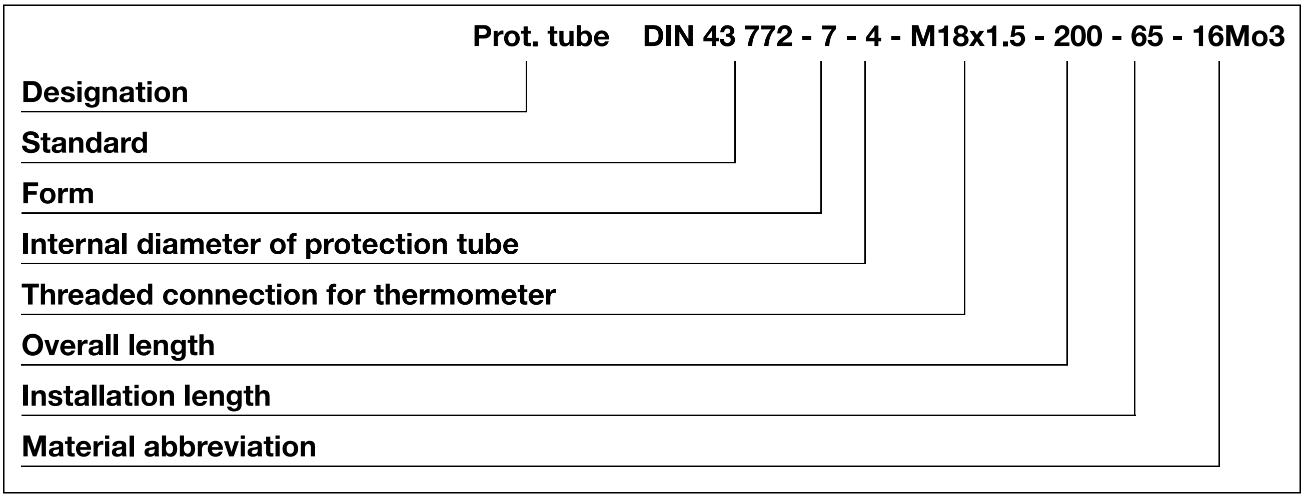
Form 1:	protection tube, push-in type
Form 2:	protection tube, push-in or weld-in type
Form 2G:	protection tube, screw-in type with G½ or G1 pipe thread as process connection
Form 2F:	protection tube, flanged type; flange DN25 / PN40 to DIN 2527, gasket Form C to DIN 2526 (or as arranged)
Form 3:	protection tube, push-in or weld-in type with swaged tip
Form 3G:	protection tube, screw-in type with G½ or G1 pipe thread process connection and swaged tip
Form 3F:	protection tube, flanged type; flange DN25 / PN40 to DIN 2527, gasket Form C to DIN 2526 (or as arranged) and swaged tip
Form 4:	protection tube, weld-in type for thermometers and extension with male thread
Form 4F	protection tube, flanged type for thermometers and extension with male thread
Form 7	protection tube, screw-in type (single-part) with external NPT thread and parallel internal thread

This will be clarified and more easily understood by the following comparison of the forms of protection tube listed in DIN standards 43 763 and DIN 43 772:

Designation	Form	Form to DIN 43 772
Metal protection tubes to DIN 43 763	A	1
	B1, B2, B3	to some extent 2G
	C1, C2	to some extent 2G
	D1, D2, D4, D5	4 and extension
	E1, E2, E3	to some extent 3
	F1, F2, F3	to some extent 3F
	G1, G2, G3	to some extent 3G
	not standardized	2F, 4F, 7

Table 20: Comparison of the forms of protection tubes to DIN 43 763 and DIN 43 722

DIN standard 43 772 (referred to earlier) also lays down the materials and protection tube lengths, as well as their description, using special abbreviations. Here is an example of a protection tube to Form 4:



Appendix A (informative) of DIN 43 772 specifies permissible pressure loadings in air, water or steam, together with the maximum flow velocity. As a result, the type of protection tube required can be carefully considered at the design stage of the installation. In this connection, it must be pointed out that the calculations are based on idealized operating conditions. No account is taken of pulsating velocities or external causes of resonance due to operating plant. The information provided is purely informative and must be checked for the specific case. The design calculations do not provide any safety margin against fracture or failure of the protection tube.

A special form of thermometer is described in DIN 43 769. It has no protection tube, and the insertion tube of the measuring insert is in direct contact with the surroundings. With this arrangement though, the underside of the terminal head is only partially sealed or not sealed at all. Because of this, it is better to use a thermometer with a thin-walled protection tube, as the interior of the terminal head is then hermetically sealed.

An additional complete description of thermometers for higher temperature ranges is provided by DIN 43 733, although this only applies to thermocouples that are mounted directly in the fitting, i.e. without measuring insert. In contrast to the standard referred to earlier, ceramic protection tubes and tubes with gas-tight inner tubes are also covered here. The following abbreviations are applicable:

A: terminal head Form A,
B: terminal head Form B,
M: metal protection tube,
MK: metal protection tube with gas-tight ceramic inner tube,
K: ceramic protection tube,
KK: ceramic protection tube with gas-tight ceramic inner tube.

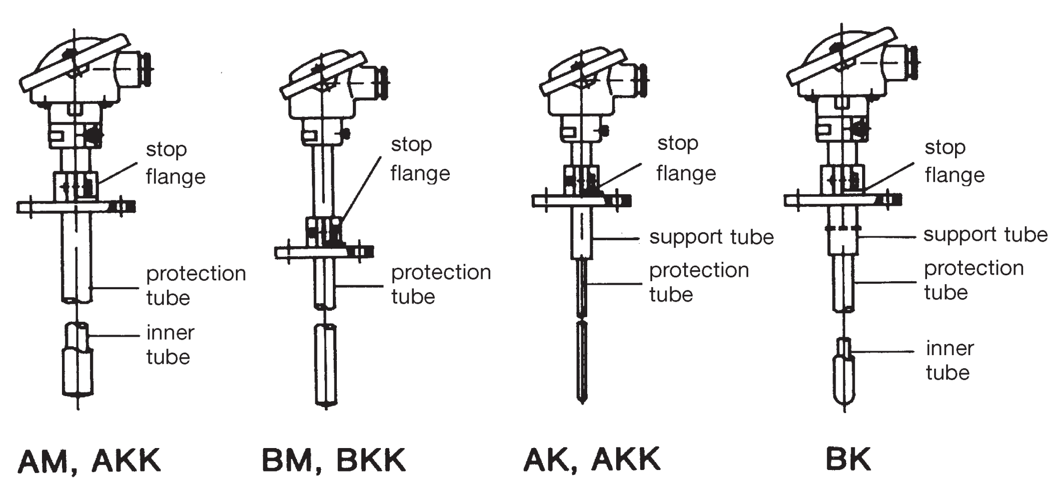


Fig. 49: Thermometers to DIN 43 733

The associated protection tubes are described in DIN 43 720 (metal) and DIN 43 724 (ceramic).

In addition to these, a multiplicity of special forms is available, some with standard terminal heads, and some in very special non-standard styles with plug connectors or with a permanently attached connecting cable.

8.3 Application-specific thermometers

The thermometers described in Chapter 8.2 are standard styles that are used primarily in the wide field of process engineering, such as the chemical and petrochemical industries, for example, or in power station construction. But these thermometers cannot be used for measurements in every situation. In many cases the overall dimensions are oversized for the measurement location at hand, as the thermometer is overloaded or the measurement requirements are increased because of mechanical vibration.

The following chapters introduce the various styles that have been optimized for specific applications.

8.3.1 Resistance thermometers for strong vibration

Temperature probes used for engine monitoring and control must fulfil very different requirements. One of these is a high resistance to mechanical vibration over a period of more than 10 years. The vibration frequency is between 500Hz and 3000Hz, and the accelerations that occur are up to 50g (50 times the acceleration due to gravity). Such conditions are encountered on air compressors or refrigeration compressors, for example, used on road and rail transport vehicles (gearbox oil temperature, cooling water temperature, turbocharger air temperature), or in shipping.
As the probe is often externally mounted below the vehicle floor, very high temperature gradients occur within the temperature probe. Internally, the measurement temperature is 180°C, whereas externally the plug connector is exposed to ambient temperature (down to -30°C), very damp conditions or water spray (e.g. vehicle driven in rain).
Because of this, both the probe and the plug connector system must be designed to provide a high degree of protection up to IP67/IP69.

As well as high mechanical stresses, the temperature probe also has to meet increased measurement requirements. The response time must be very short (t_{05} < 1.1 sec in water), so that rapidly-increasing gearbox oil temperatures are detected and overtemperatures avoided. Because of the small immersion depths, steps must be taken at the design stage to ensure that the interior of the temperature probe incorporates measures to reduce the heat conduction error.

The illustration shows a selection of such temperature probes that have all these attributes, and that have been tried and tested over a number of years.

Fig. 50: Shock-proof resistance thermometers from the JUMO VIBROtemp range

8.3.2 Resistance thermometers for the food industry

In cooking, baking and curing processes in the foodstuffs industry, measurement of the core temperature of the product is vitally important for process control. Temperatures up to 260 °C occur here. The situation is made worse by the fact that varying amounts of steam are also injected during the process. These thermometers are often cleaned by immediately immersing them completely in cold cleaning fluids, whilst the thermometer is still hot. As the air inside it contracts, the probe starts to “breathe”, and fluid tries to penetrate into the probe. If moisture reaches the measurement circuit, a shunt path is established, and the thermometer indicates a lower temperature. This case is especially bad, as too low a temperature is transmitted to the control system. The cooking process is then extended or the process temperature increased, and as a result the food product is burned.

The use of an encapsulating method specially developed for this type of thermometer successfully prevents moisture from reaching the measurement circuit and sensor, despite severe stresses over several years. A development of this type of thermometer is the use of multiple resistance thermometers and thermocouples that measure the temperature at various fixed distances along the protection tube. This allows the variation of core temperature to be tracked at various points over time, to establish a uniform cooking process.

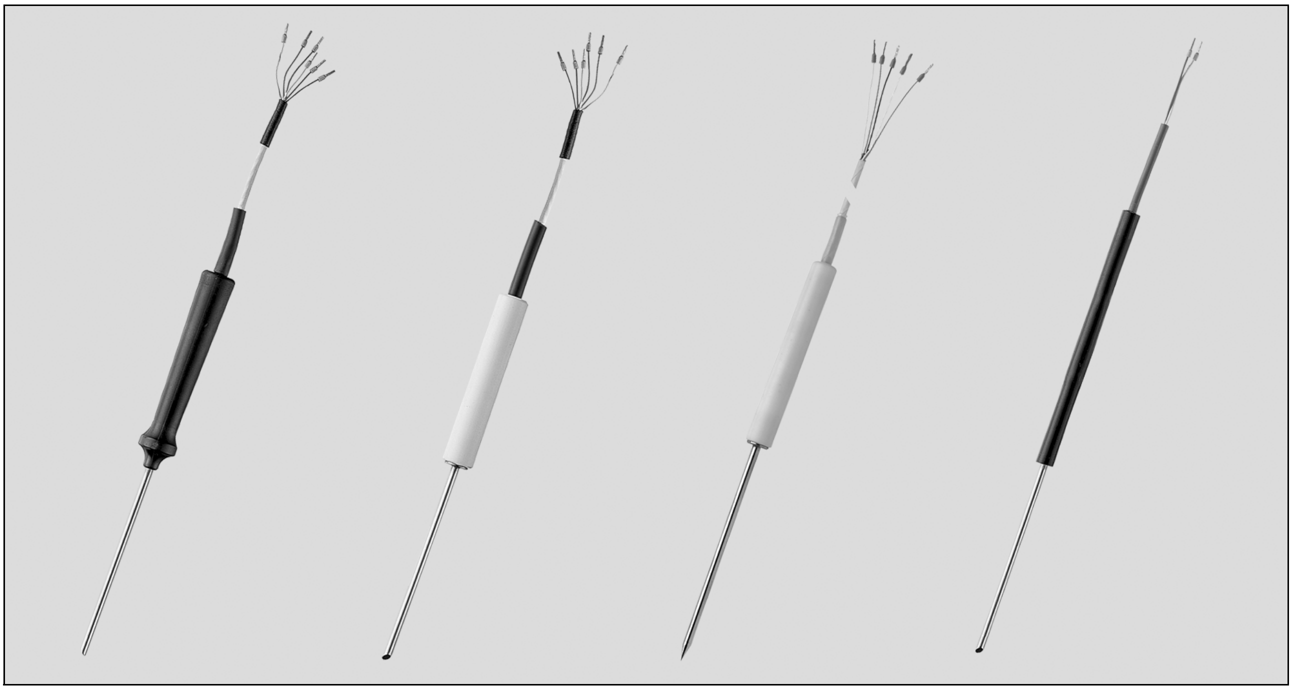


Fig. 51: Various JUMO insertion probes

8.3.3 Resistance thermometers for heat meters

In order to be able to calculate the heat given out or absorbed in a heating or cooling circuit, measurements must be taken. For this, a heat meter is often installed in the circulation system; the heat meter measures the quantities needed to calculate the amount of heat, i.e. the flow and temperature of the flow and return lines of the heating system. The arithmetic unit calculates the amounts of heat, taking into account the heat capacity of the heat carrier (normally water in heating systems); the value is stored and then displayed in statutory units. If heat meters are referred to for calculation of heating costs, they are subject to official certification and must meet certain error limits, known as the certification error limits. Before the heat meter is brought into commercial use, the components must be checked and certified for compliance with the certification error limits.

The amount of heat given out is calculated as follows:

Formula 30:

$$Q = k \cdot V \cdot \Delta\Theta$$

Q = amount of heat,
k = temperature coefficient of the heat carrier,
V = volume,
$\Delta\Theta$ = temperature difference between flow and return.

The error limits for the individual components of a heat meter are defined in both Appendix 22 of the Certification Regulations (for Germany) and in European Standard EN 1434.

For temperature probes used to measure the temperature difference between the flow and return lines, the applicable relative error limit (E) is dependent on the temperature difference to be measured, and is given by the following formula:

Formula 31:

$$E = 0.5\,\% + 3\,\% \cdot \frac{\Delta\Theta_{min}}{\Delta\Theta}$$

E = relative error,

$\Delta\Theta_{min}$ = smallest permissible measurable temperature difference (normally: 3°C),

$\Delta\Theta$ = temperature difference to be measured.

For compliance with the error limits for the temperature difference, the temperature probes must be paired in line with a mathematical procedure, taking into account the individual characteristics. For this, the individual characteristic parameters R_0, A and B of each individual temperature probe must be determined in the applicable operating range, as any two temperature probes, even with restricted tolerances (1/3 DIN, for example), do not automatically comply with the temperature difference error limits. To clearly establish the characteristic parameters, each temperature probe must be calibrated at three temperature points, with a measurement uncertainty of 0.021 °C.

The heating systems used in housing generally consist of pipes with a diameter less than 25mm, resulting in a very small immersion depth of the temperature probe, between 15mm and 30mm, depending on the mounting method. For correct temperature acquisition in the pipeline, this temperature probe must be optimized for a very small heat conduction error. In accordance with the approval criteria, the heat conduction error at the minimum insertion depth of the temperature probe must not be more than 0.1 °C. (see also Chapter 6 “Heat conduction error“).

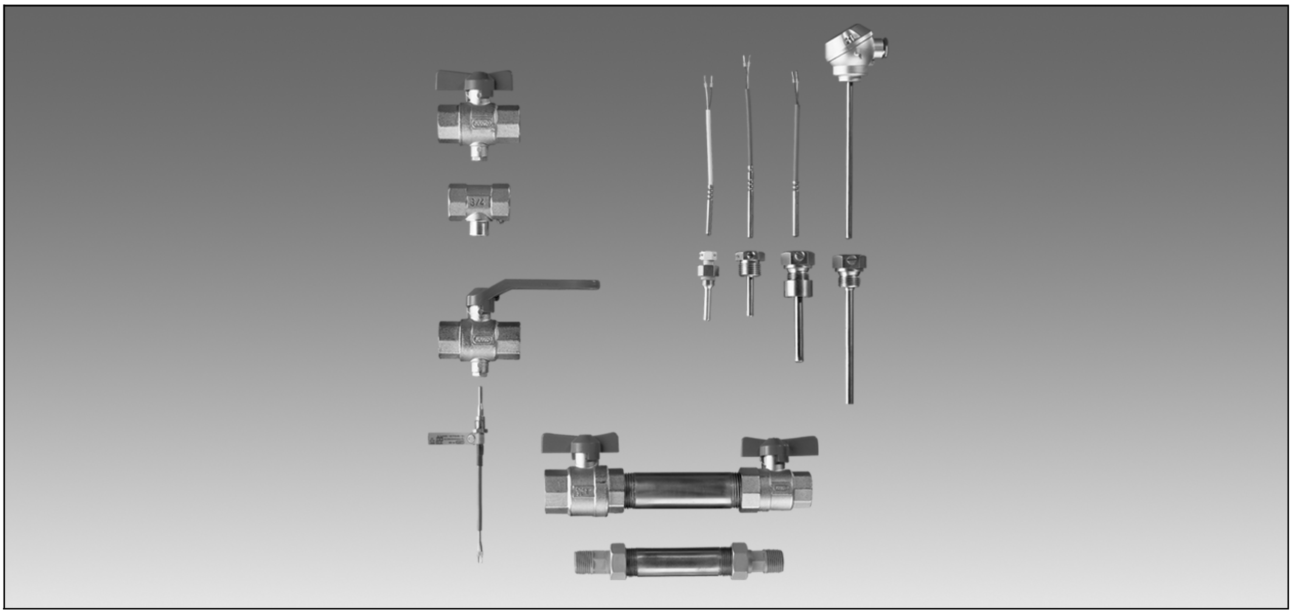


Fig. 52: Various temperature probes from the JUMO HEATtemp range

8.4 Demands on the protection tube

The thermocouple or resistance sensor is protected against mechanical and chemical effects by the protection tube. With regard to temperature stability, the demands imposed on resistance thermometers are less onerous because of their lower maximum operating temperature compared with thermocouples, if they are used in melts or case-hardening baths and the like. In addition, the protection tube must meet the mechanical requirements in both cases, and these determine the wall thickness and form of the tube, and the associated resistance to compression and bending. The many different styles described earlier are available here. The materials suitable for the different applications are fully discussed by **Lieneweg** [2]. They depend on the chemical conditions and the maximum operating temperatures that can occur. In a few applications, the protection tube can be affected by erosion, in mixers or with loose materials, for instance, or when solids are conveyed in a liquid medium. Protection against abrasive liquids of this type is provided by relatively thick coatings of hard-chromium plating, or by using protection tube materials with a high surface hardness, such as silicon carbide. With very fast-flowing media, erosion can also occur due to cavitation. In such cases, the designer must take measures to avoid the formation of a vortex at the protection tube, without creating a dead space that would adversely affect the response time.

In the high-temperature range, the protection tube is exposed to more arduous conditions with regard to its mechanical and chemical resistance. Molten salt, metal and glass are particularly critical, as they are highly reactive because of their high temperatures. Here, attention must always be paid to whether the protection tube is located in a neutral, oxidizing or reducing atmosphere, as this frequently determines the maximum permissible temperature.

It is necessary to distinguish between metallic, ceramic and ceramic-metallic (cermet) materials. Whereas the extremely brittle ceramic protection tubes are chemically resistant and highly temperature resistant, metallic protection tubes offer advantages because of their mechanical properties, thermal conductivity and their resistance to temperature changes. Ceramic materials are also used where a high standard of cleanliness is demanded, as they do not form any reaction products with the medium to be measured. As there is practically no evaporation, vacuum or high-purity furnace atmospheres are not contaminated. The maximum temperatures extend to about 1700°C.

8.4.1 Metallic protection tubes

Measurements up to around 800°C are possible with low-alloy steel protection tubes, and up to 1200°C using heat-resistant steel. Their major advantage is the mechanical strength; against this, they are very susceptible to chemical attack. Protection tubes made of rust-resistant and acid resistant steel are widely used; these are relatively corrosion-resistant and allow an upper temperature limit up to 800°C. But this conflicts with the relatively poor thermal conductivity of the material. Like all alloys, including bronze and brass, their thermal conductivity is much poorer than that of the base metal, because of the modified structure of the metal lattice. So, where there is a requirement for short to very short response times combined with high mechanical stability, which necessitates an increased wall thickness of the protection tube, it is advisable to resort to a copper protection tube, provided that the associated, increased heat conduction error is permissible. Above 300°C, copper oxidizes in air, which limits the upper temperature limit. Nickel coatings offer a suitable surface protection, and they show good adhesive properties, as the electrochemical properties of the two metals are similar.

Mineral-insulated thermocouples use a rust and acid-resistant steel, Mat. Ref. 1.4571 (V4A, Inox, Nirosta) with about 18 % chromium and 10 % nickel as the sheath material, enabling them to be used at operating temperatures up to 800°C.

An alloy with a high nickel content to Mat. Ref. 2.4816 is suitable for use at higher temperatures. It is known under the trade name Inconel (trade name of Inco Alloy). Inconel is an alloy of 72 % Ni, 14 - 17 % Cr, 6 - 10 % Fe and less than 10 % manganese, with a melting point of 1400°C, and is stable up to 1150°C in oxidizing atmospheres. The maximum temperature is reduced to 850°C in sulfurous oxidizing gases, and drops to 540°C in a simultaneously reducing atmosphere. In Endogas, good service life is possible with operating temperatures up to 1100°C: according to **Anderson** [20], the drift after 2500 hours is -0.3°C for a Type N mineral-insulated thermocouple, and 1.8 °C for a Type K. (Endogas is a carbonizing gas produced by the incomplete combustion of propane. The addition of 2 - 6 % ammonia produces a carbo-nitriding action). At higher temperatures Inconel becomes pervious to hydrogen [2]. Nicrobell (trade name of Nicrobell Pty. Ltd) is a material containing 15 % chromium, 1.5 % niobium, 80 % nickel, 1.5 % silicon. It bears a strong similarity to

Nicrosil, the material used for the positive leg of the Type N thermocouple. Nicrobell melts at 1420°C. It is very stable in oxidizing atmospheres and in vacuums, where the upper temperature limit is around 1300°C, but this is restricted by the thermocouple used (see Chapter 3.8.1).

In carburizing atmospheres such as Endogas, the operating temperature is reduced to around 500°C [20].

Its thermal conductivity of 15W/m·°C is very similar to that of Inconel and stainless steel.

The problem of corrosion resistance and the difficulty in making predictions about it are best illustrated using the following iso-corrosion diagram (Fig. 53) as an example: the question of steel's resistance to sulfuric acid can only be answered by considering two parameters, the concentration and the temperature. Steel to Mat. Ref. 1.4571, for example, shows a large resistance deficiency over the range 25 - 78 percent acid concentration. However, even above and below this range, it is still essential to take account of temperature. So, before using a material, its resistance to corrosion must really be tested under the given operating conditions.

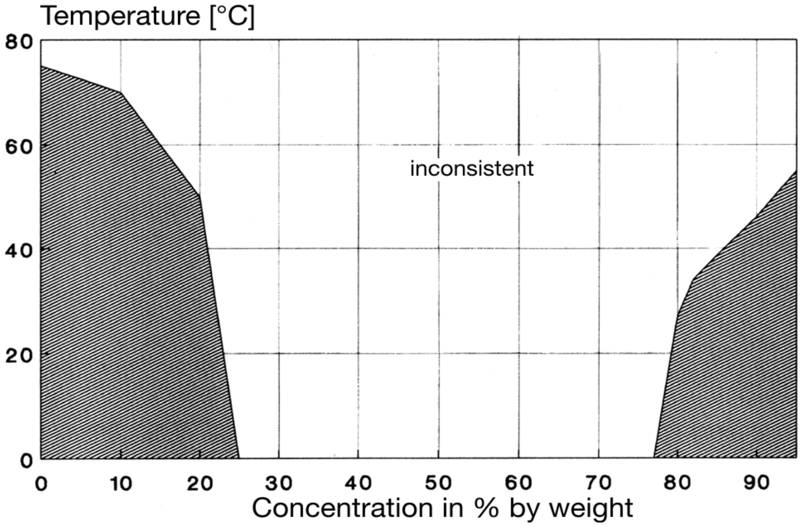


Fig. 53: Iso-corrosion diagram

8.4.2 Protection tubes for melts

With metal protection tubes for melts, the redox potential of the melt and its constituents is the determining factor on whether or not, and to what extent, corrosion of the protection tube will occur. The boundary surface between melt and air is particularly critical, as the slags found here have a strong oxidizing effect. So, in some cases, suitable measures must be taken to prevent the protection tube coming into contact with the slag. Ceramic tubes are suitable for this, or graphite tubes for non-ferrous melts; the tubes are inserted through the slag. The metal protection tube of the thermometer is then inserted through one of these ceramic or graphite tubes, so that it extends into the melt without coming into contact with the slag.

Surface coatings can improve the corrosion resistance of metal protection tubes. Common coating materials are enamel, plastic and metal.

Electroplated coatings, such as nickel, chromium or zinc plating, improve the chemical resistance. However, damage to the surface coating leads to increased corrosion of the underlying material due to the formation of local electrochemical cells. Particular account should be taken of this effect with chromium-plated steel. To some extent this offsets the advantage of the surface coating, and it can be more advantageous to use stainless steel.

Nickel coatings on copper or brass prove to be much more durable and less susceptible to crevice corrosion, as the base material and the coating are more alike electrochemically. Wherever possible, the coating should be of the same material as the vessel in which the fitting is installed. Otherwise local electrochemical cells can be formed at the fixing points, resulting in increased corrosion. In cases where the protection provided by such metal coatings is inadequate, a plastic coating should be used instead, provided that the temperatures that occur will allow this.

Enamelled tubes have a very high chemical resistance and are also not attacked by hot acids. They are used in flue gas measurements and other corrosive environments. Compared with other coatings, enamel has the disadvantage that it is brittle and tends to chip off if the protection tube bends, or when it is subjected to notching loads due to sharp, hard objects.

8.4.3 Organic coatings

Corrosion resistance can be improved not only by inorganic coating (electroplating), but also by plastic coating. The following materials are examples taken from the multiplicity of such polymers:

Hostaflon (Hoechst AG) is a thermoplastically workable fluoroplastic suitable for operating temperatures from -200°C to +150°C.

Wema-Kor is an organic coating material based on fluorine with metallic constituents, and permits operating temperatures up to 300°C. The coating is extremely weatherproof and proof against salt water spray, up to ten times better than galvanized zinc or chromium plating. The thickness of the coating is usually only 12 to 15µm, so that the dimensions of the component are very largely unchanged. Threads do not need to be recut, so the plastic prevents any binding of the thread due to rust. Because of its high weather resistance, Wema-Kor is very widely used in the automobile industry.

The material is resistant to most dilute inorganic acids and alkalis, dilute organic acids, vegetable and mineral oils, benzines and the higher alcohols, foodstuffs and cosmetics. It has limited resistance to solvents such as esters, chlorinated hydrocarbons and aromatics, organic bases and concentrated fatty acids. The material is not resistant to ketones, aldehydes, methanol, concentrated nitric, sulfuric and hydrochloric acids, and nitrous gases at high concentrations.

Halar (ethylene-chlorotrifluoroethylene or ECTFE), registered trademark of Allied Chemical Corp., is a plastic with outstanding chemical resistance in both the acidic and alkaline range. Up to 120°C the material is inert against any known chemical [21]. The maximum continuous operating temperature is about 160°C, and embrittlement only occurs below -76°C. The coating thickness used varies between 600 and 800µm, but can be as much as 1.4 mm; the minimum thickness is 300µm. Halar is not susceptible to stress crack formation, and has other outstanding features such as high ductility, abrasion resistance, elasticity and impact resistance. It is regarded as physiologically safe [6].

8.4.4 Ceramic protection tubes

Because of their relatively poor mechanical properties, ceramic protection tubes are only used when the measurement conditions preclude the use of metal fittings, either for chemical reasons or because of elevated measurement temperatures. Their main applications are in the range from 1000 °C to 1800 °C. They can either be in direct contact with the medium or can be used as a gas-tight inner tube to provide a hermetic separation between the thermocouple and the metal protection tube itself. Above 1200 °C they must be mounted suspended, so that they do not buckle or break due to bending loads. Even hairline cracks can lead to contamination of the thermocouple, and consequent drift.

The resistance of a ceramic to thermal shock increases with increasing thermal conductivity and tensile strength, but decreases with increasing thermal expansion coefficient. The wall thickness of the material is also important here; thin-walled tubes are preferable to those with thick walls.

Cracks often occur when the protection tube is subjected to a rapid change in temperature, when they are withdrawn from a hot furnace too quickly. So it is advisable to use an inner and an outer tube of gas-tight ceramic. Here the outer thin-walled tube protects the inner tube from thermal shock, as there is a insulating layer of air between them. This increases the service life of the thermometer, but only at the expense of a longer response time.

With noble metal thermocouples, increased demands are made with regard to the purity of the ceramic: platinum thermocouples are very susceptible to contamination by foreign atoms, particularly those of silicon, arsenic, phosphorus, sulfur and boron. So, with fittings for high-temperature measurements, it is important to ensure that, wherever possible, the insulation material and the protection tube material do not contain any of the elements named. In this connection, SiO_2 must be regarded as particularly harmful. The ageing caused by it appears to be set off, not by the silicon dioxide itself, but rather by accompanying iron contaminants [4]. In neutral and reducing atmospheres, the rate of contamination is much faster; this is thought to be caused by the SiO_2 being reduced to SiO, which then reacts with the platinum to form Pt_5Si_2. In reducing atmospheres, even 0.2 % SiO_2 in the insulation material or the protection tube material is sufficient for the formation of such brittle silicides [4].

For these reasons, protection tubes that are permeable to gas cannot be used in reducing atmospheres, as in annealing furnaces, for example, but they are permissible in an oxidizing atmosphere or in a protective gas. If a gas-tight ceramic inner tube is used, the outer tube can well be permeable to gas.

During the installation of the unprotected platinum thermocouple, particularly the part exposed to the measurement temperature, extreme cleanliness must be maintained, for the reasons outlined above. Grease and oil residues (sulfur), sweat on the hands (NaCl, KaCl, CaCl), or metallic contaminants (abrasive particles, corroded tools) must be strictly avoided.

In the high temperature region, the insulation properties of the material used are important too. Aluminum oxide and magnesium oxide start to conduct markedly at temperatures above 1000 °C. Beryllium oxide offers better insulating properties, but its toxicity can cause problems in some applications. Because of this, four-bore rods made of KER 710 (see Chapter 8.4.5) are used. The insulation behavior of ceramics is primarily determined by their alkali content; ceramics with a high alkali content start to conduct electrically at a comparatively low temperature of around 800 °C. Pure aluminum oxide ceramics have the best insulation properties.

8.4.5 Ceramic insulation materials

The next section introduces two ceramic materials whose properties are laid down in DIN 43 724. They are both gas-tight ceramics. The standard also lists the porous ceramic KER 530, but this material is of decreasing importance, as a gas-tight inner tube is always required with platinum thermocouples.

KER 710 (Alsint 99.7)
This is a pure oxide ceramic made up of more than 99.7 % Al_2O_3 together with traces of MgO, Si_2O and Na_2O, fire-resistant up to 1900 °C and with a melting point of 2050 °C. It is the best ceramic material available, with an insulation resistance of $10^7 \Omega \cdot$ cm at 1000 °C, good resistance to temperature changes, because of its good thermal conduction properties and relatively low thermal expansion coefficient of $8 \cdot 10^{-6}$ per °C. The thermal conductivity value, 18 W/m · °C, corresponds to that of stainless steel [22]. Its high mechanical strength (bending strength 340 MN/m^2, **Mohs**' hardness value 9) means that the material is suitable for high-temperature furnaces with reducing atmospheres containing hydrogen and carbon monoxide. KER 710 is even suitable for use in glass annealing lehrs and earthenware firing kilns with alkaline fumes up to 1600 °C, and in molten glass up to 1500 °C [2]. Under conditions of this nature, both the insulation rod and the protection tube must be made of KER 710.

KER 610 (thermometer porcelain, Pythagoras)
This material has a high alkali content (60 % Al2O3, 37 % SiO2, 3 % alkali) and therefore a low insulation resistance of approx. $10^7 \Omega \cdot$ cm at 1000 °C. It cannot be used in reducing atmospheres, because of the high silicon dioxide content. Compared with KER 710, its thermal conductivity is lower by a factor of nine, and its mechanical stability is good - bending strength 185 MN/m^2, Mohs' surface hardness value 8 [22].

The material can be used up to around 1500 °C, although the maximum temperature is reduced considerably with molten metals: tin 600 °C, aluminum 700 °C, brass 900 °C, copper 1250 °C, depending on the degree of purity of the melts [4]. There is a significant price advantage compared to KER 710, with KER 610 being about one-fifth the price.

8.4.6 Special materials

The good properties of ceramics from the point of view of temperature stability and chemical resistance are unfortunately offset by the fact that the material is extremely brittle. So the mechanical strength is clearly less than that of metal protection tubes, and the service life may not always be satisfactory. Protection tubes made of silicon carbide are highly resistant to chemicals. With a maximum temperature of 1100 °C they are especially suitable for molten aluminum, molten aluminum-zinc castings and other non-ferrous metals such as antimony and copper. Their good mechanical properties are clearly superior to those of the clay-graphite tubes that would otherwise be used for these applications, and often permit service lives of up to a year. A gas-tight inner tube of KER 710 is required for the thermocouple. Silicon carbide is, however, strongly attacked by basic slag and gases containing chlorine [2].

Protection tubes made of Cermotherm are suitable for use at even higher temperatures, up to around 1600 °C. This metallic ceramic sintered material consists of 60 % molybdenum and 40 % zirconium oxide. The mixture of an oxidizing with a reducing component makes this material very largely resistant to slags and melts. Because of the high metal content, the thermal and mechanical properties are very good.

The most important applications are in steel, cast iron, copper, brass and zinc melts, as well as in molten salt in case-hardening baths. Cermotherm protection tubes are also suitable for use in molten gold. The maximum temperature is around 1600 °C.

8.5 Operating conditions of protection tubes

The stability of the various metallic protection tubes is described in DIN 43 720, among others; the standard also lays down the dimensions and materials. Combining the information from [1] and [2] with manufacturer's data on the various materials gives the following table. The following lists (see next page) indicate a number of applications for the various protection tube materials, without claiming to be complete. The data are reference values provided without any guarantee of correctness, and do not obviate the need to check the suitability of the protection tube material for the particular operating conditions. The temperatures quoted refer to use without mechanical loading and - unless otherwise stated - to use in clean air. They depend very much on the concentration, the composition and the pH and redox potential of the medium they are used in.

The surprisingly high resistance of CrNi steel to concentrated sulfuric acid up to its boiling point (according to [1]) should be regarded as a relative value only. It only refers to absolutely anhydrous and thus undissociated acid that is reduced to SO_2, whereas in dilute acid the hydrogen is reduced. However, because of the strong hygroscopic capacity of the concentrated acid, the presence of a certain proportion of dissociated molecules should always be assumed.

	CrNi steel	KER 710	Teflon	Halar
conc. acetic acid	-	25°C	118°C	65°C
dil. sulfuric acid	-	25°C	100°C	120°C
conc. sulfuric acid	(330°C)	-	200°C	23°C
dil. hydrochloric acid	-	25°C	100°C	150°C
hydrochloric acid 38%	-	-	25°C	150°C
dil. nitric acid	-	25°C	100°C	150°C
acqua regia	-	-	-	120°C
hydrofluoric acid	-	-	25°C	120°C
aqueuos alkalis	25°C	-	100°C	120°C
conc. alkalis	-	-	-	65°C
dil. = approx. 10 %				from [1] and [6]

Table 21: Operating temperatures of various materials in aqueous solutions

8.5.1 Protection tube materials with melts

A reduced service life must be generally assumed when protection tubes are used in melts. Aluminum oxide ceramics are not resistant to molten aluminum. Slags have a particularly corrosive effect. So the protection tube must always be protected by a graphite or clay sleeve at the air-melt boundary layer (see Chapter 8.4.1).

The data are reference values, to be verified under actual operating conditions if appropriate.

Material	Temp. limit	Protection tube material
alkalis, molten, inorganic	600°C	pure iron
aluminium	700°C	X10 NiCr 32 20[1], SiC, graphite
aluminium containing magnesium	700°C	pure iron[1]
antimony	800°C	KER 710, graphite, SiC
barium chloride	1300°C	NiCr 6015
bearing metal	600°C	St. 35.8[1]
brass	900°C	X10 CrAl 24[1]
cadmium	600°C	graphite
calcium	900°C	graphite
chloride melts (except barium chloride)	no details	X10 CrSi 18[1], X10 CrAl18[1], X18 CrN 28[1], X10 CrAl 24[1]
copper	1250°C	X10 CrAl 24[1], KER 710, graphite
cyanide	950°C	St. 38.5[1], pure iron[1], X10 CrNiSi 20 25[1]
glass	1500°C	KER 710, PtRh30
lead	600°C	St. 38.5[1]
	700°C	St. 38.5 (hard chromium-plated[1]), X10 NiCr 32 20[1], NiCr 60 15[1], graphite, pure iron
lithium	800°C	tantalum
magnesium	800°C	graphite, pure iron
nickel	1600°C	KER 710
nitrate, salt	500°C	St. 38.5[1], pure iron[1]
potassium	1000°C	steel 18/8
silver	1200°C	KER 710
sodium	1000°C	steel 18/8
tin	650°C	St. 38.5[1], KER 710
zinc	480°C	St. 38.5[1], X18 CrN 28[1], X10 CrAl 24[1]
	600°C	pure iron[1], graphite, SiC

Table 22: Protection tube materials with melts

8.5.2 Resistance to gases

Körtvelessy [1] refers to the possibility of using protection tubes made of Inconel 601 (60% Ni, 14% Fe, 23% Cr, 1.4% Al) for bromine, iodine, chlorine, fluorine, carbon monoxide, carbon dioxide and sulfur dioxide, but without specifying an upper temperature limit. Tantalum protection tubes are recommended for gaseous hydrocarbons up to 800 °C, with Incoloy 825 (42% Ni, 30% Fe, 21% Cr, 2.25% Cu, 3% Mo, 1% Ti) tubes recommended for hydrogen fluoride. Provided that the mechanical conditions and required response time allow it, protection tubes made of KER 610 can also be used. In reducing gases, heat-resistant steel can also be used in the range from 900°C to 1400°C. Embrittlement occurs if the material is used below 900°C.

Ferrous protection tubes are at serious risk in carburizing and nitriding gases at higher temperatures. Materials with a high nickel content, such as Inconel 600, are better under such circumstances. Ceramic materials are also basically suitable. DIN 43 720 gives the relative resistance of those protection tube materials specified in the standard to sulfurous and nitrogenous gases and to carburization, together with the operating temperatures in air.

Inert protective gases such as argon have no effect on either the thermal material or the protection tube. The same applies for use in vacuum. So, in theory, a protection tube is not really necessary - disregarding any mechanical considerations. However, contaminants that are always present in the inert gas or in the furnace atmosphere can gradually contaminate platinum thermocouples. So a protection tube should be fitted or an M.I. thermocouple used if at all possible. Protective gases of pure hydrogen are harmful to noble thermal materials, so gas-tight ceramic protection tubes must always be used. The hydrogen permeability of high nickel-content alloys described elsewhere must be taken into account here; gas-tight ceramic tubes are recommended.

Material	Limit	Resistant to
Bronze CuSn6 F41 Mat.Ref. 2.1020.26	700°C	weather-resistant to industrial and marine atmospheres, neutral water and sea water, steam, sulfur-free fuels, alcohols, freon, frigen, solvents such as acetone, turpentine, toluene.
Brass CuZn Mat.Ref. 2.0321.30	700°C	neutral water, neutral air, frigen, freon, alcohols, acetone, toluene
Copper SFCu F30 Mat.Ref. 2.0090.30	300°C	industrial atmospheres, low-salt drinking and industrial water, neutral steam, alcohols, frigen and freon
Steel St. 35.8[1] Mat.Ref. 1.0305	570°C	water in closed systems, neutral gases
Enameled steel St. 35.8 Mat.Ref. 1.0305	600°C	water and steam, hot acids and fumes, flue gas, sulfurous fumes and gases, molten lead, tin and zinc, alkaline solutions and melts, benzene
Pure iron[1]		molten metals and salts
Steel 13 CrMo44 Mat.Ref. 1.7335	600°C	steam, nitrogen; similar to St. 35.8, but higher mechanical and thermal strength
Stainless and acid-resistant steel X6 CrNiTi810 Mat.Ref. 1.4541[1]	800°C	low-chloride water, steam, foodstuffs, greases, cleaning agents, soaps, organic solvents, chloroform, crude oil processing, petrochemicals, diesel exhausts, hot carbon dioxide, both dry and moist
Stainless and acid-resistant steel V4A X6 CrNiMoTi17122	800°C	similar to Mat.Ref. 1.4541. Better resistance to chloride-containing solutions and non-oxidizing acids (except hydrochloric acid), chemical fumes, apart from hot hydrogen sulfide and moist sulfur dioxide

Heat-resistant steel X10 CrAl24	1150°C	sulfurous gases under oxidizing and reducing conditions
Steel, Mat.Ref. 1.4762[1]	900°C	carbonaceous gases, molten brass and copper, molten chloride salts
Inconel 600 NiCr15Fe Mat.Ref. 2.4816	1150°C 550°C 590°C	reducing atmospheres sulfurous atmospheres chloride-free steam
Cermet Cermotherm 2040	1600°C	molten steel, cast iron, copper, brass, zinc, gold, molten salts in hardening baths
Ceramic KER 530	1600°C	all gases, requires gas-tight inner tube
Ceramic KER 610	1500°C	all gases, free from fluoric acids and alkaline fumes
Ceramic KER 710	1500°C	molten metal (free from phosphoric and boric acid) except aluminium, molten glass. Used in kilns for earthenware. Resistant to fluoride fumes, hydrofluoric acid.
Silicon carbide SiC	1500°C	molten metal for aluminium sand casting, aluminium-zinc die casting, molten copper and antimony, acids and alkalis, hydrofluoric acid
1. to DIN 43 720		

The data are reference values, to be verified under actual operating conditions if appropriate.

Table 23: General conditions for the use of protection tube materials

9 Explosion-proof equipment

In process control, applications are repeatedly encountered where the temperature probes are installed directly in explosive atmospheres. Certain safety precautions must be taken to avoid an explosion both during normal operation and in the event of a fault. To this end, compliance with EC Directive 94/9/EC (ATEX 95) becomes mandatory in the European Community with effect from July 1st 2003. This directive lays down the essential requirements for the design, production, testing and quality assurance of explosion-proof equipment.

For an explosion to occur at all, three conditions must be fulfilled simultaneously:

- source of ignition (heat, radiation, spark),
- oxygen,
- flammable substance (gas, dust, liquid).

Consideration of these criteria leads inevitably to the following measures to prevent an explosion:

- potentially explosive mixtures must be avoided,
- the volume of the mixture must be restricted,
- ignition must be prevented.

The avoidance of an ignition must be considered during the design of the equipment, by making the space in which a potentially explosive mixture collects very small, for example, or by keeping the activation energy of a possible ignition spark low, or by restricting the explosion itself to a small space. In this connection, it should be noted that possible sources of ignition are not restricted to simply flames or sparks; a hot surface is also a possible source.

In Europe, electrical equipment is classified in two groups. Group I covers use in mines (underground). Group II covers all other areas (mills, refineries, chemical plant). Because there are so many flammable gases and vapors, and the ignition energy to cause an explosion varies, explosive materials are further subdivided into additional groups (IIA, IIB, IIC).

Explosion group	Ignition energy	Test gas	Application
I	<200 µJ	Methane	Firedamp protection
IIA	<200 µJ	Propane	
IIB	< 60 µJ	Ethylene	Explosion protection
IIC	< 20 µJ	Hydrogen	

Table 21: Group classification of explosive substances

To assess the danger posed by flammable substances, there is a further classification according to the ignition temperature and the instantaneous ignition capacity. The ignition temperature is the lowest temperature of a heated surface at which the flammable mixture just ignites (sources of ignition are, for example, hot surfaces, flames, sparks produced electrically or mechanically, light radiation, shock waves, chemical reactions).

For this reason, gases and vapors are divided in temperature classes and the equipment assigned accordingly. The maximum surface temperature of a device must always be lower than the ignition temperature of the hazardous mixture present.

Ignition temperature/°C	**Temperature class**
>450	T1
>300	T2
>200	T3
>135	T4
>100	T5
> 85	T6

Table 22: Division of the temperature probe classes according to EN 50 014

	T1	**T2**	**T3**	**T4**	**T5**	**T6**
I	methane					
IIA	acetone ethane ethyl acetate ammonia benzene acetic acid carbon monoxide methanol propane toluene	ethanol i-amyl acetate n-butane n-butyl alcohol	gasoline diesel fuel aviation fuel fuel oil n-hexane	acetaldehyde ethyl ether		
IIB	town gas (coal gas)	ethylene				
IIC	hydrogen	acetylene			carbon disulfide	ethyl nitrate

Table 23: Division of gases and vapors in accordance with the temperature of the igniting surface

Hazardous areas are divided into zones according to the likelihood of a hazardous atmosphere occurring:

- **Zone 0** covers areas where hazardous, potentially explosive atmospheres are present continuously or for long periods.
- **Zone 1** covers areas where it must be assumed that hazardous atmospheres occur occasionally.
- **Zone 2** covers areas where it must be assumed that hazardous atmospheres only occur rarely and then only for a short time.

The plant operator is responsible for assigning the appropriate zone division.

9.1 Types of ignition protection

Explosion protection for equipment can be provided by various design features. The type of ignition protection generally used in the measurement and control field is the “i” type, described below. EN 50 014 lays down the general requirements for all types of ignition protection. The special features of the individual types of ignition protection are also described in turn in additional standards (EN 50 015 to EN 50 020).

9.1.1 Intrinsic safety “i” protection to EN 50 020

This type of ignition protection is not restricted to the design features of the electrical equipment itself, but also applies to the complete circuit that is used in the hazardous area. A circuit is intrinsically safe when no spark or thermal effect can occur (in normal operation or in the event of a fault) that could cause an explosion. In other words, if a short circuit occurs in the circuit it must not give rise to a spark, nor should the current flowing cause the equipment to heat up above the specified temperature class limit.

For a circuit to be designated as intrinsically safe, every device in the circuit must be of intrinsically safe design. In addition, a check must be made to ensure that, when the intrinsically safe devices are interconnected, the overall arrangement also fulfils the requirements for an intrinsically safe circuit. Simply interconnecting any intrinsically safe devices does not in itself guarantee an intrinsically safe circuit.

9.1.2 Temperature probes and explosion protection

Electrical equipment used in hazardous areas and category M1 or 1 (Zone 0) and M2 or 2 (Zone 1) and associated equipment used outside these hazardous areas must undergo an EC type examination. A notified body appointed by the EU member states carries out the required tests, and checks for compliance with the appropriate standards. In addition, manufacturers must undergo regular monitoring audits covering production of these devices; the audit is carried out by a notified body. JUMO holds this certification, and is therefore allowed to produce type-approved equipment in accordance with the European Directive.

Correct use of the devices and associated equipment are basic prerequisites for explosion protection. For this, both the specific requirements for the design, selection and installation of electrical equipment in hazardous areas (e.g. EN 60 079-14), and the manufacturer’s information (EC type examination certificate, marking on the device, associated operating instructions etc.) must be observed.

9.2 The intrinsically safe circuit

To clarify the definition once again: the intrinsically safe circuit is designed such that no explosion can take place. The stored energy (e.g. capacitances, inductances, power supplies) is not sufficient to produce a spark under short-circuit conditions. Furthermore, the increased temperature of the component due to the flow of current (even in the event of a fault) is below the applicable ignition temperature.

This results in some important parameters, that characterize an intrinsically safe circuit:

- capacitance,
- inductance,
- maximum voltage,
- maximum current,
- maximum power,
- self-heating behavior,
- static charge.

9.3 Interconnection of electrical equipment

Installations often consist of only two devices connected in the circuit; the intrinsically safe device (transmitter, sensor) and the associated equipment (interface). In this simple case it is really easy to check the intrinsic safety: the values in the certificates of conformity are compared and the operator/installer furnishes the proof of intrinsic safety on this basis.

In the simplest case, one device (switch, thermocouple, Pt 100) is located in the hazardous area. For this simple device, any possible energy store (indicator), together with the insulation to earth and to other explosion-proof intrinsically safe circuits must be taken into account. The materials used must be in accordance with EN 50 014 (magnesium content ≤ 6 %, surface resistance $\leq 10^9 \Omega$).
In addition, a temperature class must be defined and a statement made regarding surface temperature. If the connected device (transmitter, controller, etc.) gives out a certain power in either normal operation or on fault, this can lead to unacceptably high self-heating at the surface and thus cause an explosion.

Under normal circumstances, a resistance thermometer is operated with a measurement current that causes negligible self-heating. However, if a fault occurs in the connected electronics, a situation can arise where an unacceptably high current flows through the thermometer. The self-heating increases, and the permissible temperature of the selected temperature class is exceeded. Tests are carried out under certain measurement conditions, to determine a protection tube constant for the particular thermometer. The maximum surface temperature can then be calculated using this constant together with the technical data of the connected electronics.
For a protection tube constant SK, the following relationship applies:

Formula 32:

$$T_S = T_K - (P_i \cdot SK)$$

T_S	maximum permissible temperature at the probe tip
T_K	maximum permissible temperature dependent on the temperature class
P_i	power of the certified intrinsically safe circuit
SK	protection tube constant; external thermal resistance of the probe (probe surface to surroundings)

Example:
A thermometer has a protection tube constant of 66°C/W.
This gives the following relationship:

Formula 33:

$$T_S = T_K - (P_i \cdot 66\ °C/W)$$

If a maximum power of 0.75W occurs in the intrinsically safe circuit and the temperature probe is to be suitable for temperature class T4, a value of 130°C = 135°C (limit T4) - 5°C (safety margin) must be used for T_K. This gives a maximum temperature at the probe tip of T_S = 80.5°C. If a higher temperature needs to be measured, then suitable electronics must be selected which supply less power under fault conditions. In this context, it should be pointed out that with the JUMO dTRANS T01 transmitter, the maximum power given out on fault is only 11mW. At this power level, the measuring insert of a typical process control resistance thermometer heats up by less than 1°C.

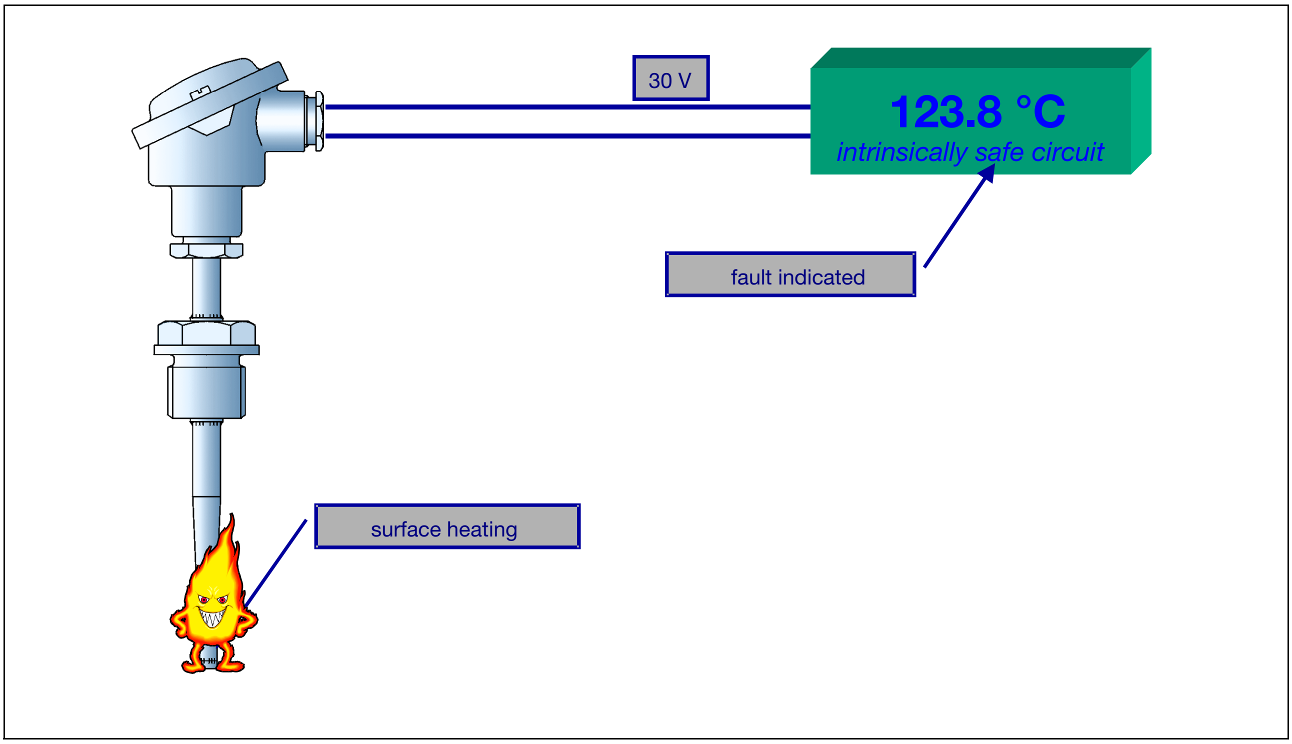


Fig. 54: How a critical surface temperature is reached

When an intrinsically safe transmitter is fitted in the terminal head of a thermometer, it must be ensured that, in the event of a fault, the limits for the transmitter in the terminal head are complied with in the same way. The interior of the terminal head heats up due to the power dissipation in the transmitter. In addition, heat flows into the terminal head via the protection tube of the thermometer, and this too increases the internal temperature.

Depending on the ambient temperature around the terminal head, and taking into account the applicable temperature class of the transmitter, this elevated temperature in the head can then be used to determine whether the limit is complied with, and thus whether the transmitter can safely be used in hazardous areas.

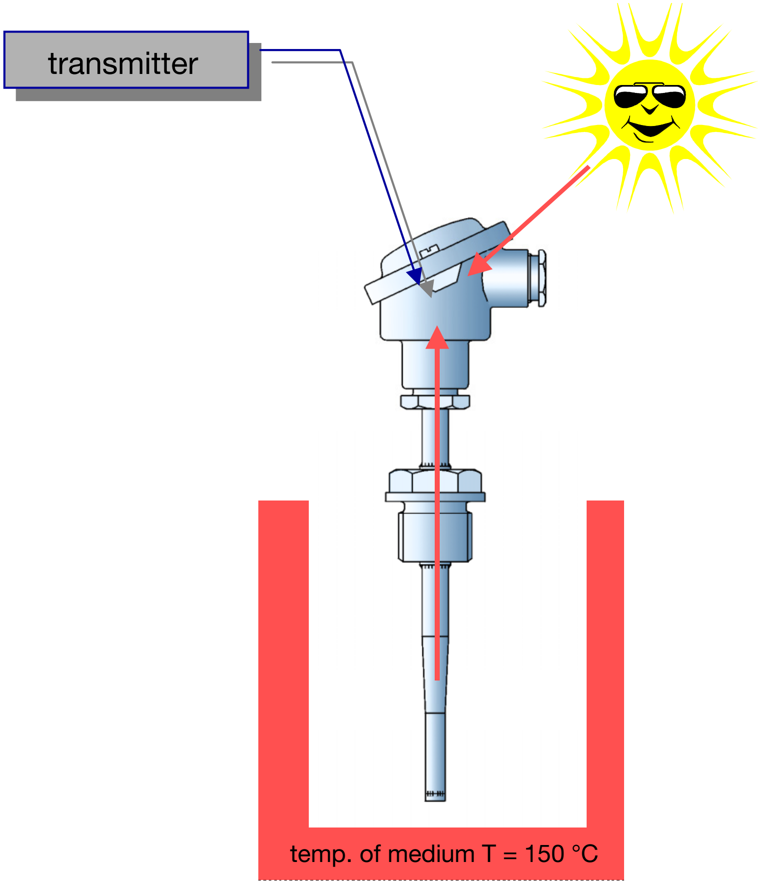


Fig. 55: Electrical thermometer with transmitter

When a transmitter is connected to an interface module, the values of V_0 (V_k), I_0 (I_k), and P_0 (P_{max}) are compared with those of V_i (V_{max}), I_i (I_{max}) and P (P_{max}) (previous nomenclature shown in brackets). To prove the intrinsic safety, the following initial checks are made:

- $V_0 \leq V_i$ and
- $I_0 \leq I_i$ and
- $P_0 \leq P_i$.

If these conditions are fulfilled, the values of $L_0(L_a)$-/$C_0(C_a)$ are then compared with those of L_i/C_i. The following conditions apply:

- $C_i \leq C_0$ (C_a) and
- $L_i \leq L_0$ (L_a).

Because the cable also has a certain value of inductance and capacitance, L_i/C_i must be considerably less than L_0/C_o. Provided that there are no more energy stores in the circuit, the resulting cable length (l_{cable}) can now be determined, based on the L/C values per km. Normally the capacitance is the critical factor here.

- $C_{cable} = C_o - C_i$
- $C_{overlay}$ = e.g. 120nF/km
- $l_{cable} = C_{cable}/120$ [km]

The same approach is also used for inductance L; the lower of the two values obtained for l_{cable} is the allowable cable length. If there are additional inductances L´ or capacitors C´ (filter, indicator) in the circuit, they must be taken into account using the approach outlined above:

- $C_{cable} = C_o - C_i - C´$ and
- $L_{cable} = L_o - L_i - L´$

Very rarely, concentrated capacitances and inductances are present simultaneously:

- maximum permissible voltage,
- maximum permissible current,
- maximum permissible power,
- energy store
  - internal capacitance data
  - internal inductance data,
- materials,
- surface resistance,
- insulation and clearance distances to the intrinsically safe circuit,
- self-heating behavior/temperature class.

All these points are design criteria that must be checked for each version of a thermometer. A type test must be carried out here to determine the self-heating behavior and the maximum permissible values for voltage, current and power.

JUMO provides a comprehensive range of probes that are approved in accordance with the new European Directives, and are delivered together with a certificate of conformity.

10 The measurement uncertainty

When the word uncertainty is used in everyday speech, it does not convey any sense of trust to the people involved. However, the situation is somewhat different when it is used in a technical context. Only a statement of the measurement uncertainty in conjunction with a measurement result can inspire trust and confidence in the measurement process performed. The knowledge of the measurement uncertainty lends quality and trust to the result. No measurement process is completely free from shortcomings and random variations. When a measurement is repeated several times under identical measurement conditions, the results obtained are not all exactly the same. The causes include short-term variations (ambient temperature, mains supply), the performance level of the observer (manual reading of instruments), systematic effects, zero error, drift of the standard value or uncertainty of a reference value.

The correct value of a measured variable can only be determined with an ideal measurement system. This correct value is referred to as the “true value” and is never known, as each measurement system has its shortcomings and is subject to variations. The aim of each measurement process is to obtain a measurement result that approaches the true value as closely as possible. If the measurement is repeated several times under identical conditions, and assuming that no systematic error is present, the mean value comes closer and closer to the true value. In the limiting case, where the measurement series has an infinite number of measurements, the mean value agrees with the true value.

In principle, the measurement uncertainty is made up of two different components:

Systematic measurement deviations

- Systematic deviations are present when the magnitude and sign of the measurement error determined under identical measurement conditions are the same each time. Systematic measurement deviations can be forecast and corrected.

- Example:
  According to the calibration certificate, a calibrated measurement system has an indication error of -0.3°C at 100°C -> the indicated value of the instrument can be corrected by +0.3°C at the point of use.

Statistical measurement deviation

- These are random deviations that cannot be corrected. The magnitude can be determined by performing multiple measurements under identical measurement conditions. As a general rule, random measurement deviations follow a normal distribution about a mean value. 68.3% of all measured values lie within the standard deviation of the normal distribution. Double the standard deviation (K = 2) gives rise to a probability of 95.4%.

10 The measurement uncertainty

10.1 The measurement process

In 1992, the concept of measurement uncertainty was newly created by the ISO/BIPM “Guide to the expression of uncertainty in measurement” (abbreviated to GUM in the following Chapter). Since then, this has been internationally acknowledged as the basis for determining the measurement uncertainty.

In general, with any measurement, a number of limiting quantities each play a part in reproducing the measurement result Y via a functional relationship.

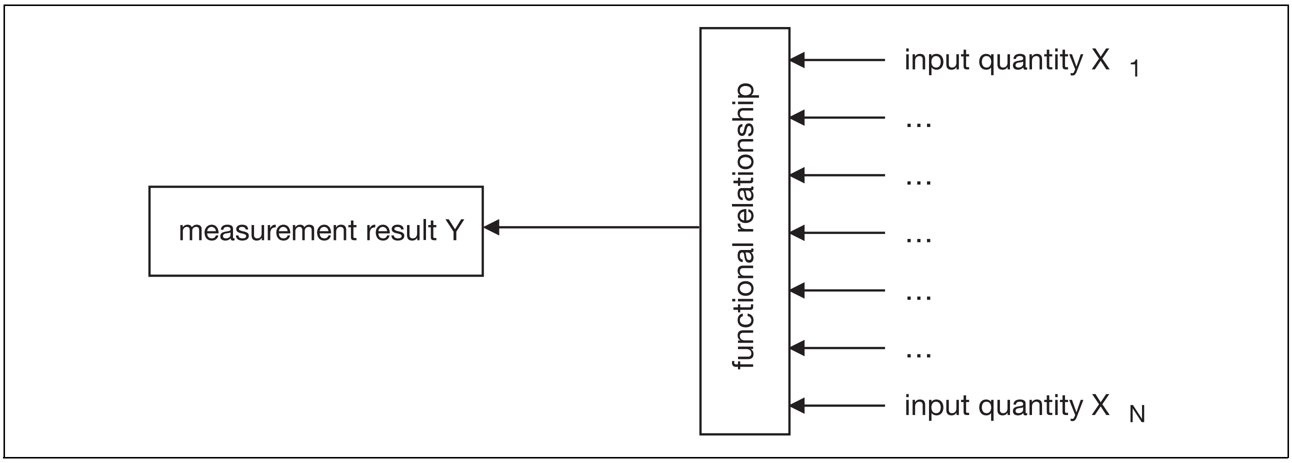


Fig. 56: The measurement process

Each small deviation of the input quantities X_i (i = 1,… ,N) affects the result Y in accordance with the associated sensitivity of the functional relationship. When considering measurement uncertainty it is therefore important to define the relationship between the input quantities and the measurement result as a function.

10.2 The simplistic approach: uncertainty interval

The measurement uncertainty is a characteristic value obtained from a large number of measurements; together with the measurement result, it indicates the range of the values that can be regarded as consistent values, taking into account the measurement conditions.

The simplistic approach to measurement uncertainty regards the entire range of consistent values as an uncertainty interval, without any weighting of the values contained within the range.

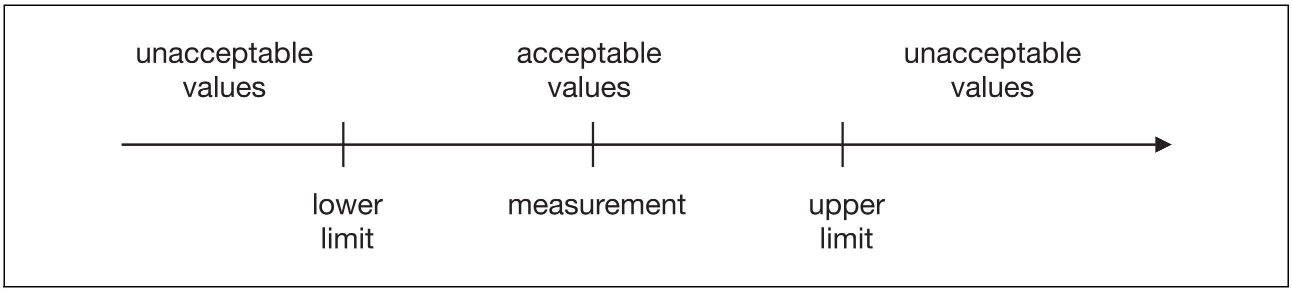


Fig. 57: The uncertainty interval

This approach to the measurement uncertainty is acceptable for measurements where only a few limiting variables occur in the correlation. The simplistic approach to measurement uncertainty is therefore only meaningful for certain rather approximate class divisions. It does not form a basis for a comprehensive quality measurement.

However, a major problem with the simplistic approach is already evident: proving that a value complies with a specification. If the measurement uncertainty is included with an uncertainty interval, this gives rise to a uncertainty range (or better still, indifference range), in addition to the ranges of compliance and non-compliance. There is only clear compliance or non-compliance when the measured value lies in the corresponding ranges. Values in the uncertainty range must be specially assessed.

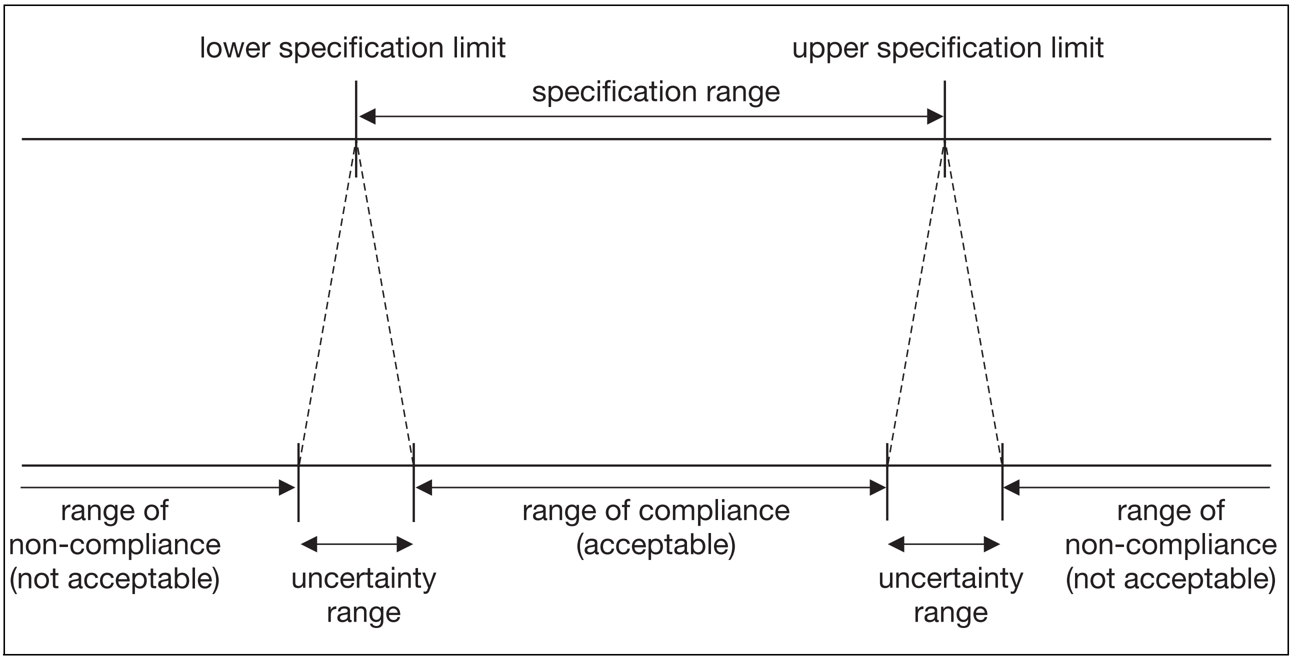


Fig. 58: Ranges of compliance and non-compliance of a measured value with a specification

10.3 The GUM approach: standard measurement uncertainty

The GUM provides a different way of approaching the measurement uncertainty. The declaration of an uncertainty interval is too global. It takes no account of the fact that not all values consistent with the measurement conditions have an equal chance of realization. We know from specialized knowledge or fundamental considerations that, in most cases, values close to the middle of the uncertainty interval are more probable than those near the limits. There are also cases where the reverse applies. The GUM assumes distributions, or more precisely, probability distributions of the acceptable values. This becomes clearer if a series of measurements with random variations is performed, and the frequency of the measured value is then plotted against the measured value. Not all measured values occur with the same probability. Measured values close to the mean value are more frequent than values further away from the mean value. The frequency distribution reflects the probability of occurrence of a measured value for the given measurement conditions. The narrower the probability of occurrence, the smaller is the measurement uncertainty of the measuring setup too.

The measured value is the expected value represented by the distribution, the measurement uncertainty assigned to it is the standard deviation. It is given by the positive square root of the variance: The mean value of the individual values is quoted as the expected value of a series of measurements. From this we have the following:

Formula 34, mean value:

$$x_0 = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Formula 35, empirical variance (standard uncertainty):

$$u(x_i) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - x_0)^2}$$

Statistical examination shows that approximately 68.3 % of all measured values lie within the interval of the standard uncertainty about the mean value. To put this another way, if a measurement is repeated under the same measurement conditions, there is a 68.3 % probability that the measured value will once again fall within the interval whose width is that of the standard uncertainty about the mean value.

To determine the standard measurement uncertainties that are assigned to the input quantities, two types of uncertainty are quoted in the GUM:

Type A should be used when an input quantity is repeatedly observed and where different values are determined (repetition measurement). Statistical methods are then used to evaluate the results. The value is the arithmetic mean of the observations (see Formula 34). The standard measurement uncertainty to be assigned is calculated using Formula 35. A minimum of 20 to 30 observations must be made, so that the standard measurement uncertainty determined represents a statistically reliable value.

Type B should be used when the complete value of an input quantity, i.e. its measured value and assigned measurement uncertainty, is known, or when a specific distribution can be assumed on the basis of experience with previous measurements. In the first case, the measured value and the assigned measurement uncertainty are given directly and can be adopted. The assigned expanded measurement uncertainty is stated in the calibration certificate; the standard measurement uncertainty is obtained by dividing the expanded measurement uncertainty by the coverage factor provided. If a specific distribution can be assumed, as is the case with the resolution of a digital instrument, the standard deviation is determined using the appropriate formula. A typical Type B case is the declaration of a measurement uncertainty in the data sheet. The only certain knowledge here is that the measured value is located within the declared interval. The probability of whether the measured value occurs in the middle of the interval or at its outer edge is not known.

The three most important distribution functions for the probability of occurrence are:

- the rectangular (or uniform) distribution,
- triangular distribution,
- normal distribution.

10.3.1 The rectangular distribution

When the only information available is the interval within which all measured values can fall, a rectangular distribution must be assumed. This means that the probability of the measured values lying within the interval is constant; outside the interval, the probability of occurrence is zero. Examples of this type of distribution are the statements made in data sheets.

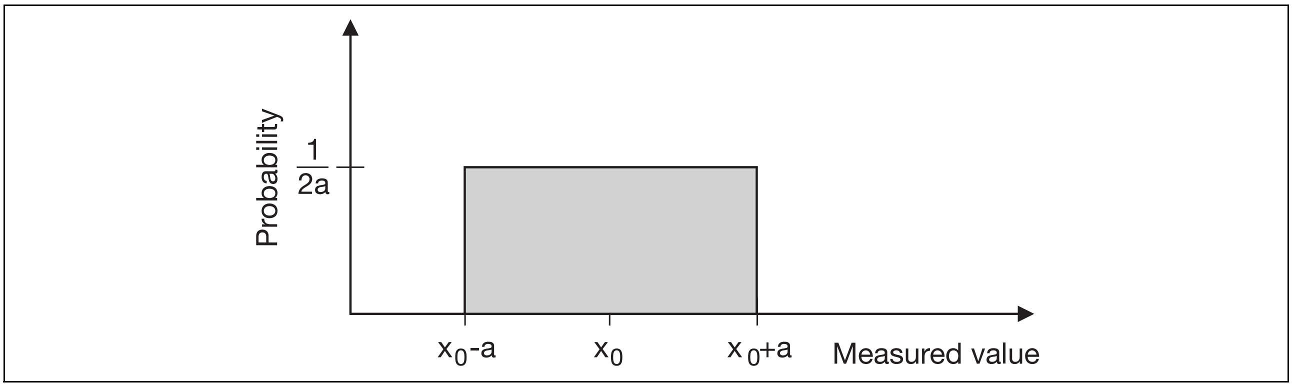


Fig. 59: Rectangular distribution

The standard uncertainty u is calculated from the interval width a as follows:

Formula 36

$$u = \frac{a}{\sqrt{3}}$$

This standard uncertainty indicates the interval in which 68.3 % of all measured values occur.

10.3.2 The triangular distribution

The distribution of the values of a sum or difference of two input quantities is more heavily concentrated about the resultant value. This results in the triangular distribution, that arises from the difference of two rectangular distributions with the same half-width. This distribution function should be used, for example, when two measured values are determined with the same instrument.

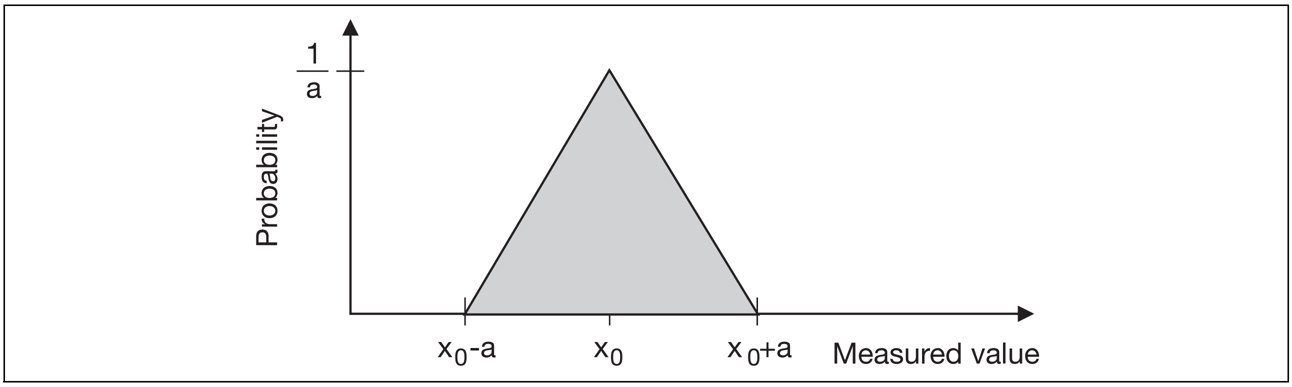


Fig. 59: Triangular distribution

The standard uncertainty u of this distribution is calculated from the interval width a as follows:

Formula 37

$$u = \frac{a}{\sqrt{6}}$$

10.3.3 The normal distribution

If three or more measured values are available, a normal distribution can be assumed as a good approximation. The standard measurement uncertainty u then corresponds to the empirical standard measurement uncertainty, see Formula 35.

10.4 Determining the measurement uncertainty to GUM

Because the measurement uncertainty is always assigned to a measured value, the analysis of measurement uncertainty is inseparably linked with the determination of the measured value. In accordance with the GUM, the measured value is obtained by substituting the values of the input quantities into the model function. Each input quantity also has a standard measurement uncertainty. The sensitivity (susceptibility) for the particular input quantity should be determined from the model equation (note: partial derivation of the functional relationship according to the input quantity). The sensitivity is then multiplied by the standard measurement uncertainty of the input quantity. The square of the standard measurement uncertainty assigned to the measured value is given by the sum of the squares of the uncertainty contributions of the individual input quantities.

Formula 38

$$u(Y) = \sqrt{u_1^2\ (Y) + u_2^2\ (Y) + \ldots + u_N^2\ (Y)}$$

$u(Y)$ = standard measurement uncertainty of the measurement result Y as a function of all input parameters with their measurement uncertainties

$u_i(Y)$ = measurement uncertainty component of the measurement result Y as a consequence of the measurement uncertainty of the input parameters X_i

The standard measurement uncertainty calculated in this way reflects the interval about the mean value that all the measured values will lie within, with a probability of 68.3 %.
OR: there is a 68.3 % probability that if a measurement is repeated under identical conditions, the measurement result will once again lie within this interval.

10.5 Industrial practice: expanded measurement uncertainty

The standard measurement uncertainty is not a suitable parameter for proving that a measured value complies with a specification. It may indicate the quality of a measurement result, but to prove compliance, a range is needed that includes a high proportion of the values that are consistent with the measurement conditions. In industry and commerce, it is standard practice to use the expanded uncertainty, which is derived from the standard measurement uncertainty. It is defined by the coverage factor. The coverage factor is chosen such that the uncertainty interval covers a high proportion of values. The proportion covered is referred to as the coverage probability. This provides another uncertainty interval that can be used for comparison purposes. The advantage here is that the calculation of the measurement uncertainty, via the intermediate stage, uses a method that combines both the frequency statistic and estimate of probability. It has been agreed internationally that a uniform coverage probability of 95 % is to be used to calculate the coverage factor. This gives a value of K = 2 for the coverage factor. The overall measurement uncertainty U of a measurement with a probability of 95 % is obtained by multiplying the standard measurement uncertainty (Y) by the factor 2.

Formula 39

$$U = 2 \cdot u(Y)$$

10.6 Uncertainty components of a temperature measurement system

Basically, when calculating the overall measurement uncertainty of a temperature measurement system, all the individual components (evaluation electronics, indicator, cable, sensor) must be included.

The sensor supplies a temperature-dependent signal that is fed to the evaluation electronics via the cable. The evaluation electronics ultimately converts the signal into either a temperature indication or a current signal. The sources of error of all three components are included in the measurement uncertainty considerations. This means that when transmitters are used, additional uncertainty components arise during the conversion of the signal to a temperature indication.

Formula 40: The model equation/
functional relationship between input quantities and measurement result:

$$I_X = t_m + \sigma M_F + \sigma M_D + \sigma M_A + \sigma M_E + \sigma M_{Th} + \sigma M_{RI} + \sigma R_{AL} + \sigma V + \sigma t_M + \sigma t_W + \sigma_B$$

I_X	output signal (indicated temperature or temperature equivalent)
t_m	temperature at the measurement point
σM_F	measurement signal deviation caused by the heat-conduction error of the thermometer
σM_D	measurement signal deviation caused by the deviation of the sensor as per EN 60 751
σM_A	measurement signal deviation caused by insufficient stabilization
σM_E	measurement signal deviation caused by the self-heating error of the sensor (resistance thermometer)
σM_{Th}	measurement signal deviation caused by thermoelectric emfs (resistance thermometer)
σM_{RI}	measurement signal deviation caused by inadequate insulation resistance (resistance thermometer)
σR_{AL}	variation in the lead resistance (resistance thermometer)
σV	indication deviation of the evaluation electronics caused by supply variations
σt_M	indication deviation caused by fluctuating ambient temperature
σt_W	processing and linearization errors in the evaluation electronics
σ_B	indication deviation caused by the influence of the input resistance (burden)

Heat-conduction error of the temperature probe (σM_F)

The temperature to be measured and thus that of the connecting cables to the probe is generally either above or below the ambient temperature. The temperature gradient within the thermometer causes a flow of heat that leads to cooling or heating of the sensor, and ultimately to an incorrect indication. The major part of the heat is conducted in or out via the connecting cables.

The indication error resulting from this undesired flow of heat is the heat conduction error.

The heat conduction error depends to a large extent on the design features of the thermometer and its insertion length in the measured medium. As a general assumption, if the insertion length is less than 80mm, there will be a heat conduction error. The heat conduction increases with increasing temperature difference between the surroundings and the measured medium.

Measures that the user can take to reduce the heat conduction error:

- avoid additional thermowells,
- choose the largest possible immersion depth (e.g. install the thermometer in a pipe bend),
- install the thermometer at the point with the highest flow rate,

- provide additional thermal insulation on the external parts of the thermometers (e.g. terminal head),
- use a thermometer with a smaller external surface,
- estimate the heat conduction error by reducing the immersion depth by 10%, for example, and observing the temperature indication at the same time.

Deviation of the temperature sensors from the standard characteristic (σM_D)

The evaluation electronics is usually set up for temperature sensors that correspond exactly to the standard characteristics (for platinum resistance thermometers EN 60 751; for thermocouples EN 60 584). However, the sensors very rarely follow the standard characteristic, but tolerance classes are permissible.

The permissible tolerance for a platinum sensor of tolerance class B is calculated from the formula (±0.3°C + 0.005 · T) (T = measured temperature). At 100°C this gives a permissible tolerance of ±0.8°C.
There are two possible ways of restricting this error:

- use closer tolerance classes (tolerance class DIN A gives a permissible tolerance for 100°C of 0.15 °C + 0.0017 · 100°C = 0.32°C,
- enter the characteristic coefficients (R_0, A, B) of the temperature probe into the evaluation electronics (of course, these parameters must be made available). For this, the temperature probe must be measured at at least three temperatures within the measurement range. The measurement uncertainty of the temperature probe is thus restricted to the measurement uncertainty with the temperature measurement.

Stabilization (σMA)

Because of the ever-present thermal resistance, the temperature sensor never immediately takes on the temperature of the medium to be measured - there is always some delay. This delay is determined by the heat transfer coefficients sensor - fill material - metal protection tube - measured medium, and is thus a design parameter of the temperature probe.

The step response provides information on the overall response. As the response time depends to a great extent on the flow rate, the measured medium and the immersion depth, EN 60 751 lays down parameters for recording the step response in air and water. The data sheet for the temperature probe normally gives figures for the half-value time t_{05} (measured value has reached 50% of the final value) and the ninety percent time t_{09} (when 90% of the final value is reached). For measurements in air, t_{09} times of 5 minutes and more are quite possible.

The measures already described for reducing the heat conduction error also lead to a reduction in the response times. In addition, the user must ensure that an adequate stabilization period is allowed before, for example, any measurements are recorded.

Self-heating (σM_E) of resistance thermometers

The measuring current that flows through the temperature sensor produces heat and leads to a systematic higher temperature indication. The power produced here is $P = R \cdot I^2$. Manufacturers usually provide information on this in the form of self-heat coefficients (E_K in mW/°C).

Reducing the measuring current invariably leads to a reduction in self-heating. However, with some commercial instruments, too small a voltage drop across the resistance thermometer leads to an increased measurement uncertainty. The following measuring currents are therefore recommended:

Nominal value/Ω	Measuring current range in mA
100	0.5 - 1.0
1000	0.1 - 0.3

Table 24: Recommended measuring currents for resistance thermometers

The measuring currents quoted are chosen so that the power loss does not exceed 0.1 mW at 0 °C, so the self-heating error can then be neglected in most cases.

The self-heat coefficient depends on the heat transfer coefficient between thermometer and measured medium. For comparison, the manufacturer's data are always determined in a freezing mixture of ice/water (0 °C) with a power loss of 5 mW. This corresponds here to the self-heat coefficient of the temperature sensor, not the complete thermometer.

For a given thermometer current and known self-heat coefficients, the self-heat error is given by:

Formula 41

$$\Delta t = \frac{I^2 \cdot R}{E_K}$$

For a given measuring current, the self-heat error is reduced by using a sensor with a lower nominal resistance.

In addition, the self-heat error can be reduced by ensuring a good heat transfer between the measured medium and the temperature probe (e.g. highest possible flow rate). This means that, particularly with measurements in gases, account must be taken of the self-heat error.

Thermoelectric emfs with resistance thermometer measurements (σM_{Th})

A measuring circuit consists of a chain of different conductor materials. Each junction forms a thermocouple, and a thermoelectric emf is produced if there is a temperature difference between the two junctions (e.g. connections between the 2-core connecting cable and the sensor). In this case, the thermoelectric emf produces an error in the measurement result. Undesired thermoelectric emfs can also occur due to an unfavorable internal construction of the thermometer (e.g. different clearance distances between the junctions and the bottom of the thermometer), or due to enclosed moisture. EN 60 751 specifies a value of <20 µV. With a measuring current of 1 mA, for a resistance thermometer with a nominal value of 100 Ω, this gives the following possible errors:

Measured temperature/°C	Measurement error/°C
0	0.05
100	0.05
200	0.05
500	0.06

Table 25: Systematic errors, caused by thermoelectric emf

Any thermoelectric emfs occurring can be determined by taking two measurements (resistance measurement with a digital multimeter), with reverse polarity measuring current in the second measurement. The bigger the absolute difference between the two indicated values, the higher is the thermoelectric emf in the measurement circuit.

Insulation resistance of the resistance thermometer (σM_{RI})

Inadequate insulation resistance produces a shunt effect at the temperature sensor (parallel circuit), leading to a systematic lower temperature indication. For the same insulation resistance, the measurement error increases with increasing nominal value of the temperature sensor. The manufacturer checks the insulation resistance in accordance with EN 60 751 (minimum requirement 100 MΩ).

The user must prevent any moisture ingress to the input terminals, and any mechanical damage to the connecting cable.

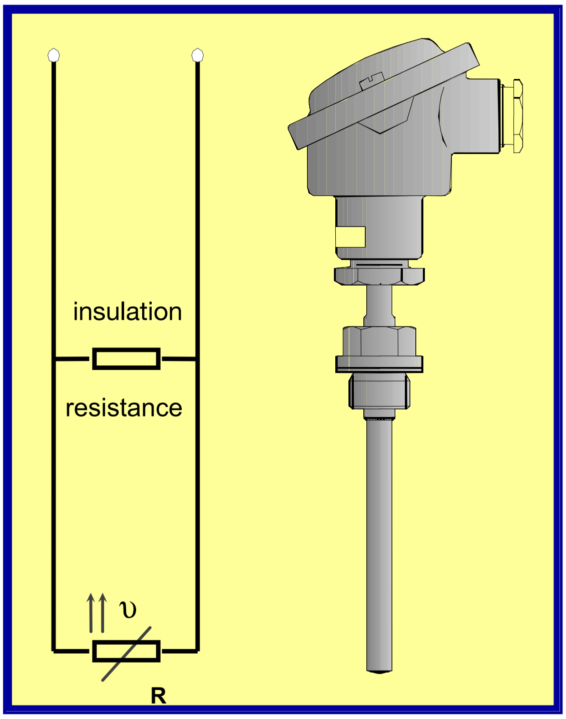


Fig. 60: Equivalent circuit for the insulation resistance inside a resistance thermometer

Sensitivity of the sensor (C_S, C_{S0})
The output signal of the temperature sensor is the resistance (platinum resistance sensor). A change in the output signal leads to a change in the temperature indication corresponding to the characteristic (gradient). This gradient is given by:

t/R (resistance thermometer) $\cong$ $\Delta t/\Delta R$ for small changes

As an approximation, the sensitivities of the standard characteristics of EN 60 751 are used.

Examples:
For a Pt 100 resistance thermometer and a measured temperature of 100 °C, the resistance values are:

R (100 °C) = 138.5055 Ω   R(101 °C) = 138.8847 Ω

➔ $\Delta t = 1\,°C$ and $\Delta R = 0.3792\,\Omega$ ➔ $C_S = 2.637\,°C/\Omega$

Lead resistance of resistance thermometers (σR_{AL})
The effect of lead resistance depends on how the resistance thermometer is connected.

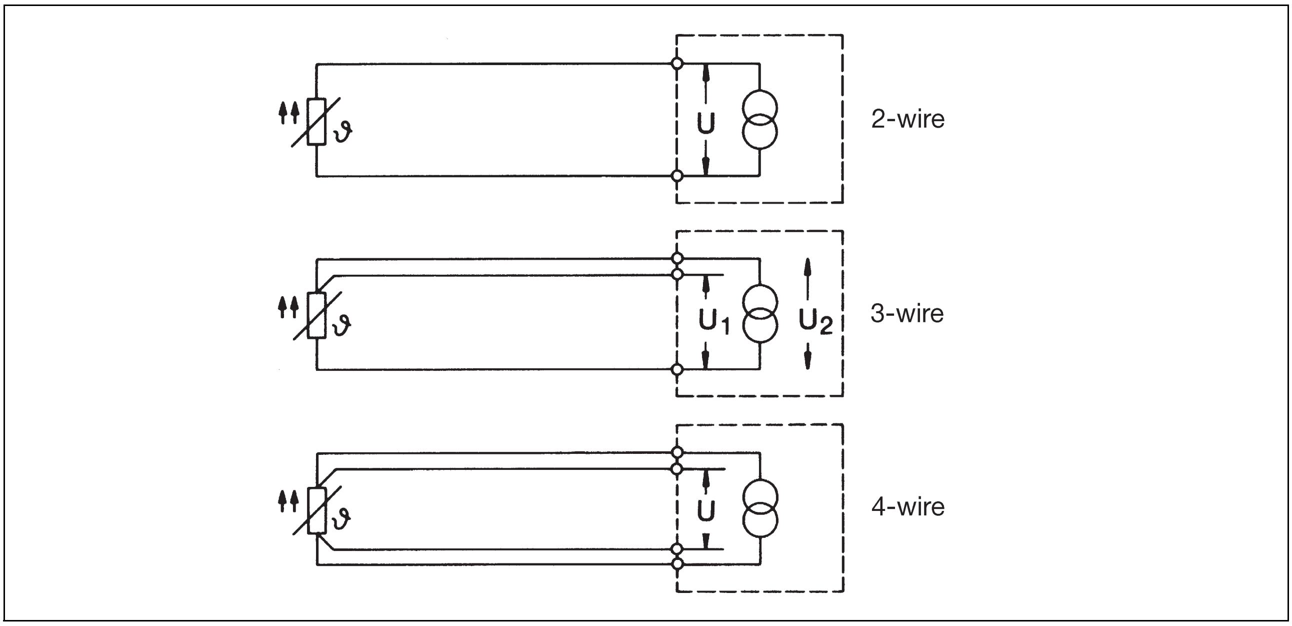


Fig. 61: Various resistance thermometer connections

2-wire circuit

The connection between the resistance thermometer and the evaluation electronics is made with a 2-core cable. The evaluation electronics measures the total resistance, made up of the temperature sensor, internal wiring of the temperature probe (in the protection tube) and the connecting cable, leading to a systematic higher indication. The sum of the resistances of the internal wiring and the connecting cable is therefore subtracted from the measured resistance. However, these resistances vary depending on the manufacturing process, and are exposed to the operating temperature to some extent, so that further uncertainties occur. The user should take particular care to ensure that the connecting cable is not lying on any sources of heat, as this gives rise to an increase in lead resistance. The variation in lead resistance is estimated to be 20 mΩ per meter

3-wire circuit

To minimize the effects of the lead resistances and their fluctuations with temperature, a 3-wire circuit is normally used. For this, an additional lead is run to one contact of the resistance thermometer. This then forms two measuring circuits, one of which is used as a reference. With the 3-wire circuit, it is possible to compensate for both the value of the lead resistance and its variation with temperature. An essential requirement is that all three conductors have identical properties (resistance) and are all exposed to the same temperatures.

4-wire circuit

The measuring current is fed to the thermometer via two supply leads. The voltage drop at the resistance sensor is picked up via the two measuring leads. If the input resistance of the connected electronics is many times higher than the lead resistance, the lead resistance can be neglected.

So, for temperature measurement systems using a 4-wire circuit, the measurement uncertainty for the lead resistance is not applicable.

However, it should be noted that the 4-wire circuit does not always run all the way to the resistance sensor, but often only to the terminal head of the thermometer, with the internal wiring run as a 2-wire circuit. As a result, the same problems are encountered with this connection - although to a much lesser degree - as those described for the 2-wire circuit.

Supply to the evaluation electronics (σV)
The data sheets for transmitters and direct-reading electronic thermometers usually quote a nominal value for the supply and a percentage error in the output signal, referenced to the deviation from the nominal value.

Ambient temperature of the evaluation electronics (σt_M)
An operating temperature is quoted in the data sheets. Once again, a percentage error in the output signal is quoted, referenced to the deviation in operating temperature.

Processing and linearization error (σt_W)
The assignment of the value of the measurement signal to the temperature is usually made with the aid of look-up tables of measured values. The total number of values in the look-up tables is limited by the available memory space. As a result, a linearization error occurs with measured values that fall between the tabulated values, as the characteristic of both resistance thermometers and thermocouples can only be reproduced exactly by using higher-order equations. This proportion of the measurement uncertainty is greater with thermocouples, as the equation is at least a ninth order, and normally a larger temperature range has to be covered by the same number of look-up table values (operating range).

Some indicators offer the possibility of entering the characteristic parameters. The temperature is then calculated accordingly, but rounding errors occur here because of the high order of the characteristic.

In addition, the resolution of the evaluation electronics is limited. The “basic error” with every digital indicator is thus ±1 digit.

Input resistance of the evaluation electronics (σ_B)
The effect of the burden must always be taken into account with transmitters.
The output signal of the transmitter is ultimately fed to the evaluation electronics, whose input resistance must be limited (quoted as the maximum burden in the data sheet), as otherwise the transmitter cannot supply a stable output signal.
Normally, the effect of the burden is quoted as a percentage error in the output signal.

Other sources of error
The following errors can have very complex causes and have not been listed in the model equation of Formula 42. A detailed description is outside the scope of this publication, so the reader is advised to refer to specialist literature at this point. A short listing with brief comments is provided below, to indicate possible problems.

Installation position of the evaluation electronics
The installation position must be as free from vibration as possible. Installation in the vicinity of electromagnetic fields (motors, transformers, etc.) should be avoided. Basically, the recommendations of the operating instructions should be followed during installation.

Mechanical stresses of resistance thermometers
The extent of the change in resistance due to pressure and vibration is heavily dependent on the design of the temperature probe and the type of sensor used. The mounting of the temperature sensors must be designed so that there is no relative movement within the mounting location and no strong acceleration occurs.
Whenever severe mechanical or chemical stresses are anticipated, the manufacturer should always be consulted for advice.

Long-term behavior of resistance thermometers
The accuracy of a sensor over its entire service life is largely determined by the operating conditions (stress due to temperature and pressure changes), the purity of the materials used and its constructional features.

Significant constructional features are, for example:

- thermal expansion coefficients of the materials used,
- mechanical coupling of the temperature-sensitive winding or thin-film layer to the surroundings,
- chemical compatibility of the materials used (when used at higher temperatures).

Drifts are caused primarily by mechanical stresses arising from temperature loadings.

Type tests are carried out on new designs of sensor; during the test, the temperature sensors are subjected to temperature variation loadings between the lower and upper operating temperatures. The measured value at the ice point of water is always used for assessment of the stability.

Worked example
Depending on which standard distribution is assumed, a divisor is produced for the individual measurement uncertainty components, since the data in the calibration certificate and data sheets are designed for K = 2 (95% probability that the measured value will lie within the stated range).

The divisor has a value of 2 for an assumed **Gaussian** normal distribution; for a triangular distribution the value is $\sqrt{3}$. The individual uncertainty contributions arise from the standard measurement uncertainty (estimated value). The sensitivity coefficients stated are used to convert the particular standard measurement uncertainty to the uncertainty contribution for the output signal. The overall measurement uncertainty for K = 1 (68.3% probability of occurrence) is obtained by adding up the squares of the individual values.

Transmitter with resistance thermometer
The overall measurement uncertainty of a JUMO dTRANS T02 programmable transmitter with a Pt 100 resistance thermometer (tolerance class DIN B) at T = 100°C is to be determined. The transmitter has a 4 — 20mA current output, and a temperature range of 0°C to 200°C.

The resistance thermometer is a cable probe, outside diameter 6mm, 2-wire circuit, with an installation length of 30mm and a 3m long connecting cable.

Formula 42**:** Model equation for calculating the measurement uncertainty:

$$I_X = t_m + \sigma M_F + \sigma M_D + \sigma M_A + \sigma M_E + \sigma M_{Th} + \sigma M_{RI} + \sigma R_{AL} + \sigma V + \sigma t_M + \sigma t_W + \sigma_B$$

It is assumed that the temperature at the measurement point is 100.50°C.
The transmitter supplies an output signal of 12.040mA.
The same assumptions have been made for σM_A, σV, σt_M, σ_B as in the example above.

Heat conduction error of the probe (σM_F)
A value of 0.06°C was determined for the heat conduction error of the probe (the difference between the nominal installation length and the fully-immersed condition).

Self-heat error (σM_E)
The transmitter operates with a measurement current of 0.6mA. This gives rise to a power loss of approx. 0.05mW. The self-heat error is thus negligible.

Thermoelectric emf (σM_{Th})
With a possible thermoelectric emf of 20mV (limitation in accordance with EN 60 751, see above) and a measuring current of 0.6mA, a possible error equivalent to 33mΩ can arise at the measured temperature of 100°C (R approx. 138Ω).

Insulation resistance (σM_{RI})
This component can be neglected with the Pt 100, when the manufacturer guarantees an insulation resistance ≥100MΩ (DIN).

Variations in lead resistance (σR_{AL})

Based on a cable length of 3 m and with the usual conductor cross-section 2 × 0.22 mm^2, variations in lead resistance of 20 mΩ should be assumed due to manufacturing tolerances. Furthermore, care must be taken to ensure that the connecting cable is not heated up unnecessarily.

Deviation of the resistance thermometer to EN 60 751 (σM_D)

The deviation limit for tolerance class DIN B is $0.3 + 0.005 \cdot t$; this gives a deviation limit of 0.8 °C for a measured temperature of 100 °C.

Linearization and processing error (σt_W)

According to the data sheet, the accuracy is 0.4 °C.

This gives a measurement uncertainty of 0.46 °C assigned to the measured temperature; for K = 2, the value is 0.92 °C.

Quantity X_i	Distribution	Standard measurement uncertainty u (estimated value)	Sensitivity coefficient C_i	Uncertainty contribution u_i (y)
σM_D	Normal	0.8 °C/2 = 0.4 °C	1.0	0.4 °C
σM_F	Rectangular	0.06 °C/√ 3 = 0.035 °C	1.0	0.035 °C
σM_{Th}	Rectangular	33 mΩ/√ 3 = 19 mΩ	2.637 °C/Ω	0.05 °C
σM_{AL}	Normal	20 mΩ/2 = 10 mΩ	2.637 °C/Ω	0.026 °C
σV	Rectangular	0.004 mA/√ 3 = 0.0023 mA	12.5 °C/mA	0.029 °C
σt_M	Rectangular	0.008 mA/√ 3 = 0.0046 mA	12.5 °C/mA	0.058 °C
σt_W	Normal	0.4 °C/2 = 0.2 °C	1.0	0.2 °C
σ_B	Rectangular	0.008 mA/√ 3 = 0.0046 mA	12.5 °C/mA	0.058 °C
I_X	100.50 °C			0.46 °C

Table 26: Overall measurement uncertainty

11.1 Summary of steel types and their various designations

Mat. Ref.	Designation as per EN 10 088-2	DIN/ SEW	ASTM type	UNS	NF	SIS	BS	CSN	JIS	GOST
1.4301	X 5 CrNi 18-10	17440/41	304	S 30400	Z 7 CN 18-09	2332/33	304 S 31	17240	SUS 304	08 Ch 18 N 10
1.4303	X 4 CrNi 18-12	17440	(305)	(S 30500)	Z 8 CN 18-12		305 S 19		SUS 305	06 Ch 18 N 11
1.4306	X 2 CrNi 19-11	17440/41	304 L	S 30403	Z 3 CN 18-10	2352	304 S 11	17249	SUS 304 L	03 Ch 18 N 11
1.4307	X 2 CrNi 18- 9		304 L	S 30403						
1.4318	X 2 CrNiN 18-7		301 LN		Z 3 CN 18- 07AZ				SUS 301 LN	
1.4401	X 5 CrNiMo 17-12-2	17440/41	316	S 31600	Z 7 CND17-11-02	2347	316 S 31	17346	SUS 316	03 Ch 17 N13 M 2
1.4404	X 2 CrNiMo 17-12-2	17440/41	316 L	S 31603	Z 3 CND17-12-02	2348	316 S 11	17349	SUS 316 L	03 Ch 17 N13 M 2
1.4435	X 2 CrNiMo 18-14-3	17440/41	316 L	S 31603	Z 3 CND17-13-03	2353	316 S 13		SUS 316 L	03 Ch 17 N14 M 2
1.4436	X 3 CrNiMo 17-13-3	17440/41	316	S 31600	Z 6 CND18-12-03	2343	316 S 33	17352	SUS 316	
1.4541	X 6 CrNiTi 18-10	17440/41	321	S 32100	Z 6 CNT 18-10	2337	321 S 31	17247	SUS 321	08 Ch 18 N 10 T
1.4561	X 1 CrNiMoTi 18-13-2	SEW 400	316 L	S 31603						
1.4571	X 6 CrNiMoTi 17-12-2	17440/41	316 Ti	S 31635	Z 6 CNDT 17-12	2350	320 S 31	17848	SUS 316 Ti	10 Ch 17 N13 M 2 T

11.2 Formulae for temperature conversion

In Celsius

Formel 43:

$$t_{\text{Celsius}} = t_{\text{Kelvin}} - 273.15$$

Formula 44:

$$t_{\text{Celsius}} = (t_{\text{Fahrenheit}} - 32) \cdot 5/9$$

Formula 45:

$$t_{\text{Celsius}} = t_{\text{Réaumur}} \cdot 5/4$$

In Kelvin

Formula 46:

$$t_{\text{Kelvin}} = t_{\text{Celsius}} + 273.15$$

Formula 47:

$$t_{\text{Kelvin}} = (t_{\text{Fahrenheit}} - 32) \cdot 5/9 + 273.15$$

Formula 48:

$$t_{\text{Kelvin}} = t_{\text{Réaumur}} \cdot 5/4 + 273.15$$

In Fahrenheit

Formula 49:

$$t_{\text{Fahrenheit}} = 9/5 \cdot t_{\text{Celsius}} + 32$$

Formula 50:

$$t_{\text{Fahrenheit}} = (t_{\text{Kelvin}} - 273.15) \cdot 9/5 + 32$$

Formula 51:

$$t_{\text{Fahrenheit}} = tR \cdot 9/4 + 32$$

In Réaumur

Formula 52:

$$t_{\text{Réaumur}} = 4/5 \times t_{\text{Celsius}}$$

Formula 53:

$$t_{\text{Réaumur}} = (t_{\text{Kelvin}} - 273.15) \cdot 4/5$$

Formula 54:

$$t_{\text{Réaumur}} = (t_{\text{Fahrenheit}} - 32) \cdot 4/9$$

11.3 Voltage tables for thermocouples

11.3.1 Iron - Constantan (Fe-Con) J

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
-210	-8.095	-8.076	-8.057	-8.037	-8.017	-7.996	-7.976	-7.955	-7.934	-7.912	-7.890
-200	-7.890	-7.868	-7.846	-7.824	-7.801	-7.778	-7.755	-7.731	-7.707	-7.683	-7.659
-190	-7.659	-7.634	-7.610	-7.585	-7.559	-7.534	-7.508	-7.482	-7.456	-7.429	-7.403
-180	-7.403	-7.376	-7.348	-7.321	-7.293	-7.265	-7.237	-7.209	-7.181	-7.152	-7.123
-170	-7.123	-7.094	-7.064	-7.035	-7.005	-6.975	-6.944	-6.914	-6.883	-6.853	-6.821
-160	-6.821	-6.790	-6.759	-6.727	-6.695	-6.663	-6.631	-6.598	-6.566	-6.533	-6.500
-150	-6.500	-6.467	-6.433	-6.400	-6.366	-6.332	-6.298	-6.263	-6.229	-6.194	-6.159
-140	-6.159	-6.124	-6.089	-6.054	-6.018	-5.982	-5.946	-5.910	-5.874	-5.838	-5.801
-130	-5.801	-5.764	-5.727	-5.690	-5.653	-5.616	-5.578	-5.541	-5.503	-5.465	-5.426
-120	-5.426	-5.388	-5.350	-5.311	-5.272	-5.233	-5.194	-5.155	-5.116	-5.076	-5.037
-110	-5.037	-4.997	-4.957	-4.917	-4.877	-4.836	-4.796	-4.755	-4.714	-4.674	-4.633
-100	-4.633	-4.591	-4.550	-4.509	-4.467	-4.425	-4.384	-4.342	-4.300	-4.257	-4.215
-90	-4.215	-4.173	-4.130	-4.088	-4.045	-4.002	-3.959	-3.916	-3.872	-3.829	-3.786
-80	-3.786	-3.742	-3.698	-3.654	-3.610	-3.566	-3.522	-3.478	-3.434	-3.389	-3.344
-70	-3.344	-3.300	-3.255	-3.210	-3.165	-3.120	-3.075	-3.029	-2.984	-2.938	-2.893
-60	-2.893	-2.847	-2.801	-2.755	-2.709	-2.663	-2.617	-2.571	-2.524	-2.478	-2.431
-50	-2.431	-2.385	-2.338	-2.291	-2.244	-2.197	-2.150	-2.103	-2.055	-2.008	-1.961
-40	-1.961	-1.913	-1.865	-1.818	-1.770	-1.722	-1.674	-1.626	-1.578	-1.530	-1.482
-30	-1.482	-1.433	-1.385	-1.336	-1.288	-1.239	-1.190	-1.142	-1.093	-1.044	-0.995
-20	-0.995	-0.946	-0.896	-0.847	-0.798	-0.749	-0.699	-0.650	-0.600	-0.550	-0.501
-10	-0.501	-0.451	-0.401	-0.351	-0.301	-0.251	-0.201	-0.151	-0.101	-0.050	0.000
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669

Iron - Constantan (Fe-Con) J

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665
270	14.665	14.720	14.776	14.831	14.887	14.942	14.998	15.053	15.109	15.164	15.219
280	15.219	15.275	15.330	15.386	15.441	15.496	15.552	15.607	15.663	15.718	15.773
290	15.773	15.829	15.884	15.940	15.995	16.050	16.106	16.161	16.216	16.272	16.327
300	16.327	16.383	16.438	16.493	16.549	16.604	16.659	16.715	16.770	16.825	16.881
310	16.881	16.936	16.991	17.046	17.102	17.157	17.212	17.268	17.323	17.378	17.434
320	17.434	17.489	17.544	17.599	17.655	17.710	17.765	17.820	17.876	17.931	17.986
330	17.986	18.041	18.097	18.152	18.207	18.262	18.318	18.373	18.428	18.483	18.538
340	18.538	18.594	18.649	18.704	18.759	18.814	18.870	18.925	18.980	19.035	19.090
350	19.090	19.146	19.201	19.256	19.311	19.366	19.422	19.477	19.532	19.587	19.642
360	19.642	19.697	19.753	19.808	19.863	19.918	19.973	20.028	20.083	20.139	20.194
370	20.194	20.249	20.304	20.359	20.414	20.469	20.525	20.580	20.635	20.690	20.745
380	20.745	20.800	20.855	20.911	20.966	21.021	21.076	21.131	21.186	21.241	21.297
390	21.297	21.352	21.407	21.462	21.517	21.572	21.627	21.683	21.738	21.793	21.848
400	21.848	21.903	21.958	22.014	22.069	22.124	22.179	22.234	22.289	22.345	22.400
410	22.400	22.455	22.510	22.565	22.620	22.676	22.731	22.786	22.841	22.896	22.952
420	22.952	23.007	23.062	23.117	23.172	23.228	23.283	23.338	23.393	23.449	23.504
430	23.504	23.559	23.614	23.670	23.725	23.780	23.835	23.891	23.946	24.001	24.057
440	24.057	24.112	24.167	24.223	24.278	24.333	24.389	24.444	24.499	24.555	24.610
450	24.610	24.665	24.721	24.776	24.832	24.887	24.943	24.998	25.053	25.109	25.164
460	25.164	25.220	25.275	25.331	25.386	25.442	25.497	25.553	25.608	25.664	25.720
470	25.720	25.775	25.831	25.886	25.942	25.998	26.053	26.109	26.165	26.220	26.276
480	26.276	26.332	26.387	26.443	26.499	26.555	26.610	26.666	26.722	26.778	26.834
490	26.834	26.889	26.945	27.001	27.057	27.113	27.169	27.225	27.281	27.337	27.393
500	27.393	27.449	27.505	27.561	27.617	27.673	27.729	27.785	27.841	27.897	27.953
510	27.953	28.010	28.066	28.122	28.178	28.234	28.291	28.347	28.403	28.460	28.516
520	28.516	28.572	28.629	28.685	28.741	28.798	28.854	28.911	28.967	29.024	29.080
530	29.080	29.137	29.194	29.250	29.307	29.363	29.420	29.477	29.534	29.590	29.647
540	29.647	29.704	29.761	29.818	29.874	29.931	29.988	30.045	30.102	30.159	30.216
550	30.216	30.273	30.330	30.387	30.444	30.502	30.559	30.616	30.673	30.730	30.788
560	30.788	30.845	30.902	30.960	31.017	31.074	31.132	31.189	31.247	31.304	31.362

Iron - Constantan (Fe-Con) J

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
570	31.362	31.419	31.477	31.535	31.592	31.650	31.708	31.766	31.823	31.881	31.939
580	31.939	31.997	32.055	32.113	32.171	32.229	32.287	32.345	32.403	32.461	32.519
590	32.519	32.577	32.636	32.694	32.752	32.810	32.869	32.927	32.985	33.044	33.102
600	33.102	33.161	33.219	33.278	33.337	33.395	33.454	33.513	33.571	33.630	33.689
610	33.689	33.748	33.807	33.866	33.925	33.984	34.043	34.102	34.161	34.220	34.279
620	34.279	34.338	34.397	34.457	34.516	34.575	34.635	34.694	34.754	34.813	34.873
630	34.873	34.932	34.992	35.051	35.111	35.171	35.230	35.290	35.350	35.410	35.470
640	35.470	35.530	35.590	35.650	35.710	35.770	35.830	35.890	35.950	36.010	36.071
650	36.071	36.131	36.191	36.252	36.312	36.373	36.433	36.494	36.554	36.615	36.675
660	36.675	36.736	36.797	36.858	36.918	36.979	37.040	37.101	37.162	37.223	37.284
670	37.284	37.345	37.406	37.467	37.528	37.590	37.651	37.712	37.773	37.835	37.896
680	37.896	37.958	38.019	38.081	38.142	38.204	38.265	38.327	38.389	38.450	38.512
690	38.512	38.574	38.636	38.698	38.760	38.822	38.884	38.946	39.008	39.070	39.132
700	39.132	39.194	39.256	39.318	39.381	39.443	39.505	39.568	39.630	39.693	39.755
710	39.755	39.818	39.880	39.943	40.005	40.068	40.131	40.193	40.256	40.319	40.382
720	40.382	40.445	40.508	40.570	40.633	40.696	40.759	40.822	40.886	40.949	41.012
730	41.012	41.075	41.138	41.201	41.265	41.328	41.391	41.455	41.518	41.581	41.645
740	41.645	41.708	41.772	41.835	41.899	41.962	42.026	42.090	42.153	42.217	42.281
750	42.281	42.344	42.408	42.472	42.536	42.599	42.663	42.727	42.791	42.855	42.919
760	42.919	42.983	43.047	43.111	43.175	43.239	43.303	43.367	43.431	43.495	43.559
770	43.559	43.624	43.688	43.752	43.817	43.881	43.945	44.010	44.074	44.139	44.203
780	44.203	44.267	44.332	44.396	44.461	44.525	44.590	44.655	44.719	44.784	44.848
790	44.848	44.913	44.977	45.042	45.107	45.171	45.236	45.301	45.365	45.430	45.494
800	45.494	45.559	45.624	45.688	45.753	45.818	45.882	45.947	46.011	46.076	46.141
810	46.141	46.205	46.270	46.334	46.399	46.464	46.528	46.593	46.657	46.722	46.786
820	46.786	46.851	46.915	46.980	47.044	47.109	47.173	47.238	47.302	47.367	47.431
830	47.431	47.495	47.560	47.624	47.688	47.753	47.817	47.881	47.946	48.010	48.074
840	48.074	48.138	48.202	48.267	48.331	48.395	48.459	48.523	48.587	48.651	48.715
850	48.715	48.779	48.843	48.907	48.971	49.034	49.098	49.162	49.226	49.290	49.353
860	49.353	49.417	49.481	49.544	49.608	49.672	49.735	49.799	49.862	49.926	49.989
870	49.989	50.052	50.116	50.179	50.243	50.306	50.369	50.432	50.495	50.559	50.622
880	50.622	50.685	50.748	50.811	50.874	50.937	51.000	51.063	51.126	51.188	51.251
890	51.251	51.314	51.377	51.439	51.502	51.565	51.627	51.690	51.752	51.815	51.877
900	51.877	51.940	52.002	52.064	52.127	52.189	52.251	52.314	52.376	52.438	52.500
910	52.500	52.562	52.624	52.686	52.748	52.810	52.872	52.934	52.996	53.057	53.119
920	53.119	53.181	53.243	53.304	53.366	53.427	53.489	53.550	53.612	53.673	53.735
930	53.735	53.796	53.857	53.919	53.980	54.041	54.102	54.164	54.225	54.286	54.347
940	54.347	54.408	54.469	54.530	54.591	54.652	54.713	54.773	54.834	54.895	54.956
950	54.956	55.016	55.077	55.138	55.198	55.259	55.319	55.380	55.440	55.501	55.561

Iron - Constantan (Fe-Con) J

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

	0	1	2	3	4	5	6	7	8	9	10
960	55.561	55.622	55.682	55.742	55.803	55.863	55.923	55.983	56.043	56.104	56.164
970	56.164	56.224	56.284	56.344	56.404	56.464	56.524	56.584	56.643	56.703	56.763
980	56.763	56.823	56.883	56.942	57.002	57.062	57.121	57.181	57.240	57.300	57.360
990	57.360	57.419	57.479	57.538	57.597	57.657	57.716	57.776	57.835	57.894	57.953
1000	57.953	58.013	58.072	58.131	58.190	58.249	58.309	58.368	58.427	58.486	58.545
1010	58.545	58.604	58.663	58.722	58.781	58.840	58.899	58.957	59.016	59.075	59.134
1020	59.134	59.193	59.252	59.310	59.369	59.428	59.487	59.545	59.604	59.663	59.721
1030	59.721	59.780	59.838	59.897	59.956	60.014	60.073	60.131	60.190	60.248	60.307
1040	60.307	60.365	60.423	60.482	60.540	60.599	60.657	60.715	60.774	60.832	60.890
1050	60.890	60.949	61.007	61.065	61.123	61.182	61.240	61.298	61.356	61.415	61.473
1060	61.473	61.531	61.589	61.647	61.705	61.763	61.822	61.880	61.938	61.996	62.054
1070	62.054	62.112	62.170	62.228	62.286	62.344	62.402	62.460	62.518	62.576	62.634
1080	62.634	62.692	62.750	62.808	62.866	62.924	62.982	63.040	63.098	63.156	63.214
1090	63.214	63.271	63.329	63.387	63.445	63.503	63.561	63.619	63.677	63.734	63.792
1100	63.792	63.850	63.908	63.966	64.024	64.081	64.139	64.197	64.255	64.313	64.370
1110	64.370	64.428	64.486	64.544	64.602	64.659	64.717	64.775	64.833	64.890	64.948
1120	64.948	65.006	65.064	65.121	65.179	65.237	65.295	65.352	65.410	65.468	65.525
1130	65.525	65.583	65.641	65.699	65.756	65.814	65.872	65.929	65.987	66.045	66.102
1140	66.102	66.160	66.218	66.275	66.333	66.391	66.448	66.506	66.564	66.621	66.679
1150	66.679	66.737	66.794	66.852	66.910	66.967	67.025	67.082	67.140	67.198	67.255
1160	67.255	67.313	67.370	67.428	67.486	67.543	67.601	67.658	67.716	67.773	67.831
1170	67.831	67.888	67.946	68.003	68.061	68.119	68.176	68.234	68.291	68.348	68.406
1180	68.406	68.463	68.521	68.578	68.636	68.693	68.751	68.808	68.865	68.923	68.980
1190	68.980	69.037	69.095	69.152	69.209	69.267	69.324	69.381	69.439	69.496	69.553

11.3.2 Iron - Constantan (Fe-Con) L

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

°C	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
-200	-5.70	-	-	-	-	-	-	-	-	-
-100	-3.40	-3.68	-3.95	-4.21	-4.46	-4.69	-4.91	-5.12	-5.32	-5.51
0	0	-0.39	-0.77	-1.14	-1.50	-1.85	-2.18	-2.50	-2.81	-3.11
°C	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0	0	0.40	0.80	1.21	1.63	2.05	2.48	2.91	3.35	3.80
100	4.25	4.71	5.18	5.65	6.13	6.62	7.12	7.63	8.15	8.67
200	9.20	9.74	10.29	10.85	11.41	11.98	12.55	13.13	13.71	14.30
300	14.90	15.50	16.10	16.70	17.31	17.92	18.53	19.14	19.76	20.38
400	21.00	21.62	22.25	22.88	23.51	24.15	24.79	25.44	26.09	26.75
500	27.41	28.08	28.75	29.43	30.11	30.80	31.49	32.19	32.89	33.60

11.3.3 Copper - Constantan (Cu-Con) T

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
-270	-6.258	-6.256	-6.255	-6.253	-6.251	-6.248	-6.245	-6.242	-6.239	-6.236	-6.232
-260	-6.232	-6.228	-6.223	-6.219	-6.214	-6.209	-6.204	-6.198	-6.193	-6.187	-6.180
-250	-6.180	-6.174	-6.167	-6.160	-6.153	-6.146	-6.138	-6.130	-6.122	-6.114	-6.105
-240	-6.105	-6.096	-6.087	-6.078	-6.068	-6.059	-6.049	-6.038	-6.028	-6.017	-6.007
-230	-6.007	-5.996	-5.985	-5.973	-5.962	-5.950	-5.938	-5.926	-5.914	-5.901	-5.888
-220	-5.888	-5.876	-5.863	-5.850	-5.836	-5.823	-5.809	-5.795	-5.782	-5.767	-5.753
-210	-5.753	-5.739	-5.724	-5.710	-5.695	-5.680	-5.665	-5.650	-5.634	-5.619	-5.603
-200	-5.603	-5.587	-5.571	-5.555	-5.539	-5.523	-5.506	-5.489	-5.473	-5.456	-5.439
-190	-5.439	-5.421	-5.404	-5.387	-5.369	-5.351	-5.334	-5.316	-5.297	-5.279	-5.261
-180	-5.261	-5.242	-5.224	-5.205	-5.186	-5.167	-5.148	-5.128	-5.109	-5.089	-5.070
-170	-5.070	-5.050	-5.030	-5.010	-4.989	-4.969	-4.949	-4.928	-4.907	-4.886	-4.865
-160	-4.865	-4.844	-4.823	-4.802	-4.780	-4.759	-4.737	-4.715	-4.693	-4.671	-4.648
-150	-4.648	-4.626	-4.604	-4.581	-4.558	-4.535	-4.512	-4.489	-4.466	-4.443	-4.419
-140	-4.419	-4.395	-4.372	-4.348	-4.324	-4.300	-4.275	-4.251	-4.226	-4.202	-4.177
-130	-4.177	-4.152	-4.127	-4.102	-4.077	-4.052	-4.026	-4.000	-3.975	-3.949	-3.923
-120	-3.923	-3.897	-3.871	-3.844	-3.818	-3.791	-3.765	-3.738	-3.711	-3.684	-3.657
-110	-3.657	-3.629	-3.602	-3.574	-3.547	-3.519	-3.491	-3.463	-3.435	-3.407	-3.379
-100	-3.379	-3.350	-3.322	-3.293	-3.264	-3.235	-3.206	-3.177	-3.148	-3.118	-3.089
-90	-3.089	-3.059	-3.030	-3.000	-2.970	-2.940	-2.910	-2.879	-2.849	-2.818	-2.788
-80	-2.788	-2.757	-2.726	-2.695	-2.664	-2.633	-2.602	-2.571	-2.539	-2.507	-2.476
-70	-2.476	-2.444	-2.412	-2.380	-2.348	-2.316	-2.283	-2.251	-2.218	-2.186	-2.153
-60	-2.153	-2.120	-2.087	-2.054	-2.021	-1.987	-1.954	-1.920	-1.887	-1.853	-1.819
-50	-1.819	-1.785	-1.751	-1.717	-1.683	-1.648	-1.614	-1.579	-1.545	-1.510	-1.475
-40	-1.475	-1.440	-1.405	-1.370	-1.335	-1.299	-1.264	-1.228	-1.192	-1.157	-1.121
-30	-1.121	-1.085	-1.049	-1.013	-0.976	-0.940	-0.904	-0.867	-0.830	-0.794	-0.757
-20	-0.757	-0.720	-0.683	-0.646	-0.608	-0.571	-0.534	-0.496	-0.459	-0.421	-0.383
-10	-0.383	-0.345	-0.307	-0.269	-0.231	-0.193	-0.154	-0.116	-0.077	-0.039	0.000
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.790
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814
90	3.814	3.860	3.907	3.953	3.999	4.046	4.092	4.138	4.185	4.232	4.279
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228
120	5.228	5.277	5.325	5.373	5.422	5.470	5.519	5.567	5.616	5.665	5.714
130	5.714	5.763	5.812	5.861	5.910	5.959	6.008	6.057	6.107	6.156	6.206
140	6.206	6.255	6.305	6.355	6.404	6.454	6.504	6.554	6.604	6.654	6.704

Copper - Constantan (Cu-Con) T

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

	0	1	2	3	4	5	6	7	8	9	10
150	6.704	6.754	6.805	6.855	6.905	6.956	7.006	7.057	7.107	7.158	7.209
160	7.209	7.260	7.310	7.361	7.412	7.463	7.515	7.566	7.617	7.668	7.720
170	7.720	7.771	7.823	7.874	7.926	7.977	8.029	8.081	8.133	8.185	8.237
180	8.237	8.289	8.341	8.393	8.445	8.497	8.550	8.602	8.654	8.707	8.759
190	8.759	8.812	8.865	8.917	8.970	9.023	9.076	9.129	9.182	9.235	9.288
200	9.288	9.341	9.395	9.448	9.501	9.555	9.608	9.662	9.715	9.769	9.822
210	9.822	9.876	9.930	9.984	10.038	10.092	10.146	10.200	10.254	10.308	10.362
220	10.362	10.417	10.471	10.525	10.580	10.634	10.689	10.743	10.798	10.853	10.907
230	10.907	10.962	11.017	11.072	11.127	11.182	11.237	11.292	11.347	11.403	11.458
240	11.458	11.513	11.569	11.624	11.680	11.735	11.791	11.846	11.902	11.958	12.013
250	12.013	12.069	12.125	12.181	12.237	12.293	12.349	12.405	12.461	12.518	12.574
260	12.574	12.630	12.687	12.743	12.799	12.856	12.912	12.969	13.026	13.082	13.139
270	13.139	13.196	13.253	13.310	13.366	13.423	13.480	13.537	13.595	13.652	13.709
280	13.709	13.766	13.823	13.881	13.938	13.995	14.053	14.110	14.168	14.226	14.283
290	14.283	14.341	14.399	14.456	14.514	14.572	14.630	14.688	14.746	14.804	14.862
300	14.862	14.920	14.978	15.036	15.095	15.153	15.211	15.270	15.328	15.386	15.445
310	15.445	15.503	15.562	15.621	15.679	15.738	15.797	15.856	15.914	15.973	16.032
320	16.032	16.091	16.150	16.209	16.268	16.327	16.387	16.446	16.505	16.564	16.624
330	16.624	16.683	16.742	16.802	16.861	16.921	16.980	17.040	17.100	17.159	17.219
340	17.219	17.279	17.339	17.399	17.458	17.518	17.578	17.638	17.698	17.759	17.819
350	17.819	17.879	17.939	17.999	18.060	18.120	18.180	18.241	18.301	18.362	18.422
360	18.422	18.483	18.543	18.604	18.665	18.725	18.786	18.847	18.908	18.969	19.030
370	19.030	19.091	19.152	19.213	19.274	19.335	19.396	19.457	19.518	19.579	19.641
380	19.641	19.702	19.763	19.825	19.886	19.947	20.009	20.070	20.132	20.193	20.255
390	20.255	20.317	20.378	20.440	20.502	20.563	20.625	20.687	20.748	20.810	20.872

11.3.4 Copper - Constantan (Cu-Con) U

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

°C	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
-200	-8.15	-	-	-	-	-	-	-	-	-
-100	-4.75	-5.15	-5.53	-5.90	-6.26	-6.60	-6.93	-7.25	-7.56	-7.86
0	0	-0.51	-1.02	-1.53	-2.03	-2.51	-2.98	-3.44	-3.89	-4.33
°C	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0	0	0.52	1.05	1.58	2.11	2.65	3.19	3.73	4.27	4.82
100	5.37	5.92	6.47	7.03	7.59	8.15	8.71	9.27	9.83	10.39
200	10.95	11.51	12.07	12.63	13.19	13.75	14.31	14.88	15.44	16.00
300	16.56	17.12	17.68	18.24	18.80	19.36	19.92	20.48	21.04	21.60
400	22.16	22.72	23.29	23.86	24.43	25.00	25.57	26.14	26.71	27.28
500	27.85	28.43	29.01	29.59	30.17	30.75	31.33	31.91	32.49	33.08
600	33.67	34.26	34.85	35.44	36.04	36.64	37.25	37.85	38.47	39.09
700	39.72	40.35	40.98	41.62	42.27	42.92	43.57	44.23	44.89	45.55
800	46.22	46.89	47.57	48.25	48.94	49.63	50.32	51.02	51.72	52.43

11.3.5 Nickel Chromium - Nickel (NiCr-Ni) K

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
-270	-6.458	-6.457	-6.456	-6.455	-6.453	-6.452	-6.450	-6.448	-6.446	-6.444	-6.441
-260	-6.441	-6.438	-6.435	-6.432	-6.429	-6.425	-6.421	-6.417	-6.413	-6.408	-6.404
-250	-6.404	-6.399	-6.393	-6.388	-6.382	-6.377	-6.370	-6.364	-6.358	-6.351	-6.344
-240	-6.344	-6.337	-6.329	-6.322	-6.314	-6.306	-6.297	-6.289	-6.280	-6.271	-6.262
-230	-6.262	-6.252	-6.243	-6.233	-6.223	-6.213	-6.202	-6.192	-6.181	-6.170	-6.158
-220	-6.158	-6.147	-6.135	-6.123	-6.111	-6.099	-6.087	-6.074	-6.061	-6.048	-6.035
-210	-6.035	-6.021	-6.007	-5.994	-5.980	-5.965	-5.951	-5.936	-5.922	-5.907	-5.891
-200	-5.891	-5.876	-5.861	-5.845	-5.829	-5.813	-5.797	-5.780	-5.763	-5.747	-5.730
-190	-5.730	-5.713	-5.695	-5.678	-5.660	-5.642	-5.624	-5.606	-5.588	-5.569	-5.550
-180	-5.550	-5.531	-5.512	-5.493	-5.474	-5.454	-5.435	-5.415	-5.395	-5.374	-5.354
-170	-5.354	-5.333	-5.313	-5.292	-5.271	-5.250	-5.228	-5.207	-5.185	-5.163	-5.141
-160	-5.141	-5.119	-5.097	-5.074	-5.052	-5.029	-5.006	-4.983	-4.960	-4.936	-4.913
-150	-4.913	-4.889	-4.865	-4.841	-4.817	-4.793	-4.768	-4.744	-4.719	-4.694	-4.669
-140	-4.669	-4.644	-4.618	-4.593	-4.567	-4.542	-4.516	-4.490	-4.463	-4.437	-4.411
-130	-4.411	-4.384	-4.357	-4.330	-4.303	-4.276	-4.249	-4.221	-4.194	-4.166	-4.138
-120	-4.138	-4.110	-4.082	-4.054	-4.025	-3.997	-3.968	-3.939	-3.911	-3.882	-3.852
-110	-3.852	-3.823	-3.794	-3.764	-3.734	-3.705	-3.675	-3.645	-3.614	-3.584	-3.554
-100	-3.554	-3.523	-3.492	-3.462	-3.431	-3.400	-3.368	-3.337	-3.306	-3.274	-3.243
-90	-3.243	-3.211	-3.179	-3.147	-3.115	-3.083	-3.050	-3.018	-2.986	-2.953	-2.920
-80	-2.920	-2.887	-2.854	-2.821	-2.788	-2.755	-2.721	-2.688	-2.654	-2.620	-2.587
-70	-2.587	-2.553	-2.519	-2.485	-2.450	-2.416	-2.382	-2.347	-2.312	-2.278	-2.243
-60	-2.243	-2.208	-2.173	-2.138	-2.103	-2.067	-2.032	-1.996	-1.961	-1.925	-1.889
-50	-1.889	-1.854	-1.818	-1.782	-1.745	-1.709	-1.673	-1.637	-1.600	-1.564	-1.527
-40	-1.527	-1.490	-1.453	-1.417	-1.380	-1.343	-1.305	-1.268	-1.231	-1.194	-1.156
-30	-1.156	-1.119	-1.081	-1.043	-1.006	-0.968	-0.930	-0.892	-0.854	-0.816	-0.778
-20	-0.778	-0.739	-0.701	-0.663	-0.624	-0.586	-0.547	-0.508	-0.470	-0.431	-0.392
-10	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000
0	0.000	0.075	0.114	0.154	0.193	0.233	0.273	0.313	0.352	0.392	0.432
10	0.432	0.472	0.512	0.552	0.592	0.632	0.672	0.713	0.753	0.793	0.833
20	0.833	0.874	0.914	0.954	0.995	1.035	1.076	1.117	1.157	1.198	1.238
30	1.238	1.279	1.320	1.361	1.402	1.442	1.483	1.524	1.565	1.606	1.647
40	1.647	1.688	1.729	1.770	1.811	1.852	1.893	1.935	1.976	2.017	2.058
50	2.058	2.100	2.141	2.182	2.223	2.265	2.306	2.347	2.389	2.430	2.472
60	2.472	2.513	2.555	2.596	2.637	2.679	2.720	2.762	2.803	2.845	2.886
70	2.886	2.928	2.970	3.011	3.053	3.094	3.136	3.177	3.219	3.260	3.302
80	3.302	3.343	3.385	3.426	3.468	3.510	3.551	3.593	3.634	3.676	3.717
90	3.717	3.759	3.800	3.842	3.883	3.924	3.966	4.007	4.049	4.090	4.131
100	4.131	4.173	4.214	4.255	4.297	4.338	4.379	4.421	4.462	4.503	4.544
110	4.544	4.585	4.627	4.668	4.709	4.750	4.791	4.832	4.873	4.914	4.955

Nickel Chromium - Nickel (NiCr-Ni) K

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
120	4.955	4.996	5.037	5.078	5.119	5.160	5.200	5.241	5.282	5.323	5.364
130	5.364	5.404	5.445	5.486	5.526	5.567	5.608	5.648	5.689	5.729	5.770
140	5.770	5.810	5.851	5.891	5.932	5.972	6.012	6.053	6.093	6.133	6.174
150	6.174	6.214	6.254	6.294	6.335	6.375	6.415	6.455	6.495	6.535	6.575
160	6.575	6.616	6.656	6.696	6.736	6.776	6.816	6.856	6.896	6.936	6.976
170	6.976	7.016	7.056	7.096	7.136	7.176	7.216	7.255	7.295	7.335	7.375
180	7.375	7.415	7.455	7.495	7.535	7.575	7.615	7.655	7.695	7.734	7.774
190	7.774	7.814	7.854	7.894	7.934	7.974	8.014	8.054	8.094	8.134	8.174
200	8.174	8.214	8.254	8.294	8.334	8.374	8.414	8.454	8.494	8.534	8.574
210	8.574	8.614	8.654	8.694	8.734	8.774	8.814	8.855	8.895	8.935	8.975
220	8.975	9.015	9.056	9.096	9.136	9.176	9.217	9.257	9.297	9.338	9.378
230	9.378	9.418	9.459	9.499	9.539	9.580	9.620	9.661	9.701	9.742	9.782
240	9.782	9.823	9.863	9.904	9.945	9.985	10.026	10.067	10.107	10.148	10.189
250	10.189	10.229	10.270	10.311	10.352	10.392	10.433	10.474	10.515	10.556	10.597
260	10.597	10.637	10.678	10.719	10.760	10.801	10.842	10.883	10.924	10.965	11.006
270	11.006	11.047	11.088	11.129	11.170	11.212	11.253	11.294	11.335	11.376	11.417
280	11.417	11.459	11.500	11.541	11.582	11.623	11.665	11.706	11.747	11.789	11.830
290	11.830	11.871	11.913	11.954	11.995	12.037	12.078	12.119	12.161	12.202	12.244
300	12.244	12.285	12.327	12.368	12.410	12.451	12.493	12.534	12.576	12.617	12.659
310	12.659	12.700	12.742	12.783	12.825	12.867	12.908	12.950	12.992	13.033	13.075
320	13.075	13.116	13.158	13.200	13.242	13.283	13.325	13.367	13.408	13.450	13.492
330	13.492	13.534	13.575	13.617	13.659	13.701	13.742	13.784	13.826	13.868	13.910
340	13.910	13.952	13.993	14.035	14.077	14.119	14.161	14.203	14.245	14.286	14.328
350	14.328	14.370	14.412	14.454	14.496	14.538	14.580	14.622	14.664	14.706	14.748
360	14.748	14.790	14.832	14.874	14.916	14.958	15.000	15.042	15.084	15.126	15.168
370	15.168	15.210	15.252	15.294	15.336	15.378	15.420	15.462	15.505	15.547	15.589
380	15.589	15.631	15.673	15.715	15.757	15.799	15.842	15.884	15.926	15.968	16.010
390	16.010	16.052	16.095	16.137	16.179	16.221	16.263	16.306	16.348	16.390	16.432
400	16.432	16.475	16.517	16.559	16.601	16.644	16.686	16.728	16.770	16.813	16.855
410	16.855	16.897	16.940	16.982	17.024	17.067	17.109	17.151	17.194	17.236	17.278
420	17.278	17.321	17.363	17.405	17.448	17.490	17.532	17.575	17.617	17.660	17.702
430	17.702	17.744	17.787	17.829	17.872	17.914	17.957	17.999	18.041	18.084	18.126
440	18.126	18.169	18.211	18.254	18.296	18.339	18.381	18.424	18.466	18.509	18.551
450	18.551	18.594	18.636	18.678	18.721	18.764	18.806	18.849	18.891	18.934	18.976
460	18.976	19.019	19.061	19.104	19.146	19.189	19.231	19.274	19.316	19.359	19.402
470	19.402	19.444	19.487	19.529	19.572	19.614	19.657	19.700	19.742	19.785	19.827
480	19.827	19.870	19.912	19.955	19.998	20.040	20.083	20.125	20.168	20.211	20.253
490	20.253	20.296	20.339	20.381	20.424	20.466	20.509	20.552	20.594	20.637	20.679
500	20.679	20.722	20.765	20.807	20.850	20.893	20.935	20.978	21.021	21.063	21.106

Nickel Chromium - Nickel (NiCr-Ni) K

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
510	21.106	21.148	21.191	21.234	21.276	21.319	21.362	21.404	21.447	21.490	21.532
520	21.532	21.575	21.618	21.660	21.703	21.746	21.788	21.831	21.873	21.916	21.959
530	21.959	22.001	22.044	22.087	22.129	22.172	22.215	22.257	22.300	22.343	22.385
540	22.385	22.428	22.471	22.513	22.556	22.598	22.641	22.684	22.726	22.769	22.812
550	22.812	22.854	22.897	22.940	22.982	23.025	23.067	23.110	23.153	23.195	23.238
560	23.238	23.281	23.323	23.366	23.408	23.451	23.494	23.536	23.579	23.621	23.664
570	23.664	23.707	23.749	23.792	23.834	23.877	23.920	23.962	24.005	24.047	24.090
580	24.090	24.132	24.175	24.218	24.260	24.303	24.345	24.388	24.430	24.473	24.515
590	24.515	24.558	24.601	24.643	24.686	24.728	24.771	24.813	24.856	24.898	24.941
600	24.941	24.983	25.026	25.068	25.111	25.153	25.196	25.238	25.281	25.323	25.366
610	25.366	25.408	25.450	25.493	25.535	25.578	25.620	25.663	25.705	25.748	25.790
620	25.790	25.832	25.875	25.917	25.960	26.002	26.044	26.087	26.129	26.171	26.214
630	26.214	26.256	26.299	26.341	26.383	26.426	26.468	26.510	26.553	26.595	26.637
640	26.637	26.680	26.722	26.764	26.806	26.849	26.891	26.933	26.976	27.018	27.060
650	27.060	27.102	27.145	27.187	27.229	27.271	27.313	27.356	27.398	27.440	27.482
660	27.482	27.524	27.567	27.609	27.651	27.693	27.735	27.777	27.820	27.862	27.904
670	27.904	27.946	27.988	28.030	28.072	28.114	28.156	28.198	28.241	28.283	28.325
680	28.325	28.367	28.409	28.451	28.493	28.535	28.577	28.619	28.661	28.703	28.745
690	28.745	28.787	28.829	28.871	28.913	28.955	28.997	29.038	29.080	29.122	29.164
700	29.164	29.206	29.248	29.290	29.332	29.374	29.415	29.457	29.499	29.541	29.583
710	29.583	29.625	29.666	29.708	29.750	29.792	29.834	29.875	29.917	29.959	30.001
720	30.001	30.042	30.084	30.126	30.167	30.209	30.251	30.292	30.334	30.376	30.417
730	30.417	30.459	30.501	30.542	30.584	30.626	30.667	30.709	30.750	30.792	30.833
740	30.833	30.875	30.917	30.958	31.000	31.041	31.083	31.124	31.166	31.207	31.249
750	31.249	31.290	31.332	31.373	31.414	31.456	31.497	31.539	31.580	31.622	31.663
760	31.663	31.704	31.746	31.787	31.828	31.870	31.911	31.952	31.994	32.035	32.076
770	32.076	32.118	32.159	32.200	32.241	32.283	32.324	32.365	32.406	32.447	32.489
780	32.489	32.530	32.571	32.612	32.653	32.694	32.736	32.777	32.818	32.859	32.900
790	32.900	32.941	32.982	33.023	33.064	33.105	33.147	33.188	33.229	33.270	33.311
800	33.311	33.352	33.393	33.434	33.475	33.515	33.556	33.597	33.638	33.679	33.720
810	33.720	33.761	33.802	33.843	33.884	33.924	33.965	34.006	34.047	34.088	34.129
820	34.129	34.169	34.210	34.251	34.292	34.333	34.373	34.414	34.455	34.495	34.536
830	34.536	34.577	34.618	34.658	34.699	34.740	34.780	34.821	34.862	34.902	34.943
840	34.943	34.983	35.024	35.065	35.105	35.146	35.186	35.227	35.267	35.308	35.348
850	35.348	35.389	35.429	35.470	35.510	35.551	35.591	35.632	35.672	35.712	35.753
860	35.753	35.793	35.834	35.874	35.914	35.955	35.995	36.035	36.076	36.116	36.156
870	36.156	36.197	36.237	36.277	36.318	36.358	36.398	36.438	36.479	36.519	36.559
880	36.559	36.599	36.639	36.680	36.720	36.760	36.800	36.840	36.880	36.920	36.961
890	36.961	37.001	37.041	37.081	37.121	37.161	37.201	37.241	37.281	37.321	37.361

Nickel Chromium - Nickel (NiCr-Ni) K

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

	0	1	2	3	4	5	6	7	8	9	10
900	37.361	37.401	37.441	37.481	37.521	37.561	37.601	37.641	37.681	37.721	37.761
910	37.761	37.801	37.840	37.880	37.920	37.960	38.000	38.040	38.080	38.119	38.159
920	38.159	38.199	38.239	38.279	38.318	38.358	38.398	38.438	38.477	38.517	38.557
930	38.557	38.596	38.636	38.676	38.715	38.755	38.795	38.834	38.874	38.914	38.953
940	38.953	38.993	39.032	39.072	39.112	39.151	39.191	39.230	39.270	39.309	39.349
950	39.349	39.388	39.428	39.467	39.507	39.546	39.586	39.625	39.664	39.704	39.743
960	39.743	39.783	39.822	39.861	39.901	39.940	39.979	40.019	40.058	40.097	40.137
970	40.137	40.176	40.215	40.254	40.294	40.333	40.372	40.411	40.451	40.490	40.529
980	40.529	40.568	40.607	40.647	40.686	40.725	40.764	40.803	40.842	40.881	40.920
990	40.920	40.960	40.999	41.038	41.077	41.116	41.155	41.194	41.233	41.272	41.311
1000	41.311	41.350	41.389	41.428	41.467	41.506	41.545	41.583	41.622	41.661	41.700
1010	41.700	41.739	41.778	41.817	41.856	41.894	41.933	41.972	42.011	42.050	42.088
1020	42.088	42.127	42.166	42.205	42.243	42.282	42.321	42.359	42.398	42.437	42.475
1030	42.475	42.514	42.553	42.591	42.630	42.669	42.707	42.746	42.784	42.823	42.862
1040	42.862	42.900	42.939	42.977	43.016	43.054	43.093	43.131	43.170	43.208	43.246
1050	43.246	43.285	43.323	43.362	43.400	43.439	43.477	43.515	43.554	43.592	43.630
1060	43.630	43.669	43.707	43.745	43.783	43.822	43.860	43.898	43.937	43.975	44.013
1070	44.013	44.051	44.089	44.128	44.166	44.204	44.242	44.280	44.318	44.356	44.394
1080	44.394	44.433	44.471	44.509	44.547	44.585	44.623	44.661	44.699	44.737	44.775
1090	44.775	44.813	44.851	44.889	44.927	44.965	45.002	45.040	45.078	45.116	45.154
1100	45.154	45.192	45.230	45.267	45.305	45.343	45.381	45.419	45.456	45.494	45.532
1110	45.532	45.570	45.607	45.645	45.683	45.720	45.758	45.796	45.833	45.871	45.908
1120	45.908	45.946	45.984	46.021	46.059	46.096	46.134	46.171	46.209	46.246	46.284
1130	46.284	46.321	46.359	46.396	46.434	46.471	46.508	46.546	46.583	46.621	46.658
1140	46.658	46.695	46.733	46.770	46.807	46.844	46.882	46.919	46.956	46.993	47.031
1150	47.031	47.068	47.105	47.142	47.179	47.217	47.254	47.291	47.328	47.365	47.402
1160	47.402	47.439	47.476	47.513	47.550	47.587	47.624	47.661	47.698	47.735	47.772
1170	47.772	47.809	47.846	47.883	47.920	47.957	47.993	48.030	48.067	48.104	48.141
1180	48.141	48.177	48.214	48.251	48.288	48.324	48.361	48.398	48.434	48.471	48.508
1190	48.508	48.544	48.581	48.618	48.654	48.691	48.727	48.764	48.800	48.837	48.873
1200	48.873	48.910	48.946	48.983	49.019	49.056	49.092	49.129	49.165	49.201	49.238
1210	49.238	49.274	49.310	49.347	49.383	49.419	49.455	49.492	49.528	49.564	49.600
1220	49.600	49.636	49.673	49.709	49.745	49.781	49.817	49.853	49.889	49.925	49.961
1230	49.961	49.997	50.033	50.069	50.105	50.141	50.177	50.213	50.249	50.285	50.321
1240	50.321	50.357	50.393	50.429	50.464	50.500	50.536	50.572	50.608	50.643	50.679
1250	50.679	50.715	50.750	50.786	50.822	50.858	50.893	50.929	50.964	51.000	51.036
1260	51.036	51.071	51.107	51.142	51.178	51.213	51.249	51.284	51.320	51.355	51.390
1270	51.390	51.426	51.461	51.497	51.532	51.567	51.603	51.638	51.673	51.708	51.744
1280	51.744	51.779	51.814	51.849	51.885	51.920	51.955	51.990	52.025	52.060	52.095

Nickel Chromium - Nickel (NiCr-Ni) K

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1290	52.095	52.130	52.166	52.201	52.236	52.271	52.306	52.341	52.376	52.411	52.445
1300	52.445	52.480	52.515	52.550	52.585	52.620	52.655	52.690	52.724	52.759	52.794
1310	52.794	52.829	52.864	52.898	52.933	52.968	53.002	53.037	53.072	53.106	53.141
1320	53.141	53.176	53.210	53.245	53.279	53.314	53.348	53.383	53.417	53.452	53.486
1330	53.486	53.521	53.555	53.590	53.624	53.659	53.693	53.727	53.762	53.796	53.830
1340	53.830	53.865	53.899	53.933	53.968	54.002	54.036	54.070	54.105	54.139	54.173
1350	54.173	54.207	54.241	54.275	54.310	54.344	54.378	54.412	54.446	54.480	54.514
1360	54.514	54.548	54.582	54.616	54.650	54.684	54.718	54.752	54.786	54.820	54.854
1370	54.854	54.888	54.922								

11.3.6 Nickel Chromium - Constantan (NiCr-Con) E

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

	0	1	2	3	4	5	6	7	8	9	10
-270	-9.835	-9.833	-9.831	-9.828	-9.825	-9.821	-9.817	-9.813	-9.808	-9.802	-9.797
-260	-9.797	-9.790	-9.784	-9.777	-9.770	-9.762	-9.754	-9.746	-9.737	-9.728	-9.718
-250	-9.718	-9.709	-9.698	-9.688	-9.677	-9.666	-9.654	-9.642	-9.630	-9.617	-9.604
-240	-9.604	-9.591	-9.577	-9.563	-9.548	-9.534	-9.519	-9.503	-9.487	-9.471	-9.455
-230	-9.455	-9.438	-9.421	-9.404	-9.386	-9.368	-9.350	-9.331	-9.313	-9.293	-9.274
-220	-9.274	-9.254	-9.234	-9.214	-9.193	-9.172	-9.151	-9.129	-9.107	-9.085	-9.063
-210	-9.063	-9.040	-9.017	-8.994	-8.971	-8.947	-8.923	-8.899	-8.874	-8.850	-8.825
-200	-8.825	-8.799	-8.774	-8.748	-8.722	-8.696	-8.669	-8.643	-8.616	-8.588	-8.561
-190	-8.561	-8.533	-8.505	-8.477	-8.449	-8.420	-8.391	-8.362	-8.333	-8.303	-8.273
-180	-8.273	-8.243	-8.213	-8.183	-8.152	-8.121	-8.090	-8.059	-8.027	-7.995	-7.963
-170	-7.963	-7.931	-7.899	-7.866	-7.833	-7.800	-7.767	-7.733	-7.700	-7.666	-7.632
-160	-7.632	-7.597	-7.563	-7.528	-7.493	-7.458	-7.423	-7.387	-7.351	-7.315	-7.279
-150	-7.279	-7.243	-7.206	-7.170	-7.133	-7.096	-7.058	-7.021	-6.983	-6.945	-6.907
-140	-6.907	-6.869	-6.831	-6.792	-6.753	-6.714	-6.675	-6.636	-6.596	-6.556	-6.516
-130	-6.516	-6.476	-6.436	-6.396	-6.355	-6.314	-6.273	-6.232	-6.191	-6.149	-6.107
-120	-6.107	-6.065	-6.023	-5.981	-5.939	-5.896	-5.853	-5.810	-5.767	-5.724	-5.681
-110	-5.681	-5.637	-5.593	-5.549	-5.505	-5.461	-5.417	-5.372	-5.327	-5.282	-5.237
-100	-5.237	-5.192	-5.147	-5.101	-5.055	-5.009	-4.963	-4.917	-4.871	-4.824	-4.777
-90	-4.777	-4.731	-4.684	-4.636	-4.589	-4.542	-4.494	-4.446	-4.398	-4.350	-4.302
-80	-4.302	-4.254	-4.205	-4.156	-4.107	-4.058	-4.009	-3.960	-3.911	-3.861	-3.811
-70	-3.811	-3.761	-3.711	-3.661	-3.611	-3.561	-3.510	-3.459	-3.408	-3.357	-3.306
-60	-3.306	-3.255	-3.204	-3.152	-3.100	-3.048	-2.996	-2.944	-2.892	-2.840	-2.787
-50	-2.787	-2.735	-2.682	-2.629	-2.576	-2.523	-2.469	-2.416	-2.362	-2.309	-2.255
-40	-2.255	-2.201	-2.147	-2.093	-2.038	-1.984	-1.929	-1.874	-1.820	-1.765	-1.709
-30	-1.709	-1.654	-1.599	-1.543	-1.488	-1.432	-1.376	-1.320	-1.264	-1.208	-1.152
-20	-1.152	-1.095	-1.039	-0.982	-0.925	-0.868	-0.811	-0.754	-0.697	-0.639	-0.582
-10	-0.582	-0.524	-0.466	-0.408	-0.350	-0.292	-0.234	-0.176	-0.117	-0.059	0.000
0	0.000	0.059	0.118	0.176	0.235	0.294	0.354	0.413	0.472	0.532	0.591
10	0.591	0.651	0.711	0.770	0.830	0.890	0.950	1.010	1.071	1.131	1.192
20	1.192	1.252	1.313	1.373	1.434	1.495	1.556	1.617	1.678	1.740	1.801
30	1.801	1.862	1.924	1.986	2.047	2.109	2.171	2.233	2.295	2.357	2.420
40	2.420	2.482	2.545	2.607	2.670	2.733	2.795	2.858	2.921	2.984	3.048
50	3.048	3.111	3.174	3.238	3.301	3.365	3.429	3.492	3.556	3.620	3.685
60	3.685	3.749	3.813	3.877	3.942	4.006	4.071	4.136	4.200	4.265	4.330
70	4.330	4.395	4.460	4.526	4.591	4.656	4.722	4.788	4.853	4.919	4.985
80	4.985	5.051	5.117	5.183	5.249	5.315	5.382	5.448	5.514	5.581	5.648
90	5.648	5.714	5.781	5.848	5.915	5.982	6.049	6.117	6.184	6.251	6.319
100	6.319	6.386	6.454	6.522	6.590	6.658	6.725	6.794	6.862	6.930	6.998
110	6.998	7.066	7.135	7.203	7.272	7.341	7.409	7.478	7.547	7.616	7.685

Nickel Chromium - Constantan (NiCr-Con) E

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
120	7.685	7.754	7.823	7.892	7.962	8.031	8.101	8.170	8.240	8.309	8.379
130	8.379	8.449	8.519	8.589	8.659	8.729	8.799	8.869	8.940	9.010	9.081
140	9.081	9.151	9.222	9.292	9.363	9.434	9.505	9.576	9.647	9.718	9.789
150	9.789	9.860	9.931	10.003	10.074	10.145	10.217	10.288	10.360	10.432	10.503
160	10.503	10.575	10.647	10.719	10.791	10.863	10.935	11.007	11.080	11.152	11.224
170	11.224	11.297	11.369	11.442	11.514	11.587	11.660	11.733	11.805	11.878	11.951
180	11.951	12.024	12.097	12.170	12.243	12.317	12.390	12.463	12.537	12.610	12.684
190	12.684	12.757	12.831	12.904	12.978	13.052	13.126	13.199	13.273	13.347	13.421
200	13.421	13.495	13.569	13.644	13.718	13.792	13.866	13.941	14.015	14.090	14.164
210	14.164	14.239	14.313	14.388	14.463	14.537	14.612	14.687	14.762	14.837	14.912
220	14.912	14.987	15.062	15.137	15.212	15.287	15.362	15.438	15.513	15.588	15.664
230	15.664	15.739	15.815	15.890	15.966	16.041	16.117	16.193	16.269	16.344	16.420
240	16.420	16.496	16.572	16.648	16.724	16.800	16.876	16.952	17.028	17.104	17.181
250	17.181	17.257	17.333	17.409	17.486	17.562	17.639	17.715	17.792	17.868	17.945
260	17.945	18.021	18.098	18.175	18.252	18.328	18.405	18.482	18.559	18.636	18.713
270	18.713	18.790	18.867	18.944	19.021	19.098	19.175	19.252	19.330	19.407	19.484
280	19.484	19.561	19.639	19.716	19.794	19.871	19.948	20.026	20.103	20.181	20.259
290	20.259	20.336	20.414	20.492	20.569	20.647	20.725	20.803	20.880	20.958	21.036
300	21.036	21.114	21.192	21.270	21.348	21.426	21.504	21.582	21.660	21.739	21.817
310	21.817	21.895	21.973	22.051	22.130	22.208	22.286	22.365	22.443	22.522	22.600
320	22.600	22.678	22.757	22.835	22.914	22.993	23.071	23.150	23.228	23.307	23.386
330	23.386	23.464	23.543	23.622	23.701	23.780	23.858	23.937	24.016	24.095	24.174
340	24.174	24.253	24.332	24.411	24.490	24.569	24.648	24.727	24.806	24.885	24.964
350	24.964	25.044	25.123	25.202	25.281	25.360	25.440	25.519	25.598	25.678	25.757
360	25.757	25.836	25.916	25.995	26.075	26.154	26.233	26.313	26.392	26.472	26.552
370	26.552	26.631	26.711	26.790	26.870	26.950	27.029	27.109	27.189	27.268	27.348
380	27.348	27.428	27.507	27.587	27.667	27.747	27.827	27.907	27.986	28.066	28.146
390	28.146	28.226	28.306	28.386	28.466	28.546	28.626	28.706	28.786	28.866	28.946

11.3.7 Nicrosil - Nisil (NiCrSi-NiSi) N

(Thermoelectric emf in mV, referred to a cold junction temperature of 0 °C)

	0	1	2	3	4	5	6	7	8	9	10
-270	-4.345	-4.345	-4.344	-4.344	-4.343	-4.342	-4.341	-4.340	-4.339	-4.337	-4.336
-260	-4.336	-4.334	-4.332	-4.330	-4.328	-4.326	-4.324	-4.321	-4.319	-4.316	-4.313
-250	-4.313	-4.310	-4.307	-4.304	-4.300	-4.297	-4.293	-4.289	-4.285	-4.281	-4.277
-240	-4.277	-4.273	-4.268	-4.263	-4.258	-4.254	-4.248	-4.243	-4.238	-4.232	-4.226
-230	-4.226	-4.221	-4.215	-4.209	-4.202	-4.196	-4.189	-4.183	-4.176	-4.169	-4.162
-220	-4.162	-4.154	-4.147	-4.140	-4.132	-4.124	-4.116	-4.108	-4.100	-4.091	-4.083
-210	-4.083	-4.074	-4.066	-4.057	-4.048	-4.038	-4.029	-4.020	-4.010	-4.000	-3.990
-200	-3.990	-3.980	-3.970	-3.960	-3.950	-3.939	-3.928	-3.918	-3.907	-3.896	-3.884
-190	-3.884	-3.873	-3.862	-3.850	-3.838	-3.827	-3.815	-3.803	-3.790	-3.778	-3.766
-180	-3.766	-3.753	-3.740	-3.728	-3.715	-3.702	-3.688	-3.675	-3.662	-3.648	-3.634
-170	-3.634	-3.621	-3.607	-3.593	-3.578	-3.564	-3.550	-3.535	-3.521	-3.506	-3.491
-160	-3.491	-3.476	-3.461	-3.446	-3.431	-3.415	-3.400	-3.384	-3.368	-3.352	-3.336
-150	-3.336	-3.320	-3.304	-3.288	-3.271	-3.255	-3.238	-3.221	-3.205	-3.188	-3.171
-140	-3.171	-3.153	-3.136	-3.119	-3.101	-3.084	-3.066	-3.048	-3.030	-3.012	-2.994
-130	-2.994	-2.976	-2.958	-2.939	-2.921	-2.902	-2.883	-2.865	-2.846	-2.827	-2.808
-120	-2.808	-2.789	-2.769	-2.750	-2.730	-2.711	-2.691	-2.672	-2.652	-2.632	-2.612
-110	-2.612	-2.592	-2.571	-2.551	-2.531	-2.510	-2.490	-2.469	-2.448	-2.428	-2.407
-100	-2.407	-2.386	-2.365	-2.344	-2.322	-2.301	-2.280	-2.258	-2.237	-2.215	-2.193
-90	-2.193	-2.172	-2.150	-2.128	-2.106	-2.084	-2.062	-2.039	-2.017	-1.995	-1.972
-80	-1.972	-1.950	-1.927	-1.905	-1.882	-1.859	-1.836	-1.813	-1.790	-1.767	-1.744
-70	-1.744	-1.721	-1.698	-1.674	-1.651	-1.627	-1.604	-1.580	-1.557	-1.533	-1.509
-60	-1.509	-1.485	-1.462	-1.438	-1.414	-1.390	-1.366	-1.341	-1.317	-1.293	-1.269
-50	-1.269	-1.244	-1.220	-1.195	-1.171	-1.146	-1.122	-1.097	-1.072	-1.048	-1.023
-40	-1.023	-0.998	-0.973	-0.948	-0.923	-0.898	-0.873	-0.848	-0.823	-0.798	-0.772
-30	-0.772	-0.747	-0.722	-0.696	-0.671	-0.646	-0.620	-0.595	-0.569	-0.544	-0.518
-20	-0.518	-0.492	-0.467	-0.441	-0.415	-0.390	-0.364	-0.338	-0.312	-0.286	-0.260
-10	-0.260	-0.234	-0.209	-0.183	-0.157	-0.131	-0.104	-0.078	-0.052	-0.026	0.000
0	0.000	0.026	0.052	0.078	0.104	0.130	0.156	0.182	0.208	0.235	0.261
10	0.261	0.287	0.313	0.340	0.366	0.393	0.419	0.446	0.472	0.499	0.525
20	0.525	0.552	0.578	0.605	0.632	0.659	0.685	0.712	0.739	0.766	0.793
30	0.793	0.820	0.847	0.874	0.901	0.928	0.955	0.983	1.010	1.037	1.065
40	1.065	1.092	1.119	1.147	1.174	1.202	1.229	1.257	1.284	1.312	1.340
50	1.340	1.368	1.395	1.423	1.451	1.479	1.507	1.535	1.563	1.591	1.619
60	1.619	1.647	1.675	1.703	1.732	1.760	1.788	1.817	1.845	1.873	1.902
70	1.902	1.930	1.959	1.988	2.016	2.045	2.074	2.102	2.131	2.160	2.189
80	2.189	2.218	2.247	2.276	2.305	2.334	2.363	2.392	2.421	2.450	2.480
90	2.480	2.509	2.538	2.568	2.597	2.626	2.656	2.685	2.715	2.744	2.774
100	2.774	2.804	2.833	2.863	2.893	2.923	2.953	2.983	3.012	3.042	3.072
110	3.072	3.102	3.133	3.163	3.193	3.223	3.253	3.283	3.314	3.344	3.374

Nicrosil - Nisil (NiCrSi-NiSi) N

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
120	3.374	3.405	3.435	3.466	3.496	3.527	3.557	3.588	3.619	3.649	3.680
130	3.680	3.711	3.742	3.772	3.803	3.834	3.865	3.896	3.927	3.958	3.989
140	3.989	4.020	4.051	4.083	4.114	4.145	4.176	4.208	4.239	4.270	4.302
150	4.302	4.333	4.365	4.396	4.428	4.459	4.491	4.523	4.554	4.586	4.618
160	4.618	4.650	4.681	4.713	4.745	4.777	4.809	4.841	4.873	4.905	4.937
170	4.937	4.969	5.001	5.033	5.066	5.098	5.130	5.162	5.195	5.227	5.259
180	5.259	5.292	5.324	5.357	5.389	5.422	5.454	5.487	5.520	5.552	5.585
190	5.585	5.618	5.650	5.683	5.716	5.749	5.782	5.815	5.847	5.880	5.913
200	5.913	5.946	5.979	6.013	6.046	6.079	6.112	6.145	6.178	6.211	6.245
210	6.245	6.278	6.311	6.345	6.378	6.411	6.445	6.478	6.512	6.545	6.579
220	6.579	6.612	6.646	6.680	6.713	6.747	6.781	6.814	6.848	6.882	6.916
230	6.916	6.949	6.983	7.017	7.051	7.085	7.119	7.153	7.187	7.221	7.255
240	7.255	7.289	7.323	7.357	7.392	7.426	7.460	7.494	7.528	7.563	7.597
250	7.597	7.631	7.666	7.700	7.734	7.769	7.803	7.838	7.872	7.907	7.941
260	7.941	7.976	8.010	8.045	8.080	8.114	8.149	8.184	8.218	8.253	8.288
270	8.288	8.323	8.358	8.392	8.427	8.462	8.497	8.532	8.567	8.602	8.637
280	8.637	8.672	8.707	8.742	8.777	8.812	8.847	8.882	8.918	8.953	8.988
290	8.988	9.023	9.058	9.094	9.129	9.164	9.200	9.235	9.270	9.306	9.341
300	9.341	9.377	9.412	9.448	9.483	9.519	9.554	9.590	9.625	9.661	9.696
310	9.696	9.732	9.768	9.803	9.839	9.875	9.910	9.946	9.982	10.018	10.054
320	10.054	10.089	10.125	10.161	10.197	10.233	10.269	10.305	10.341	10.377	10.413
330	10.413	10.449	10.485	10.521	10.557	10.593	10.629	10.665	10.701	10.737	10.774
340	10.774	10.810	10.846	10.882	10.918	10.955	10.991	11.027	11.064	11.100	11.136
350	11.136	11.173	11.209	11.245	11.282	11.318	11.355	11.391	11.428	11.464	11.501
360	11.501	11.537	11.574	11.610	11.647	11.683	11.720	11.757	11.793	11.830	11.867
370	11.867	11.903	11.940	11.977	12.013	12.050	12.087	12.124	12.160	12.197	12.234
380	12.234	12.271	12.308	12.345	12.382	12.418	12.455	12.492	12.529	12.566	12.603
390	12.603	12.640	12.677	12.714	12.751	12.788	12.825	12.862	12.899	12.937	12.974
400	12.974	13.011	13.048	13.085	13.122	13.159	13.197	13.234	13.271	13.308	13.346
410	13.346	13.383	13.420	13.457	13.495	13.532	13.569	13.607	13.644	13.682	13.719
420	13.719	13.756	13.794	13.831	13.869	13.906	13.944	13.981	14.019	14.056	14.094
430	14.094	14.131	14.169	14.206	14.244	14.281	14.319	14.356	14.394	14.432	14.469
440	14.469	14.507	14.545	14.582	14.620	14.658	14.695	14.733	14.771	14.809	14.846
450	14.846	14.884	14.922	14.960	14.998	15.035	15.073	15.111	15.149	15.187	15.225
460	15.225	15.262	15.300	15.338	15.376	15.414	15.452	15.490	15.528	15.566	15.604
470	15.604	15.642	15.680	15.718	15.756	15.794	15.832	15.870	15.908	15.946	15.984
480	15.984	16.022	16.060	16.099	16.137	16.175	16.213	16.251	16.289	16.327	16.366
490	16.366	16.404	16.442	16.480	16.518	16.557	16.595	16.633	16.671	16.710	16.748
500	16.748	16.786	16.824	16.863	16.901	16.939	16.978	17.016	17.054	17.093	17.131

Nicrosil - Nisil (NiCrSi-NiSi) N

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
510	17.131	17.169	17.208	17.246	17.285	17.323	17.361	17.400	17.438	17.477	17.515
520	17.515	17.554	17.592	17.630	17.669	17.707	17.746	17.784	17.823	17.861	17.900
530	17.900	17.938	17.977	18.016	18.054	18.093	18.131	18.170	18.208	18.247	18.286
540	18.286	18.324	18.363	18.401	18.440	18.479	18.517	18.556	18.595	18.633	18.672
550	18.672	18.711	18.749	18.788	18.827	18.865	18.904	18.943	18.982	19.020	19.059
560	19.059	19.098	19.136	19.175	19.214	19.253	19.292	19.330	19.369	19.408	19.447
570	19.447	19.485	19.524	19.563	19.602	19.641	19.680	19.718	19.757	19.796	19.835
580	19.835	19.874	19.913	19.952	19.990	20.029	20.068	20.107	20.146	20.185	20.224
590	20.224	20.263	20.302	20.341	20.379	20.418	20.457	20.496	20.535	20.574	20.613
600	20.613	20.652	20.691	20.730	20.769	20.808	20.847	20.886	20.925	20.964	21.003
610	21.003	21.042	21.081	21.120	21.159	21.198	21.237	21.276	21.315	21.354	21.393
620	21.393	21.432	21.471	21.510	21.549	21.588	21.628	21.667	21.706	21.745	21.784
630	21.784	21.823	21.862	21.901	21.940	21.979	22.018	22.058	22.097	22.136	22.175
640	22.175	22.214	22.253	22.292	22.331	22.370	22.410	22.449	22.488	22.527	22.566
650	22.566	22.605	22.644	22.684	22.723	22.762	22.801	22.840	22.879	22.919	22.958
660	22.958	22.997	23.036	23.075	23.115	23.154	23.193	23.232	23.271	23.311	23.350
670	23.350	23.389	23.428	23.467	23.507	23.546	23.585	23.624	23.663	23.703	23.742
680	23.742	23.781	23.820	23.860	23.899	23.938	23.977	24.016	24.056	24.095	24.134
690	24.134	24.173	24.213	24.252	24.291	24.330	24.370	24.409	24.448	24.487	24.527
700	24.527	24.566	24.605	24.644	24.684	24.723	24.762	24.801	24.841	24.880	24.919
710	24.919	24.959	24.998	25.037	25.076	25.116	25.155	25.194	25.233	25.273	25.312
720	25.312	25.351	25.391	25.430	25.469	25.508	25.548	25.587	25.626	25.666	25.705
730	25.705	25.744	25.783	25.823	25.862	25.901	25.941	25.980	26.019	26.058	26.098
740	26.098	26.137	26.176	26.216	26.255	26.294	26.333	26.373	26.412	26.451	26.491
750	26.491	26.530	26.569	26.608	26.648	26.687	26.726	26.766	26.805	26.844	26.883
760	26.883	26.923	26.962	27.001	27.041	27.080	27.119	27.158	27.198	27.237	27.276
770	27.276	27.316	27.355	27.394	27.433	27.473	27.512	27.551	27.591	27.630	27.669
780	27.669	27.708	27.748	27.787	27.826	27.866	27.905	27.944	27.983	28.023	28.062
790	28.062	28.101	28.140	28.180	28.219	28.258	28.297	28.337	28.376	28.415	28.455
800	28.455	28.494	28.533	28.572	28.612	28.651	28.690	28.729	28.769	28.808	28.847
810	28.847	28.886	28.926	28.965	29.004	29.043	29.083	29.122	29.161	29.200	29.239
820	29.239	29.279	29.318	29.357	29.396	29.436	29.475	29.514	29.553	29.592	29.632
830	29.632	29.671	29.710	29.749	29.789	29.828	29.867	29.906	29.945	29.985	30.024
840	30.024	30.063	30.102	30.141	30.181	30.220	30.259	30.298	30.337	30.376	30.416
850	30.416	30.455	30.494	30.533	30.572	30.611	30.651	30.690	30.729	30.768	30.807
860	30.807	30.846	30.886	30.925	30.964	31.003	31.042	31.081	31.120	31.160	31.199
870	31.199	31.238	31.277	31.316	31.355	31.394	31.433	31.473	31.512	31.551	31.590
880	31.590	31.629	31.668	31.707	31.746	31.785	31.824	31.863	31.903	31.942	31.981
890	31.981	32.020	32.059	32.098	32.137	32.176	32.215	32.254	32.293	32.332	32.371

Nicrosil - Nisil (NiCrSi-NiSi) N

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
900	32.371	32.410	32.449	32.488	32.527	32.566	32.605	32.644	32.683	32.722	32.761
910	32.761	32.800	32.839	32.878	32.917	32.956	32.995	33.034	33.073	33.112	33.151
920	33.151	33.190	33.229	33.268	33.307	33.346	33.385	33.424	33.463	33.502	33.541
930	33.541	33.580	33.619	33.658	33.697	33.736	33.774	33.813	33.852	33.891	33.930
940	33.930	33.969	34.008	34.047	34.086	34.124	34.163	34.202	34.241	34.280	34.319
950	34.319	34.358	34.396	34.435	34.474	34.513	34.552	34.591	34.629	34.668	34.707
960	34.707	34.746	34.785	34.823	34.862	34.901	34.940	34.979	35.017	35.056	35.095
970	35.095	35.134	35.172	35.211	35.250	35.289	35.327	35.366	35.405	35.444	35.482
980	35.482	35.521	35.560	35.598	35.637	35.676	35.714	35.753	35.792	35.831	35.869
990	35.869	35.908	35.946	35.985	36.024	36.062	36.101	36.140	36.178	36.217	36.256
1000	36.256	36.294	36.333	36.371	36.410	36.449	36.487	36.526	36.564	36.603	36.641
1010	36.641	36.680	36.718	36.757	36.796	36.834	36.873	36.911	36.950	36.988	37.027
1020	37.027	37.065	37.104	37.142	37.181	37.219	37.258	37.296	37.334	37.373	37.411
1030	37.411	37.450	37.488	37.527	37.565	37.603	37.642	37.680	37.719	37.757	37.795
1040	37.795	37.834	37.872	37.911	37.949	37.987	38.026	38.064	38.102	38.141	38.179
1050	38.179	38.217	38.256	38.294	38.332	38.370	38.409	38.447	38.485	38.524	38.562
1060	38.562	38.600	38.638	38.677	38.715	38.753	38.791	38.829	38.868	38.906	38.944
1070	38.944	38.982	39.020	39.059	39.097	39.135	39.173	39.211	39.249	39.287	39.326
1080	39.326	39.364	39.402	39.440	39.478	39.516	39.554	39.592	39.630	39.668	39.706
1090	39.706	39.744	39.783	39.821	39.859	39.897	39.935	39.973	40.011	40.049	40.087
1100	40.087	40.125	40.163	40.201	40.238	40.276	40.314	40.352	40.390	40.428	40.466
1110	40.466	40.504	40.542	40.580	40.618	40.655	40.693	40.731	40.769	40.807	40.845
1120	40.845	40.883	40.920	40.958	40.996	41.034	41.072	41.109	41.147	41.185	41.223
1130	41.223	41.260	41.298	41.336	41.374	41.411	41.449	41.487	41.525	41.562	41.600
1140	41.600	41.638	41.675	41.713	41.751	41.788	41.826	41.864	41.901	41.939	41.976
1150	41.976	42.014	42.052	42.089	42.127	42.164	42.202	42.239	42.277	42.314	42.352
1160	42.352	42.390	42.427	42.465	42.502	42.540	42.577	42.614	42.652	42.689	42.727
1170	42.727	42.764	42.802	42.839	42.877	42.914	42.951	42.989	43.026	43.064	43.101
1180	43.101	43.138	43.176	43.213	43.250	43.288	43.325	43.362	43.399	43.437	43.474
1190	43.474	43.511	43.549	43.586	43.623	43.660	43.698	43.735	43.772	43.809	43.846
1200	43.846	43.884	43.921	43.958	43.995	44.032	44.069	44.106	44.144	44.181	44.218
1210	44.218	44.255	44.292	44.329	44.366	44.403	44.440	44.477	44.514	44.551	44.588
1220	44.588	44.625	44.662	44.699	44.736	44.773	44.810	44.847	44.884	44.921	44.958
1230	44.958	44.995	45.032	45.069	45.105	45.142	45.179	45.216	45.253	45.290	45.326
1240	45.326	45.363	45.400	45.437	45.474	45.510	45.547	45.584	45.621	45.657	45.694
1250	45.694	45.731	45.767	45.804	45.841	45.877	45.914	45.951	45.987	46.024	46.060
1260	46.060	46.097	46.133	46.170	46.207	46.243	46.280	46.316	46.353	46.389	46.425
1270	46.425	46.462	46.498	46.535	46.571	46.608	46.644	46.680	46.717	46.753	46.789
1280	46.789	46.826	46.862	46.898	46.935	46.971	47.007	47.043	47.079	47.116	47.152
1290	47.152	47.188	47.224	47.260	47.296	47.333	47.369	47.405	47.441	47.477	47.513

11.3.8 Platinum Rhodium - Platinum (Pt10Rh-Pt) S

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
-50	-0.236	-0.232	-0.228	-0.224	-0.219	-0.215	-0.211	-0.207	-0.203	-0.199	-0.194
-40	-0.194	-0.190	-0.186	-0.181	-0.177	-0.173	-0.168	-0.164	-0.159	-0.155	-0.150
-30	-0.150	-0.146	-0.141	-0.136	-0.132	-0.127	-0.122	-0.117	-0.113	-0.108	-0.103
-20	-0.103	-0.098	-0.093	-0.088	-0.083	-0.078	-0.073	-0.068	-0.063	-0.058	-0.053
-10	-0.053	-0.048	-0.042	-0.037	-0.032	-0.027	-0.021	-0.016	-0.011	-0.005	0.000
0	0.000	0.005	0.011	0.016	0.022	0.027	0.033	0.038	0.044	0.050	0.055
10	0.055	0.061	0.067	0.072	0.078	0.084	0.090	0.095	0.101	0.107	0.113
20	0.113	0.119	0.125	0.131	0.137	0.143	0.149	0.155	0.161	0.167	0.173
30	0.173	0.179	0.185	0.191	0.197	0.204	0.210	0.216	0.222	0.229	0.235
40	0.235	0.241	0.248	0.254	0.260	0.267	0.273	0.280	0.286	0.292	0.299
50	0.299	0.305	0.312	0.319	0.325	0.332	0.338	0.345	0.352	0.358	0.365
60	0.365	0.372	0.378	0.385	0.392	0.399	0.405	0.412	0.419	0.426	0.433
70	0.433	0.440	0.446	0.453	0.460	0.467	0.474	0.481	0.488	0.495	0.502
80	0.502	0.509	0.516	0.523	0.530	0.538	0.545	0.552	0.559	0.566	0.573
90	0.573	0.580	0.588	0.595	0.602	0.609	0.617	0.624	0.631	0.639	0.646
100	0.646	0.653	0.661	0.668	0.675	0.683	0.690	0.698	0.705	0.713	0.720
110	0.720	0.727	0.735	0.743	0.750	0.758	0.765	0.773	0.780	0.788	0.795
120	0.795	0.803	0.811	0.818	0.826	0.834	0.841	0.849	0.857	0.865	0.872
130	0.872	0.880	0.888	0.896	0.903	0.911	0.919	0.927	0.935	0.942	0.950
140	0.950	0.958	0.966	0.974	0.982	0.990	0.998	1.006	1.013	1.021	1.029
150	1.029	1.037	1.045	1.053	1.061	1.069	1.077	1.085	1.094	1.102	1.110
160	1.110	1.118	1.126	1.134	1.142	1.150	1.158	1.167	1.175	1.183	1.191
170	1.191	1.199	1.207	1.216	1.224	1.232	1.240	1.249	1.257	1.265	1.273
180	1.273	1.282	1.290	1.298	1.307	1.315	1.323	1.332	1.340	1.348	1.357
190	1.357	1.365	1.373	1.382	1.390	1.399	1.407	1.415	1.424	1.432	1.441
200	1.441	1.449	1.458	1.466	1.475	1.483	1.492	1.500	1.509	1.517	1.526
210	1.526	1.534	1.543	1.551	1.560	1.569	1.577	1.586	1.594	1.603	1.612
220	1.612	1.620	1.629	1.638	1.646	1.655	1.663	1.672	1.681	1.690	1.698
230	1.698	1.707	1.716	1.724	1.733	1.742	1.751	1.759	1.768	1.777	1.786
240	1.786	1.794	1.803	1.812	1.821	1.829	1.838	1.847	1.856	1.865	1.874
250	1.874	1.882	1.891	1.900	1.909	1.918	1.927	1.936	1.944	1.953	1.962
260	1.962	1.971	1.980	1.989	1.998	2.007	2.016	2.025	2.034	2.043	2.052
270	2.052	2.061	2.070	2.078	2.087	2.096	2.105	2.114	2.123	2.132	2.141
280	2.141	2.151	2.160	2.169	2.178	2.187	2.196	2.205	2.214	2.223	2.232
290	2.232	2.241	2.250	2.259	2.268	2.277	2.287	2.296	2.305	2.314	2.323
300	2.323	2.332	2.341	2.350	2.360	2.369	2.378	2.387	2.396	2.405	2.415
310	2.415	2.424	2.433	2.442	2.451	2.461	2.470	2.479	2.488	2.497	2.507
320	2.507	2.516	2.525	2.534	2.544	2.553	2.562	2.571	2.581	2.590	2.599
330	2.599	2.609	2.618	2.627	2.636	2.646	2.655	2.664	2.674	2.683	2.692

Platinum Rhodium - Platinum (Pt10Rh-Pt) S

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
340	2.692	2.702	2.711	2.720	2.730	2.739	2.748	2.758	2.767	2.776	2.786
350	2.786	2.795	2.805	2.814	2.823	2.833	2.842	2.851	2.861	2.870	2.880
360	2.880	2.889	2.899	2.908	2.917	2.927	2.936	2.946	2.955	2.965	2.974
370	2.974	2.983	2.993	3.002	3.012	3.021	3.031	3.040	3.050	3.059	3.069
380	3.069	3.078	3.088	3.097	3.107	3.116	3.126	3.135	3.145	3.154	3.164
390	3.164	3.173	3.183	3.192	3.202	3.212	3.221	3.231	3.240	3.250	3.259
400	3.259	3.269	3.279	3.288	3.298	3.307	3.317	3.326	3.336	3.346	3.355
410	3.355	3.365	3.374	3.384	3.394	3.403	3.413	3.423	3.432	3.442	3.451
420	3.451	3.461	3.471	3.480	3.490	3.500	3.509	3.519	3.529	3.538	3.548
430	3.548	3.558	3.567	3.577	3.587	3.596	3.606	3.616	3.626	3.635	3.645
440	3.645	3.655	3.664	3.674	3.684	3.694	3.703	3.713	3.723	3.732	3.742
450	3.742	3.752	3.762	3.771	3.781	3.791	3.801	3.810	3.820	3.830	3.840
460	3.840	3.850	3.859	3.869	3.879	3.889	3.898	3.908	3.918	3.928	3.938
470	3.938	3.947	3.957	3.967	3.977	3.987	3.997	4.006	4.016	4.026	4.036
480	4.036	4.046	4.056	4.065	4.075	4.085	4.095	4.105	4.115	4.125	4.134
490	4.134	4.144	4.154	4.164	4.174	4.184	4.194	4.204	4.213	4.223	4.233
500	4.233	4.243	4.253	4.263	4.273	4.283	4.293	4.303	4.313	4.323	4.332
510	4.332	4.342	4.352	4.362	4.372	4.382	4.392	4.402	4.412	4.422	4.432
520	4.432	4.442	4.452	4.462	4.472	4.482	4.492	4.502	4.512	4.522	4.532
530	4.532	4.542	4.552	4.562	4.572	4.582	4.592	4.602	4.612	4.622	4.632
540	4.632	4.642	4.652	4.662	4.672	4.682	4.692	4.702	4.712	4.722	4.732
550	4.732	4.742	4.752	4.762	4.772	4.782	4.793	4.803	4.813	4.823	4.833
560	4.833	4.843	4.853	4.863	4.873	4.883	4.893	4.904	4.914	4.924	4.934
570	4.934	4.944	4.954	4.964	4.974	4.984	4.995	5.005	5.015	5.025	5.035
580	5.035	5.045	5.055	5.066	5.076	5.086	5.096	5.106	5.116	5.127	5.137
590	5.137	5.147	5.157	5.167	5.178	5.188	5.198	5.208	5.218	5.228	5.239
600	5.239	5.249	5.259	5.269	5.280	5.290	5.300	5.310	5.320	5.331	5.341
610	5.341	5.351	5.361	5.372	5.382	5.392	5.402	5.413	5.423	5.433	5.443
620	5.443	5.454	5.464	5.474	5.485	5.495	5.505	5.515	5.526	5.536	5.546
630	5.546	5.557	5.567	5.577	5.588	5.598	5.608	5.618	5.629	5.639	5.649
640	5.649	5.660	5.670	5.680	5.691	5.701	5.712	5.722	5.732	5.743	5.753
650	5.753	5.763	5.774	5.784	5.794	5.805	5.815	5.826	5.836	5.846	5.857
660	5.857	5.867	5.878	5.888	5.898	5.909	5.919	5.930	5.940	5.950	5.961
670	5.961	5.971	5.982	5.992	6.003	6.013	6.024	6.034	6.044	6.055	6.065
680	6.065	6.076	6.086	6.097	6.107	6.118	6.128	6.139	6.149	6.160	6.170
690	6.170	6.181	6.191	6.202	6.212	6.223	6.233	6.244	6.254	6.265	6.275
700	6.275	6.286	6.296	6.307	6.317	6.328	6.338	6.349	6.360	6.370	6.381
710	6.381	6.391	6.402	6.412	6.423	6.434	6.444	6.455	6.465	6.476	6.486
720	6.486	6.497	6.508	6.518	6.529	6.539	6.550	6.561	6.571	6.582	6.593

Platinum Rhodium - Platinum (Pt10Rh-Pt) S

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
730	6.593	6.603	6.614	6.624	6.635	6.646	6.656	6.667	6.678	6.688	6.699
740	6.699	6.710	6.720	6.731	6.742	6.752	6.763	6.774	6.784	6.795	6.806
750	6.806	6.817	6.827	6.838	6.849	6.859	6.870	6.881	6.892	6.902	6.913
760	6.913	6.924	6.934	6.945	6.956	6.967	6.977	6.988	6.999	7.010	7.020
770	7.020	7.031	7.042	7.053	7.064	7.074	7.085	7.096	7.107	7.117	7.128
780	7.128	7.139	7.150	7.161	7.172	7.182	7.193	7.204	7.215	7.226	7.236
790	7.236	7.247	7.258	7.269	7.280	7.291	7.302	7.312	7.323	7.334	7.345
800	7.345	7.356	7.367	7.378	7.388	7.399	7.410	7.421	7.432	7.443	7.454
810	7.454	7.465	7.476	7.487	7.497	7.508	7.519	7.530	7.541	7.552	7.563
820	7.563	7.574	7.585	7.596	7.607	7.618	7.629	7.640	7.651	7.662	7.673
830	7.673	7.684	7.695	7.706	7.717	7.728	7.739	7.750	7.761	7.772	7.783
840	7.783	7.794	7.805	7.816	7.827	7.838	7.849	7.860	7.871	7.882	7.893
850	7.893	7.904	7.915	7.926	7.937	7.948	7.959	7.970	7.981	7.992	8.003
860	8.003	8.014	8.026	8.037	8.048	8.059	8.070	8.081	8.092	8.103	8.114
870	8.114	8.125	8.137	8.148	8.159	8.170	8.181	8.192	8.203	8.214	8.226
880	8.226	8.237	8.248	8.259	8.270	8.281	8.293	8.304	8.315	8.326	8.337
890	8.337	8.348	8.360	8.371	8.382	8.393	8.404	8.416	8.427	8.438	8.449
900	8.449	8.460	8.472	8.483	8.494	8.505	8.517	8.528	8.539	8.550	8.562
910	8.562	8.573	8.584	8.595	8.607	8.618	8.629	8.640	8.652	8.663	8.674
920	8.674	8.685	8.697	8.708	8.719	8.731	8.742	8.753	8.765	8.776	8.787
930	8.787	8.798	8.810	8.821	8.832	8.844	8.855	8.866	8.878	8.889	8.900
940	8.900	8.912	8.923	8.935	8.946	8.957	8.969	8.980	8.991	9.003	9.014
950	9.014	9.025	9.037	9.048	9.060	9.071	9.082	9.094	9.105	9.117	9.128
960	9.128	9.139	9.151	9.162	9.174	9.185	9.197	9.208	9.219	9.231	9.242
970	9.242	9.254	9.265	9.277	9.288	9.300	9.311	9.323	9.334	9.345	9.357
980	9.357	9.368	9.380	9.391	9.403	9.414	9.426	9.437	9.449	9.460	9.472
990	9.472	9.483	9.495	9.506	9.518	9.529	9.541	9.552	9.564	9.576	9.587
1000	9.587	9.599	9.610	9.622	9.633	9.645	9.656	9.668	9.680	9.691	9.703
1010	9.703	9.714	9.726	9.737	9.749	9.761	9.772	9.784	9.795	9.807	9.819
1020	9.819	9.830	9.842	9.853	9.865	9.877	9.888	9.900	9.911	9.923	9.935
1030	9.935	9.946	9.958	9.970	9.981	9.993	10.005	10.016	10.028	10.040	10.051
1040	10.051	10.063	10.075	10.086	10.098	10.110	10.121	10.133	10.145	10.156	10.168
1050	10.168	10.180	10.191	10.203	10.215	10.227	10.238	10.250	10.262	10.273	10.285
1060	10.285	10.297	10.309	10.320	10.332	10.344	10.356	10.367	10.379	10.391	10.403
1070	10.403	10.414	10.426	10.438	10.450	10.461	10.473	10.485	10.497	10.509	10.520
1080	10.520	10.532	10.544	10.556	10.567	10.579	10.591	10.603	10.615	10.626	10.638
1090	10.638	10.650	10.662	10.674	10.686	10.697	10.709	10.721	10.733	10.745	10.757
1100	10.757	10.768	10.780	10.792	10.804	10.816	10.828	10.839	10.851	10.863	10.875
1110	10.875	10.887	10.899	10.911	10.922	10.934	10.946	10.958	10.970	10.982	10.994

Platinum Rhodium - Platinum (Pt10Rh-Pt) S

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1120	10.994	11.006	11.017	11.029	11.041	11.053	11.065	11.077	11.089	11.101	11.113
1130	11.113	11.125	11.136	11.148	11.160	11.172	11.184	11.196	11.208	11.220	11.232
1140	11.232	11.244	11.256	11.268	11.280	11.291	11.303	11.315	11.327	11.339	11.351
1150	11.351	11.363	11.375	11.387	11.399	11.411	11.423	11.435	11.447	11.459	11.471
1160	11.471	11.483	11.495	11.507	11.519	11.531	11.542	11.554	11.566	11.578	11.590
1170	11.590	11.602	11.614	11.626	11.638	11.650	11.662	11.674	11.686	11.698	11.710
1180	11.710	11.722	11.734	11.746	11.758	11.770	11.782	11.794	11.806	11.818	11.830
1190	11.830	11.842	11.854	11.866	11.878	11.890	11.902	11.914	11.926	11.939	11.951
1200	11.951	11.963	11.975	11.987	11.999	12.011	12.023	12.035	12.047	12.059	12.071
1210	12.071	12.083	12.095	12.107	12.119	12.131	12.143	12.155	12.167	12.179	12.191
1220	12.191	12.203	12.216	12.228	12.240	12.252	12.264	12.276	12.288	12.300	12.312
1230	12.312	12.324	12.336	12.348	12.360	12.372	12.384	12.397	12.409	12.421	12.433
1240	12.433	12.445	12.457	12.469	12.481	12.493	12.505	12.517	12.529	12.542	12.554
1250	12.554	12.566	12.578	12.590	12.602	12.614	12.626	12.638	12.650	12.662	12.675
1260	12.675	12.687	12.699	12.711	12.723	12.735	12.747	12.759	12.771	12.783	12.796
1270	12.796	12.808	12.820	12.832	12.844	12.856	12.868	12.880	12.892	12.905	12.917
1280	12.917	12.929	12.941	12.953	12.965	12.977	12.989	13.001	13.014	13.026	13.038
1290	13.038	13.050	13.062	13.074	13.086	13.098	13.111	13.123	13.135	13.147	13.159
1300	13.159	13.171	13.183	13.195	13.208	13.220	13.232	13.244	13.256	13.268	13.280
1310	13.280	13.292	13.305	13.317	13.329	13.341	13.353	13.365	13.377	13.390	13.402
1320	13.402	13.414	13.426	13.438	13.450	13.462	13.474	13.487	13.499	13.511	13.523
1330	13.523	13.535	13.547	13.559	13.572	13.584	13.596	13.608	13.620	13.632	13.644
1340	13.644	13.657	13.669	13.681	13.693	13.705	13.717	13.729	13.742	13.754	13.766
1350	13.766	13.778	13.790	13.802	13.814	13.826	13.839	13.851	13.863	13.875	13.887
1360	13.887	13.899	13.911	13.924	13.936	13.948	13.960	13.972	13.984	13.996	14.009
1370	14.009	14.021	14.033	14.045	14.057	14.069	14.081	14.094	14.106	14.118	14.130
1380	14.130	14.142	14.154	14.166	14.178	14.191	14.203	14.215	14.227	14.239	14.251
1390	14.251	14.263	14.276	14.288	14.300	14.312	14.324	14.336	14.348	14.360	14.373
1400	14.373	14.385	14.397	14.409	14.421	14.433	14.445	14.457	14.470	14.482	14.494
1410	14.494	14.506	14.518	14.530	14.542	14.554	14.567	14.579	14.591	14.603	14.615
1420	14.615	14.627	14.639	14.651	14.664	14.676	14.688	14.700	14.712	14.724	14.736
1430	14.736	14.748	14.760	14.773	14.785	14.797	14.809	14.821	14.833	14.845	14.857
1440	14.857	14.869	14.881	14.894	14.906	14.918	14.930	14.942	14.954	14.966	14.978
1450	14.978	14.990	15.002	15.015	15.027	15.039	15.051	15.063	15.075	15.087	15.099
1460	15.099	15.111	15.123	15.135	15.148	15.160	15.172	15.184	15.196	15.208	15.220
1470	15.220	15.232	15.244	15.256	15.268	15.280	15.292	15.304	15.317	15.329	15.341
1480	15.341	15.353	15.365	15.377	15.389	15.401	15.413	15.425	15.437	15.449	15.461
1490	15.461	15.473	15.485	15.497	15.509	15.521	15.534	15.546	15.558	15.570	15.582
1500	15.582	15.594	15.606	15.618	15.630	15.642	15.654	15.666	15.678	15.690	15.702

Platinum Rhodium - Platinum (Pt10Rh-Pt) S

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1510	15.702	15.714	15.726	15.738	15.750	15.762	15.774	15.786	15.798	15.810	15.822
1520	15.822	15.834	15.846	15.858	15.870	15.882	15.894	15.906	15.918	15.930	15.942
1530	15.942	15.954	15.966	15.978	15.990	16.002	16.014	16.026	16.038	16.050	16.062
1540	16.062	16.074	16.086	16.098	16.110	16.122	16.134	16.146	16.158	16.170	16.182
1550	16.182	16.194	16.205	16.217	16.229	16.241	16.253	16.265	16.277	16.289	16.301
1560	16.301	16.313	16.325	16.337	16.349	16.361	16.373	16.385	16.396	16.408	16.420
1570	16.420	16.432	16.444	16.456	16.468	16.480	16.492	16.504	16.516	16.527	16.539
1580	16.539	16.551	16.563	16.575	16.587	16.599	16.611	16.623	16.634	16.646	16.658
1590	16.658	16.670	16.682	16.694	16.706	16.718	16.729	16.741	16.753	16.765	16.777
1600	16.777	16.789	16.801	16.812	16.824	16.836	16.848	16.860	16.872	16.883	16.895
1610	16.895	16.907	16.919	16.931	16.943	16.954	16.966	16.978	16.990	17.002	17.013
1620	17.013	17.025	17.037	17.049	17.061	17.072	17.084	17.096	17.108	17.120	17.131
1630	17.131	17.143	17.155	17.167	17.178	17.190	17.202	17.214	17.225	17.237	17.249
1640	17.249	17.261	17.272	17.284	17.296	17.308	17.319	17.331	17.343	17.355	17.366
1650	17.366	17.378	17.390	17.401	17.413	17.425	17.437	17.448	17.460	17.472	17.483
1660	17.483	17.495	17.507	17.518	17.530	17.542	17.553	17.565	17.577	17.588	17.600
1670	17.600	17.612	17.623	17.635	17.647	17.658	17.670	17.682	17.693	17.705	17.717
1680	17.717	17.728	17.740	17.751	17.763	17.775	17.786	17.798	17.809	17.821	17.832
1690	17.832	17.844	17.855	17.867	17.878	17.890	17.901	17.913	17.924	17.936	17.947
1700	17.947	17.959	17.970	17.982	17.993	18.004	18.016	18.027	18.039	18.050	18.061
1710	18.061	18.073	18.084	18.095	18.107	18.118	18.129	18.140	18.152	18.163	18.174
1720	18.174	18.185	18.196	18.208	18.219	18.230	18.241	18.252	18.263	18.274	18.285
1730	18.285	18.297	18.308	18.319	18.330	18.341	18.352	18.362	18.373	18.384	18.395
1740	18.395	18.406	18.417	18.428	18.439	18.449	18.460	18.471	18.482	18.493	18.503
1750	18.503	18.514	18.525	18.535	18.546	18.557	18.567	18.578	18.588	18.599	18.609
1760	18.609	18.620	18.630	18.641	18.651	18.661	18.672	18.682	18.693		

11.3.9 Platinum Rhodium - Platinum (Pt13Rh-Pt) R

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
-50	-0.226	-0.223	-0.219	-0.215	-0.211	-0.208	-0.204	-0.200	-0.196	-0.192	-0.188
-40	-0.188	-0.184	-0.180	-0.175	-0.171	-0.167	-0.163	-0.158	-0.154	-0.150	-0.145
-30	-0.145	-0.141	-0.137	-0.132	-0.128	-0.123	-0.119	-0.114	-0.109	-0.105	-0.100
-20	-0.100	-0.095	-0.091	-0.086	-0.081	-0.076	-0.071	-0.066	-0.061	-0.056	-0.051
-10	-0.051	-0.046	-0.041	-0.036	-0.031	-0.026	-0.021	-0.016	-0.011	-0.005	0.000
0	0.000	0.005	0.011	0.016	0.021	0.027	0.032	0.038	0.043	0.049	0.054
10	0.054	0.060	0.065	0.071	0.077	0.082	0.088	0.094	0.100	0.105	0.111
20	0.111	0.117	0.123	0.129	0.135	0.141	0.147	0.153	0.159	0.165	0.171
30	0.171	0.177	0.183	0.189	0.195	0.201	0.207	0.214	0.220	0.226	0.232
40	0.232	0.239	0.245	0.251	0.258	0.264	0.271	0.277	0.284	0.290	0.296
50	0.296	0.303	0.310	0.316	0.323	0.329	0.336	0.343	0.349	0.356	0.363
60	0.363	0.369	0.376	0.383	0.390	0.397	0.403	0.410	0.417	0.424	0.431
70	0.431	0.438	0.445	0.452	0.459	0.466	0.473	0.480	0.487	0.494	0.501
80	0.501	0.508	0.516	0.523	0.530	0.537	0.544	0.552	0.559	0.566	0.573
90	0.573	0.581	0.588	0.595	0.603	0.610	0.618	0.625	0.632	0.640	0.647
100	0.647	0.655	0.662	0.670	0.677	0.685	0.693	0.700	0.708	0.715	0.723
110	0.723	0.731	0.738	0.746	0.754	0.761	0.769	0.777	0.785	0.792	0.800
120	0.800	0.808	0.816	0.824	0.832	0.839	0.847	0.855	0.863	0.871	0.879
130	0.879	0.887	0.895	0.903	0.911	0.919	0.927	0.935	0.943	0.951	0.959
140	0.959	0.967	0.976	0.984	0.992	1.000	1.008	1.016	1.025	1.033	1.041
150	1.041	1.049	1.058	1.066	1.074	1.082	1.091	1.099	1.107	1.116	1.124
160	1.124	1.132	1.141	1.149	1.158	1.166	1.175	1.183	1.191	1.200	1.208
170	1.208	1.217	1.225	1.234	1.242	1.251	1.260	1.268	1.277	1.285	1.294
180	1.294	1.303	1.311	1.320	1.329	1.337	1.346	1.355	1.363	1.372	1.381
190	1.381	1.389	1.398	1.407	1.416	1.425	1.433	1.442	1.451	1.460	1.469
200	1.469	1.477	1.486	1.495	1.504	1.513	1.522	1.531	1.540	1.549	1.558
210	1.558	1.567	1.575	1.584	1.593	1.602	1.611	1.620	1.629	1.639	1.648
220	1.648	1.657	1.666	1.675	1.684	1.693	1.702	1.711	1.720	1.729	1.739
230	1.739	1.748	1.757	1.766	1.775	1.784	1.794	1.803	1.812	1.821	1.831
240	1.831	1.840	1.849	1.858	1.868	1.877	1.886	1.895	1.905	1.914	1.923
250	1.923	1.933	1.942	1.951	1.961	1.970	1.980	1.989	1.998	2.008	2.017
260	2.017	2.027	2.036	2.046	2.055	2.064	2.074	2.083	2.093	2.102	2.112
270	2.112	2.121	2.131	2.140	2.150	2.159	2.169	2.179	2.188	2.198	2.207
280	2.207	2.217	2.226	2.236	2.246	2.255	2.265	2.275	2.284	2.294	2.304
290	2.304	2.313	2.323	2.333	2.342	2.352	2.362	2.371	2.381	2.391	2.401
300	2.401	2.410	2.420	2.430	2.440	2.449	2.459	2.469	2.479	2.488	2.498
310	2.498	2.508	2.518	2.528	2.538	2.547	2.557	2.567	2.577	2.587	2.597
320	2.597	2.607	2.617	2.626	2.636	2.646	2.656	2.666	2.676	2.686	2.696
330	2.696	2.706	2.716	2.726	2.736	2.746	2.756	2.766	2.776	2.786	2.796

Platinum Rhodium - Platinum (Pt13Rh-Pt) R

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
340	2.796	2.806	2.816	2.826	2.836	2.846	2.856	2.866	2.876	2.886	2.896
350	2.896	2.906	2.916	2.926	2.937	2.947	2.957	2.967	2.977	2.987	2.997
360	2.997	3.007	3.018	3.028	3.038	3.048	3.058	3.068	3.079	3.089	3.099
370	3.099	3.109	3.119	3.130	3.140	3.150	3.160	3.171	3.181	3.191	3.201
380	3.201	3.212	3.222	3.232	3.242	3.253	3.263	3.273	3.284	3.294	3.304
390	3.304	3.315	3.325	3.335	3.346	3.356	3.366	3.377	3.387	3.397	3.408
400	3.408	3.418	3.428	3.439	3.449	3.460	3.470	3.480	3.491	3.501	3.512
410	3.512	3.522	3.533	3.543	3.553	3.564	3.574	3.585	3.595	3.606	3.616
420	3.616	3.627	3.637	3.648	3.658	3.669	3.679	3.690	3.700	3.711	3.721
430	3.721	3.732	3.742	3.753	3.764	3.774	3.785	3.795	3.806	3.816	3.827
440	3.827	3.838	3.848	3.859	3.869	3.880	3.891	3.901	3.912	3.922	3.933
450	3.933	3.944	3.954	3.965	3.976	3.986	3.997	4.008	4.018	4.029	4.040
460	4.040	4.050	4.061	4.072	4.083	4.093	4.104	4.115	4.125	4.136	4.147
470	4.147	4.158	4.168	4.179	4.190	4.201	4.211	4.222	4.233	4.244	4.255
480	4.255	4.265	4.276	4.287	4.298	4.309	4.319	4.330	4.341	4.352	4.363
490	4.363	4.373	4.384	4.395	4.406	4.417	4.428	4.439	4.449	4.460	4.471
500	4.471	4.482	4.493	4.504	4.515	4.526	4.537	4.548	4.558	4.569	4.580
510	4.580	4.591	4.602	4.613	4.624	4.635	4.646	4.657	4.668	4.679	4.690
520	4.690	4.701	4.712	4.723	4.734	4.745	4.756	4.767	4.778	4.789	4.800
530	4.800	4.811	4.822	4.833	4.844	4.855	4.866	4.877	4.888	4.899	4.910
540	4.910	4.922	4.933	4.944	4.955	4.966	4.977	4.988	4.999	5.010	5.021
550	5.021	5.033	5.044	5.055	5.066	5.077	5.088	5.099	5.111	5.122	5.133
560	5.133	5.144	5.155	5.166	5.178	5.189	5.200	5.211	5.222	5.234	5.245
570	5.245	5.256	5.267	5.279	5.290	5.301	5.312	5.323	5.335	5.346	5.357
580	5.357	5.369	5.380	5.391	5.402	5.414	5.425	5.436	5.448	5.459	5.470
590	5.470	5.481	5.493	5.504	5.515	5.527	5.538	5.549	5.561	5.572	5.583
600	5.583	5.595	5.606	5.618	5.629	5.640	5.652	5.663	5.674	5.686	5.697
610	5.697	5.709	5.720	5.731	5.743	5.754	5.766	5.777	5.789	5.800	5.812
620	5.812	5.823	5.834	5.846	5.857	5.869	5.880	5.892	5.903	5.915	5.926
630	5.926	5.938	5.949	5.961	5.972	5.984	5.995	6.007	6.018	6.030	6.041
640	6.041	6.053	6.065	6.076	6.088	6.099	6.111	6.122	6.134	6.146	6.157
650	6.157	6.169	6.180	6.192	6.204	6.215	6.227	6.238	6.250	6.262	6.273
660	6.273	6.285	6.297	6.308	6.320	6.332	6.343	6.355	6.367	6.378	6.390
670	6.390	6.402	6.413	6.425	6.437	6.448	6.460	6.472	6.484	6.495	6.507
680	6.507	6.519	6.531	6.542	6.554	6.566	6.578	6.589	6.601	6.613	6.625
690	6.625	6.636	6.648	6.660	6.672	6.684	6.695	6.707	6.719	6.731	6.743
700	6.743	6.755	6.766	6.778	6.790	6.802	6.814	6.826	6.838	6.849	6.861
710	6.861	6.873	6.885	6.897	6.909	6.921	6.933	6.945	6.956	6.968	6.980
720	6.980	6.992	7.004	7.016	7.028	7.040	7.052	7.064	7.076	7.088	7.100

Platinum Rhodium - Platinum (Pt13Rh-Pt) R

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
730	7.100	7.112	7.124	7.136	7.148	7.160	7.172	7.184	7.196	7.208	7.220
740	7.220	7.232	7.244	7.256	7.268	7.280	7.292	7.304	7.316	7.328	7.340
750	7.340	7.352	7.364	7.376	7.389	7.401	7.413	7.425	7.437	7.449	7.461
760	7.461	7.473	7.485	7.498	7.510	7.522	7.534	7.546	7.558	7.570	7.583
770	7.583	7.595	7.607	7.619	7.631	7.644	7.656	7.668	7.680	7.692	7.705
780	7.705	7.717	7.729	7.741	7.753	7.766	7.778	7.790	7.802	7.815	7.827
790	7.827	7.839	7.851	7.864	7.876	7.888	7.901	7.913	7.925	7.938	7.950
800	7.950	7.962	7.974	7.987	7.999	8.011	8.024	8.036	8.048	8.061	8.073
810	8.073	8.086	8.098	8.110	8.123	8.135	8.147	8.160	8.172	8.185	8.197
820	8.197	8.209	8.222	8.234	8.247	8.259	8.272	8.284	8.296	8.309	8.321
830	8.321	8.334	8.346	8.359	8.371	8.384	8.396	8.409	8.421	8.434	8.446
840	8.446	8.459	8.471	8.484	8.496	8.509	8.521	8.534	8.546	8.559	8.571
850	8.571	8.584	8.597	8.609	8.622	8.634	8.647	8.659	8.672	8.685	8.697
860	8.697	8.710	8.722	8.735	8.748	8.760	8.773	8.785	8.798	8.811	8.823
870	8.823	8.836	8.849	8.861	8.874	8.887	8.899	8.912	8.925	8.937	8.950
880	8.950	8.963	8.975	8.988	9.001	9.014	9.026	9.039	9.052	9.065	9.077
890	9.077	9.090	9.103	9.115	9.128	9.141	9.154	9.167	9.179	9.192	9.205
900	9.205	9.218	9.230	9.243	9.256	9.269	9.282	9.294	9.307	9.320	9.333
910	9.333	9.346	9.359	9.371	9.384	9.397	9.410	9.423	9.436	9.449	9.461
920	9.461	9.474	9.487	9.500	9.513	9.526	9.539	9.552	9.565	9.578	9.590
930	9.590	9.603	9.616	9.629	9.642	9.655	9.668	9.681	9.694	9.707	9.720
940	9.720	9.733	9.746	9.759	9.772	9.785	9.798	9.811	9.824	9.837	9.850
950	9.850	9.863	9.876	9.889	9.902	9.915	9.928	9.941	9.954	9.967	9.980
960	9.980	9.993	10.006	10.019	10.032	10.046	10.059	10.072	10.085	10.098	10.111
970	10.111	10.124	10.137	10.150	10.163	10.177	10.190	10.203	10.216	10.229	10.242
980	10.242	10.255	10.268	10.282	10.295	10.308	10.321	10.334	10.347	10.361	10.374
990	10.374	10.387	10.400	10.413	10.427	10.440	10.453	10.466	10.480	10.493	10.506
1000	10.506	10.519	10.532	10.546	10.559	10.572	10.585	10.599	10.612	10.625	10.638
1010	10.638	10.652	10.665	10.678	10.692	10.705	10.718	10.731	10.745	10.758	10.771
1020	10.771	10.785	10.798	10.811	10.825	10.838	10.851	10.865	10.878	10.891	10.905
1030	10.905	10.918	10.932	10.945	10.958	10.972	10.985	10.998	11.012	11.025	11.039
1040	11.039	11.052	11.065	11.079	11.092	11.106	11.119	11.132	11.146	11.159	11.173
1050	11.173	11.186	11.200	11.213	11.227	11.240	11.253	11.267	11.280	11.294	11.307
1060	11.307	11.321	11.334	11.348	11.361	11.375	11.388	11.402	11.415	11.429	11.442
1070	11.442	11.456	11.469	11.483	11.496	11.510	11.524	11.537	11.551	11.564	11.578
1080	11.578	11.591	11.605	11.618	11.632	11.646	11.659	11.673	11.686	11.700	11.714
1090	11.714	11.727	11.741	11.754	11.768	11.782	11.795	11.809	11.822	11.836	11.850
1100	11.850	11.863	11.877	11.891	11.904	11.918	11.931	11.945	11.959	11.972	11.986
1110	11.986	12.000	12.013	12.027	12.041	12.054	12.068	12.082	12.096	12.109	12.123

Platinum Rhodium - Platinum (Pt13Rh-Pt) R

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1120	12.123	12.137	12.150	12.164	12.178	12.191	12.205	12.219	12.233	12.246	12.260
1130	12.260	12.274	12.288	12.301	12.315	12.329	12.342	12.356	12.370	12.384	12.397
1140	12.397	12.411	12.425	12.439	12.453	12.466	12.480	12.494	12.508	12.521	12.535
1150	12.535	12.549	12.563	12.577	12.590	12.604	12.618	12.632	12.646	12.659	12.673
1160	12.673	12.687	12.701	12.715	12.729	12.742	12.756	12.770	12.784	12.798	12.812
1170	12.812	12.825	12.839	12.853	12.867	12.881	12.895	12.909	12.922	12.936	12.950
1180	12.950	12.964	12.978	12.992	13.006	13.019	13.033	13.047	13.061	13.075	13.089
1190	13.089	13.103	13.117	13.131	13.145	13.158	13.172	13.186	13.200	13.214	13.228
1200	13.228	13.242	13.256	13.270	13.284	13.298	13.311	13.325	13.339	13.353	13.367
1210	13.367	13.381	13.395	13.409	13.423	13.437	13.451	13.465	13.479	13.493	13.507
1220	13.507	13.521	13.535	13.549	13.563	13.577	13.590	13.604	13.618	13.632	13.646
1230	13.646	13.660	13.674	13.688	13.702	13.716	13.730	13.744	13.758	13.772	13.786
1240	13.786	13.800	13.814	13.828	13.842	13.856	13.870	13.884	13.898	13.912	13.926
1250	13.926	13.940	13.954	13.968	13.982	13.996	14.010	14.024	14.038	14.052	14.066
1260	14.066	14.081	14.095	14.109	14.123	14.137	14.151	14.165	14.179	14.193	14.207
1270	14.207	14.221	14.235	14.249	14.263	14.277	14.291	14.305	14.319	14.333	14.347
1280	14.347	14.361	14.375	14.390	14.404	14.418	14.432	14.446	14.460	14.474	14.488
1290	14.488	14.502	14.516	14.530	14.544	14.558	14.572	14.586	14.601	14.615	14.629
1300	14.629	14.643	14.657	14.671	14.685	14.699	14.713	14.727	14.741	14.755	14.770
1310	14.770	14.784	14.798	14.812	14.826	14.840	14.854	14.868	14.882	14.896	14.911
1320	14.911	14.925	14.939	14.953	14.967	14.981	14.995	15.009	15.023	15.037	15.052
1330	15.052	15.066	15.080	15.094	15.108	15.122	15.136	15.150	15.164	15.179	15.193
1340	15.193	15.207	15.221	15.235	15.249	15.263	15.277	15.291	15.306	15.320	15.334
1350	15.334	15.348	15.362	15.376	15.390	15.404	15.419	15.433	15.447	15.461	15.475
1360	15.475	15.489	15.503	15.517	15.531	15.546	15.560	15.574	15.588	15.602	15.616
1370	15.616	15.630	15.645	15.659	15.673	15.687	15.701	15.715	15.729	15.743	15.758
1380	15.758	15.772	15.786	15.800	15.814	15.828	15.842	15.856	15.871	15.885	15.899
1390	15.899	15.913	15.927	15.941	15.955	15.969	15.984	15.998	16.012	16.026	16.040
1400	16.040	16.054	16.068	16.082	16.097	16.111	16.125	16.139	16.153	16.167	16.181
1410	16.181	16.196	16.210	16.224	16.238	16.252	16.266	16.280	16.294	16.309	16.323
1420	16.323	16.337	16.351	16.365	16.379	16.393	16.407	16.422	16.436	16.450	16.464
1430	16.464	16.478	16.492	16.506	16.520	16.534	16.549	16.563	16.577	16.591	16.605
1440	16.605	16.619	16.633	16.647	16.662	16.676	16.690	16.704	16.718	16.732	16.746
1450	16.746	16.760	16.774	16.789	16.803	16.817	16.831	16.845	16.859	16.873	16.887
1460	16.887	16.901	16.915	16.930	16.944	16.958	16.972	16.986	17.000	17.014	17.028
1470	17.028	17.042	17.056	17.071	17.085	17.099	17.113	17.127	17.141	17.155	17.169
1480	17.169	17.183	17.197	17.211	17.225	17.240	17.254	17.268	17.282	17.296	17.310
1490	17.310	17.324	17.338	17.352	17.366	17.380	17.394	17.408	17.423	17.437	17.451
1500	17.451	17.465	17.479	17.493	17.507	17.521	17.535	17.549	17.563	17.577	17.591

Platinum Rhodium - Platinum (Pt13Rh-Pt) R

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1510	17.591	17.605	17.619	17.633	17.647	17.661	17.676	17.690	17.704	17.718	17.732
1520	17.732	17.746	17.760	17.774	17.788	17.802	17.816	17.830	17.844	17.858	17.872
1530	17.872	17.886	17.900	17.914	17.928	17.942	17.956	17.970	17.984	17.998	18.012
1540	18.012	18.026	18.040	18.054	18.068	18.082	18.096	18.110	18.124	18.138	18.152
1550	18.152	18.166	18.180	18.194	18.208	18.222	18.236	18.250	18.264	18.278	18.292
1560	18.292	18.306	18.320	18.334	18.348	18.362	18.376	18.390	18.404	18.417	18.431
1570	18.431	18.445	18.459	18.473	18.487	18.501	18.515	18.529	18.543	18.557	18.571
1580	18.571	18.585	18.599	18.613	18.627	18.640	18.654	18.668	18.682	18.696	18.710
1590	18.710	18.724	18.738	18.752	18.766	18.779	18.793	18.807	18.821	18.835	18.849
1600	18.849	18.863	18.877	18.891	18.904	18.918	18.932	18.946	18.960	18.974	18.988
1610	18.988	19.002	19.015	19.029	19.043	19.057	19.071	19.085	19.098	19.112	19.126
1620	19.126	19.140	19.154	19.168	19.181	19.195	19.209	19.223	19.237	19.250	19.264
1630	19.264	19.278	19.292	19.306	19.319	19.333	19.347	19.361	19.375	19.388	19.402
1640	19.402	19.416	19.430	19.444	19.457	19.471	19.485	19.499	19.512	19.526	19.540
1650	19.540	19.554	19.567	19.581	19.595	19.609	19.622	19.636	19.650	19.663	19.677
1660	19.677	19.691	19.705	19.718	19.732	19.746	19.759	19.773	19.787	19.800	19.814
1670	19.814	19.828	19.841	19.855	19.869	19.882	19.896	19.910	19.923	19.937	19.951
1680	19.951	19.964	19.978	19.992	20.005	20.019	20.032	20.046	20.060	20.073	20.087
1690	20.087	20.100	20.114	20.127	20.141	20.154	20.168	20.181	20.195	20.208	20.222
1700	20.222	20.235	20.249	20.262	20.275	20.289	20.302	20.316	20.329	20.342	20.356
1710	20.356	20.369	20.382	20.396	20.409	20.422	20.436	20.449	20.462	20.475	20.488
1720	20.488	20.502	20.515	20.528	20.541	20.554	20.567	20.581	20.594	20.607	20.620
1730	20.620	20.633	20.646	20.659	20.672	20.685	20.698	20.711	20.724	20.736	20.749
1740	20.749	20.762	20.775	20.788	20.801	20.813	20.826	20.839	20.852	20.864	20.877
1750	20.877	20.890	20.902	20.915	20.928	20.940	20.953	20.965	20.978	20.990	21.003
1760	21.003	21.015	21.027	21.040	21.052	21.065	21.077	21.089	21.101		

11.3.10 Platinum Rhodium - Platinum (Pt30Rh-Pt6Rh) B

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.000	0.000	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.002	-0.002
10	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.003	-0.003	-0.003
20	-0.003	-0.003	-0.003	-0.003	-0.003	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
30	-0.002	-0.002	-0.002	-0.002	-0.002	-0.001	-0.001	-0.001	-0.001	-0.001	0.000
40	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.002
50	0.002	0.003	0.003	0.003	0.004	0.004	0.004	0.005	0.005	0.006	0.006
60	0.006	0.007	0.007	0.008	0.008	0.009	0.009	0.010	0.010	0.011	0.011
70	0.011	0.012	0.012	0.013	0.014	0.014	0.015	0.015	0.016	0.017	0.017
80	0.017	0.018	0.019	0.020	0.020	0.021	0.022	0.022	0.023	0.024	0.025
90	0.025	0.026	0.026	0.027	0.028	0.029	0.030	0.031	0.031	0.032	0.033
100	0.033	0.034	0.035	0.036	0.037	0.038	0.039	0.040	0.041	0.042	0.043
110	0.043	0.044	0.045	0.046	0.047	0.048	0.049	0.050	0.051	0.052	0.053
120	0.053	0.055	0.056	0.057	0.058	0.059	0.060	0.062	0.063	0.064	0.065
130	0.065	0.066	0.068	0.069	0.070	0.072	0.073	0.074	0.075	0.077	0.078
140	0.078	0.079	0.081	0.082	0.084	0.085	0.086	0.088	0.089	0.091	0.092
150	0.092	0.094	0.095	0.096	0.098	0.099	0.101	0.102	0.104	0.106	0.107
160	0.107	0.109	0.110	0.112	0.113	0.115	0.117	0.118	0.120	0.122	0.123
170	0.123	0.125	0.127	0.128	0.130	0.132	0.134	0.135	0.137	0.139	0.141
180	0.141	0.142	0.144	0.146	0.148	0.150	0.151	0.153	0.155	0.157	0.159
190	0.159	0.161	0.163	0.165	0.166	0.168	0.170	0.172	0.174	0.176	0.178
200	0.178	0.180	0.182	0.184	0.186	0.188	0.190	0.192	0.195	0.197	0.199
210	0.199	0.201	0.203	0.205	0.207	0.209	0.212	0.214	0.216	0.218	0.220
220	0.220	0.222	0.225	0.227	0.229	0.231	0.234	0.236	0.238	0.241	0.243
230	0.243	0.245	0.248	0.250	0.252	0.255	0.257	0.259	0.262	0.264	0.267
240	0.267	0.269	0.271	0.274	0.276	0.279	0.281	0.284	0.286	0.289	0.291
250	0.291	0.294	0.296	0.299	0.301	0.304	0.307	0.309	0.312	0.314	0.317
260	0.317	0.320	0.322	0.325	0.328	0.330	0.333	0.336	0.338	0.341	0.344
270	0.344	0.347	0.349	0.352	0.355	0.358	0.360	0.363	0.366	0.369	0.372
280	0.372	0.375	0.377	0.380	0.383	0.386	0.389	0.392	0.395	0.398	0.401
290	0.401	0.404	0.407	0.410	0.413	0.416	0.419	0.422	0.425	0.428	0.431
300	0.431	0.434	0.437	0.440	0.443	0.446	0.449	0.452	0.455	0.458	0.462
310	0.462	0.465	0.468	0.471	0.474	0.478	0.481	0.484	0.487	0.490	0.494
320	0.494	0.497	0.500	0.503	0.507	0.510	0.513	0.517	0.520	0.523	0.527
330	0.527	0.530	0.533	0.537	0.540	0.544	0.547	0.550	0.554	0.557	0.561
340	0.561	0.564	0.568	0.571	0.575	0.578	0.582	0.585	0.589	0.592	0.596
350	0.596	0.599	0.603	0.607	0.610	0.614	0.617	0.621	0.625	0.628	0.632
360	0.632	0.636	0.639	0.643	0.647	0.650	0.654	0.658	0.662	0.665	0.669
370	0.669	0.673	0.677	0.680	0.684	0.688	0.692	0.696	0.700	0.703	0.707
380	0.707	0.711	0.715	0.719	0.723	0.727	0.731	0.735	0.738	0.742	0.746

Platinum Rhodium - Platinum (Pt30Rh-Pt6Rh) B

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
390	0.746	0.750	0.754	0.758	0.762	0.766	0.770	0.774	0.778	0.782	0.787
400	0.787	0.791	0.795	0.799	0.803	0.807	0.811	0.815	0.819	0.823	0.828
410	0.828	0.832	0.836	0.840	0.844	0.849	0.853	0.857	0.861	0.865	0.870
420	0.870	0.874	0.878	0.883	0.887	0.891	0.895	0.900	0.904	0.908	0.913
430	0.913	0.917	0.922	0.926	0.930	0.935	0.939	0.944	0.948	0.952	0.957
440	0.957	0.961	0.966	0.970	0.975	0.979	0.984	0.988	0.993	0.997	1.002
450	1.002	1.007	1.011	1.016	1.020	1.025	1.029	1.034	1.039	1.043	1.048
460	1.048	1.053	1.057	1.062	1.067	1.071	1.076	1.081	1.086	1.090	1.095
470	1.095	1.100	1.105	1.109	1.114	1.119	1.124	1.128	1.133	1.138	1.143
480	1.143	1.148	1.153	1.158	1.162	1.167	1.172	1.177	1.182	1.187	1.192
490	1.192	1.197	1.202	1.207	1.212	1.217	1.222	1.227	1.232	1.237	1.242
500	1.242	1.247	1.252	1.257	1.262	1.267	1.272	1.277	1.282	1.287	1.293
510	1.293	1.298	1.303	1.308	1.313	1.318	1.323	1.329	1.334	1.339	1.344
520	1.344	1.350	1.355	1.360	1.365	1.371	1.376	1.381	1.386	1.392	1.397
530	1.397	1.402	1.408	1.413	1.418	1.424	1.429	1.434	1.440	1.445	1.451
540	1.451	1.456	1.461	1.467	1.472	1.478	1.483	1.489	1.494	1.500	1.505
550	1.505	1.511	1.516	1.522	1.527	1.533	1.538	1.544	1.549	1.555	1.561
560	1.561	1.566	1.572	1.577	1.583	1.589	1.594	1.600	1.606	1.611	1.617
570	1.617	1.623	1.628	1.634	1.640	1.646	1.651	1.657	1.663	1.669	1.674
580	1.674	1.680	1.686	1.692	1.697	1.703	1.709	1.715	1.721	1.727	1.732
590	1.732	1.738	1.744	1.750	1.756	1.762	1.768	1.774	1.780	1.786	1.792
600	1.792	1.797	1.803	1.809	1.815	1.821	1.827	1.833	1.839	1.845	1.852
610	1.852	1.858	1.864	1.870	1.876	1.882	1.888	1.894	1.900	1.906	1.912
620	1.912	1.919	1.925	1.931	1.937	1.943	1.949	1.955	1.962	1.968	1.974
630	1.974	1.981	1.987	1.993	1.999	2.006	2.012	2.018	2.025	2.031	2.037
640	2.037	2.043	2.050	2.056	2.062	2.069	2.075	2.082	2.088	2.094	2.101
650	2.101	2.107	2.113	2.120	2.126	2.133	2.139	2.146	2.152	2.158	2.165
660	2.165	2.171	2.178	2.184	2.191	2.197	2.204	2.210	2.217	2.224	2.230
670	2.230	2.237	2.243	2.250	2.256	2.263	2.270	2.276	2.283	2.289	2.296
680	2.296	2.303	2.309	2.316	2.323	2.329	2.336	2.343	2.350	2.356	2.363
690	2.363	2.370	2.376	2.383	2.390	2.397	2.403	2.410	2.417	2.424	2.431
700	2.431	2.437	2.444	2.451	2.458	2.465	2.472	2.479	2.485	2.492	2.499
710	2.499	2.506	2.513	2.520	2.527	2.534	2.541	2.548	2.555	2.562	2.569
720	2.569	2.576	2.583	2.590	2.597	2.604	2.611	2.618	2.625	2.632	2.639
730	2.639	2.646	2.653	2.660	2.667	2.674	2.681	2.688	2.696	2.703	2.710
740	2.710	2.717	2.724	2.731	2.738	2.746	2.753	2.760	2.767	2.775	2.782
750	2.782	2.789	2.796	2.803	2.811	2.818	2.825	2.833	2.840	2.847	2.854
760	2.854	2.862	2.869	2.876	2.884	2.891	2.898	2.906	2.913	2.921	2.928
770	2.928	2.935	2.943	2.950	2.958	2.965	2.973	2.980	2.987	2.995	3.002

Platinum Rhodium - Platinum (Pt30Rh-Pt6Rh) B

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
780	3.002	3.010	3.017	3.025	3.032	3.040	3.047	3.055	3.062	3.070	3.078
790	3.078	3.085	3.093	3.100	3.108	3.116	3.123	3.131	3.138	3.146	3.154
800	3.154	3.161	3.169	3.177	3.184	3.192	3.200	3.207	3.215	3.223	3.230
810	3.230	3.238	3.246	3.254	3.261	3.269	3.277	3.285	3.292	3.300	3.308
820	3.308	3.316	3.324	3.331	3.339	3.347	3.355	3.363	3.371	3.379	3.386
830	3.386	3.394	3.402	3.410	3.418	3.426	3.434	3.442	3.450	3.458	3.466
840	3.466	3.474	3.482	3.490	3.498	3.506	3.514	3.522	3.530	3.538	3.546
850	3.546	3.554	3.562	3.570	3.578	3.586	3.594	3.602	3.610	3.618	3.626
860	3.626	3.634	3.643	3.651	3.659	3.667	3.675	3.683	3.692	3.700	3.708
870	3.708	3.716	3.724	3.732	3.741	3.749	3.757	3.765	3.774	3.782	3.790
880	3.790	3.798	3.807	3.815	3.823	3.832	3.840	3.848	3.857	3.865	3.873
890	3.873	3.882	3.890	3.898	3.907	3.915	3.923	3.932	3.940	3.949	3.957
900	3.957	3.965	3.974	3.982	3.991	3.999	4.008	4.016	4.024	4.033	4.041
910	4.041	4.050	4.058	4.067	4.075	4.084	4.093	4.101	4.110	4.118	4.127
920	4.127	4.135	4.144	4.152	4.161	4.170	4.178	4.187	4.195	4.204	4.213
930	4.213	4.221	4.230	4.239	4.247	4.256	4.265	4.273	4.282	4.291	4.299
940	4.299	4.308	4.317	4.326	4.334	4.343	4.352	4.360	4.369	4.378	4.387
950	4.387	4.396	4.404	4.413	4.422	4.431	4.440	4.448	4.457	4.466	4.475
960	4.475	4.484	4.493	4.501	4.510	4.519	4.528	4.537	4.546	4.555	4.564
970	4.564	4.573	4.582	4.591	4.599	4.608	4.617	4.626	4.635	4.644	4.653
980	4.653	4.662	4.671	4.680	4.689	4.698	4.707	4.716	4.725	4.734	4.743
990	4.743	4.753	4.762	4.771	4.780	4.789	4.798	4.807	4.816	4.825	4.834
1000	4.834	4.843	4.853	4.862	4.871	4.880	4.889	4.898	4.908	4.917	4.926
1010	4.926	4.935	4.944	4.954	4.963	4.972	4.981	4.990	5.000	5.009	5.018
1020	5.018	5.027	5.037	5.046	5.055	5.065	5.074	5.083	5.092	5.102	5.111
1030	5.111	5.120	5.130	5.139	5.148	5.158	5.167	5.176	5.186	5.195	5.205
1040	5.205	5.214	5.223	5.233	5.242	5.252	5.261	5.270	5.280	5.289	5.299
1050	5.299	5.308	5.318	5.327	5.337	5.346	5.356	5.365	5.375	5.384	5.394
1060	5.394	5.403	5.413	5.422	5.432	5.441	5.451	5.460	5.470	5.480	5.489
1070	5.489	5.499	5.508	5.518	5.528	5.537	5.547	5.556	5.566	5.576	5.585
1080	5.585	5.595	5.605	5.614	5.624	5.634	5.643	5.653	5.663	5.672	5.682
1090	5.682	5.692	5.702	5.711	5.721	5.731	5.740	5.750	5.760	5.770	5.780
1100	5.780	5.789	5.799	5.809	5.819	5.828	5.838	5.848	5.858	5.868	5.878
1110	5.878	5.887	5.897	5.907	5.917	5.927	5.937	5.947	5.956	5.966	5.976
1120	5.976	5.986	5.996	6.006	6.016	6.026	6.036	6.046	6.055	6.065	6.075
1130	6.075	6.085	6.095	6.105	6.115	6.125	6.135	6.145	6.155	6.165	6.175
1140	6.175	6.185	6.195	6.205	6.215	6.225	6.235	6.245	6.256	6.266	6.276
1150	6.276	6.286	6.296	6.306	6.316	6.326	6.336	6.346	6.356	6.367	6.377
1160	6.377	6.387	6.397	6.407	6.417	6.427	6.438	6.448	6.458	6.468	6.478

Platinum Rhodium - Platinum (Pt30Rh-Pt6Rh) B

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1170	6.478	6.488	6.499	6.509	6.519	6.529	6.539	6.550	6.560	6.570	6.580
1180	6.580	6.591	6.601	6.611	6.621	6.632	6.642	6.652	6.663	6.673	6.683
1190	6.683	6.693	6.704	6.714	6.724	6.735	6.745	6.755	6.766	6.776	6.786
1200	6.786	6.797	6.807	6.818	6.828	6.838	6.849	6.859	6.869	6.880	6.890
1210	6.890	6.901	6.911	6.922	6.932	6.942	6.953	6.963	6.974	6.984	6.995
1220	6.995	7.005	7.016	7.026	7.037	7.047	7.058	7.068	7.079	7.089	7.100
1230	7.100	7.110	7.121	7.131	7.142	7.152	7.163	7.173	7.184	7.194	7.205
1240	7.205	7.216	7.226	7.237	7.247	7.258	7.269	7.279	7.290	7.300	7.311
1250	7.311	7.322	7.332	7.343	7.353	7.364	7.375	7.385	7.396	7.407	7.417
1260	7.417	7.428	7.439	7.449	7.460	7.471	7.482	7.492	7.503	7.514	7.524
1270	7.524	7.535	7.546	7.557	7.567	7.578	7.589	7.600	7.610	7.621	7.632
1280	7.632	7.643	7.653	7.664	7.675	7.686	7.697	7.707	7.718	7.729	7.740
1290	7.740	7.751	7.761	7.772	7.783	7.794	7.805	7.816	7.827	7.837	7.848
1300	7.848	7.859	7.870	7.881	7.892	7.903	7.914	7.924	7.935	7.946	7.957
1310	7.957	7.968	7.979	7.990	8.001	8.012	8.023	8.034	8.045	8.056	8.066
1320	8.066	8.077	8.088	8.099	8.110	8.121	8.132	8.143	8.154	8.165	8.176
1330	8.176	8.187	8.198	8.209	8.220	8.231	8.242	8.253	8.264	8.275	8.286
1340	8.286	8.298	8.309	8.320	8.331	8.342	8.353	8.364	8.375	8.386	8.397
1350	8.397	8.408	8.419	8.430	8.441	8.453	8.464	8.475	8.486	8.497	8.508
1360	8.508	8.519	8.530	8.542	8.553	8.564	8.575	8.586	8.597	8.608	8.620
1370	8.620	8.631	8.642	8.653	8.664	8.675	8.687	8.698	8.709	8.720	8.731
1380	8.731	8.743	8.754	8.765	8.776	8.787	8.799	8.810	8.821	8.832	8.844
1390	8.844	8.855	8.866	8.877	8.889	8.900	8.911	8.922	8.934	8.945	8.956
1400	8.956	8.967	8.979	8.990	9.001	9.013	9.024	9.035	9.047	9.058	9.069
1410	9.069	9.080	9.092	9.103	9.114	9.126	9.137	9.148	9.160	9.171	9.182
1420	9.182	9.194	9.205	9.216	9.228	9.239	9.251	9.262	9.273	9.285	9.296
1430	9.296	9.307	9.319	9.330	9.342	9.353	9.364	9.376	9.387	9.398	9.410
1440	9.410	9.421	9.433	9.444	9.456	9.467	9.478	9.490	9.501	9.513	9.524
1450	9.524	9.536	9.547	9.558	9.570	9.581	9.593	9.604	9.616	9.627	9.639
1460	9.639	9.650	9.662	9.673	9.684	9.696	9.707	9.719	9.730	9.742	9.753
1470	9.753	9.765	9.776	9.788	9.799	9.811	9.822	9.834	9.845	9.857	9.868
1480	9.868	9.880	9.891	9.903	9.914	9.926	9.937	9.949	9.961	9.972	9.984
1490	9.984	9.995	10.007	10.018	10.030	10.041	10.053	10.064	10.076	10.088	10.099
1500	10.099	10.111	10.122	10.134	10.145	10.157	10.168	10.180	10.192	10.203	10.215
1510	10.215	10.226	10.238	10.249	10.261	10.273	10.284	10.296	10.307	10.319	10.331
1520	10.331	10.342	10.354	10.365	10.377	10.389	10.400	10.412	10.423	10.435	10.447
1530	10.447	10.458	10.470	10.482	10.493	10.505	10.516	10.528	10.540	10.551	10.563
1540	10.563	10.575	10.586	10.598	10.609	10.621	10.633	10.644	10.656	10.668	10.679
1550	10.679	10.691	10.703	10.714	10.726	10.738	10.749	10.761	10.773	10.784	10.796

Platinum Rhodium - Platinum (Pt30Rh-Pt6Rh) B

(Thermoelectric emf in mV, referred to a cold junction temperature of 0°C)

	0	1	2	3	4	5	6	7	8	9	10
1560	10.796	10.808	10.819	10.831	10.843	10.854	10.866	10.877	10.889	10.901	10.913
1570	10.913	10.924	10.936	10.948	10.959	10.971	10.983	10.994	11.006	11.018	11.029
1580	11.029	11.041	11.053	11.064	11.076	11.088	11.099	11.111	11.123	11.134	11.146
1590	11.146	11.158	11.169	11.181	11.193	11.205	11.216	11.228	11.240	11.251	11.263
1600	11.263	11.275	11.286	11.298	11.310	11.321	11.333	11.345	11.357	11.368	11.380
1610	11.380	11.392	11.403	11.415	11.427	11.438	11.450	11.462	11.474	11.485	11.497
1620	11.497	11.509	11.520	11.532	11.544	11.555	11.567	11.579	11.591	11.602	11.614
1630	11.614	11.626	11.637	11.649	11.661	11.673	11.684	11.696	11.708	11.719	11.731
1640	11.731	11.743	11.754	11.766	11.778	11.790	11.801	11.813	11.825	11.836	11.848
1650	11.848	11.860	11.871	11.883	11.895	11.907	11.918	11.930	11.942	11.953	11.965
1660	11.965	11.977	11.988	12.000	12.012	12.024	12.035	12.047	12.059	12.070	12.082
1670	12.082	12.094	12.105	12.117	12.129	12.141	12.152	12.164	12.176	12.187	12.199
1680	12.199	12.211	12.222	12.234	12.246	12.257	12.269	12.281	12.292	12.304	12.316
1690	12.316	12.327	12.339	12.351	12.363	12.374	12.386	12.398	12.409	12.421	12.433
1700	12.433	12.444	12.456	12.468	12.479	12.491	12.503	12.514	12.526	12.538	12.549
1710	12.549	12.561	12.572	12.584	12.596	12.607	12.619	12.631	12.642	12.654	12.666
1720	12.666	12.677	12.689	12.701	12.712	12.724	12.736	12.747	12.759	12.770	12.782
1730	12.782	12.794	12.805	12.817	12.829	12.840	12.852	12.863	12.875	12.887	12.898
1740	12.898	12.910	12.921	12.933	12.945	12.956	12.968	12.980	12.991	13.003	13.014
1750	13.014	13.026	13.037	13.049	13.061	13.072	13.084	13.095	13.107	13.119	13.130
1760	13.130	13.142	13.153	13.165	13.176	13.188	13.200	13.211	13.223	13.234	13.246
1770	13.246	13.257	13.269	13.280	13.292	13.304	13.315	13.327	13.338	13.350	13.361
1780	13.361	13.373	13.384	13.396	13.407	13.419	13.430	13.442	13.453	13.465	13.476
1790	13.476	13.488	13.499	13.511	13.522	13.534	13.545	13.557	13.568	13.580	13.591
1800	13.591	13.603	13.614	13.626	13.637	13.649	13.660	13.672	13.683	13.694	13.706
1810	13.706	13.717	13.729	13.740	13.752	13.763	13.775	13.786	13.797	13.809	13.820

11.4 Reference values for Pt 100

(Resistance in Ω)

	0	1	2	3	4	5	6	7	8	9	10
-200	18.520	18.952	19.384	19.815	20.247	20.677	21.108	21.538	21.967	22.397	22.825
-190	22.825	23.254	23.682	24.110	24.538	24.965	25.392	25.819	26.245	26.671	27.096
-180	27.096	27.522	27.947	28.371	28.796	29.220	29.643	30.067	30.490	30.913	31.335
-170	31.335	31.757	32.179	32.601	33.022	33.443	33.864	34.284	34.704	35.124	35.543
-160	35.543	35.963	36.382	36.800	37.219	37.637	38.055	38.472	38.889	39.306	39.723
-150	39.723	40.140	40.556	40.972	41.388	41.803	42.218	42.633	43.048	43.462	43.876
-140	43.876	44.290	44.704	45.117	45.531	45.944	46.356	46.769	47.181	47.593	48.005
-130	48.005	48.416	48.828	49.239	49.649	50.060	50.470	50.881	51.291	51.700	52.110
-120	52.110	52.519	52.928	53.337	53.746	54.154	54.562	54.970	55.378	55.786	56.193
-110	56.193	56.600	57.007	57.414	57.821	58.227	58.633	59.039	59.445	59.850	60.256
-100	60.256	60.661	61.066	61.471	61.876	62.280	62.684	63.088	63.492	63.896	64.300
-90	64.300	64.703	65.106	65.509	65.912	66.315	66.717	67.120	67.522	67.924	68.325
-80	68.325	68.727	69.129	69.530	69.931	70.332	70.733	71.134	71.534	71.934	72.335
-70	72.335	72.735	73.134	73.534	73.934	74.333	74.732	75.131	75.530	75.929	76.328
-60	76.328	76.726	77.125	77.523	77.921	78.319	78.717	79.114	79.512	79.909	80.306
-50	80.306	80.703	81.100	81.497	81.894	82.290	82.687	83.083	83.479	83.875	84.271
-40	84.271	84.666	85.062	85.457	85.853	86.248	86.643	87.038	87.432	87.827	88.222
-30	88.222	88.616	89.010	89.404	89.798	90.192	90.586	90.980	91.373	91.767	92.160
-20	92.160	92.553	92.946	93.339	93.732	94.124	94.517	94.909	95.302	95.694	96.086
-10	96.086	96.478	96.870	97.261	97.653	98.044	98.436	98.827	99.218	99.609	100.000
0	100.000	100.391	100.781	101.172	101.562	101.953	102.343	102.733	103.123	103.513	103.903
10	103.903	104.292	104.682	105.071	105.460	105.849	106.238	106.627	107.016	107.405	107.794
20	107.794	108.182	108.570	108.959	109.347	109.735	110.123	110.510	110.898	111.286	111.673
30	111.673	112.060	112.447	112.835	113.221	113.608	113.995	114.382	114.768	115.155	115.541
40	115.541	115.927	116.313	116.699	117.085	117.470	117.856	118.241	118.627	119.012	119.397
50	119.397	119.782	120.167	120.552	120.936	121.321	121.705	122.090	122.474	122.858	123.242
60	123.242	123.626	124.009	124.393	124.777	125.160	125.543	125.926	126.309	126.692	127.075
70	127.075	127.458	127.840	128.223	128.605	128.987	129.370	129.752	130.133	130.515	130.897
80	130.897	131.278	131.660	132.041	132.422	132.803	133.184	133.565	133.946	134.326	134.707
90	134.707	135.087	135.468	135.848	136.228	136.608	136.987	137.367	137.747	138.126	138.506
100	138.506	138.885	139.264	139.643	140.022	140.400	140.779	141.158	141.536	141.914	142.293
110	142.293	142.671	143.049	143.426	143.804	144.182	144.559	144.937	145.314	145.691	146.068
120	146.068	146.445	146.822	147.198	147.575	147.951	148.328	148.704	149.080	149.456	149.832
130	149.832	150.208	150.583	150.959	151.334	151.710	152.085	152.460	152.835	153.210	153.584
140	153.584	153.959	154.333	154.708	155.082	155.456	155.830	156.204	156.578	156.952	157.325
150	157.325	157.699	158.072	158.445	158.818	159.191	159.564	159.937	160.309	160.682	161.054
160	161.054	161.427	161.799	162.171	162.543	162.915	163.286	163.658	164.030	164.401	164.772
170	164.772	165.143	165.514	165.885	166.256	166.627	166.997	167.368	167.738	168.108	168.478
180	168.478	168.848	169.218	169.588	169.958	170.327	170.696	171.066	171.435	171.804	172.173

Reference values for Pt 100

(Resistance in Ω)

	0	1	2	3	4	5	6	7	8	9	10
190	172.173	172.542	172.910	173.279	173.648	174.016	174.384	174.752	175.120	175.488	175.856
200	175.856	176.224	176.591	176.959	177.326	177.693	178.060	178.427	178.794	179.161	179.528
210	179.528	179.894	180.260	180.627	180.993	181.359	181.725	182.091	182.456	182.822	183.188
220	183.188	183.553	183.918	184.283	184.648	185.013	185.378	185.743	186.107	186.472	186.836
230	186.836	187.200	187.564	187.928	188.292	188.656	189.019	189.383	189.746	190.110	190.473
240	190.473	190.836	191.199	191.562	191.924	192.287	192.649	193.012	193.374	193.736	194.098
250	194.098	194.460	194.822	195.183	195.545	195.906	196.268	196.629	196.990	197.351	197.712
260	197.712	198.073	198.433	198.794	199.154	199.514	199.875	200.235	200.595	200.954	201.314
270	201.314	201.674	202.033	202.393	202.752	203.111	203.470	203.829	204.188	204.546	204.905
280	204.905	205.263	205.622	205.980	206.338	206.696	207.054	207.411	207.769	208.127	208.484
290	208.484	208.841	209.198	209.555	209.912	210.269	210.626	210.982	211.339	211.695	212.052
300	212.052	212.408	212.764	213.120	213.475	213.831	214.187	214.542	214.897	215.252	215.608
310	215.608	215.962	216.317	216.672	217.027	217.381	217.736	218.090	218.444	218.798	219.152
320	219.152	219.506	219.860	220.213	220.567	220.920	221.273	221.626	221.979	222.332	222.685
330	222.685	223.038	223.390	223.743	224.095	224.447	224.799	225.151	225.503	225.855	226.206
340	226.206	226.558	226.909	227.260	227.612	227.963	228.314	228.664	229.015	229.366	229.716
350	229.716	230.066	230.417	230.767	231.117	231.467	231.816	232.166	232.516	232.865	233.214
360	233.214	233.564	233.913	234.262	234.610	234.959	235.308	235.656	236.005	236.353	236.701
370	236.701	237.049	237.397	237.745	238.093	238.440	238.788	239.135	239.482	239.829	240.176
380	240.176	240.523	240.870	241.217	241.563	241.910	242.256	242.602	242.948	243.294	243.640
390	243.640	243.986	244.331	244.677	245.022	245.367	245.713	246.058	246.403	246.747	247.092
400	247.092	247.437	247.781	248.125	248.470	248.814	249.158	249.502	249.845	250.189	250.533
410	250.533	250.876	251.219	251.562	251.906	252.248	252.591	252.934	253.277	253.619	253.962
420	253.962	254.304	254.646	254.988	255.330	255.672	256.013	256.355	256.696	257.038	257.379
430	257.379	257.720	258.061	258.402	258.743	259.083	259.424	259.764	260.105	260.445	260.785
440	260.785	261.125	261.465	261.804	262.144	262.483	262.823	263.162	263.501	263.840	264.179
450	264.179	264.518	264.857	265.195	265.534	265.872	266.210	266.548	266.886	267.224	267.562
460	267.562	267.900	268.237	268.574	268.912	269.249	269.586	269.923	270.260	270.597	270.933
470	270.933	271.270	271.606	271.942	272.278	272.614	272.950	273.286	273.622	273.957	274.293
480	274.293	274.628	274.963	275.298	275.633	275.968	276.303	276.638	276.972	277.307	277.641
490	277.641	277.975	278.309	278.643	278.977	279.311	279.644	279.978	280.311	280.644	280.978
500	280.978	281.311	281.643	281.976	282.309	282.641	282.974	283.306	283.638	283.971	284.303
510	284.303	284.634	284.966	285.298	285.629	285.961	286.292	286.623	286.954	287.285	287.616
520	287.616	287.947	288.277	288.608	288.938	289.268	289.599	289.929	290.258	290.588	290.918
530	290.918	291.247	291.577	291.906	292.235	292.565	292.894	293.222	293.551	293.880	294.208
540	294.208	294.537	294.865	295.193	295.521	295.849	296.177	296.505	296.832	297.160	297.487
550	297.487	297.814	298.142	298.469	298.795	299.122	299.449	299.775	300.102	300.428	300.754
560	300.754	301.080	301.406	301.732	302.058	302.384	302.709	303.035	303.360	303.685	304.010
570	304.010	304.335	304.660	304.985	305.309	305.634	305.958	306.282	306.606	306.930	307.254

Reference values for Pt 100

(Resistance in Ω)

	0	1	2	3	4	5	6	7	8	9	10
580	307.254	307.578	307.902	308.225	308.549	308.872	309.195	309.518	309.841	310.164	310.487
590	310.487	310.810	311.132	311.454	311.777	312.099	312.421	312.743	313.065	313.386	313.708
600	313.708	314.029	314.351	314.672	314.993	315.314	315.635	315.956	316.277	316.597	316.918
610	316.918	317.238	317.558	317.878	318.198	318.518	318.838	319.157	319.477	319.796	320.116
620	320.116	320.435	320.754	321.073	321.391	321.710	322.029	322.347	322.666	322.984	323.302
630	323.302	323.620	323.938	324.256	324.573	324.891	325.208	325.526	325.843	326.160	326.477
640	326.477	326.794	327.110	327.427	327.744	328.060	328.376	328.692	329.008	329.324	329.640
650	329.640	329.956	330.271	330.587	330.902	331.217	331.533	331.848	332.162	332.477	332.792
660	332.792	333.106	333.421	333.735	334.049	334.363	334.677	334.991	335.305	335.619	335.932
670	335.932	336.246	336.559	336.872	337.185	337.498	337.811	338.123	338.436	338.748	339.061
680	339.061	339.373	339.685	339.997	340.309	340.621	340.932	341.244	341.555	341.867	342.178
690	342.178	342.489	342.800	343.111	343.422	343.732	344.043	344.353	344.663	344.973	345.284
700	345.284	345.593	345.903	346.213	346.522	346.832	347.141	347.451	347.760	348.069	348.378
710	348.378	348.686	348.995	349.303	349.612	349.920	350.228	350.536	350.844	351.152	351.460
720	351.460	351.768	352.075	352.382	352.690	352.997	353.304	353.611	353.918	354.224	354.531
730	354.531	354.837	355.144	355.450	355.756	356.062	356.368	356.674	356.979	357.285	357.590
740	357.590	357.896	358.201	358.506	358.811	359.116	359.420	359.725	360.029	360.334	360.638
750	360.638	360.942	361.246	361.550	361.854	362.158	362.461	362.765	363.068	363.371	363.674
760	363.674	363.977	364.280	364.583	364.886	365.188	365.491	365.793	366.095	366.397	366.699
770	366.699	367.001	367.303	367.604	367.906	368.207	368.508	368.810	369.111	369.412	369.712
780	369.712	370.013	370.314	370.614	370.914	371.215	371.515	371.815	372.115	372.414	372.714
790	372.714	373.013	373.313	373.612	373.911	374.210	374.509	374.808	375.107	375.406	375.704
800	375.704	376.002	376.301	376.599	376.897	377.195	377.493	377.790	378.088	378.385	378.683
810	378.683	378.980	379.277	379.574	379.871	380.167	380.464	380.761	381.057	381.353	381.650
820	381.650	381.946	382.242	382.537	382.833	383.129	383.424	383.720	384.015	384.310	384.605
830	384.605	384.900	385.195	385.489	385.784	386.078	386.373	386.667	386.961	387.255	387.549
840	387.549	387.843	388.136	388.430	388.723	389.016	389.310	389.603	389.896	390.188	390.481
850	390.481	390.774	391.066	391.359	391.651	391.943	392.235	392.527	392.819	393.110	393.402

11.5 Reference values for Ni 100

(Resistance in Ω)

	0	1	2	3	4	5	6	7	8	9	10
-60	69.520	69.987	70.456	70.926	71.397	71.870	72.344	72.820	73.297	73.775	74.255
-50	74.255	74.736	75.219	75.703	76.189	76.676	77.164	77.654	78.145	78.637	79.131
-40	79.131	79.626	80.123	80.621	81.121	81.621	82.123	82.627	83.132	83.638	84.146
-30	84.146	84.655	85.165	85.677	86.190	86.704	87.220	87.737	88.256	88.775	89.296
-20	89.296	89.819	90.343	90.868	91.394	91.922	92.451	92.982	93.514	94.047	94.582
-10	94.582	95.117	95.655	96.193	96.733	97.274	97.817	98.360	98.906	99.452	100.000
0	100.000	100.549	101.100	101.651	102.205	102.759	103.315	103.872	104.431	104.990	105.552
10	105.552	106.114	106.678	107.243	107.809	108.377	108.946	109.517	110.089	110.662	111.236
20	111.236	111.812	112.390	112.968	113.548	114.129	114.712	115.296	115.881	116.468	117.056
30	117.056	117.645	118.236	118.828	119.421	120.016	120.613	121.210	121.809	122.409	123.011
40	123.011	123.614	124.219	124.825	125.432	126.041	126.651	127.262	127.875	128.489	129.105
50	129.105	129.722	130.341	130.961	131.582	132.205	132.829	133.455	134.082	134.710	135.340
60	135.340	135.972	136.605	137.239	137.875	138.512	139.151	139.791	140.433	141.076	141.721
70	141.721	142.367	143.015	143.664	144.315	144.967	145.621	146.276	146.933	147.592	148.251
80	148.251	148.913	149.576	150.240	150.907	151.574	152.244	152.914	153.587	154.261	154.937
90	154.937	155.614	156.293	156.973	157.655	158.339	159.024	159.711	160.400	161.090	161.783
100	161.783	162.476	163.172	163.869	164.567	165.268	165.970	166.674	167.379	168.087	168.796
110	168.796	169.507	170.219	170.933	171.649	172.367	173.087	173.808	174.532	175.257	175.984
120	175.984	176.712	177.443	178.175	178.909	179.646	180.384	181.123	181.865	182.609	183.354
130	183.354	184.102	184.851	185.602	186.356	187.111	187.868	188.627	189.388	190.151	190.917
140	190.917	191.684	192.453	193.224	193.997	194.773	195.550	196.329	197.111	197.895	198.680
150	198.680	199.468	200.258	201.050	201.844	202.641	203.440	204.240	205.043	205.848	206.656
160	206.656	207.465	208.277	209.091	209.908	210.727	211.548	212.371	213.196	214.024	214.855
170	214.855	215.687	216.522	217.359	218.199	219.041	219.886	220.733	221.582	222.434	223.289
180	223.289	224.145	225.005	225.867	226.731	227.598	228.467	229.339	230.214	231.091	231.971
190	231.971	232.854	233.739	234.626	235.517	236.410	237.306	238.204	239.105	240.009	240.916
200	240.916	241.825	242.738	243.653	244.571	245.491	246.415	247.342	248.271	249.203	250.138
210	250.138	251.076	252.017	252.961	253.908	254.858	255.811	256.767	257.726	258.688	259.654
220	259.654	260.622	261.593	262.568	263.546	264.527	265.511	266.498	267.488	268.482	269.479
230	269.479	270.479	271.483	272.490	273.500	274.514	275.531	276.551	277.575	278.602	279.633
240	279.633	280.667	281.704	282.745	283.790	284.838	285.890	286.945	288.004	289.067	290.133
250	290.133										

12 Standards and literature

12.1 Standards

EN 50112	Measurement and control - electrical temperature sensors - metal protection tubes
EN 50212	Plug connections for thermocouples
EN 60584-1	Thermocouples - Part 1 : Reference tables
EN 60584-2	Thermocouples - Part 2: Tolerances
EN 60751	Industrial platinum resistance thermometer sensors
EN 61515	Sheathed thermocouple leads and sheathed base-metal thermocouples
DIN 1345	Thermodynamics, symbols, units
DIN 13402	Medical electronics temperature meter
DIN 16160	Thermometers, concepts
DIN 16179	Screwed-in ends and protection tubes for glass thermometers for industrial purposes (invalid, replaced by DIN 43772)
DIN 28147	Thermopockets in steel for agitator vessels; dimensions
DIN 28149	Protection tubes for thermometers for agitator vessels; connecting dimensions
DIN 43710	Reference tables for thermocouple types U and L (invalid)
DIN 43712	Wires for thermocouples (invalid)
DIN 43714	Compensating cables for thermocouple thermometers (invalid)
DIN 43720	Metal protection tubes for thermocouples
DIN 43721	Mineral insulated thermocables and mineral insulated thermocouples
DIN 43724	Ceramic protection tubes and fixing rings for thermocouples
DIN 43725	Insulating tubes for thermocouples
DIN 43729	Connecting heads for thermocouple and resistance thermometers
DIN 43732	Thermocouples for thermocouple thermometers
DIN 43733	Straight thermocouple thermometers without interchangeable sensor units
DIN 43734	Stop flanges for thermocouple and resistance thermometers
DIN 43735	Sensor units for thermocouple thermometers
DIN 43760	Reference tables for nickel and platinum resistors in resistance thermometers
DIN 43762	Sensor units for resistance thermometers
DIN 43763	Metal protection tubes for thermometers with inserted sensor units (invalid, replaced by DIN 43772)
DIN 43764	Straight thermometers with interchangeable sensor units
DIN 43765	Threaded stem thermometers with G½ thread
DIN 43766	Threaded stem thermometers with G1 thread
DIN 43767	Welded stem thermometers
DIN 43769	Thermometers not fitted with protection tubes
DIN 43770	Survey of straight thermocouples and resistance thermometers
VDE/VDI 3511	Technical temperature measurement
VDE/VDI 3522	Time response of contact thermometers

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