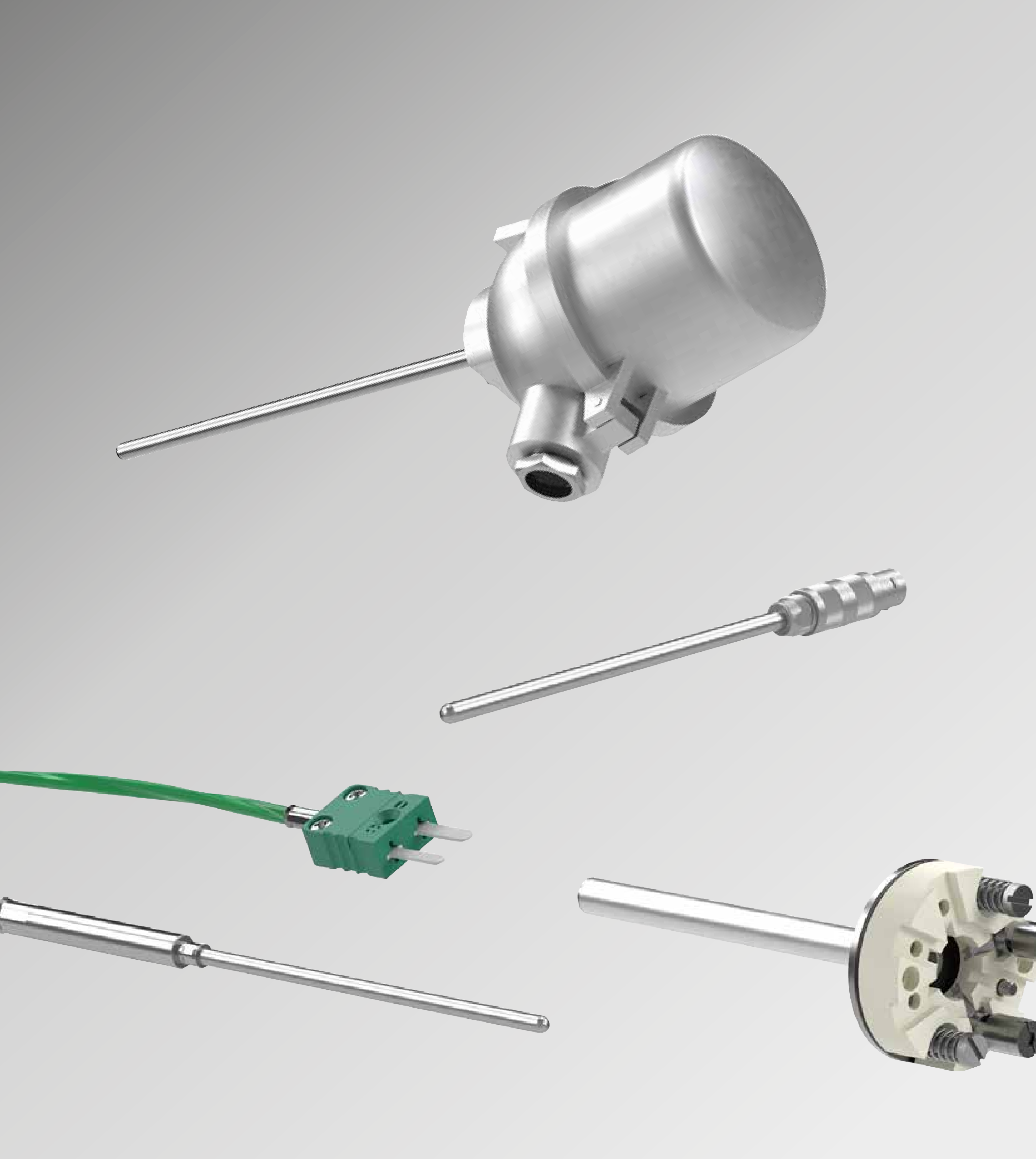

RÖSSEL MESSTECHNIK

THERMOCOUPLES

IN INDUSTRIAL APPLICATIONS

Consultation. Solution. Innovation.

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Date: 01/2024

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THERMOCOUPLES IN INDUSTRIAL APPLICATIONS

1. INTRODUCTION

In many industrial sectors, heat treatment or combustion processes play a key role in the manufacturing cycle and in the quality of the end product. Examples include tempering, hardening and normalization processes. The combustion process is a key factor in the quality of the ceramic – technical ceramics as well as utility ceramics or bricks, for example.

Many combustion processes are actually sintering processes by nature – the manufacture of sintered metals and carbides falls into this category. Not forgetting the incineration processes in power stations, refuse incinerators and, of course, in combustion engines.

And all of these applications have one thing in common:

Thermocouples are used in the vast majority of cases due to the high temperatures involved. In addition to thermocouples containing no precious metals (usually based on iron, nickel and nickel-chromium alloys), increasing use is being made of thermocouples made of platinum-rhodium alloys. Thermocouples made of tungsten-rhenium alloys are used in applications involving extremely high temperatures.

These thermocouples must be protected against contamination and corrosive/abrasive influences resulting from the surrounding conditions. A broad range of designs featuring different thermowell materials are available to achieve this aim.

2. FUNCTIONAL PRINCIPLE OF THERMOCOUPLES

2.1 Thermoelectricity, Seebeck effect, Peltier effect, Thomson effect

This observation highlights the application of thermodynamic principles to electrical effects and describes the conversion of heat into electrical energy and vice versa.

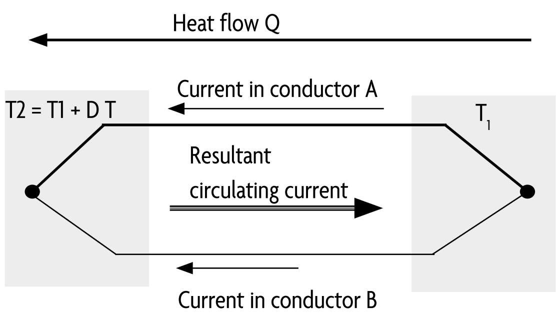


Fig. 1: Schematic representation of the Seebeck effect

In a nutshell: Heat flow and electron flow are directly and inextricably linked. One cannot exist without the other. Inevitably, this means that thermocouples can be used only to measure temperature differences.

These differences in temperature are represented by a DC voltage called "thermoelectric voltage". That said, thermoelectric voltage is often a troublesome source of error when it comes to precisely measuring small electrical quantities. A knowledge of thermoelectric effects is required to eliminate these systematic errors. Essentially, "only" four effects need to be known to understand the functional principle of thermocouples:

2.2. The Joule effect

In a metallic conductor through which an electric current I flows, Joule heat is generated due to ohmic resistance R --> QJoule = I2 x R.

2.3 The Thomson effect

A chemically homogeneous conductor is physically inhomogeneous if there is a temperature gradient along the conductor. The physical inhomogeneity affects the energy states of the conduction electrons, similar to the chemical inhomogeneity at the contact point of two metals (Seebeck/Peltier effect).

If a temperature gradient occurs in a current-carrying, chemically homogeneous conductor, a Peltier effect, referred to as the Thomson effect, is continuously distributed over the entire conductor.

A distinction is drawn between positive Thomson heat (conductor heats up when current passes through it {no Joule heat!}) and negative Thomson heat (conductor cools down when current passes through it). This depends on the direction of an externally applied direct current relative to the temperature gradient.

2.4. The thermoelectric effect (Seebeck effect)

In a conductor circuit made of two different metals, a DC voltage is generated if the points where the two metals join (the contact points) are kept at different temperatures.

In a conductive solid that is exposed to a temperature gradient, electrical charges shift – this effect is called thermodiffusion. In simple terms, the reason for the build-up of thermoelectric fields (thermoelectricity) is the temperature-dependent and hence location-dependent speed distribution of the charge carriers. Macroscopically measurable effects occur when different materials are combined:

If, for example, two conductors are joined together to form a loop and the transition points are brought to different temperatures, thermoelectricity manifests itself in a stationary electrical circulating current (Fig. 1).

It is driven by thermoelectric voltage and this can also be measured directly when the circuit is open, i.e. when there is no current (Seebeck effect). With small temperature differences, the amount of thermoelectric voltage usually increases linearly with the temperature difference between the contact points. With temperature differences upwards of 100 K, voltages of up to a few mV are typically measured for metal-metal combinations. For doped semiconductors, on the other hand, voltages of up to a few 100 mV are measured.

Given that the thermoelectric voltage is formed due to the thermal diffusion of charges along the conductors, the measured values are highly sensitive to the specific transport properties of the materials used. This means that structural defects or impurities have a major impact at low temperatures.

The Seebeck effect has an important practical application:

Because thermoelectric voltage is a measure of temperature difference, thermocouples can be used as temperature sensors.

- The transport of heat is coupled to the flow of "free" charge carriers.
- As a result, a current is generated in both conductors due to the Thomson effect.
- Because material A is not the same as material B, the conductor currents are different.
- This results in a circulating current in a closed circuit.

2.5. Conclusions

- The transport of heat is inextricably linked to the flow of free electrical charge carriers (valence electrons).
- A transport of charge carriers always generates a transport of heat – conversely, a transport of heat generates a transport of charge.
- A thermoelectric voltage is only generated if heat is transported in a thermocouple of dissimilar conductors due to a temperature difference.
- No thermoelectric voltage is generated in a homogeneous temperature field.
- In a homogeneous conductor, the magnitude of the thermoelectric voltage depends solely on the temperature difference between the measuring point and the reference junction.
- No thermoelectric voltage is generated in the junction (weld) of the hot side!

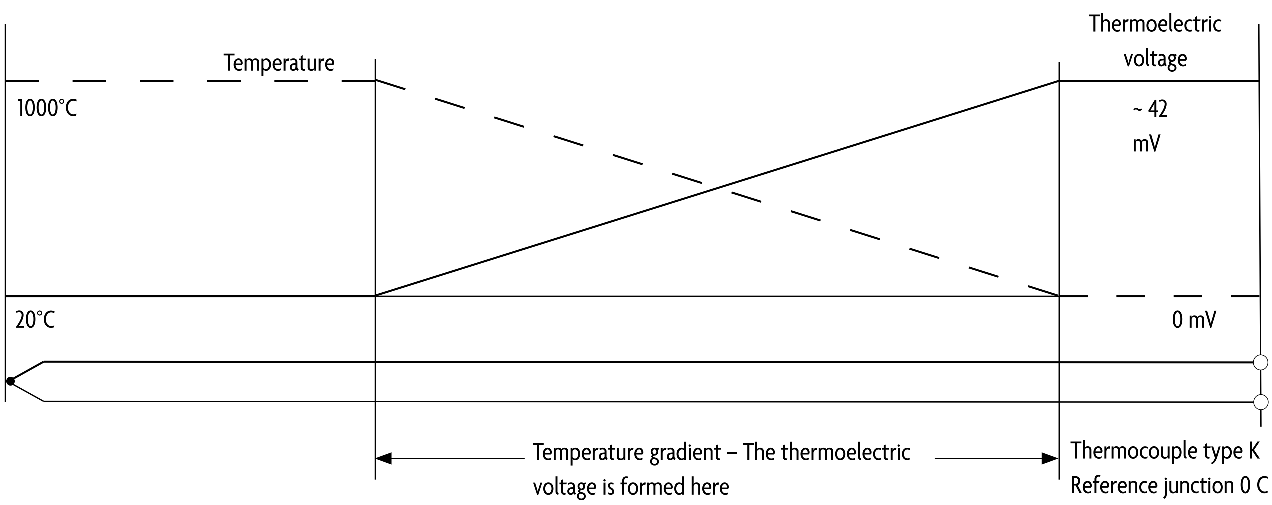


Fig. 2: Schematic representation of the thermoelectric voltage curve

2.6. The law of linear superposition

A thermocouple can be imagined as a series connection (infinite) of many differentially small thermocouples, the thermoelectric voltages of which add up linearly.

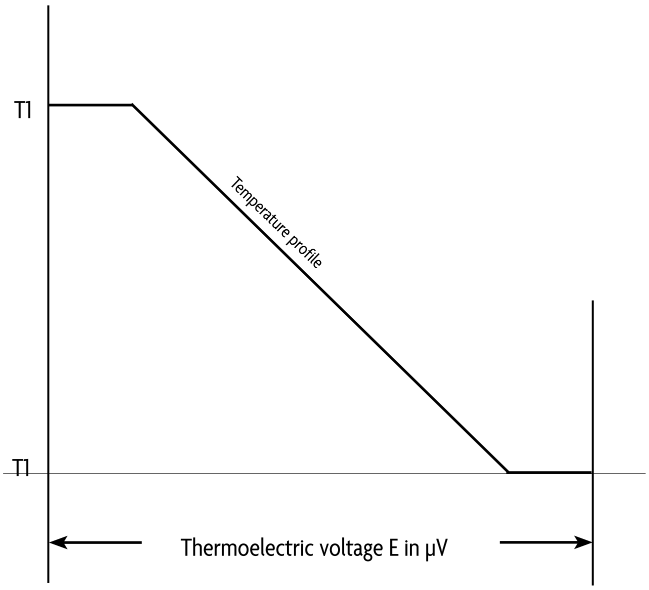


Fig. 3a: Ideal temperature profile

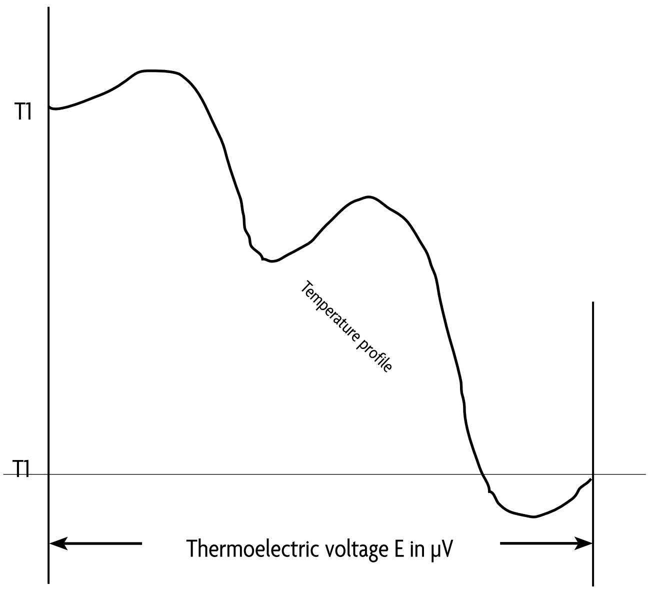


Fig. 3b: Realistic temperature profile

The thermoelectric voltage generated at the ends of the conductors is the algebraic sum of all partial voltages along those conductors. The polarity of the thermoelectric voltage depends on the direction of the temperature gradient.

A hot zone introduced in addition has no influence, as the extra thermoelectric voltages cancel each other out. For a given temperature difference, it is always the same, regardless of the distribution of the temperature gradients.

2.7. The Peltier effect

The basis for the Peltier effect (Fig. 4) is the contact between two (semi-) conductors that have a different energy level of the conduction bands. As soon as current is passed through two successive contact points of these materials, thermal energy must be absorbed at one contact point so that the electron reaches the energetically higher conduction band of the neighboring semiconductor material. This results in cooling. At the other contact point, the electron falls from a higher to a lower energy level, so that energy is released here in the form of heat (reversal of the thermoelectric Seebeck effect). If the direction of the current is reversed, cooling and heating are reversed. Although occurring with metals, the effect is very small and almost completely masked by the heat of the current and the high thermal conductivity of the metals.

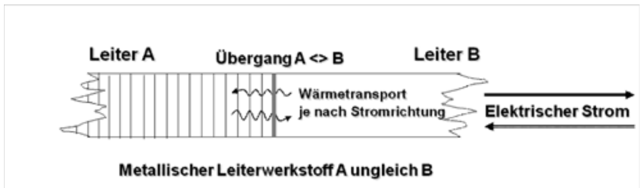


Fig. 4: Peltier effect

A Peltier element (Fig. 5) consists of two or more small cuboids, each made of p- and n-doped semiconductor material (bismuth tellurite, Bi2Te3, silicon-germanium), which are alternately connected at the top and bottom by metal bridges. The metal bridges also form the thermal contact surfaces and are insulated by an overlying foil or ceramic plate. Two different cuboids are always connected to one another in such a way that they form a series connection. The electric current supplied flows through all the cuboids in succession. Depending on the strength and direction of the current, the upper connection points cool down while the lower ones heat up. As a result, the current pumps heat from one side to the other and creates a temperature difference between the plates.

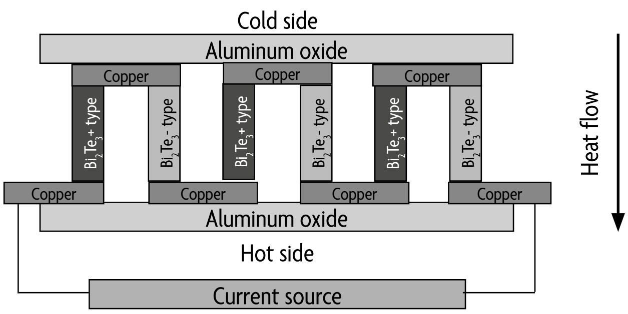


Fig. 5: Peltier element

3. STRUCTURE OF THERMOCOUPLE MEASURING CIRCUITS

As already mentioned in the "Functional principle" section, a thermocouple can only convert a temperature difference into a proportional thermoelectric voltage. This relationship is highly non-linear and is described mathematically by a higher-order polynomial. For practical purposes, a comparison or reference temperature must also be defined and generated or simulated.

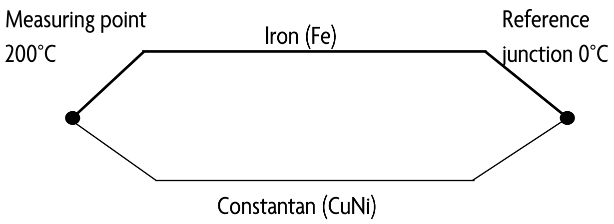


Fig. 6: Basic structure of a thermocouple measuring circuit

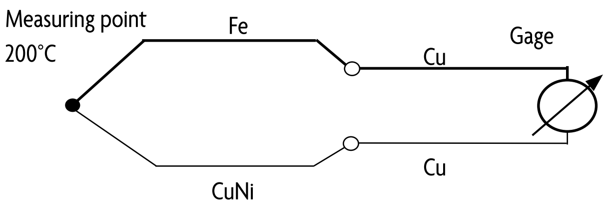


Fig. 7: Thermocouple measuring circuit with display unit

Figure 6 shows the basic structure of a thermocouple measuring circuit. The resultant circulating current generated in it is not directly measurable. The measuring circuit must therefore be disconnected and connected to an ammeter or voltmeter. Due to the relatively high specific resistance of the thermal materials, an ammeter is not used. Instead, a voltmeter with high internal resistance is used so that the thermoelectric voltage can be measured without load.

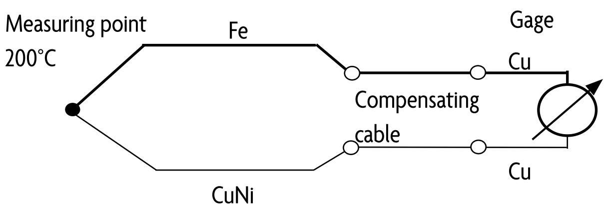


Fig. 8: Thermocouple measuring circuit with compensating cable

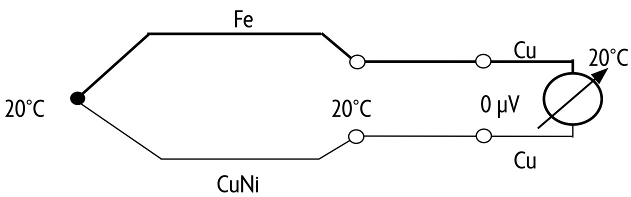


Fig. 9: Zero point on the gage

This inevitably creates a material transition between the thermal materials and the internal copper connections of the measuring device. This transition forms as two additional thermocouples, hence leading to incorrect measurements.

Furthermore, as shown in Figure 8, the measuring device should display its reference junction temperature (e.g. 20°C), although the temperature difference is 0°C and therefore the thermoelectric voltage is also 0 mV. Since the ambient temperature (20°C in the above example) is generally unknown and by no means stable, a stable and precisely known reference temperature must be used to ensure a reliable measurement.

The reference junction temperature 0°C has proved nationally and internationally to be extremely practical and easy to realize (ice-water mixture).

All tabulated values of the standardized thermocouples are based on this reference junction temperature.

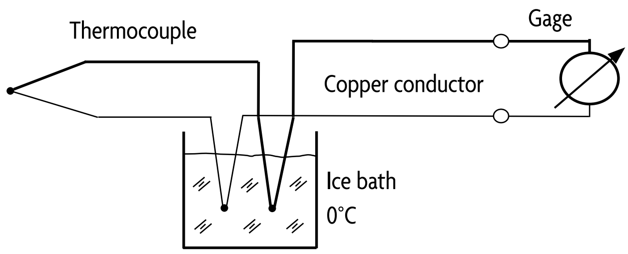


Fig. 10: Classical reference junction

Figure 10 shows the classical reference junction method using an "ice bath" – a mixture of finely crushed ice made from distilled water and distilled water itself. The advantages of this method are outstanding stability, known temperature and simple realization. This type of reference junction is still used in many calibration laboratories. However, the main disadvantage is obvious: this method is wholly impractical for industrial measurements. Only the simulated reference junction is used there. (Fig. 11)

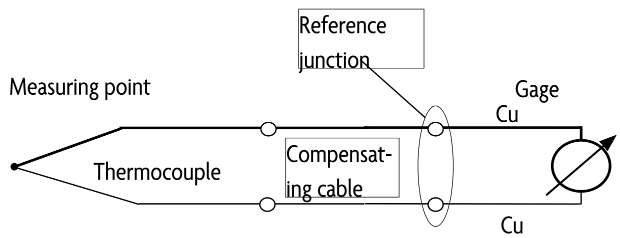


Fig. 11: Simulated reference junction

Figure 12 shows the analog type of reference junction compensation. A sensor measures the temperature of the isothermal compensation block and adds a proportional voltage (in µV) to the input signal. The sum signal is then graphically or electronically linearized and displayed.

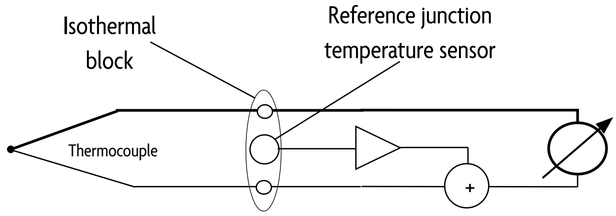


Fig. 12: Analog reference junction compensation

The digital reference junction compensation as shown in Figure 13 also uses a sensor to measure the temperature of the isothermal compensation block. This signal is digitized and added to the input signal, which is also digitized. The sum signal is mathematically linearized and displayed or made available for further processing.

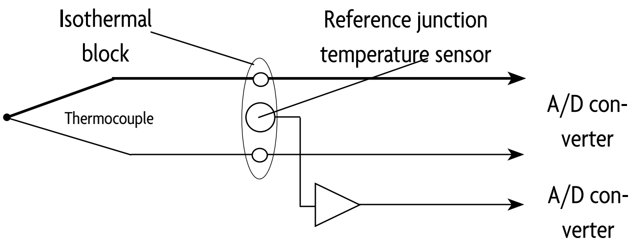


Fig. 13: Digital reference junction compensator

4. OVERVIEW OF TEMPERATURE SCALES, THERMOCOUPLES AND STANDARDS

Of the many possible metal combinations from which thermocouples can be formed, eight have so far been selected and standardized both internationally and nationally.

Material combinations were selected that had proven to be practicable, partly for historical and partly for practical technical reasons. In addition to historical reasons, the main criteria for the selection included:

- Price and availability of the thermal materials
- Stability and repeatability
- Interchangeability
- Broad range of temperatures

In particular, the galvanic series (basic value series), the tolerances (also referred to as measurement uncertainty) and the color coding were standardized, not the exact material composition. The following eight thermocouples are standardized: Types E, J, K, N, T, S, R and B (see para. 5.2)

5. HISTORICAL OVERVIEW

Our current national and international standards are of course closely linked to the development of temperature sensors and the internationally recognized temperature scales. A brief historical overview to provide some clarity here:

HISTORICAL OVERVIEW OF THE DEVELOPMENT OF TEMPERATURE SENSORS

1592 Indirect sources refer to Galileo Galilei as the inventor of the open thermoscope

1642 First closed liquid thermometer by Ferdinand II, 5th Grand Duke of Tuscany

1724 First liquid-in-glass thermometer with mercury filling by Daniel Gabriel Fahrenheit

1745 0 to 100 degree scale based on 2 fixed points by Carolus Linnaeus and Anders Celsius

1800 Development of the first simple bimetallic thermometers by Antoine Louis Bréguet

1818 Discovery of the temperature dependence of the electrical resistance of metallic conductors by Hans Christian Oersted

1821 Description of the thermoelectric effect by Thomas Johann Seebeck

1821 Construction of the first thermocouple by Humphry Davy

1840 Construction of a thermocouple made of iron (Fe) and nickel silver (CuNi) by Christian Poggendorf

1852 Establishment of the thermodynamic temperature scale, based on the 2nd law of thermodynamics by William Thomson (later Lord Kelvin of Largs)

1871 Construction of a platinum resistance thermometer by Werner von Siemens

1885 Advancement of the platinum resistance thermometer into a precision instrument for higher temperatures by Hugh Lonbourne Callendar

1887 Manufacture of technical thermocouples by Henry Louis le Chantelier & Carl Barus

1892 Development of the first usable spectral pyrometer by Henry Louis le Chantelier

Essentially, all the electrical contact thermometers and pyrometers still in use today had been invented or developed by the end of the 19th century. Rømer, Newton, Réaumur, Fahrenheit, Delisle, Celsius, Kelvin and Rankine had already developed temperature scales named after them between 1700 and 1860.

A total of 71 (!) different national temperature scales are known. That said, only the Fahrenheit, Celsius and Kelvin scales are still in use today. However, Poggendorf, Callendar and le Chantelier also proposed temperature scales based on fixed points with the corresponding standard instruments.

DEVELOPMENT OF THE INTERNATIONAL TEMPERATURE SCALES (ITS)

1889 Callendar proposes 3 fixed points: Solidification and boiling point of water as well as the boiling point of sulfur with a platinum resistance thermometer as a standard instrument.

1911 The PTR (later PTB), together with the NPL (England) and BS (later NBS or NIST, USA), proposes a thermodynamic scale as the first "International Temperature Scale" ITS.

1913 This scale was supposed to be approved at the 5th Conférence Générale des Poids et Mesures (CGPM). The imminent outbreak of World War 1 prevented the conference from taking place.

1923 PTR, NPL and BS establish a temperature scale based on fixed points (solidification point mercury to boiling point sulfur) and extrapolated up to 650°C with platinum thermometers, and up to 1100°C with thermocouple Pt10%Rh-Pt - today standardized as type S.

1925 The scale of 1923 is extended downwards to -193°C and

supplemented at the top by the fixed points antimony, silver and gold.

1927 The first "International Temperature Scale of 1927" is accepted as ITS 27 by the 7th CGPM.

1937 The "Consultative Committee on Thermometry" (CCT) is founded.

1948 The CCT initiates the first revision of ITS 27 and brings it into force as ITS 48.

1958 The 1958 4He scale for the temperature range 0.5 to 5.23 K is introduced.

1962 The 1962 3He scale for the temperature range < 0.9 K is introduced.

1968 The 2nd revision of ITS 27 comes into force in the form of IPTS 68. Four sub-areas are defined:

(a) 13.81 K to 273.15 K; Normal instrument: Platinum resistance thermometer
(b) 0°C to 630.74°C; Normal instrument: As (a)
(c) 630.74°C to 1064.43°C; Normal instrument: Thermocouple Platinum10%Rhodium/Platinum) and
(d) above 1064.43°C; Normal instrument: Spectral pyrometer

1976 The Bureau International des Poids et Mesures (CIPM) establishes the 1976 Provisional 0.5 K to 30 K Temperature Scale (EPT-76)

1990 The "International Temperature Scale of 1990" (ITS-90) attains worldwide validity on January 1, 1990

and replaces the IPTS-68 and EPT-76.

However, the thermocouples are superseded as normal instruments for approximating the ITS-90

by platinum resistance thermometers in the range of:

13.8 K (-259.35°C, triple point H2) to 1234.93 K (961.78°C, solidification point Ag)

6. BASIC VALUES OF THE THERMOELECTRIC VOLTAGE AS DEFINED IN IEC 584-1 (DIN EN 60 584-1)

The ITS-90 is currently the globally binding temperature scale and, as such, the basis of the following valid standards – DIN IEC 60 571 for industrial resistance thermometers and DIN EN 60 584 for thermocouples. In the latter, eight thermocouples are standardized in two groups. The group of non-precious metal thermocouples comprises types E, J, K, N and T, while the group of precious metal thermocouples comprises types S, R and B.

6.1. Non-precious metal thermocouples according to DIN EN 60 584-

Code	Designation	Measuring range in °C	Thermoelectric voltage in µV
E	NiCr-CuNi	-200 to 1000	-8825 to 76373
J	Fe-CuNi	-210 to 1200	-8095 to 69553
K	NiCr–Ni	-200 to 1372	-5891 to 54886
N	NiCrSi-NiSi	-200 to 1300	-3990 to 47513
T	Cu–CuNi	-200 to 400	-5603 to 20872

Table 1: Non-precious metal thermocouples

6.2. Precious metal thermocouples according to DIN EN 60 584-

Code	Designation	Measuring range in °C	Thermoelectric voltage in µV
S	Pt10%Rh-Pt	-50 to 1768	-235 to 18694
R	Pt13%Rh-Pt	-50 to 1768	-226 to 21103
B	Pt30%Rh-Pt6%Rh	250 to 1820	291 to 13820

Table 2: Precious metal thermocouples

6.3. Thermocouples type L and U

The German Institute for Standardization (DIN) had a predecessor standard for thermocouples that defined two types:

DIN 43 710: Type L (Fe-CuNi)
and type U (Cu-CuNi)

In terms of the nominal alloy, these were identical to types J and T in DIN EN 60 584, although the basic value series were different.

This standard was withdrawn in October 1997.

Type L was used in large numbers in plant construction (especially power stations), and so there is still a considerable demand for this type of thermocouple today. Given the withdrawal of the DIN standard, type U has become completely irrelevant and no longer has any use today.

The following table is provided for your information:

6.3. Thermocouple type L according to DIN 43 710 (10/97 withdrawn)

Code	Designation	Measuring range in °C	Thermoelectric voltage in µV
L	Fe-CuNi	-200 to 760	-8166 to 53147

Table 3: Thermocouple type L

6.4. Outlook for the revision of IEC 584

A revision of IEC 584, the "parent standard" of DIN EN 60 584, is currently pending. Working Group 5 (WG 5 – Temperature Sensors) in Sub Committee 65B (SC 65B - Devices & Process Analysis) of the International Electricity Commission (IEC) has been commissioned to revise the standard. In Germany, the "German Commission for Electrical, Electronic & Information Technologies of DIN and VDE" (DKE) is involved in this work through its committee K 961 (Electrical transducers and transducers).

There is an international effort to include two new tungsten-rhenium high-temperature thermocouples in the standard. These are type C (W5%Re-W26%Re) from ASTM E 988 (USA) and type A (W5%Re-W20%Re) from GOST 8-585 (Russia). Type C in particular is becoming increasingly important in all areas of industrial production in which reducing operating conditions prevail at very high temperatures. The table below is provided for information:

Code	Designation	Measuring range in °C	Thermoelectric voltage in µV
C ASTM 988	W5%Re-W26%Re	0 to 2315	0 to 36931
A GOST 8-585	W5%Re-W20%Re	0 to 2500	0 to 33640

Table 4: High-temperature thermocouples

In the graph (Diagram 1), the thermoelectric voltage generated by the thermocouples is plotted against the temperature in accordance with Tables 1 to 4. This shows that the relationship between temperature and thermoelectric voltage is not linear.

This is evident especially in the negative temperature range. Higher-order polynomials are used to linearize and calculate the table values. The polynomial coefficients are contained in the specified standards.

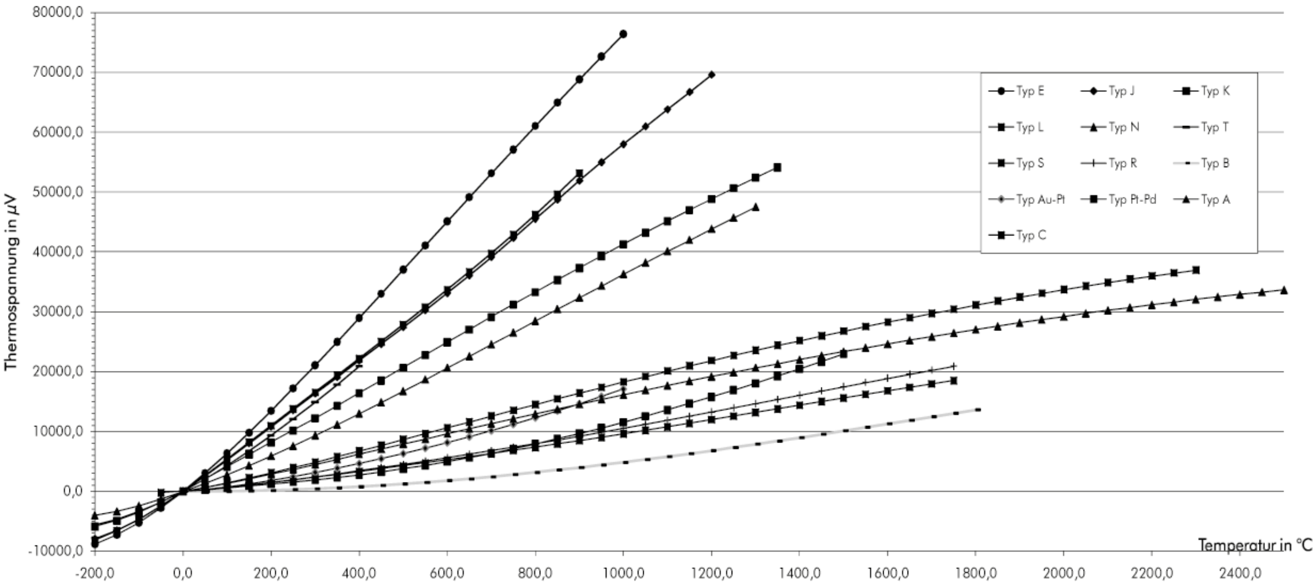


Diagram 1: Thermoelectric voltage as a function of temperature

In the graph in diagram 2, the specific thermoelectric voltage (Seebeck coefficient) of the thermocouples is plotted as a function of temperature in accordance with tables 1 to 4. This clearly shows that the relationship between temperature and thermoelectric voltage is not linear. Type J, K and L thermocouples in particular can only be described by divided polynomials. Type N – in principle a modified type K trimmed for stability – can be calculated with an undivided polynomial.

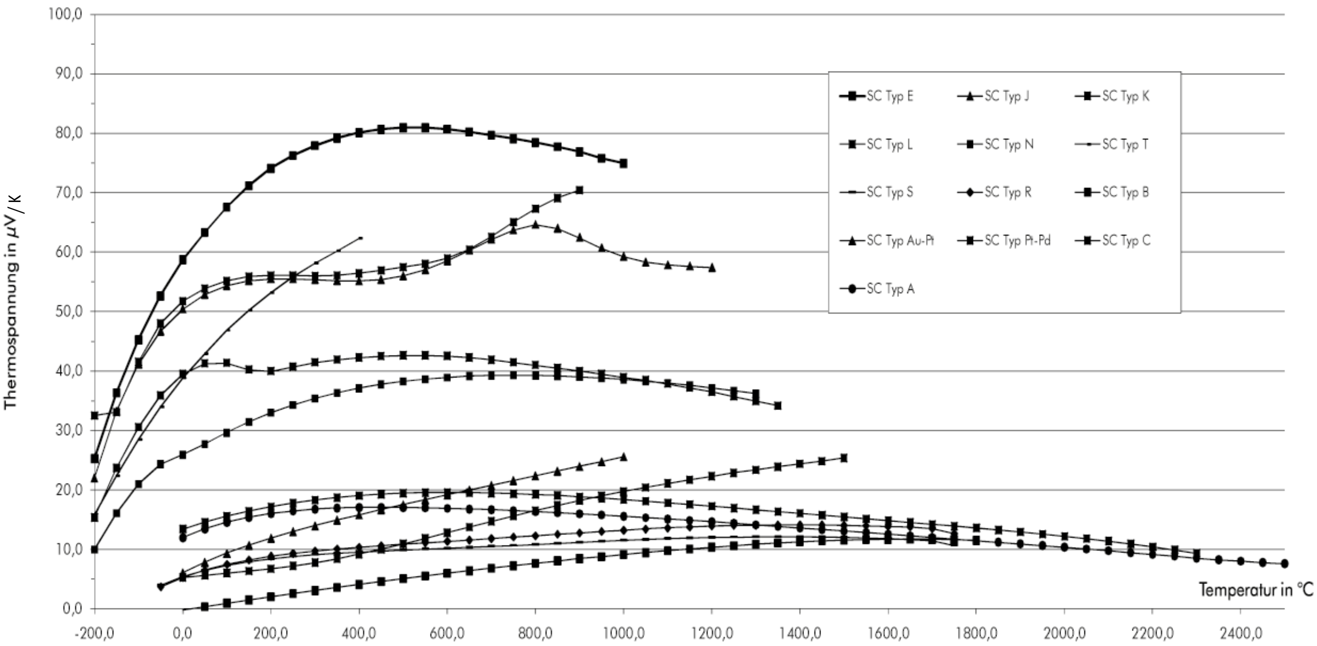


Diagram 2: Seebeck coefficient as a function of temperature

7. TOLERANCES AS DEFINED IN IEC 584-2 (DIN EN 60 584-2)

The measurement uncertainties – often called tolerances – are also standardized internationally and nationally. Three classes are defined, the tolerance and the temperature range (validity range) being specified for each. In industrial applications, classes 1 and 2 have become established as quasi standards. Class 3 is reserved for the relatively rare low-temperature applications.

The tolerances for types A and C given in the following list are international recommendations based on the respective national standards. As part of the upcoming revision of IEC 584, these values will be reviewed and revised if necessary.

The thermal material normally available meets the required class accuracies (class 1 or 2), but not necessarily Class 3. If type E, J, K, N and T thermal materials, which comply with both Class 2 and Class 3 tolerances, are required, specially selected materials must be used.

	Class 1	Class 2	Class 3
Tolerance	(±) 0.5°C or 0.004 * [t]	1°C or 0.0075 * [t]	1°C or 0.015 * [t]
Type T (Cu-CuNi)	-40 to 350°C	-40 to 350°C	-200 to +40°C
Tolerance	(±) 1.5°C or 0.004 * [t]	2.5°C or 0.0075 * [t]	2.5°C or 0.015 * [t]
Type E (NiCr-CuNi)	-40 to 800°C	-40 to 900°C	-200 to +40°C
Type J (Fe-CuNi)	-40 to 750°C	-40 to 750°C	---
Type K (NiCr-Ni)	-40 to 1000°C	-40 to 1200°C	-200 to +40°C
Type N (NiCrSi-NiSi)	-40 to 1000°C	-40 to 1200°C	-200 to +40°C
Tolerance	(±) 1°C or [1 + 0.003(t-1100)]	1.5°C or 0.0025 * [t]	4°C or 0.005 * (t)
Type S (Pt10%Rh-Pt)	0 to 1600°C	0 to 1600°C	---
Type R (Pt13%Rh-Pt)	0 to 1600°C	0 to 1600°C	---
Type B (Pt30%Rh-Pt6%Rh)	---	600 to 1700°C	600 to 1700°C
Tolerance	---	(±) 0.01 * (t)	---
Type C (W5%Re-W26%Re)	---	426 to 2315°C	---
Tolerance	(±) 0.005 * (t)	(±) 0.007 * (t)	---
Type A (W5%Re-W20%Re)	1000 to 2500°C	1000 to 2500°C	---

The tolerance is specified in °C or as a function of the absolute value of the temperature in °C. The larger value applies in each case.
Table 5: Tolerances of thermocouples

8. TOLERANCE OF THE CONNECTION CABLE

In the vast majority of cases, the thermocouple is not long enough to bridge the distance between the installation site and the evaluation device. For this reason and also for practical purposes, flexible connection cables are required. Two basic versions are available:

Thermocouple cables: Flexible cables containing thermocouple material. These cables have an "X" after the codes for the thermocouple, e.g. KX or NX. The "X" comes from the expression "extension cable". In some cases, the "X" is omitted from the type designation.

Compensating cables: Flexible cables containing thermocouple-like material. These cables have a "C" after the codes for the thermocouple, e.g. KC or NC. Compensating cables have the same thermoelectric properties as the thermocouple itself only in a narrowly limited temperature range and also have larger tolerances. The "C" comes from the expression "compensating cable".

Notes:

- Compensating cables are only available in Class 2 – see table below.
- For types J, T, E and L, only thermocouple cables are commercially available.
- For the precious metal types S and R, thermocouple cables are only used in exceptional cases due to the extremely high cost of the material.
- Compensating cables for types S and R contain the same conductor material.
- No compensating cable is specified for type B – copper cable is used.
- Class 1 thermocouples fitted with Class 1 thermocouple cable normally comply with Class 1 overall.

Thermocouples fitted with compensating cable do not necessarily have to comply with Class 1. This information is contained in ANSI MC 96 - 1. It does not appear in IEC 584-2 (DIN EN 60 584-2). This sub-standard is currently being revised with regard to this important aspect. Table 6 below provides an overview.

Type	Class 1	Class 2	Ambient temperature	Measuring temperature
JX	±85 µV (±1.5°C)	±140 µV (±2.5°C)	-25 to +200°C	500°C
TX	±30 µV (±0.5°C)	±60 µV (±1.0°C)	-25 to +100°C	300°C
EX	±120 µV (±1.5°C)	±200 µV (±2.5°C)	-25 to +200°C	500°C
KX	±60 µV (±1.5°C)	±100 µV (±2.5°C)	-25 to +200°C	900°C
NX	±60 µV (±1.5°C)	±100 µV (±2.5°C)	-25 to +200°C	900°C
KCA	---	±100 µV (±2.5°C)	0 to +150°C	900°C
KCB	---	±100 µV (±2.5°C)	0 to +100°C	900°C
NC	---	±100 µV (±2.5°C)	0 to +150°C	900°C
RCA	---	±30 µV (±2.5°C)	0 to +100°C	1000°C
RCB	---	±60 µV (±5.0°C)	0 to +200°C	1000°C
SCA	---	±30 µV (±2.5°C)	0 to +100°C	1000°C
SCB	---	±60 µV (±5.0°C)	0 to +200°C	1000°C
CC	---	±110 µV (±9°C)	0 to +871°C	2000°C
AC	---	±110 µV (±11°C)	0 to +871°C	2000°C

Table 6: Tolerance for connection cables

Notes:

- The specified ambient temperature refers to the conductor material used. The temperature range of the cable's insulating materials may differ!
- Copper cable is used for type B in the ambient temperature range 0 to 50°C. The expected additional measurement uncertainty component is max. ± 10 µV (± 1.5°C) at a measuring temperature of 1400°C. In the 0 to 100°C range, the proportion is ± 40 µV (± 3.5°C) at the same measuring temperature.
- The tolerances are given in µV. Due to the non-linear relationship between temperature and thermoelectric voltage, the temperature specifications in parentheses apply only at the specified measuring temperature. In most cases, the error is greater at significantly lower or higher measuring temperatures.

8.1. Color coding as defined in IEC 60 584-3

To conclude this rather dry chapter on temperature scales, thermocouples and standards, a few more paragraphs about the color coding of thermocouples, especially the thermocouple and compensating cables. Given that the thermoelectric voltage is a DC voltage, the polarity of the conductors must be clearly marked. In addition to full series of national standards, an international standard – IEC 60 584-3 – has also been available since December 2008.

Code	+ pole	- pole	Sheath
E	Violet	White	Violet
J	Black	White	Black
K	Green	White	Green
L	Red	Blue	Blue
N	Pink	White	Pink
T	Brown	White	Brown
B	Gray	White	Gray
R	Orange	White	Orange
S	Orange	White	Orange
A	Red	White	Red
C	Yellow	White	Yellow

Table 7: Color coding

Notes:

- The color coding for type L originates from the withdrawn standard DIN 43 714. It is still used in some cases, however.
- The color coding for thermocouples according to DIN EN 60 584 is regulated in DIN 43 722 and corresponds to IEC 60 584-3.
- The color coding of type A and C thermocouples are at present recommendations and based on national standards.

9. EXAMPLES OF INDUSTRIAL DESIGNS

Two main types of industrial design have become established:

- Straight thermocouples DIN EN 50 446
- Sheathed thermocouples DIN 61 515

9.1. Straight thermocouples with metallic or ceramic thermowell

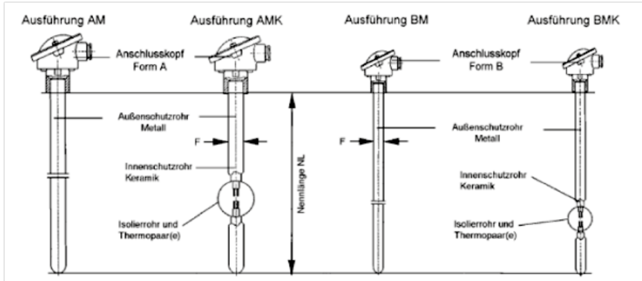


Fig. 14: Straight thermocouple with metal thermowell

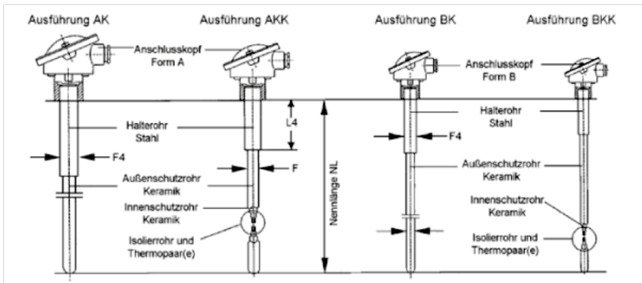


Fig. 15: Straight thermocouple with ceramic thermowell

Straight thermocouples essentially consist of the following components:

- Connection head for connecting the thermocouple or compensating cable.
- Metallic or ceramic thermowell, with ceramic inner thermowell if necessary. See Table 8/9 on the next page.
- Metallic holding tube – only for designs with ceramic thermowell.
- Ceramic multi-hole insulating rod with thermocouple according to Table 10.

The connection heads are preferably made of aluminum, more rarely of plastic (polyamide), stainless steel or gray cast iron. Two sizes (form A and B) are available. In many cases, a transmitter is installed in the connection head.

The metallic or ceramic thermowells form the "protective wall" for the thermocouples against the predominantly harsh operating conditions or process atmospheres. A number of different materials are available for thermowells.

Table 8 provides a brief overview of those most commonly used. In addition, there is a wide range of special materials for what are mostly highly specific applications.

Where precious metal thermocouples are used in metallic thermowells, a ceramic inner thermowell is generally employed to protect against contamination by metal ions. A ceramic inner thermowell is generally recommended for applications in the higher temperature range in particular.

The ceramic thermowell is cemented into the metal holding tubes (stainless steel material no: 1.4571) by means of a special ceramic putty. A number of different materials are available for thermowells. Table 9 provides a brief overview of those most commonly used

The thermocouples (Table 10) are drawn into the ceramic insulating rods – also referred to as capillary tubes. All standardized types are in use. For reasons of scaling and service life, larger wire diameters (1.0 - 1.38 - 2.0 and 3.0 mm) are generally used for non-precious metal thermocouples. For cost reasons, smaller wire diameters (0.5 or 0.35 mm) are used for the precious metal types.

A connection base, also ceramic, is attached to the connection side. This carries the terminals for connecting the thermal or compensating cable.

Insulating rods with 2 to 16 capillaries for 1 to 8 thermocouples are commonly used. The ceramic materials used for insulating rods are types C 610 for non-precious metal thermocouples and C 799 for precious metal thermocouples.

The table below provides an overview of selected thermowells and applications.10. SHEATHED THERMOCOUPLES

Sheathed thermocouples have been successfully used in temperature measurement technology for many years. The standard versions are used in the range between -270°C and +1200°C and combine the advantages of easy bendability with good handling and an extremely wide temperature range. They are complemented by high-temperature thermocouples with application temperatures of well over 2000°C.

Inconel 600 (material no: 2.4816), a nickel-based alloy, is predominantly used as the sheath material. This material is easy to weld and solder, has excellent strength properties even at high temperatures and can withstand most environmental conditions.

The thermocouple is often type K (NiCr-Ni) according to DIN EN 60 584 (IEC 584). Types L and J (Fe-CuNi) are also widely used, as are the precious metal types S, R and B in the higher temperature range, each based on platinum-rhodium alloys.

The thermocouple wires are embedded in a compact insulation made of high-purity Mg0 and surrounded by a metal sheath made of a nickel-chromium-iron alloy or stainless steel. The compact insulation completely fixes the wires so that neither strong vibrations nor bending stress can cause damage. Short circuits between the conductors or between the conductor and the sheath are also virtually impossible.

Sheathed thermocouples are produced in very large quantities.

Code	Name or symbol	Material No.
BF	St 35.8	1.0305
DU	X 18 CrNi 28	1.4749
R	X 10 CrAl 24	1.4762
D	X 15 CrNiSi 2520	1.4841
Y [1]	Incoloy 800	1.4876
CS [1]	Kanthal Super	---
B	X 6 CrNiMoTi 17-12-2	1.4571
N [1]	Molybdenum	---
O [1]	Tantalum	---

[1] Deviating diameters

Table 8: Codes for metal thermowells

Code	Material in acc. with DIN 40 685 Part 1 VDE 0335 Part1
CX	C 530 (K 530)
CY	C 610 (K 610)
CZ	C 799 (K 710
RSiC [1]	Silicon carbide, recrystallized
SiSiC [1]	Silicon carbide, reaction-bonded

[1] Deviating diameters

Table 9: Codes for ceramic thermowells

Code letter	Thermocouple DIN EN 60 584 ASTM 988 and GOST 8-585
E	NiCr-CuNi
J	Fe-CuNi
K	NiCr-Ni
N	NiCrSi-NiSi
S	Pt10%Rh-Pt
R	Pt13%Rh Pt
B	Pt30%Rh-Pt6%Rh
L [1]	Fe-CuNi
C (W5)	W5%Re-W26%Re
A (A1)	W5%Re-W20%Re

[1] Norm 07/97 withdrawn

Table 10: Codes for thermocouples

The table below provides an overview of selected thermowells and applications.

Material	Max. application temp. in °C	Property/application	Remark
Titanium	600	Hardening baths	Strongly oxidizing in air
Pure iron 1.1003	900	Salt baths containing saltpeter, chloride and cyanide	
Steel, enameled	600	Zinc smelting	
1.0305	900	Tempering furnaces, saltpeter baths up to 500°C, bearing metal, lead and tin melts up to 650°C	For lead oxide formation with hard-chromium coating
1.4571	800	Good chemical resistance	Largely acid-resistant
1.4762	1200	High resistance to sulfurous gases (oxidizing and reducing), medium resistance to carburization	
1.4749	1100	Lead and tin smelting, annealing and hardening processes with gases containing sulfur and carbon	
1.4772	1250	Copper and brass melting	
1.4821	1350	Salt baths containing saltpeter, chloride and cyanide	
1.4841	1200	Cyan baths up to 950°C, lead smelters up to 700°C, furnaces with nitrogenous, low-oxygen gases	
Gray cast iron	700	Bearing metal, lead, aluminum and zinc melts	
Gray cast iron with ceramic coating	800	Aluminum and zinc melts	
Cr-Al oxide CrAl2O3 77/23	1200	Gas-tight, oxidation-resistant, resistant to thermal shock, copper, tin, zinc, magnesium, lead melts, cement furnaces, SO2, SO3 gas, H2SO4 acid	Not for aluminum and glass melts and salt baths
Molybdenum disilicide MoSi2	1700	Abrasion-resistant, impact-resistant, highly resistant to thermal shock, vitrified on the surface, chemically resistant, waste incineration, fluidized bed combustion	Brittle at low temperature, tough from approx. 1400°C
Molybdenum zirconium oxide MoZrO 60/40	1700	Resistant to thermal shock, hard impact-resistant, Cast iron, copper, zinc melts + slags, BaCl hardening baths	Oxidizes in air from 500°C
C 530	1500	Gases of all types with AKK version, resistant to thermal shock	Gas-tight inner tube in straight thermocouples
C 610	1600	Gases of all types with AKK version, less resistant to thermal shock than C 530	Gas-tight inner tube in straight thermocouples
C 799	1600	Gases of all kinds, contact with hydrofluoric acid, metal oxide alkali vapors, glass tanks	Glass melts with platinum coating
Silicon carbide SiC, recrystallized	1300	Gas-tight, high mechanical resilience, highly resistant to thermal shock, high thermal conductivity, 8 – 12% free silicon	Not for Al and Cu melts
Silicon carbide SiC, reaction-bonded	1600	Porous, mechanically highly resilient, high thermal conductivity, can be used under inert gas or in a vacuum up to 2000°C	Not for Al, Cu, Ni, Fe melts, medium resistance to thermal shock
Silicon nitride Si3N4	1000	Resistant to thermal shock, no wetting in aluminum and brass melts	Sensitive to impact
Silicon nitride/Aluminum oxide Si3N4 + Al2O3	1300	Resistant to thermal shock, copper and aluminum melts	
Graphite	1250	Oxygen-free copper, brass and aluminum melts	High oxidation in air
Aluminum titanate Al2TiO5	1000	Gas-tight, aluminum melt	Sensitive to impact
Sapphire	2000	Monocrystalline aluminum oxide, gas-tight, transparent, semiconductor industry	Sensitive to impact, medium resistance to thermal shock

The table above makes no claim to completeness. All information is without obligation and does not constitute a warranted characteristic. The details must be checked very carefully in the context of the application concerned

They cover almost all conceivable areas of application.
They are used as measuring inserts (DIN 43 735) for thermowells (DIN 43 772) in the chemical industry and in power station construction, as well as in the straight thermocouples mentioned above. The main strength is that sheathed thermocouples (STC) cover the outer diameter range from 0.25 mm to 10.0 mm in small increments. The length of a STC can range from a few millimeters to several tens of meters, depending on the outer diameter. In addition to STC with only one thermocouple, versions with 2 and 3 thermocouples are also available.

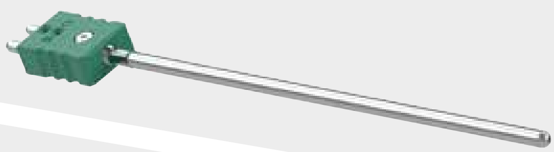
All standardized thermocouple types (Table 1 – 4) and connection cables (Table 6) are available. Sheathed thermocouples are extremely robust temperature sensors. They are easy to handle, easy to bend and virtually insensitive to vibrations. STC are used in the automotive industry, in power plants, refineries, smelting works, in shipbuilding, in the chemical industry, on and in combustion engines, engine test benches, gas and steam turbines, in medical technology, in boiler and furnace systems, in the metallurgical industry, in the aviation industry, in vacuum and high vacuum systems, in pressure sintering systems for hard metals, ... etc.

Effective heat transfer between the metal sheath and the thermocouple guarantees short response times (t0.5 from 0.15s) and a low degree of measurement uncertainty. The smallest bending radius is 5 to 7 x the outer diameter. The minimum installation length should not be less than 20 x the outer diameter, but at least 50 mm. A variety of different designs are available. An overview of the most commonly used models is provided below. In addition, special designs can be realized in the vast majority of cases.

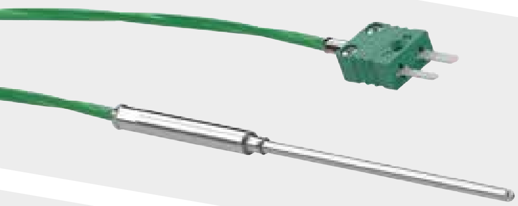
11. RESPONSE BEHAVIOR AND INSTALLATION LENGTHS

With the **AL version**, the connection cable is permanently attached. The transition sleeve has a Øof 6 mm. The standard length is 50 mm. The cable type (wire cross-section, insulation structure, shielding) is variable within broad limits.

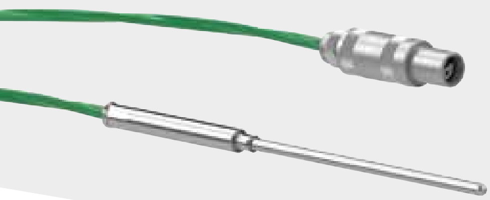
With **type S**, the plug system is attached to the sheathed thermocouple itself. The size of the coupling is equivalent to type RLK size 0 (up to 1.6 mm sheath Ø), above that size 1. The positive pole is on the pin. The contacts are made of brass and are gold-plated.



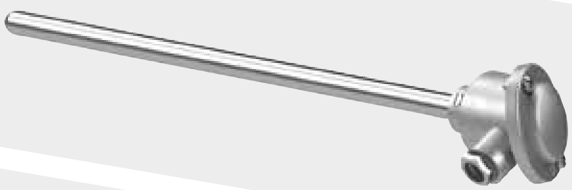
With **type STE**, the plug is attached to the sheathed thermocouple itself. The standard is a mini plug (TC Ø </= 1.6 mm) or standard plug. The contacts are made of thermocouple material, the outer body of temperature-resistant plastic.



Type ALSTE is an extension of the AL design with a thermocouple plug. This version has either a mini or a standard plug, depending on the specification. The contacts are made of thermocouple material, the outer body of temperature-resistant plastic.



Type ALS is an extension of the AL design with a round coupling. This version has either a size 0 or size 1 round coupling, depending on the specification or cable diameter. Other sizes are possible as well. The contacts are made of brass and are gold-plated. The outer body is also made of brass and is matt chrome-plated.



This design (e.g. B-KB) consists of a measuring insert with connection base and sheathed terminals, installed in an aluminum connection head, form B, according to EN 50 446. A special tube fitting holds the measuring insert in place. The nominal length is specified from the bottom edge of the fitting. Other heads are available on request.

Measuring insert with connection base, sheathed terminals and pressing fixture. Suitable for installation in connection heads, type B

A. Sheath diameter 3.0 mm, continuous
B. Sheath diameter 6.0 mm, continuous
C. Sheath diameter 6.0 mm, measuring tip reinforced to 8 mm Ø x 50 mm in length
D. Sheath diameter 8.0 mm, continuous

The response time of a contact thermometer is an indication of how quickly the thermometer follows a sudden change in temperature. The VDI/VDE recommendation 3522 "Time response of contact thermometers" addresses this topic in detail and shows the schematic structure of devices for measuring the step response.

The time response of a temperature sensor is described by an exponential function. The sensor (and the surrounding medium) should initially be at temperature T1. The temperature of the medium then changes abruptly to T2. The sensor accepts this value only after a delay. The measurement signal progression represents the transition function. Two values have been chosen to characterize this function: t0.5 and t0.9. The transition function refers to the time it takes for the measurement signal to reaches 50%, the half-life, or 90% of its final value. The function is plotted in Figure 15.

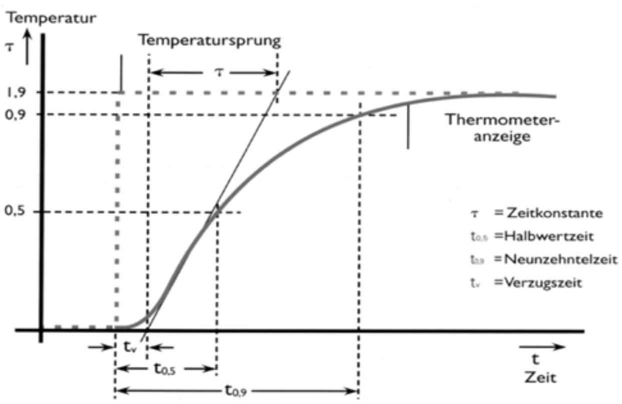


Fig. 16: Response behavior

The following parameters are used as a basis:

- Laminar air flow at 2 m/s; 10 ... 15°C
- Temperature jump from room temperature
- Laminar water flow at 0.2 m/s
- Temperature jump from approx. 25°C to approx. 35°C
- Normal air pressure 1013 hPa

Guide values for the response time of sheathed thermocouples in seconds (-5% / +15%)

Measuring condition	Value time	Measuring point isolated from the sheath						
		Sheath diameter in mm						
	Sec.	0.5	1.0	1.5	3.0	4.5	6.0	8.0
Water 0.2 m/s	50%	0.06	0.15	0.21	1.2	2.5	4.0	7
	90%	0.13	0.5	0.6	2.9	5.9	9.6	17
Air 2 m/s	50%	1.8	3	8	23	37	60	100
	90%	5.9	15	25	80	120	200	360

Table 11: Response time

Notes:

The response times for thermocouples at which the measuring point is welded to the base are approx. 10 ... 15% shorter. Resistance thermometers have an approx. 15 ... 25% longer response time than thermocouples of the same design.

11.1. Installation length and heat conduction error

Because of the system, temperature measurement with a contact thermometer is always prone to a heat conduction error. Although this error can be minimized, it cannot be eliminated completely.

The tables below list the recommended minimum installation lengths for temperature sensors with and without a thermowell. Installation length = wetted length

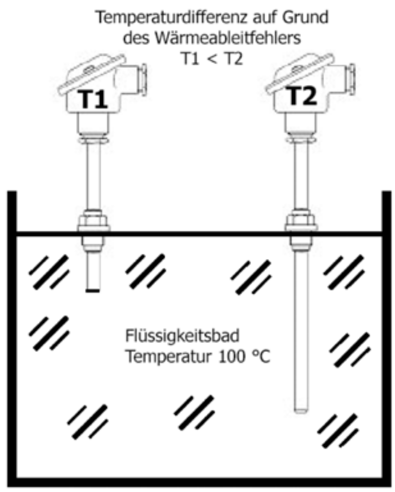


Fig. 17: Heat conduction error

However, these installation conditions cannot always be met in real technical systems. If the recommended installation lengths are not reached, measurement errors due to heat conduction (heat conduction error) must be expected.

The quantitative magnitude of the error depends on the installation conditions concerned, the sensor design, the wall thickness of the thermowell, the medium and so on. It can therefore only ever be estimated.

If an adequate laboratory setup is available, the magnitude of the heat conduction error can also be determined quantitatively. Sometimes, it proves to be unexpectedly difficult to convert the results found in industrial applications.

The table below provides guidelines for the recommended immersion depth of sheathed thermocouples.

	Sensor diameter in mm		
	1.5/1.6	3.0/3.2	5.0/6.0
Medium	Minimum installation length in mm)1		
Gaseous)2	22 ... 30	45 ... 60	75 ... 120
Liquid)2	8 ... 15	15 ... 30	25 ... 50
Solid)3	8 ... 12	15 ... 20	20 ... 30

Table 12: Immersion depth

1) For resistance thermometers, the length of the measuring resistor (15 ... 30 mm, depending on type) must be added to the table values.
2) Larger value --> stagnant medium,
smaller value --> flowing medium
3) Larger value --> narrow bore tolerance,
smaller value --> soldered into the mounting bore

The following rules of thumb can be used as a general guide:

For use in gases, min. installation length
15 ... 20 x outside diameter

For use in liquids, min. installation length
5 ... 10 x outside diameter

12. AGING, DRIFT AND INHOMOGENEITIES

Temperature sensors are subject to unavoidable operational changes when used for their intended purpose! These changes are irreversible.

The broad term for this extremely complex process is "drift" or "aging". The long-term behavior (long-term stability) of a temperature sensor under operating conditions results from a series of influencing factors.

These factors can be metallurgical, chemical or physical in nature, or a combination thereof. It is practically impossible to predict the drift process of a temperature sensor under given operating conditions.

Generally speaking, there are three main causes of drift:

- Mechanical changes to the thermometer or sensor element
- Metallurgical changes in the sensor material due to changes in the crystal structure
- Metallurgical changes to the sensor material due to contamination.

The most important forms of mechanical changes are severe bends below the permissible minimum bending radius, high process pressures and rapid temperature changes – especially rapid cooling rates.

Metallurgical changes in the sensor materials due to changes in the crystal structure occur in practically all two-component and multi-component alloys. The K effect (short range ordering effect) is well known in type K thermocouples. It causes the thermocouple to become inhomogeneous. However, all other precious metal-free thermocouples with one leg consisting of a NiCr alloy also exhibit this effect to some extent. It manifests even in PtRh thermocouples – to a very small, yet detectable extent.

In the case of Tungsten Rhenium (W-Re) thermocouples, a recrystallization process is extremely pronounced in the lower alloyed leg during the first heating periods above approx. 1280°C. It leads to a permanent change and can account for up to 0.4% of the measured value.

The metallurgical change in the sensor material due to contamination is one of the most common causes of drift. To ensure that the thermoelectric voltages of the thermocouples comply with the normative specifications, the alloys and the purity of the thermocouple wires must be precisely maintained. The thermocouples react very sensitively throughout to metallic impurities that change the composition of the alloys.

Depending on the thermocouple in question, impurities in the range of just a few ppm can cause significant deviations from the basic value series. Thermocouples in which one leg consists of a pure metal are highly sensitive to impurities. These foreign materials can originate in the sheath material, the thermowell material, the insulating ceramic or the process medium.

However, the two legs of a thermocouple also influence one another at higher temperatures through diffusion mechanisms – e.g. at the joint (weld, also known as the thermocouple junction). Rhodium diffusion in Pt-Rh thermocouples across the weld is a well-known phenomenon.

Table 13 below shows the influence of various typical impurities on the thermoelectric voltage of a wire made of pure platinum (purity > 99.99%)

Element	dU_{th} in µV/ppm	Element	dU_{th} in µV/ppm
Fe (Iron)	2.30	Cu (Copper)	0.07
Ni (Nickel	0.50	Pd (Palladium)	0.03
Ir (Iridium)	0.35	Ag (Silver)	-0.07
Mn (Manganese)	0.32	Au (Gold)	3.00
Rh (Rhodium)	0.20	Pb (Lead)	4.04
Cr (Chromium)	0.12	Si (Silicon)	~ 20

Table 13: Contamination

12.1. Common cases of contamination

- Pure materials such as Fe, Cu and Pt drift due to the diffusion of foreign atoms. Precious metals react more strongly than base metals.
- Strong Pt poisons are Si and P. Si alloys Pt to form a brittle alloy with a melting point of 1340°C. P causes extreme brittleness and disintegration of the wire when the temperature changes.
- With Pt thermocouples, rhodium diffusion occurs across the measuring point Measurement errors with temperature gradients.
- Two-component alloys are prone to initial drifting due to the healing of production-related lattice stresses and defects.
- NiCr legs are sensitive to diffused sulfur and hydrogen.
- Type K and N thermocouples undergo comparatively low drift in the presence of impurities. This is because the two legs drift in the same direction and therefore largely cancel each other out in terms of thermoelectricity.

Finally, green rot (selective chromium oxidation) should be mentioned here as an example. Green rot occurs primarily in NiCr alloys under a low-oxygen or reducing atmosphere in combination with moisture in the temperature range from approx. 800 to 1000°C.

The moisture can develop from diffused hydrogen and the resultant reduced metal oxide – the insulating material inside the sheath thermocouple. The water is dissociated into hydrogen and oxygen on the hot metal surfaces.

The conductor is depleted of chromium due to the formation of chromium oxide, as a stabilizing "skin" of nickel oxide is reduced to nickel hydride. Nickel hydride can be gaseous depending on the temperature/pressure ratio. It diffuses towards the cold end of the thermocouple, where it decomposes into metallic nickel.

The measuring point migrates, so to speak, towards the cold end, and this can lead to a measurement error of up to several 100 K.

12.2. Summary

Drift: A change in output or setpoint value over a long period of time due to factors such as a change in the ambient conditions, change in the operating conditions, aging of components, aging of the sensor, contamination, ..., etc.

Conclusion: The measurement result becomes increasingly uncertain over time, as the course of the drift is unpredictable and therefore unknown. The aging of thermocouples in particular cannot be calculated!

Significant influencing factors that lead to drift (aging) in electrical contact thermometers:

- High continuous operating temperature
- Rapid temperature changes
- High cooling rates
- Contamination from process media
- Decomposition due to process media
- Contamination due to metal ions – diffusion
- Other influences due to manufacture and design

Drift is generally unavoidable even if the sensor is used as intended.

13. CONCLUDING REMARKS

As already explained in paragraph 5, the development of contact temperature sensors was essentially complete by the end of the 19th century. Contactless temperature measurement, on the other hand, only began in around 1890. Today, it is steadily gaining ground on contact thermometers.

The first endeavors to create standardized criteria – scales – for temperature measurement were made as early as the beginning of the 18th century. These endeavors are still ongoing today, in the 21st century. Now, though, the discussion revolves around millikelvins and microkelvins.

The pure development of temperature sensors took around 250 years. In the 110 years or so that followed, up to the present day, temperature has become the most frequently measured parameter of all. Thermocouples play a key role here – they account for around 60% of production and application figures.

The functional principle of temperature sensors has not changed fundamentally since their very beginnings in the 17th century. The apparent disadvantage, that the electrical measured value of thermocouples is in the range of a few millivolts, is more than countered by cutting edge device technology.

The ability to adapt thermocouples in particular to virtually any industrial measuring task makes them an almost ideal sensor.

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Seidnitzer Weg 9
01237 Dresden, Germany

+49 (0) 351 31225-0

info@roessel-messtechnik.de
www.roessel-messtechnik.de

RÖSSEL Messtechnik GmbH
Lohstraße 2
59368 Werne, Germany

+49 (0) 2389 409-0

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