Application of thermocouples

In industrial electrical temperature measurement, two groups of sensors are commonly used:
- Resistance temperature detectors (RTD)
- Thermocouples (TC)

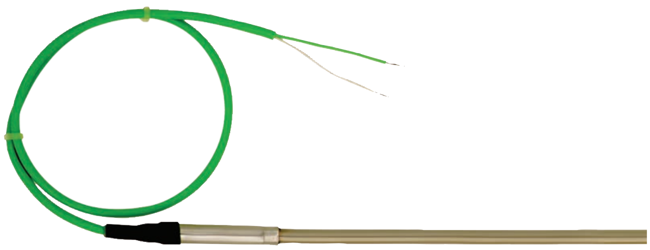
Both sensor types have their advantages and disadvantages. The commonly used Pt100 RTDs are especially suited for measurements in the lower to middle temperature range (-200 ... +600 °C). Thermocouples, however, (apart from a few exceptions) have their advantages at higher temperatures (up to 1700 °C).
Some thermocouples can measure even higher temperatures (tungsten-rhenium, gold-platinum or platinum-palladium). These very specific thermocouples are not described in this document.

While in Europe Pt100 sensors are primarily used for measuring low and medium temperatures, in North America a clear predominated use of thermocouples can be observed. However, this does not always apply, e.g a refinery built in Europe is equipped with temperature measurement technology which is based on North American standards if the plant has been designed in the USA. This can also apply to the other direction.

Another criterion for selecting a thermocouple is the smallest diameter possible of a sheathed thermocouple (see chapter “Sheathed thermocouples”). The diameters of 0.25 mm, 0.5 mm or 1 mm allow in astonishingly short response times. In general, thermocouples react faster than RTD's.

If the thermometer is built into a (massive) thermowell, the response times of the two sensor groups approach. When taking into account the mass of an assembled thermowell, its heat conduction and the insulation between medium and sensor relativise in this case the speed advantage of the thermocouple. Although it is still measurable, but often irrelevant as the response time in this case can be in the doubledigit minute range.

Straight thermocouple assembly with metal protection tube

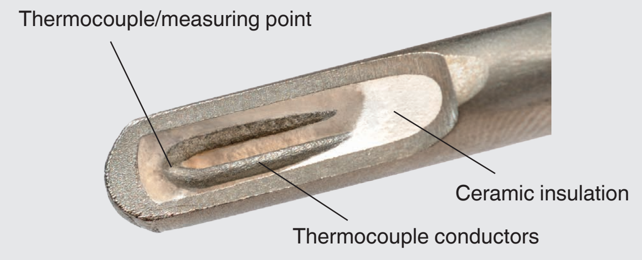


Cable thermocouple, model TC40
(Design: Sheathed measuring cable (MI cable))

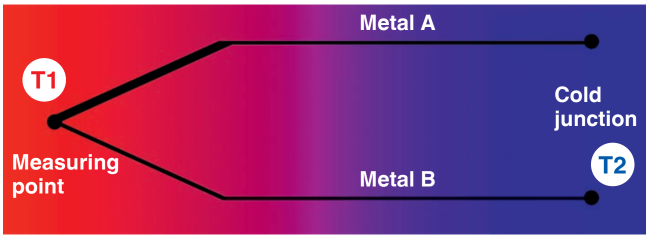
Samples of thermowells

Basics

A thermocouple consists of two conductors of dissimilar metals connected together at one end, whereby the connection node is the measuring point.



When the measuring point is heated, the voltage on the wire ends (cold junction) is measured; it represents the temperature of the measuring point.
(Thermoelectric effect = Seebeck effect)



This voltage (EMF = electromotive force) is produced due to different electron density of the two (dissimilar) metal conductors of the wires used - in combination with the temperature difference between measuring point and cold junction.

Simply, a thermocouple measures not the absolute temperature, but the differential temperature between the

- **T1**: Measuring point (hot junction)

  and
- **T2**: Cold point (cold junction)

Since the voltage is often measured at ambient temperature, the displayed voltage value would be too low by the value of the voltage of the ambient temperature. To obtain the value for the absolute measuring point temperature, the so-called "cold junction compensation" is used.

In the past (in calibration laboratories still today), it was achieved by means of immersing the joint of the cold end of the thermocouple and the wires of the voltage meter into an ice bath.

In current instruments with thermocouple input (transmitters, portable measuring instruments or panel mounted devices, etc.), an electronic cold junction compensation is included in the circuitry of the instrument.

Every metal has a material-specific electronegativity. (Electronegativity = tendency of atoms rather to accept or release electrons)

To achieve the highest possible thermoelectric voltages, special material pairings whose individual electronegativities are as far apart as possible are used to form thermocouples. These material pairings have certain limitations - for example due to the maximum operating temperature of the thermocouple.

Following standards define thermocouples
IEC 60584-1: Thermocouples: basic and tolerance values of the thermoelectric voltages
IEC 60584-3: Thermocouples: Thermocouple cables and compensating cables

ASTM E230:
Standard specification and temperature-electromotive force (EMF) tables for standardised thermocouples.

Thermoelectric voltages

Reference temperature: 0 °C

Temperature	Thermocouple							
in °C	Type K	Type J	Type N	Type E	Type T	Type S	Type R	Type B
-200					-5.603			
-180					-5.261			
-160					-4.865			
-140					-4.419			
-120					-3.923			
-100					-3.379			
-80					-2.788			
-60					-2.153			
-40	-1.527	-1.961	-1.023	-2.255	-1.475			
-20	-0.777	-0.995	-0.518	-1.152	-0.757			
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
20	0.798	1.019	0.525	1.192	0.790	0.113	0.111	
40	1.612	2.059	1.065	2.420	1.612	0.235	0.232	
60	2.436	3.116	1.619	3.685	2.467	0.365	0.363	
80	3.267	4.187	2.189	4.985	3.358	0.502	0.501	
100	4.096	5.269	2.774	6.319	4.279	0.646	0.647	
150	6.138	8.010	4.302	9.789	6.704	1.029	1.041	
200	8.138	10.779	5.913	13.421	9.288	1.441	1.469	
250	10.153	13.555	7.597	17.181	12.013	1.874	1.923	
300	12.209	16.327	9.341	21.036	14.862	2.323	2.401	
350	14.293	19.090	11.136	24.964	17.819	2.786	2.896	
370	15.133	20.194	11.867	26.552	19.030	2.974	3.099	
400	16.397	21.848	12.974	28.946		3.259	3.408	
450	18.516	24.610	14.846	32.965		3.742	3.933	
500	20.644	27.393	16.748	37.005		4.233	4.471	
550	22.776	30.216	18.672	41.053		4.732	5.021	
600	24.905	33.102	20.613	45.093		5.239	5.583	1.792
650	27.025	36.071	22.566	49.116		5.753	6.041	2.101
700	29.129	39.132	24.527	53.112		6.275	6.743	2.431
750	31.213	42.281	26.491	57.080		6.806	7.340	2.782
760	31.628	42.919	26.883	57.970		6.913	7.461	2.854
800	33.275		28.455	61.017		7.345	7.950	3.154
850	35.313		30.416	64.922		7.893	8.571	3.546
870	36.121		31.199	66.473		8.114	8.823	3.708
900	37.326		32.371	68.787		8.449	9.205	3.957
950	39.314		34.319			9.014	9.850	4.387
1000	41.276		36.256			9.587	10.506	4.834
1050	43.211		38.179			10.168	11.173	5.299
1100	45.119		40.087			10.757	11.850	5.780
1150	46.995		41.976			11.351	12.535	6.276
1200	48.838		43.846			11.951	13.228	6.786
1250	50.644		45.694			12.554	13.926	7.311
1260	51.000		46.060			12.675	14.066	7.417
1300						13.159	14.629	7.848
1350						13.766	15.334	8.397
1400						14.373	16.040	8.956
1450						14.978	16.746	9.524
1480						15.341	17.169	9.868
1500						15.582	17.451	10.099
1550						16.182	18.152	10.679

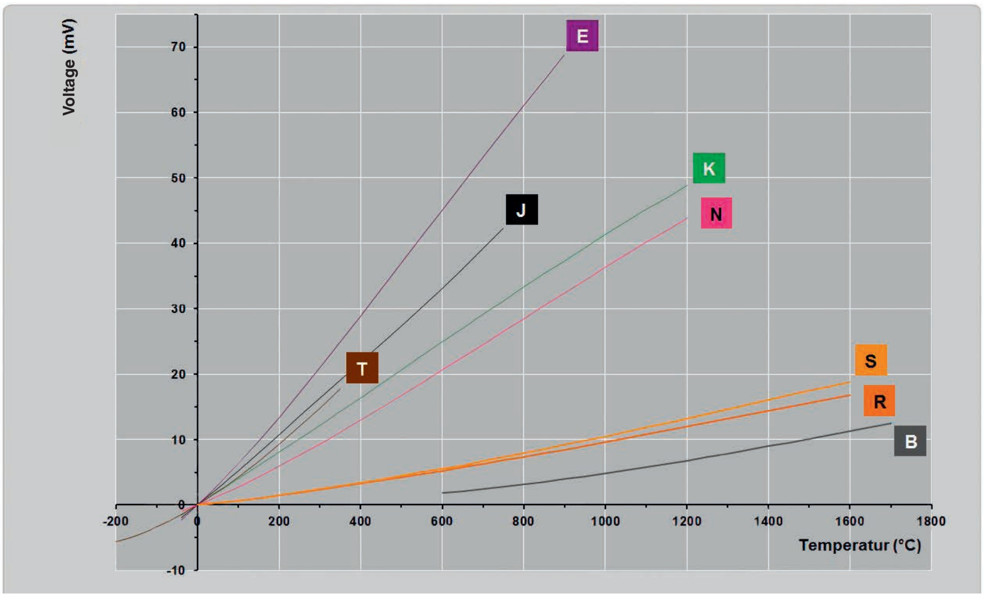
Continued on next page

Temperature	Thermocouple							
in °C	Type K	Type J	Type N	Type E	Type T	Type S	Type R	Type B
1600						16.777	18.849	11.263
1650								11.850
1700								12.430

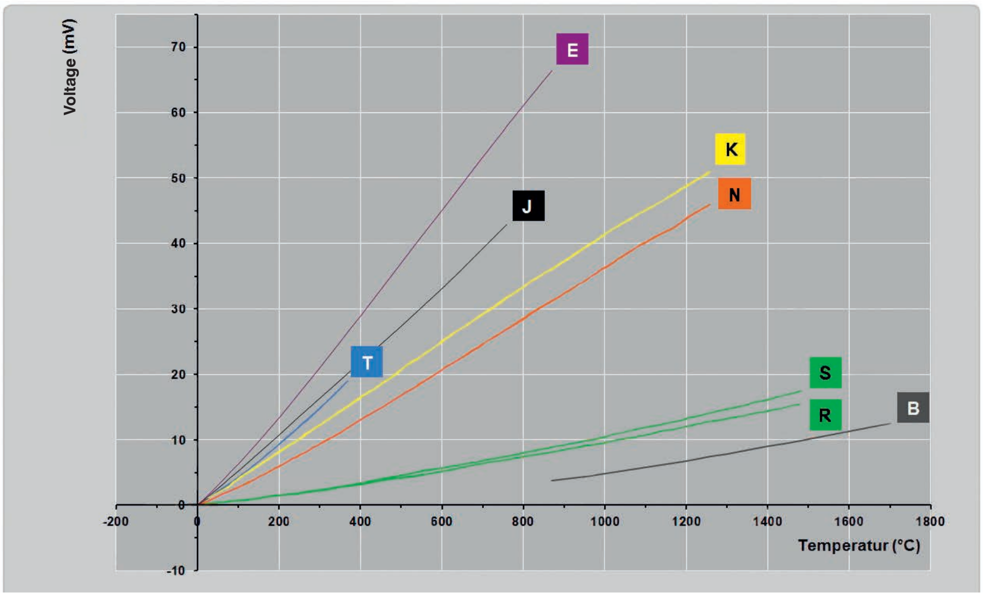
Legend:
Black: IEC 60584-1 and ASTM E230
Blue: IEC 60584-1 only
Red: ASTM E230 only

Thermoelectric voltage curves

■ IEC 60584-1



■ ASTM E230



The charts illustrate the curves corresponding to the relevant temperature ranges of IEC 60584-1 / ASTM E230. Outside these temperature ranges, the permissible tolerance value is not standardised.

Operating limits and accuracies of thermocouples (IEC 60584, ASTM E230)

The following table contains permissible tolerance values of IEC 60584-1 incl. the tolerance values of ASTM E230 standard which is common in North America:

Tolerance values of the thermocouples per IEC 60584-1 / ASTM E230 (Reference temperature 0 °C)

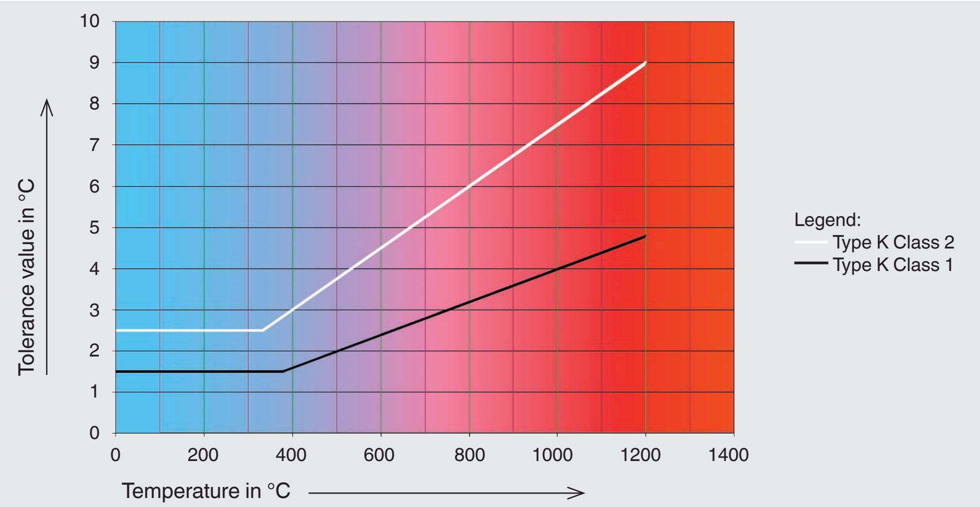
Type	Thermocouple	Tolerance value	Class	Temperature range	Tolerance value
K N	NiCr-NiAl (NiCr-Ni) NiCrSi-NiSi	IEC 60584-1	1	-40 ... +1000 °C	±1.5 °C or 0.0040 · | t | 1) 2)
			2	-40 ... +1200 °C	±2.5 °C or 0.0075 · | t |
		ASTM E230	Special	0 ... +1260 °C	±1.1 °C or ±0.4 %
			Standard	0 ... +1260 °C	±2.2 °C or ±0.75 %
J	Fe-CuNi	IEC 60584-1	1	-40 ... +750 °C	±1.5 °C or 0.0040 · | t |
			2	-40 ... +750 °C	±2.5 °C or 0.0075 · | t |
		ASTM E230	Special	0 ... +760 °C	±1.1 °C or ±0.4 %
			Standard	0 ... +760 °C	±2.2 °C or ±0.75 %
E	NiCr-CuNi	IEC 60584-1	1	-40 ... +800 °C	±1.5 °C or 0.0040 · | t |
			2	-40 ... +900 °C	±2.5 °C or 0.0075 · | t |
		ASTM E230	Special	0 ... +870 °C	±1.0 °C or ±0.4 %
			Standard	0 ... +870 °C	±1.7 °C or ±0.5 %
T	Cu-CuNi	IEC 60584-1	1	-40 ... +350 °C	±0.5 °C or 0.0040 · | t |
			2	-40 ... +350 °C	±1.0 °C or 0.0075 · | t |
			3	-200 ... +40 °C	±1.0 °C or 0.015 · | t |
		ASTM E230	Special	0 ... +370 °C	±0.5 °C or ±0.4 %
			Standard	-200 ... 0 °C	±1.0 °C or ±1.5 %
			Standard	0 ... +370 °C	±1.0 °C or ±0.75 %
R S	Pt13%Rh-Pt Pt10%Rh-Pt	IEC 60584-1	1	0 ... +1600 °C	±1.0 °C or ±[1 + 0.003 (t - 1100)] °C
			2	0 ... +1600 °C	±1.5 °C or ±0.0025 · | t |
		ASTM E230	Special	0 ... +1480 °C	±0.6 °C or ±0.1 %
			Standard	0 ... +1480 °C	±1.5 °C or ±0.25 %
B	Pt30%Rh-Pt6%Rh	IEC 60584-1	2	+600 ... +1700 °C	±0.0025 · | t |
			3	+600 ... +1700 °C	±4.0 °C or ±0.005 · | t |
		ASTM E230	Special	-	-
			Standard	+870 ... +1700 °C	±0.5 %

1) ItI is the value of the temperature in °C without consideration of the sign
2) The greater value applies

There are different notations of type K thermocouples in Europe and North America:
Europe: NiCr-NiAl or NiCr-Ni
North America: Ni-Cr / Ni-Al
There is no physical difference, it is just the naming caused by historical reasons.

Types R, S and B
Not available as MI-cable version in class 1 per IEC 60584 or “Special” per ASTM E230

For the tolerance value of thermocouples, a cold junction temperature of 0 °C has been taken as the basis. When using a compensating cable or thermocouple cable, an additional measuring deviation must be considered.



Example:
Tolerance value of the accuracy classes 1 and 2 of thermocouple type K

Information on the application of thermocouples

Base-metal thermocouples

Type K

+ leg		- leg
NiCr	-	NiAl
Nickel-Chromium	-	Nickel-Aluminum (ferromagnetic)

NiCr-NiAl thermocouples are suitable for use in oxidising or inert gas atmospheres up to 1200 °C (ASTM E230: 1260 °C) with the largest wire size.
Protect thermocouples from sulphurous atmospheres. Since they are less susceptible to oxidation than thermocouples made of other materials, they are mostly used for applications at temperatures above 550 °C up to the maximum working pressure of the thermocouple.

Type J

+ leg		- leg
Fe	-	CuNi
Iron (ferromagnetic)	-	Copper-Nickel

Fe-CuNi thermocouples are suitable for use in vacuum, in oxidising and reducing atmospheres or inert gas atmospheres. They are used for temperature measurements up to 750 °C (ASTM E230: 760 °C) with the largest wire size.

Type N

+ leg		- leg
NiCrSi	-	NiSi
Nickel-Chromium-Silicon	-	Nickel-Silicon

NiCrSi-NiSi thermocouples are suitable for use in oxidising atmospheres, in inert gas atmospheres or dry reduction atmospheres up to 1200 °C (ASTM E230: 1260 °C).
They must be protected from sulphurous atmospheres. They are very accurate at high temperatures. The source voltage (EMF) and the temperature range are almost the same as with type K. They are used in applications where a longer service life and greater stability are required.

Type E

+ leg		- leg
NiCr	-	CuNi
Nickel-Chromium	-	Copper-Nickel

NiCr-CuNi thermocouples are suitable for use in oxidising or inert gas atmospheres up to 900 °C (ASTM E230: 870 °C) with the largest wire size. Type E thermocouples, of all the commonly used thermocouples, develop the highest source voltage (EMF) per °C.

Type T

+ leg		- leg
Cu	-	CuNi
Copper	-	Copper-Nickel

Cu-CuNi thermocouples are suitable for temperatures below 0 °C with an upper temperature limit of 350 °C (ASTM E230: 370 °C) and can be used in oxidising, reducing or inert gas atmospheres. They do not corrode in moist atmospheres.

Precious-metal thermocouples

Type S

+ leg		- leg
Pt10%Rh	-	Pt
Platinum-10%Rhodium	-	Platinum

Type S thermocouples are suitable for continuous use in oxidizing or inert atmospheres at temperatures up to 1600 °C. Beware of embrittlement due to contamination.

Type R

+ leg		- leg
Pt13%Rh	-	Pt
Platinum-13%Rhodium	-	Platinum

Type R thermocouples are suitable for continuous use in oxidising or inert gas atmospheres at temperatures up to 1600 °C. Beware of embrittlement due to contamination.

Type B

+ leg		- leg
Pt30%Rh	-	Pt6%Rh
Platinum-30%Rhodium	-	Platinum-6%Rhodium

Type B thermocouples are suitable for continuous use in oxidising or inert gas atmospheres and for short-term use in vacuum environments for temperatures up to 1700 °C. Beware of embrittlement due to contamination.

Type R, S and B thermocouples are commonly installed in a pure ceramic closed-ended protection tube. If a metal thermowell or protection tube is used, an inner closed-ended protection tube is required. Precious metal thermocouples are susceptible to contamination. It is strongly recommended to surround these thermocouples with ceramic material.

Recommended upper temperature limit

(Continuous operation)

■ Sheathed thermocouples (see also table "Thermoelectric voltages per IEC 60584-1")

Thermocouple type	Recommended upper temperature limit in °C							
	With sheath diameter in mm							
	0.5	1.0	1.5	2.0	3.0	4.5	6.0	8.0
K	700	700	920	920	1070	1100	1100	1100
J	260	260	440	440	520	620	720	720
N	700	700	920	920	1070	1100	1100	1100
E	300	300	510	510	650	730	820	820
T	260	260	260	260	315	350	350	350

Sheath material: Inconel 2.4816 (Inconel 600)

Specifications under consideration of optimum laboratory conditions (relating to air without harmful gases).
Other materials are available resulting in different temperature limits.

■ Straight thermocouple assembly (see also table "Thermoelectric voltages per IEC 60584-1")

Thermocouple type	Recommended upper temperature limit in °C			
	With wire diameter in mm			
	0.35	0.5	1.0	3.0
K	700	700	800	1000
J	400	400	600	700
N	700	700	800	1000
E	400	400	600	700
T	200	200	300	350
S	1300	1300	-	-
R	1300	1300	-	-
B	1500	1500	-	-

Specifications under consideration of optimum laboratory conditions (relating to air without harmful gases).

■ Protected thermocouples (see also table "Suggested upper temperature limits for protected thermocouples" per ASTM E230)

Thermocouple type	Upper temperature limit for various wire sizes (Awg) in °C					
	No. 30 gauge 0.25 mm [0.010 inch]	No. 28 gauge 0.33 mm [0.013 inch]	No. 24 gauge 0.51 mm [0.020 inch]	No. 20 gauge 0.81 mm [0.032 inch]	No. 14 gauge 1.63 mm [0.064 inch]	No. 8 gauge 3.25 mm [0.128 inch]
T	150	200	200	260	370	
J	320	370	370	480	590	760
E	370	430	430	540	650	870
K and N	760	870	870	980	1090	1260
R and S			1480			
B			1700			

Note:
The specified maximum operating temperatures apply to the thermocouple under optimal environmental conditions. The maximum working temperature of the thermowells is often well under the temperature of the thermocouple!

- Sheathed thermocouples (see also table “Suggested upper temperature limits for sheathed thermocouples” per ASTM E608/E608M)

Nominal sheath diameter		Upper temperature limit for various sheath diameters in °C			
		Thermocouple type			
mm	inch	T	J	E	K and N
0.5	**0.020**	260	260	300	700
-	**0.032**	260	260	300	700
1.0	**0.040**	260	260	300	700
1.5	**0.062**	260	440	510	920
2.0	**-**	260	440	510	920
-	**0.093**	260	480	580	1000
3.0	**0.125**	315	520	650	1070
4.5	**0.188**	370	620	730	1150
6.0	**0.250**	370	720	820	1150
8.0	**0.375**	370	720	820	1150

Note:
The specified maximum operating temperatures apply to the thermocouple under optimal environmental conditions. The maximum working temperature of the thermowells is often well under the temperature of the thermocouple!

Potential measurement uncertainties

Important factors which counteract the long-term stability of thermocouples

Ageing effects/contamination

- Oxidation processes in thermocouples which are not appropriately protected (“bare” thermocouple wires) result in falsifications of the characteristic curves
- Foreign atoms (poisoning) that diffuse into the original alloys lead to changes of these original alloys and thus falsify the characteristic curve.
- The influence of hydrogen leads to the embrittlement of the thermocouples.

“Base-metal” thermocouples are subject to ageing and thereby change their temperature/thermal voltage characteristic curve.
“Precious” PtRh-Pt thermocouples of the types R and S show virtually no ageing up to 1400 °C.
However, they are very sensitive to contamination. Silicon and phosphorous destroy the Platinum rapidly. In the presence of Platinum, Silicon can be released from the isolating ceramic parts, even in slightly reducing atmosphere. The reduction of SiO_2 to Si contaminates the Pt-leg of the thermocouple. This leads to errors of 10 °C and more even if the volume of Silicon is in the range of a few ppm.

Due to a better ratio of the total material volume to the surface sensitive to poisoning, the long-term stability of the precious-metal thermocouples increases with increasing thermocouple wire diameter. This is why the sensors of the types S, R and B with thermocouple wire diameters Ø 0.35 mm or Ø 0.5 mm (0.015" or 0.020") are available. But: thermocouple wires with Ø 0.5 mm (0.020") have twice the area of cross section of the wires with Ø 0.35 mm (0.015") – and are thereby also twice as expensive. Nevertheless, it can be worth it as a considerably longer service life can equalise the possibly high service costs (downtime of the plant).

The Ni leg of the type K thermocouple is often damaged by sulphur that is present in exhaust gases. Thermocouples of the types J and T age slightly as the pure metal leg oxidises first.

In general, rising temperatures cause accelerated ageing effects.

Green rot

If type K thermocouples are used at temperatures from approx. 800 °C to 1050 °C, considerable changes of the thermoelectric voltage can occur. The cause of this is a chromium depletion or the chrome oxidation in the NiCr leg (+ leg). The precondition for this is a low concentration of oxygen or steam in the immediate environment of the thermocouple. The nickel leg is not affected by it. The consequence of this effect is a drift of the measured value caused by decreasing thermoelectric voltage. This effect is accelerated if there is a shortage of oxygen (reducing atmosphere), since a complete oxide layer, which would protect it from further oxidation of the chromium, cannot be formed on the surface of the thermocouple.

The thermocouple is permanently destroyed by this process. The name green rot is derived from the greenish shimmering colouration on the breaking point of the wire.

The thermocouple type N (NiCrSi-NiSi) has in this regard an advantage due to its Silicon content. Here, a protective oxide layer forms on its surface under the same conditions.

K effect

The NiCr leg of a type K thermocouple has an ordered alignment with respect to the alignment in the crystal lattice below approx. 400 °C. If the thermocouple is heated further, a transition to a disordered state occurs in the temperature range between approx. 400 °C and 600 °C. Above 600 °C, an ordered crystal lattice is restored.
If these thermocouples cool too quickly (quicker than approx. 100 °C per hour), the undesirable disordered crystal lattice occurs again during cooling in the range from approx. 600 °C to approx. 400 °C. In the characteristic curve of type K, however, a consistently ordered alignment state is assumed and provided with values. This results in a fault of thermoelectric voltage of up to approx. 0.8 mV (approx. 5 °C) in this range.
The K effect is reversible and is largely eliminated again by annealing above 700 °C, followed by correspondingly slow cooling.

Thin sheathed thermocouples are particularly sensitive in this regard. Cooling in resting air can already lead to deviations of 1 °C.

In type N thermocouple (NiCrSi-NiSi), it has been possible to reduce this short-range-order effect by alloying both legs with Silicon.

Standard designs of thermocouples

Sheathed thermocouples

Sheathed thermocouples consist of an outer metallic sheath, containing internal leads, which are embedded and isolated by a highly compressed ceramic compound. (mineral-insulated cable, also called MI cable).
Sheathed thermocouples are bendable and may be bent to a minimum radius of five times the sheath diameter. Due to this, sheathed thermocouples can also be used in places that are difficult to access.
The extreme vibration resistance is another good reason for using sheathed thermocouples.

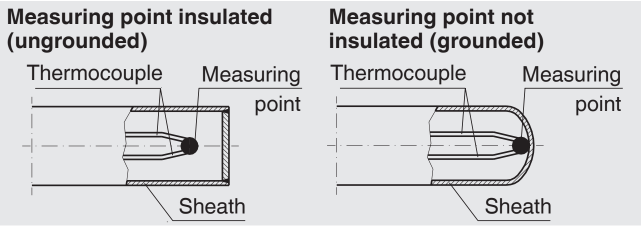
Available sheath diameters

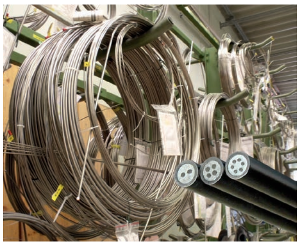
- 0.5 mm
- 1.0 mm
- 1.5 mm
- 3.0 mm
- 4.5 mm
- 6.0 mm
- 8.0 mm

Sheath materials

- Ni-alloy 2.4816 (Inconel 600)
  - up to 1200 °C (air)
  - standard material for applications which require specific corrosion resistance properties under exposure to high temperatures, resistant to induced stress corrosion cracking and pitting in media containing chloride
  - resistant to corrosion caused by aqueous ammonia in all temperatures and concentrations
  - highly resistant to halogens, chlorine, hydrogen chloride
- Stainless steel 316
  - up to 850 °C (air)
  - good corrosion resistance with aggressive media as well as steam and flue gases in chemical media
- Other materials on request

Design of measuring points



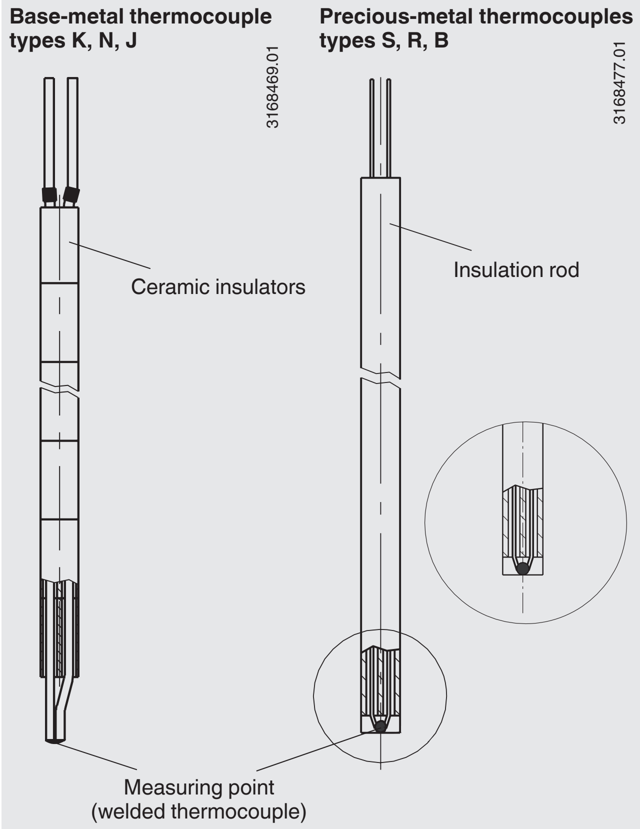


Raw material MI cable

Straight thermocouple assembly with metal or ceramic protection tube

Different designs, model TC80

Internal design of the thermocouples, straight version



Precious-metal thermocouples types S, R, B

Thermocouple wire: Ø 0.35 mm or Ø 0.5 mm
Insulation: Insulation rod, ceramic C 799 / alumina

Base-metal thermocouple types K, N, J

Thermocouple wire: Ø 1 mm or Ø 3 mm
Insulation: Ceramic insulators, ceramic C 610 / mullite

Connecting cables for thermocouples

To bridge the distance between thermocouple and instrumentation, special connection cables must be used with thermocouples.

A distinction is made here between **thermocouple cables** (the wire material corresponds to the original material of the thermocouple) and so-called **compensating cables**.
With compensation cables, the wire material corresponds in a limited temperature range to the thermoelectric properties of the original thermocouple. These temperature limits are listed in IEC 60584-3 or ASTM E230. Information about the accuracy classes of the cables are shown there as well.
The use of these special wire materials is required to avoid "parasitic thermocouples".

■ **Thermocouple cable**
The internal leads of the thermocouple cable are made of original materials of the thermocouple (not available for precious thermocouples for cost reasons).
The cables are available in the accuracy classes 1 and 2.

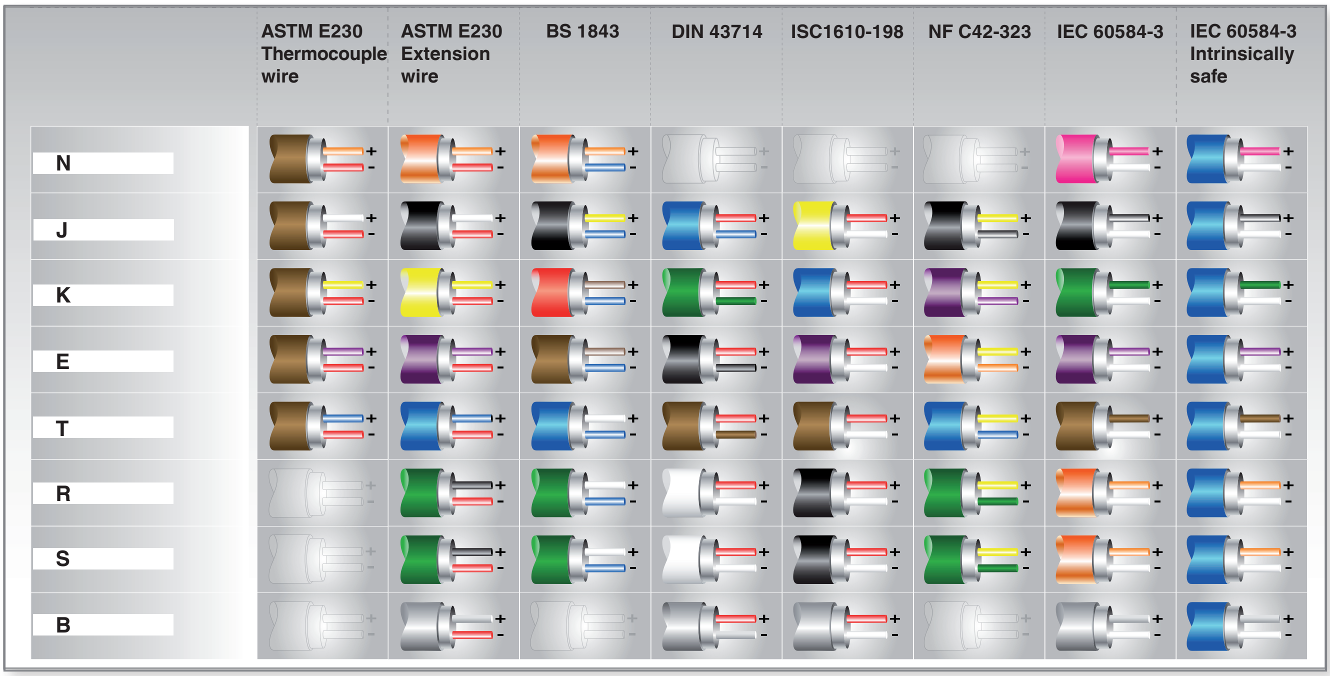
■ **Compensating cable**
The internal leads of the compensating cable are made of materials which correspond to the thermoelectric properties of the original thermocouples. This applies to a temperature range defined in IEC 60584 / ASTM E230 on the transition cable ↔ thermocouple, and to the entire length of the cable.
Available only in accuracy class 2.

For thermocouple type B, the use of internal leads made of copper is allowed.
Expected error (example): 40 µV / 3.5 °C
This is true within a temperature range of 0 ... 100 °C at the junction of thermocouple and compensating cable.
The temperature of the measuring point in this example is 1400 °C.

Note:
The potential faults of thermocouple and connecting cable are added!

Connecting cable

Thermocouple and extension wire colour codes



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