Error Analysis of a Temperature Measurement System

with worked examples

Gerd Scheller

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To make measurements comparable, the quality must be stated by specifying the measurement uncertainty. The ISO/BIPM “Guide to the Expression of Uncertainty in Measurement” published in 1993, normally abbreviated to GUM, introduced a unified method of determining and specifying the measurement uncertainty. This method was adopted by the calibration laboratories worldwide. Its application, however, requires some mathematical knowledge. The simplified approach used in the following chapters makes the measurement uncertainty clearly understandable for everyone who uses temperature measurement systems.

Mistakes made when installing temperature sensors and connecting the evaluation electronics lead to increased measurement error.
In addition, there are the measurement uncertainty components of the sensor and evaluation electronics themselves. After an explanation of the measurement uncertainty components, a number of worked examples are set out.

A knowledge of the measurement uncertainty components and their order of magnitude enables the user to reduce individual components by changing the installation conditions or selecting a different instrument. The crucial factor is always the measurement uncertainty required for a measurement task. Where, for example, a standard specifies limits for the deviation of the temperature from the nominal value, the measurement uncertainty of the measurement method used should not exceed 1/3 of the limit.

This publication, particularly the worked examples set out in Chapter 3, represents an aid in assessing the measurement uncertainty. If any problems occur, we are happy to discuss specific cases with our customers and provide practical help and support.

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Gerd Scheller

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1 General/explanation of terms

1.1 The temperature measurement system

A temperature measurement system consists of the temperature sensor (temperature-dependent resistor or thermocouple) and the evaluation electronics. The sensor is normally fitted in a protection tube together with a suitable means of heat transfer.

Between the two components of the measurement system is a connecting cable. The sensor and evaluation electronics are often combined in a temperature probe (terminal head). The evaluation electronics can be either a transmitter (standardized output signal) or a direct-reading electronic indicating instrument (digital indication of the temperature).

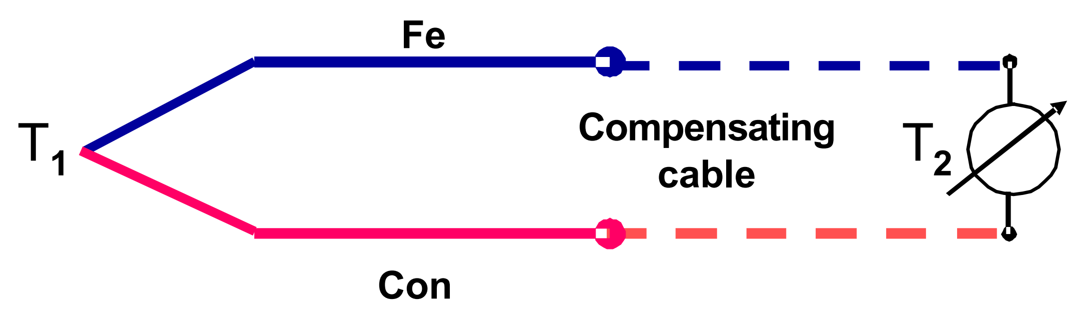

Fig. 1: Features of the temperature measurement system with thermocouple

A thermocouple always measures the temperature difference between the measurement point and the reference junction. The temperature T2 (reference junction terminal temperature at the transition from thermocouple to copper cable) must be known in order to be able to measure the temperature T1. A compensating cable which has the same thermoelectric properties as the thermocouple itself is used to connect the thermocouple to the evaluation electronics. This prevents an additional thermoelectric emf arising at the junction. However, it is essential that the appropriate compensating cable is always used. With enclosure entries with different internal and external temperatures, plugs and sockets free from thermoelectric emf must be used.

All the thermoelectric emfs quoted in the tables are referred to a reference junction temperature of 0 °C. This cannot normally be realized with measurement systems and so the terminal temperature must be measured or held constant. If the terminal temperature is 20 °C, for example, the result (from the measured thermoelectric emf) must be corrected by +20 °C.

EN 60 584 specifies error limits for all standard thermocouples dependent on the measured temperature. It should be noted that error limits also apply to the compensating cables (Class 1 and 2), so that an overall tolerance is obtained for each thermocouple, made up of the tolerances of the thermocouple and the compensating cable.

Thermocouples normally show a worse drift behavior than platinum resistance thermometers (absorption of materials from the surroundings, chemical reaction, recrystallization, mechanical stress), so it is impossible to make a general statement about the service life of thermocouples. However, the measurement uncertainty should be checked on a regular basis with a reference thermometer, such as a measurement system calibrated by the DKD (German Calibration Service) using a resistance thermometer connected in a 4-wire circuit), ideally in a liquid-filled thermostatic bath.

1 General/explanation of terms

1.1.1 Calibration

"Calibration means the determination and recording of the deviation of the indication of an instrument (or the indicated value of a representation of a measurement) from the correct value of the measured quantity", see 5 /1/.

No alteration to the instrument occurs during calibration, however, correction tables and/or correction functions are prepared.

1.1.2 Adjustment

Adjustment is the setting or balancing of a measuring instrument to eliminate systematic measurement deviations to the necessary extent or as far as possible. Adjustment therefore requires an action which permanently alters the instrument.

Temperature measuring instruments are normally adjusted using fixed resistors to EN 60 751. Therefore, no statement about the overall measurement uncertainty of the measurement system can be derived from this, as the deviation of the temperature probe connected at a later stage is not normally considered.

1.1.3 Testing

During testing, the extent to which an object under test fulfills a specific requirement (e.g. tolerance class) is determined. Testing is thus always linked to a comparison under specified conditions. The nature and scope of the measurement checks made on the test equipment are left to the discretion of the respective organization or test laboratory. No statements about measurement uncertainty are made.

1.1.4 The standard

The purpose of the standard is to represent one or more known values of a quantity and to pass these on to other instruments by means of comparison measurements.

1.1.5 Reference standard

The standard that represents the highest available accuracy at a particular place, from which the measurements made at that place are derived.
In Germany, the national reference standard is controlled and passed on by the PTB (Physical-Technical Laboratory).

At JUMO these reference standards are PTB-calibrated thermometers (for various temperature ranges) that are recalibrated every two years. For customers, this standard can be, for example, a thermometer calibrated by the DKD (German Calibration Service) at JUMO.

1.1.6 Factory/workshop standard

The working standard that is calibrated against a reference standard using suitable instruments, and then used routinely to calibrate or test items of test equipment.

This means that in the DKD calibration laboratory, factory/workshop standards are checked against the PTB-calibrated reference standards and then used for routine calibrations.

1.1.7 Traceability

The term “traceability” describes a process by which the value indicated by an instrument (or by a representation of a measurement) can be compared, via one or more steps, with the national standards for the quantity concerned, see 5 /2/.
The chain of the individual steps must be continuous. The measurement uncertainty increases with each additional step.

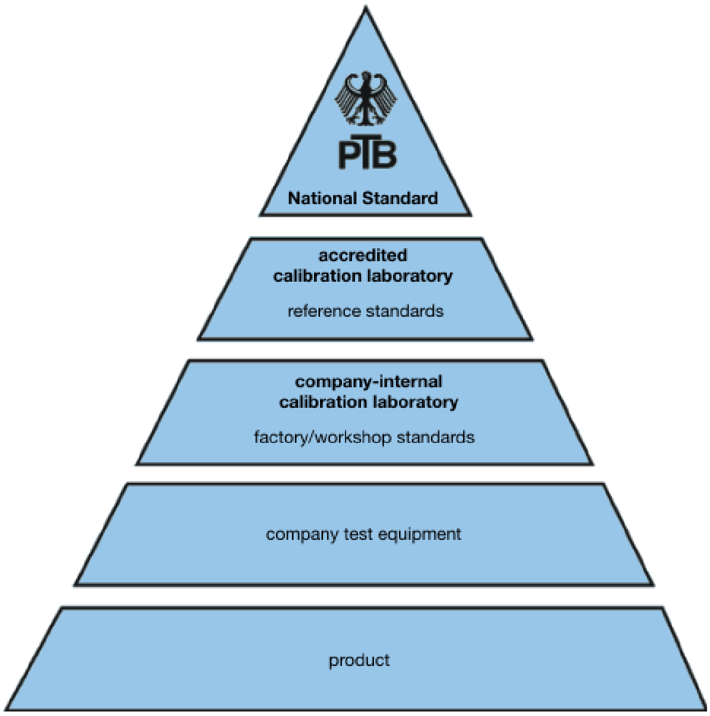

Fig. 2: Standards ranked in order of importance

1.1.8 German Calibration Service (DKD)

Calibration laboratories affiliated with the DKD are accredited and are subject to regular checks by the DKD office and PTB specialist laboratories.

1.1.9 Measurement uncertainty

The measurement result of a measurement series is the mean value corrected for the known systematic deviations (evident with each measurement), linked to an interval within which the true value of the measured quantity can be assumed to lie. The difference between the upper boundary of this interval and the corrected mean value and the difference between the corrected mean value and the lower boundary of this interval is called measurement uncertainty. Usually, but not always, both differences have the same value. The overall width of the interval must not be referred to as measurement uncertainty.

Numerous publications have appeared covering the calculation processes and mathematical relationships, and reference should be made to additional technical literature for a better understanding and more in-depth knowledge of the subject (see Chapter 5 “Recommended literature”).

1.1.10 Systematic measurement deviations

Systematic measurement uncertainties occur 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.

1.1.11 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. Twice the standard deviation (K = 2) gives rise to a probability of 95.4 %.

2 Measurement uncertainty components

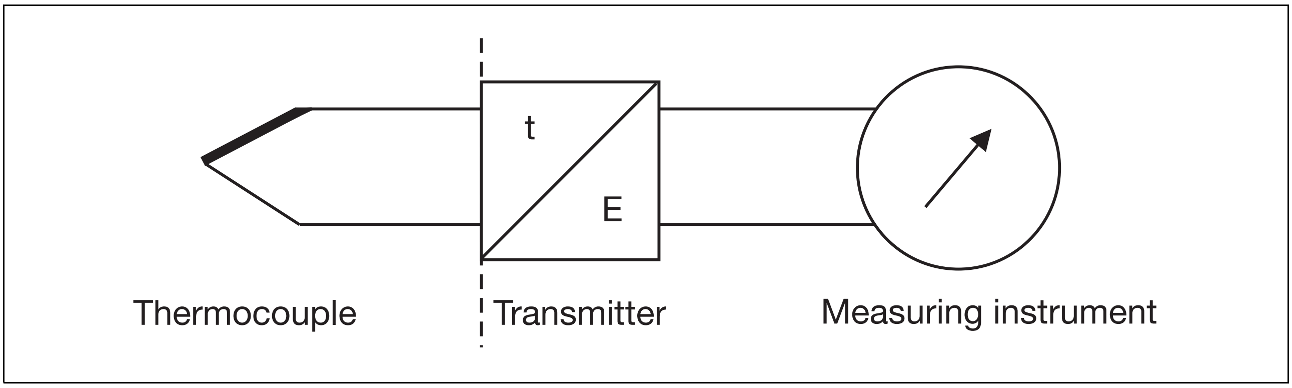

Fig. 3: The temperature measurement system with thermocouple

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

The sensor provides a temperature-dependent signal that is fed via the cable to the evaluation electronics, where it is ultimately converted to a temperature indication or to a current signal. The error sources of all three components have to be included in the consideration of measurement uncertainty. This means that additional measurement uncertainty components are introduced once again, when transmitters are used during the conversion into a temperature indication.

$$I_X = t_m + \sigma M_F(^{**}) + \sigma M_D + \sigma M_A + \sigma M_E(^{**}) + \sigma M_{Th}(^{**}) + \sigma M_{RI}(^{**}) - C_S * \sigma t_{0S}(^{*}) + \sigma V_{LX}(^{*}) + \sigma R_{AL}(^{**}) + \sigma V + \sigma t_M + \sigma t_W + \sigma_B + \sigma_{LZ} \quad (1)$$

(*) only when thermocouples are used
(**) only when resistance thermometers are used
I_X output signal (indicated temperature or temperature equivalent)
t_m temperature at the measurement point

Measurement uncertainties at the sensor and in the cables

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 (resistance thermometer) or as per EN 60 584 (thermocouple)
σM_A measurement signal deviation caused by insufficient stabilization
σM_E measurement signal deviation caused by the self-heating of the sensor (only with 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)
C_S sensitivity of the sensor, e.g. in °C/µV (thermocouple)
σt_{0S} temperature deviation caused by the reference temperature deviating from the assumed value
σV_{LX} voltage deviation caused by the compensating cables (thermocouples)
σR_{AL} variation in the lead resistance (resistance thermometer)

Measurement uncertainties at the transmitter and indication

σV deviation of the evaluation electronics caused by supply variations (effect of voltage)
σt_M deviation caused by fluctuating ambient temperature (effect of temperature)

σt_W processing and linearization errors in the evaluation electronics
σ_B indication deviation caused by the influence of the input resistance (effect of burden)
σ_{LZ} long-term stability of the evaluation electronics (deviation caused by component ageing)

σ = sigma (18th letter of the Greek alphabet)

In the following section we would like to consider the individual measurement uncertainty components:

2.1 Heat conduction error of the temperature probe (σM_F)

The temperature to be measured is generally 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 error increases with increasing temperature difference between the surroundings and the measured medium.
Design aspects that have a decisive influence include primarily the material of the protection tube (thermal conduction properties), the protection tube diameter (surface) and the internal construction of the temperature probe (fill material, sensor size, etc.). These design aspects can be suitably optimized by the manufacturer and tailored to the respective application.
The heat conduction error can be determined by, for example, immersing the temperature probe in an accurately regulated temperature bath and determining the difference between the temperature indicated with the actual insertion length used and with full immersion. With an outside diameter of 5.0mm, an insertion depth of 25mm and a measured temperature of 85°C (measured medium water with v = 0.12m/sec), the heat conduction error is approx. 0.05°C.

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
- fit additional thermal insulation to the external parts of the thermometer (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

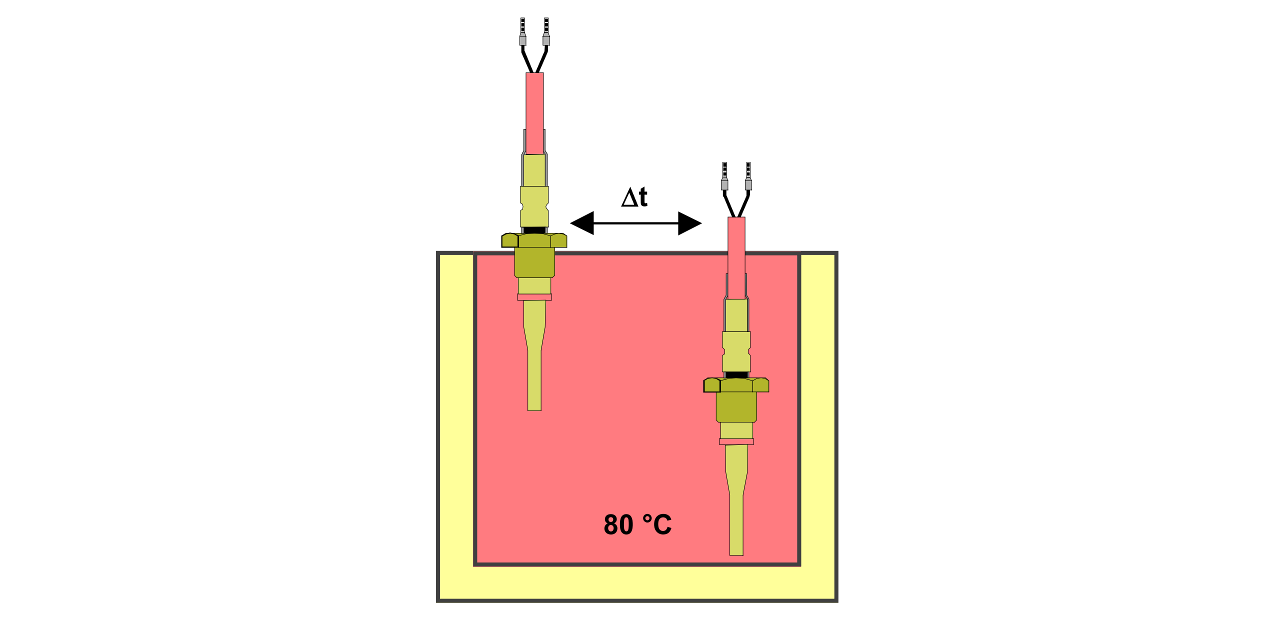

Fig. 4: Determination of the heat conduction error of a resistance thermometer

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

The evaluation electronics is usually set up for temperature sensors which behave exactly in accordance with the appropriate standard characteristic (EN 60 751 for platinum resistance thermometers; EN 60 584 for thermocouples). However, the sensors very rarely follow the standard characteristic, but tolerance classes are permitted.

The permissible tolerance for a platinum sensor of tolerance class B is calculated from the formula ±(0.3 °C + 0.005 t) where t = measured temperature in °C. At 100 °C this gives a permissible tolerance of ±0.8 °C.

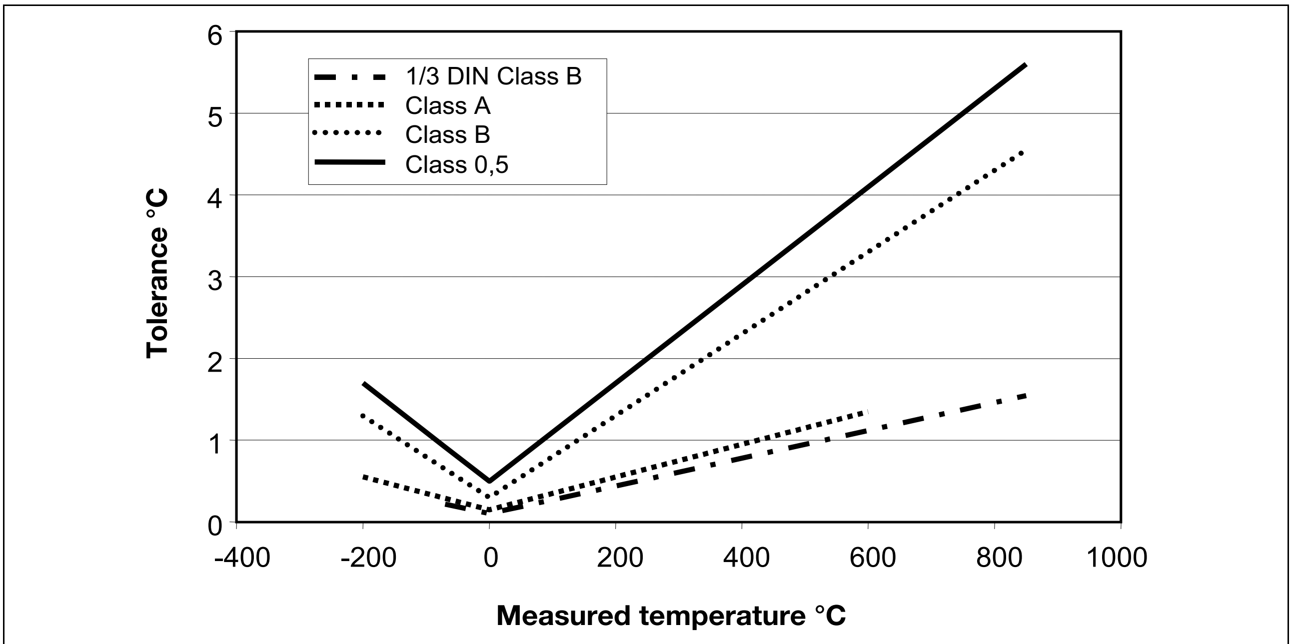

Fig. 5: Permissible deviation limits for platinum temperature sensors

This error can be limited by:

- using 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)
- entering the characteristic coefficients (R_0, A, B) of the temperature probe in the evaluation electronics (of course, these parameters must be made available). For this the temperature probe must be checked at at least three temperatures within the measurement range. The measurement uncertainty component of the temperature sensor is thus restricted to the measurement uncertainty during temperature measurement. For more information see Chapter 5 “Recommended literature” /1/.

2.3 Stabilization (σM_A)

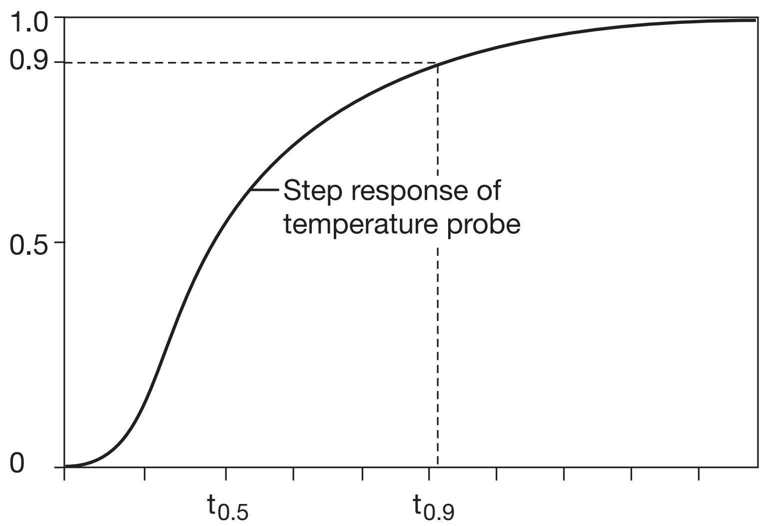

Fig. 6: Transfer function after a sudden change in temperature

Because of the ever-present thermal resistance (the magnitude is dependent on the materials used), the temperature sensor never takes on the temperature of the measured medium immediately - 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 large extent on the flow rate, the measured medium used and the immersion depth, EN 60 751 lays down conditions for recording the step response in air and water (e.g. surrounded by a flow of air, flow rate 3.0 ±0.3 m/sec). 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} (measured value has reached 90 % of the final value). For measurements in air, t_{09} times of five minutes and more are quite possible here.
The measures already described for reducing the heat conduction error also lead to a reduction in response times. In addition, the user must ensure that an adequate stabilization time is allowed before, for example, any measurements are recorded.

2.4 Self-heating of resistance thermometers (σM_E)

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

Reducing the measuring current invariably leads to a reduction in the 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 in Ω	**Measuring current range in mA**
100	0.5 — 1.0
1000	0.1 — 0.3

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

For a given thermometer current and known self-heating coefficient, the self-heating error is given by:

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

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

In addition, the self-heating 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-heating error.

2.5 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. Undesirable thermoelectric emfs can also occur due to an unfavorable internal construction of the resistance 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 mV. 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 in °C	Measurement error in °C
0	0.05
100	0.05
200	0.05
500	0.06

Table 1: Measurement errors caused by thermoelectric emf

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

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

Inadequate insulation resistances produce 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 sensor. The manufacturer checks the insulation resistance as per 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.

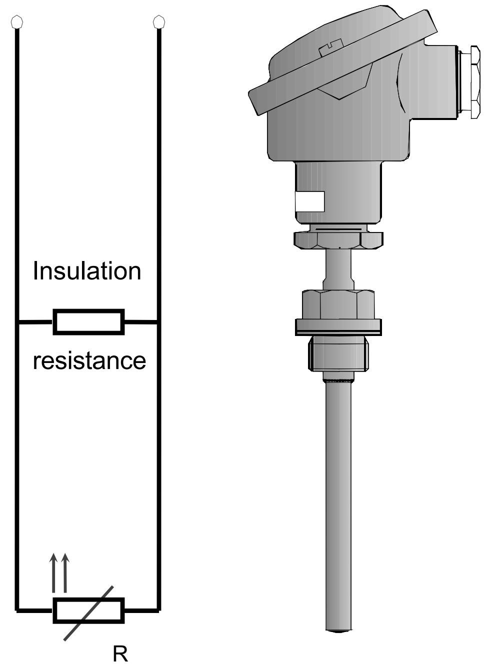

Fig. 7: Equivalent circuit for the insulation resistance inside a resistance thermometer

2.7 Sensitivity of the sensor (C_S)

The output signal of the temperature sensor is the resistance (platinum sensor) or the thermoelectric emf (thermocouple). A change in the output signal leads to a change in the temperature indication corresponding to the characteristic (gradient). This gradient is given by:

$\partial t/\partial E$ (thermocouple) $\cong$ $\Delta t/\Delta E$ for small changes and
$\partial t/\partial R$ (resistance thermometer) $\cong$ $\Delta t/\Delta R$ for small changes

("A temperature change X leads to a thermoelectric emf or resistance change of Y")

As an approximation, the sensitivities of the standard DIN characteristics are used.

Examples:
For a Type K thermocouple and a measured temperature of 400 °C, the thermoelectric emfs are:
E (400 °C) = 16397 µV E (401 °C) = 16439 µV
→ Δt = 1 °C and ΔE = 42 µV → C_S = 0.024 °C/µV

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
→ Δt = 1 °C and ΔR = 0.3792 Ω → C_S = 2.637 °C/Ω

C_S is used, as ultimately the temperature is the output signal that is of interest.

2.8 Deviation of the reference junction temperature (σt_{0S})

As already explained, the reference junction is generally located in the evaluation electronics. Temperature differences between the reference junction and the measured temperature can occur due to the electronics heating up.

2.9 Compensating cables (σV_{LX})

Two error classes are defined for the tolerances of compensating cables. Here, Class 1 applies only for compensating cables that are made from the same materials as the thermocouple. However, substitute materials that have the same thermoelectric properties as the thermocouple are normally used for the compensating cables, on grounds of cost. Class 2 cables are normally supplied as standard.

Most Class 2 compensating cables have a tolerance of ±2.5 °C. The upper operating temperature of the compensating cables is limited to 200 °C (terminal temperature of the thermocouple wires).

2.10 Lead resistance of resistance thermometers (σR_{AL})

The effect of lead resistance depends on how the resistance thermometer is connected.

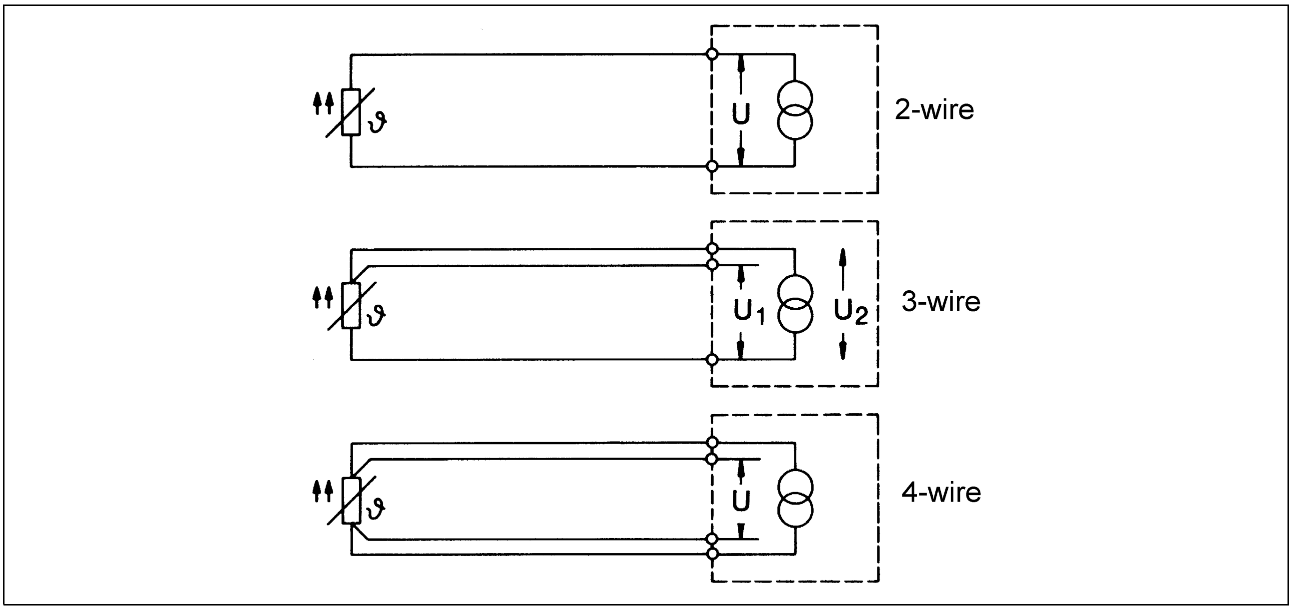

Fig. 8: Various resistance thermometer connections

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 systematically higher indication.

The sum of the resistances of the internal wiring and the connecting cable are 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 in contact with any sources of heat, as this gives rise to an increase in lead resistance. Regular check measurements show that the fluctuation in lead resistance is approx. 5% of the loop resistance (each meter of the connecting cable must be regarded as part of the loop). As an example, the figure quoted in the data sheet for the loop resistance of the connecting cable with a cross-section of 0.22 mm^2 is 162 mΩ (per meter), so, using the 5% figure, the variation in lead resistance is estimated to be 8 mΩ/m.

3-wire circuit

To minimize the effects of the lead resistance 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 lesser degree - as those described for the 2-wire circuit.

2.11 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.

2.12 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.

2.13 Processing and linearization error (σt_W)

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

Some indicating instruments 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.

2.14 Input resistance of the evaluation electronics (σB)

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.

In most cases, the effect of the burden is quoted as a percentage error in the output signal.

2.15 Other sources of error

The following errors can have very complex causes and have not been listed in the above model equation. A detailed description is outside the scope of this publication, so the reader is advised to refer to specialist literature at this point (see Chapter 5). A short listing with brief comments is provided below, to indicate possible problems.

2.15.1 Installation site of the evaluation electronics

The installation site must be as free from vibration as possible. Installation in the vicinity of electromagnetic fields (motors, transformers, etc.) must be avoided. In general, the instructions given in the operating manual must be followed during installation.

2.15.2 Galvanic currents with thermocouples

Moisture in a thermocouple can produce a local galvanic cell between the two thermocouple legs. The interfering voltage is a DC voltage and is added to or subtracted from the thermoelectric emf. The interfering voltage can lead to errors of up to 20%, particularly with low-sensitivity thermocouples.

The user must be aware that, when used in damp locations, the compensating cable intended for this application must be used.

2.15.3 Leakage currents with thermocouples

- Inductive coupling between the connecting cables and power cables running parallel to them can be avoided by using twisted conductors, screening, and single-end grounding.
- With fast-response thermocouples, the thermocouple wire is often welded to the protection tube, which can lead to coupling of voltages via the protection tube. This can be prevented by the electrical isolation between the instrument and the supply (most instruments incorporate this feature).
- A conductor loop can arise between several thermocouple inputs (e.g. PLC). This can be counteracted by electrical isolation of the measurement inputs.
- The insulation resistance of ceramic materials reduces drastically at operating temperatures above 1000°C, causing leakage currents to occur despite the insulated construction of the thermocouples. This effect can be prevented or severely limited by electrical isolation between the measurement inputs and the supply and other inputs, together with equipotential bonding between the thermocouples.

2.15.4 Mechanical stress of thermocouples

Mechanical deformation can lead to local inhomogeneity in the thermocouple wire, to large temperature gradients along the deformation and therefore to an incorrect thermoelectric emf. The homogeneity of the thermocouple wires can be improved by stress-relieving or recrystallization heat treatment at a temperature of approx. 900°C.

2.15.5 Chemical stress of thermocouples

Chemical stress can lead to incorrect measurements due to a whole range of effects (see suitable specialist literature on this subject). In principle, the effect can be reduced by using suitable protection tubes.

2.15.6 Mechanical stress 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 sensors 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 contacted for advice.

2.15.7 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 temperature 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 sensors are subjected to temperature cycling between the lower and upper operating temperatures. The measured value at the ice point of water is always used for assessment of the stability.

3.1 Distribution functions

If a measurement is repeated several times under the same measurement conditions, the individual values are not identical. A random scattering of the measured values results, as shown in Fig. 9.

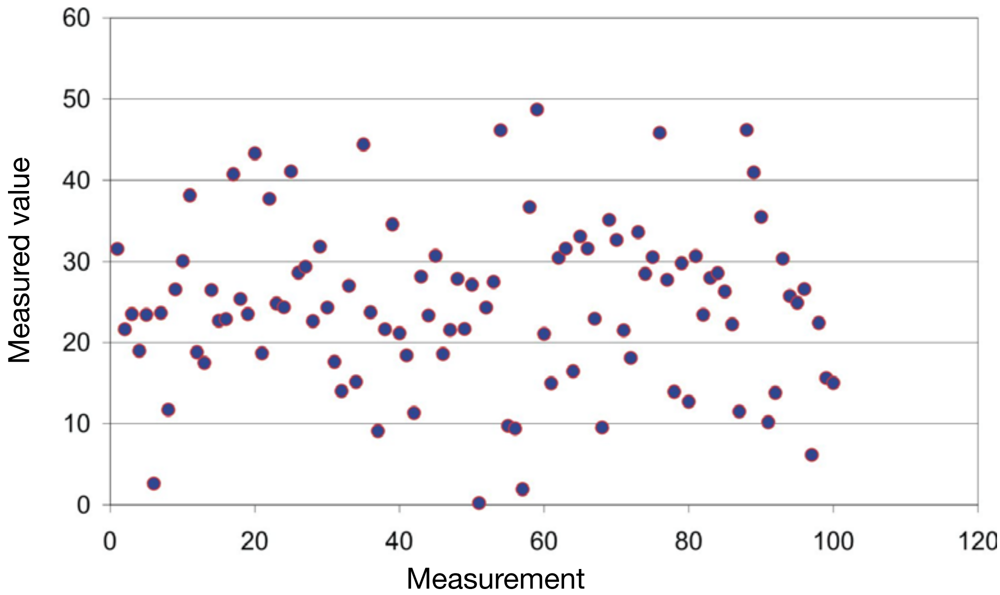

Fig. 9: Example of measured values with 100 repeat measurements

If the frequency of the measured value is plotted against the measured value, a distribution function is obtained (Fig. 10, arising from the measured values in Fig. 9) in which certain values occur more frequently than others. The distribution function reflects the probability of the same measurement result being obtained when a measurement is repeated. If the measured values are scattered purely at random, the distribution function corresponds to a Gaussian normal distribution. It must be pointed out here that, in theory, the normal distribution only applies for an infinite number of measured values. However, even with a small number of measured values (≥ 30) the pattern is already very close to the normal distribution.

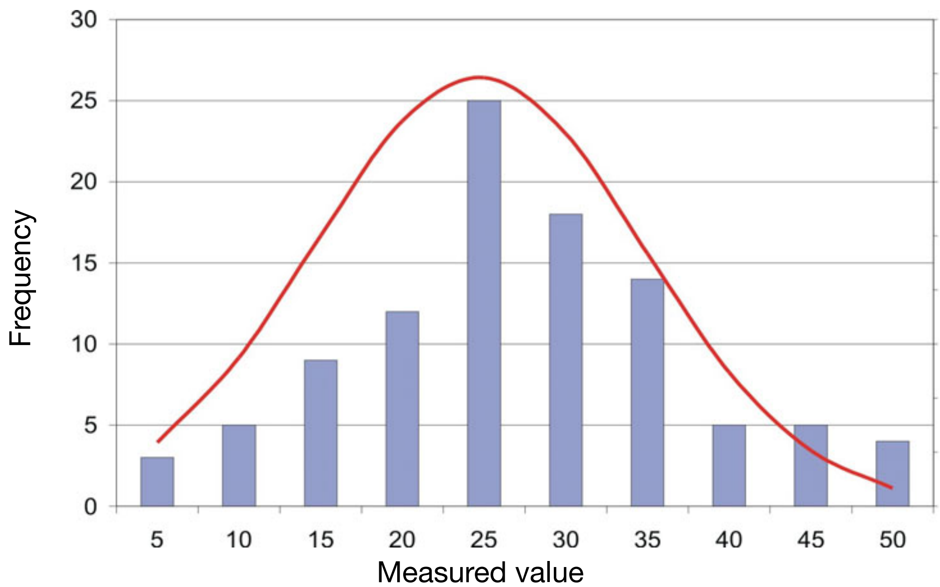

Fig. 10: Frequency of the individual measured values from Fig. 9

It is noticeable that a great many of the values lie around the arithmetic mean value. This value occurs with the greatest probability; the further the measured value lies from the mean value, the less is the probability of occurrence.

As well as the mean value, the distribution function is also characterized by another parameter, the standard deviation (simple measurement uncertainty). The mean value and the standard deviation together describe the interval within which 68.3 % of all measurements lie. To put this another way, this means that if a measurement is repeated, there is a 68.3 % probability that the measured value will lie within the interval.

However, a statement of the simple measurement uncertainty is too low for a reliable statement of measurement uncertainty. Thus, for the standard measurement uncertainty a confidence interval of 95 % is required, which corresponds to double the standard deviation.

If a measurement result is made up of a number of input quantities, which also have measurement uncertainties σi (i = 1…N), the individual measurement uncertainty components must be added geometrically as simple standard deviations (68.3 % confidence interval). The resultant standard measurement uncertainty σ is then multiplied by 2 to obtain the overall measurement uncertainty with a confidence interval of 95 %.

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots + \sigma_N^2} \qquad (3)$$

When measurement uncertainties are quoted on calibration certificates, they are generally based on a normal distribution, as the results of the calibration are not derived from a one-off measurement, but from several repeat calibrations. The measurement uncertainties are quoted with a 95 % confidence level, so that this figure must be divided by 2 to calculate the standard measurement uncertainty (68.3 % confidence level).

If only a tolerance interval of a quantity is known and no information on the distribution is available, a rectangular distribution must be assumed. Examples of this type of distribution are the statements made in data sheets. If the quantity is measured again, the only certainty is that the measured value will once more lie within the tolerance interval and there is also zero probability of measuring a value outside the interval. Within the interval (x_0 - a, x_0 + a) the probability of occurrence is constant for each value. So the probability of occurrence for the total interval is 100 %.

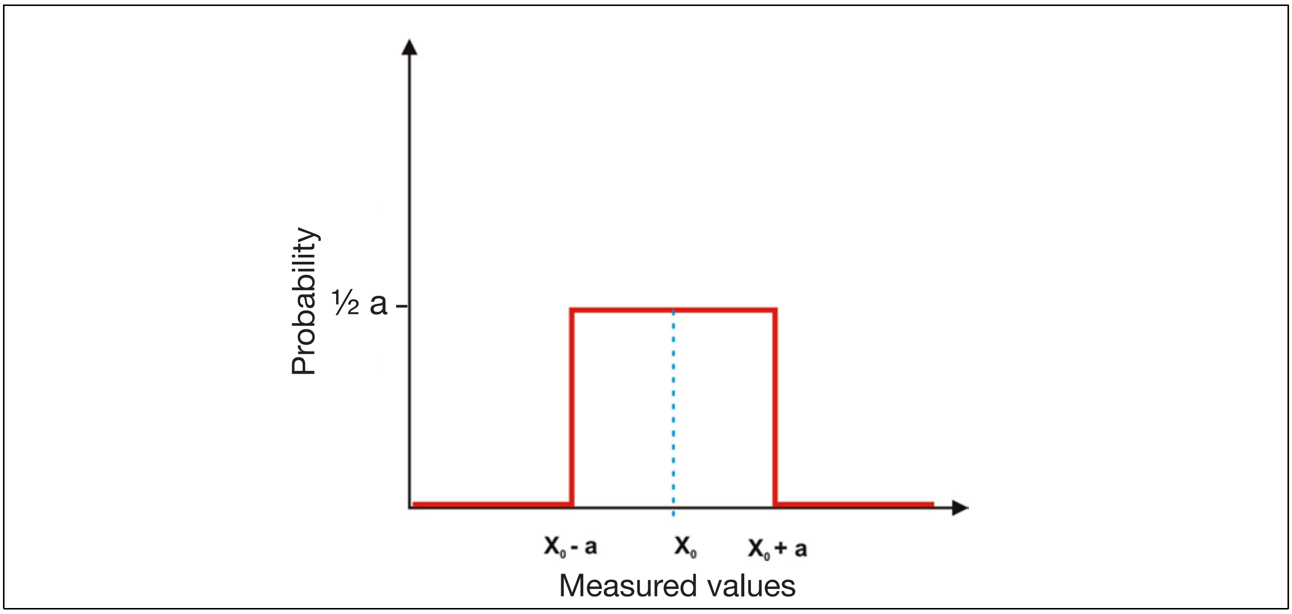

Fig. 11: Rectangular distribution

To calculate the standard uncertainty with the 68.3% probability of occurrence, the tolerance width must be divided by √3. With this, we now have a common basis for calculating the overall measurement uncertainty from the measurement uncertainty components with different distribution functions.

3.2 Transmitter with thermocouple

The overall measurement uncertainty of a programmable transmitter with a Type K thermocouple (tolerance class 2) at T = 400°C is to be determined. The transmitter has a 4 — 20 mA current output and a temperature range of 0°C to 500°C.

Information in the data sheet for the transmitter:

Processing and linearization accuracy with a Type K thermocouple:	0.25%
Reference junction accuracy:	±1°C
Effect of burden:	≤ ±0.02%/100Ω
Effect of temperature:	≤ ±0.005%/°C deviation from 22°C
Long-term stability:	≤ ±0.05%/year, but ≥ 0.1°C/year

(The % figures refer to the set span)

Model equation for calculation of the overall measurement uncertainty
Equation (1) can be simplified to:

$$I_X = t_m + \sigma M_D + \sigma M_A + C_S \cdot t_{05} + \sigma V_{LX} + \sigma V + \sigma t_M + \sigma t_W + \sigma_B + \sigma_{LZ} \quad (4)$$

It is assumed that the temperature at the measurement point is 400.50°C. The transmitter supplies an output signal of 16.816mA.

Deviation of the thermocouple as per EN 60 584 (σM_D)

The deviation limit for tolerance class 2 is 0.0075 × t; this gives a deviation limit of 3°C for a measured temperature of 400°C.

Measurement signal deviation caused by insufficient stabilization (σM_A)

It is assumed that the measured value has stabilized, so that this uncertainty component can be neglected.

Measurement signal deviation caused by deviation of the reference temperature (σt_{0S})

The data sheet for the transmitter quotes a figure of ±1°C for the reference junction accuracy.

Measurement deviation caused by the compensating cables (σV_{LX})

The full deviation limit of ±2.5°C must be assumed.

Deviation caused by supply variations (σV) (effect of supply)

According to the data sheet, a supply in the range of 20.4V to 25.4V can be connected to the transmitter. The uncertainty component is 0.01% per V deviation from 24V (referred to the max. output signal of 20mA). If we assume an actual supply voltage of 22V, this gives a percentage error of 0.02% and thus an uncertainty component of 0.004mA. This corresponds to 0.125°C at a given sensitivity of 0.032mA/°C. (The sensitivity is given by the output signal span of 16mA divided by the range span (500°C)).

Deviation caused by ambient temperature (σt_M) (effect of temperature)

According to the data sheet, the effect of ambient temperature is ±0.005% per °C deviation from 22°C. Let us assume that the ambient temperature is 30°C. This gives an uncertainty component in the output signal of: 8 °C × 0.00005/°C × 20 mA = 0.008 mA

This corresponds to 0.25 °C (from sensitivity of 0.032 mA/°C).

Linearization and processing error (σt_W)

According to the data sheet, the accuracy is 0.25 % of the full range span for the thermocouple, so this gives rise to an uncertainty component of 0.0025 × 1572 °C = 3.93 °C (possible range for a Type K thermocouple is from -200 °C to +1372 °C).

Effect of the burden of the evaluation electronics (σ_B)

Assumption: the evaluation electronics (indication) has an input resistance of 200 Ω. The effect of the burden is 0.02 %/100 Ω. This gives an uncertainty component of 0.0002/100 Ω × 200 Ω × 20 mA = 0.008 mA, which corresponds to 0.25 °C.

Long-term stability of the transmitter (σ_{LZ})

A figure of 0.05 %/year of the measurement span is quoted. The measurement span is 500 °C, so the uncertainty component is 0.25 °C/year.

Quantity X_i	Source	Distribution	Uncertainty contribution (estimated value)
σM_D	Deviation as per DIN	Rectangular	3.0 °C/√3 = 1.73 °C
σt_{0S}	Reference junction temperature	Rectangular	1.0 °C/√3 = 0.58 °C
σV_{LX}	Compensating cables	Rectangular	2.5 °C/√3 = 1.44 °C
σV	Supply	Rectangular	0.125 °C/√3 = 0.072 °C
σt_M	Ambient temperature	Rectangular	0.25 °C/√3 = 0.144 °C
σt_W	Linearization and processing	Normal	3.93 °C/2 = 1.965 °C
σ_B	Effect of burden	Rectangular	0.25 °C/√3 = 0.144 °C
σ_{LZ}	Long-term stability	Rectangular	0.25 °C/√3 = 0.144 °C
I_X		400.50 °C	3.05 °C

Table 2: Overall measurement uncertainty for K = 1

Geometric addition $0 = \sqrt{(1.73\ °C)^2 + (0.58\ °C)^2 + (1.44\ °C)^2 ...}$ gives us a measurement uncertainty of 3.06 °C (0.098 mA); for K = 2 the measurement uncertainty is 3.06 °C × 2 = 6.12 °C (0.196 mA).

3.3 Transmitter with resistance thermometer

The overall measurement uncertainty of a 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 — 20 mA current output and a temperature range of 0 °C to 200 °C. The resistance thermometer is a cable probe (outside diameter 6 mm), 2-wire circuit, with an insertion length of 30 mm and a 3 m long connecting cable.

Model equation for calculation of the overall measurement uncertainty

Equation (1) can be simplified to:

$$I_X = t_m + \sigma M_F + \sigma M_D + \sigma M_A + \sigma M_E + \sigma M_{Th} + \sigma M_{RI} + \sigma R_{AL} + \sigma V + \sigma t_M + \sigma t_W + \sigma_B + \sigma_{LZ} \qquad (5)$$

It is assumed that the temperature at the measurement point is 100.50 °C. The transmitter supplies an output signal of 12.040 mA.

The same assumptions are made for σM_A, σV, σt_M, σB, σ_{LZ} as in the example above:

- In this example it is also assumed that the sensor is at the same temperature as the medium, so that the error caused by σM_A is 0
- It is also assumed here that the supply to the transmitter is 22V, which gives a deviation of 2V from the nominal 24V supply. As before, the uncertainty component is therefore 0.004mA. With the available sensitivity of 0.08mA/°C (16mA/200°C), this corresponds to an uncertainty in the temperature signal of 0.05°C
- The ambient temperature deviates by 8°C from 22°C in our example. The temperature effect of the transmitter is 0.005%/°C. This gives a measurement uncertainty of 0.008mA in the output signal here. Taking into account the sensitivity of 0.08mA/°C, the magnitude of the measurement uncertainty caused by σt_M is 0.1°C.
- As before, the input resistance of the connected indication is 200Ω. The effect of burden is 0.02%/100Ω. This gives a measurement uncertainty in the output signal of 0.008mA in this example too. Taking into account the sensitivity of 0.08mA/°C, the magnitude of the measurement uncertainty caused by σ_B is 0.1°C.
- The long-term stability is 0.05%/year. With a span of 200°C this gives a measurement uncertainty component of 0.1°C/year.

Heat conduction error of the probe (σM_F)

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

Deviation of the resistance thermometer as per EN 60 751 (σM_D)

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

Self-heating error (σM_E)

The transmitter operates with a measuring current of 0.6mA. This gives rise to a power loss of approx. 0.05mW. The self-heating error is thus negligible.

Thermoelectric emf (σM_{Th})

With a possible thermoelectric emf of 20mV (limitation in accordance with EN 60 751, see Chapter 2.5) and a measuring current of 0.6mA, a possible error of 33mΩ (20 µV / 0.06mA) can arise at the measured temperature of 100°C (R approx. 138Ω). This corresponds to a temperature of 0.086°C.

Insulation resistance (σM_{RI})

This component can be neglected with the Pt 100, when the manufacturer guarantees an insulation resistance of ≥100MΩ (DIN).

Variations in lead resistance (σR_{AL})

Based on the cable length of 3m and the usual cross-section 2 × 0.22mm^2, variations in lead resistance of 8mΩ/m should be assumed here (see Chapter 2.10). Furthermore, care must be taken to ensure that the connecting cable is not heated up unnecessarily. With a 3m long connecting cable, this gives an uncertainty component of 24mΩ, so this gives a temperature uncertainty component of 0.063°C (0.024Ω * 2.637°C/Ω, see Chapter 2.7).

Linearization and processing error (σt_W)

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

Quantity X_i	Source	Distribution	Uncertainty contribution (estimated value)
σM_F	Heat conduction error	Normal	0.06 °C/2 = 0.03 °C
σM_D	Deviation as per DIN	Rectangular	0.8 °C/√3 = 0.46 °C
σM_{Th}	Thermoelectric emf	Rectangular	0.086 °C/√3 = 0.05 °C
σR_{AL}	Variations in lead resistance	Rectangular	0.063 °C/√3 = 0.036 °C
σV	Supply	Rectangular	0.05 °C/√3 = 0.029 °C
σt_M	Ambient temperature	Rectangular	0.1 °C/√3 = 0.058 °C
σt_W	Linearization and processing	Normal	0.4 °C/2 = 0.2 °C
σ_B	Effect of burden	Rectangular	0.1 °C/√3 = 0.057 °C
σ_{LZ}	Long-term stability	Rectangular	0.1 °C/√3 = 0.057 °C
I_X	100.50 °C		0.52 °C

Table 3: Overall measurement uncertainty for K = 1

Geometric addition gives us a measurement uncertainty of 0.52 °C assigned to the measured temperature (this corresponds to 0.042 mA with a sensitivity of 0.08 mA/°C); for K = 2 the measurement uncertainty is 1.04 °C (0.083 mA).

3.4 Precision indicating instrument

The overall measurement uncertainty of a P650 direct-reading electronic thermometer (resolution 0.01 °C, range -200 °C to +200 °C; but restricted application in the range 0 to 200°C) with a 90.286-F30 precision resistance thermometer (insertion length 300 mm), 4-wire circuit, at T = 200 °C is to be determined. The indicating instrument and resistance thermometer are connected together via a 1.5 m long, 4-core connecting cable. The instrument operates with a measuring current of 1 mA, and is adjusted to the resistance thermometer as follows:

1. Thermometer brought to the lower operating temperature
2. Entry of the associated actual temperature (determined with a reference thermometer)
3. Thermometer brought to the upper operating temperature.
4. Entry of the associated actual temperature (determined with a reference thermometer)

This temperature measurement system is an example of a relatively small overall measurement uncertainty and is available from JUMO together with an associated calibration certificate. Of course, the smaller measurement uncertainty does involve increased expenditure and costs. Before the measured values of the calibration are determined, the indicating instrument is adjusted to the resistance thermometer in the way described above.

Model equation for calculating the overall measurement uncertainty
Here we obtain a slightly modified model equation:

$$I_X = t_m + \sigma M_F + \sigma M_D + \sigma M_{AG} + \sigma M_E + \sigma M_{Th} + \sigma M_{RI} + \sigma R_{AL} + \sigma V + \sigma t_M + \sigma t_W + \sigma M_{LZV} \quad (6)$$

It is assumed that the temperature at the measurement point is 199.50 °C.

Heat conduction error of the probe (σM_F)
If the temperature probe is used with a minimum insertion length of 100 mm, no heat conduction

error occurs in the permissible temperature range of the probe (-50 °C to +250 °C).

Deviation of the resistance thermometer as per EN 60 751 (σM_D)

This component is omitted, as the instrument is individually adjusted to the connected resistance thermometer (see above for uncertainty component).

Adjustment of the measuring instrument (σM_{AG})

This component is made up of the uncertainty of the temperature representation (σM_{AG1}) and the accuracy (resolution) of the actual temperature entered (σM_{AG2}).

σM_{AG1}: in our calibration laboratory for temperature, the uncertainty of the temperature representation at 200 °C is 0.015 °C (direct traceability to national standards, precision instruments). If the adjustment is made with other test devices, the measurement uncertainty of the temperature representation normally increases. For example, in the Final Test department of our production it is 0.040 °C.

σM_{AG2}: the actual temperature can only be entered in 1/100 °C steps, so that an error of 0.005 °C can arise.

Self-heating error (σM_E)

The transmitter operates with a measuring current of 1 mA. This results in a power loss of approx. 0.2 mW (R approx. 212 Ω). The self-heating error is thus negligible.

Thermoelectric emf (σM_{Th})

During manufacture, precision resistance thermometers are checked for compliance with the maximum permissible thermoelectric emf of 3 mV. This gives rise to a possible error of 3 mΩ, since the measuring current of this indicating instrument is 1 mA.

Taking into account the above sensitivity, the result is an uncertainty component of 3 mΩ × 2.717 °C/Ω = 0.00815 °C.

Insulation resistance (σM_{RI})

Where the manufacturer guarantees an insulation resistance ≥100 MΩ (DIN), this component is 0.3 mΩ.

(The resistance at 199.5 °C is 175.672 Ω. So, in the worst case (insulation resistance = 100 MΩ), it should be assumed that these two resistances are in parallel.

For the Pt 100, the resistance values either side of a measured temperature of 199.5°C are:

R (199 °C) = 175.488 Ω R (200 °C) = 175.856 Ω
→ Δt = 1 °C and ΔR = 0.368 Ω → sensitivity of the sensor C_S = 2.717 °C /Ω

So the component of the insulation resistance causes an uncertainty in the temperature of 0.3 mΩ × 2.717 °C/Ω = 0.0008 °C.

Variations in lead resistance (σR_{AL})

This component is omitted as the resistance thermometer uses a 4-wire circuit.

Supply (σV)

The instrument is supplied from a stabilized power supply unit. Unacceptable voltage fluctuations are indicated as error messages, so this component is omitted.

Ambient temperature (σt_M)

For this, extensive measurements were carried out in a climatic cabinet. With an ambient temperature between 10 °C and 30 °C the uncertainty component is 0.010 °C.

Linearization and processing error (σt_W)

According to the data sheet, the accuracy of the instrument is 0.03 °C.

Long-term behavior of the precision resistance thermometer (σM_{LZV})

For this, extensive repeat measurements were carried out after temperature cycling. In addition, numerous results of recalibrations are available. When correctly handled (precision resistance thermometers are sensitive to shock and vibration), the uncertainty will not exceed 0.03 °C with annual checks. If the instrument is recalibrated and suitably readjusted every six months, a figure of 0.02 °C can be assumed for this uncertainty component.

Quantity Xi	Source	Distribution	Uncertainty contribution (estimated value)
σM_{AG1}	Temperature representation	Normal	0.015 °C /2 = 0.0075 °C
σM_{AG2}	Actual temperature input	Rectangular	0.005 °C /√3 = 0.00289 °C
σM_{Th}	Thermoelectric emf	Rectangular	0.00815 °C /√3 = 0.00471 °C
σM_{RI}	Insulation resistance	Rectangular	0.0008 °C /√3= 0.00046 °C
σt_M	Ambient temperature	Rectangular	0.01°C /√3 = 0.00578 °C
σt_W	Linearization and processing	Normal	0.03°C /2 = 0.015 °C
σM_{LZV}	Long-term behavior of resistance thermometer	Normal	0.03°C /2 = 0.015 °C
I_X	199.50 °C		0.02389 °C

Table 4: Overall measurement uncertainty of a P650 indicator with a precision resistance thermometer

This gives us a measurement uncertainty of approx. 0.024 °C assigned to the measured temperature; for K = 2 the figure is 0.048 °C.

It should be noted that, in the last example, unlike the worked examples with transmitters, a component is included for the long-term drift of the temperature probe.

4 German Calibration Service (DKD)

The opening up of the European market through new quality standards such as ISO 9000 and later standards, together with 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.

If an organization is certified to ISO 9001, all test equipment used in the production process must have proven traceability back to the nationally recognized standards for the respective measured quantity.

A high demand for calibrated instruments has developed. It is neither worthwhile (costs) nor possible on grounds of capacity, to cover all calibration requirements by a direct link to the national standards of the PTB. Because of this, the PTB, on request, appoints and monitors calibration laboratories in industry. These laboratories are affiliated with the German Calibration Service (DKD). The regular checks of the DKD calibration laboratories are undertaken by the DKD office and the PTB specialist laboratories. For example, as well as the annual audits, national and international circular comparisons are also carried out.

Because the traceability to the reference standards is the central issue for accreditation of DKD laboratories, DKD calibration certificates must be accepted as documentation of traceability. Otherwise the proof must be furnished by linking to the national standards.

DKD calibration certificates are accepted in most European countries and in many non-European countries. DKD calibration certificates represent a legal and unequivocal proof of fulfillment of the duty of care and compliance with assured properties on delivery.

For the reasons described, DKD-calibrated thermometers and temperature measurement systems should be used as factory/workshop reference standards. As well as the test devices used, the measurement uncertainty of all test equipment depends primarily on the stability and accuracy of these reference standards. For this reason, JUMO has developed resistance thermometers which feature high precision and good long-term stability, yet have a reasonable price. The precision resistance thermometers are available in various versions with calibration certificates for the desired temperature range.

Of course, there is always a close relationship between costs and the required measurement uncertainty. The complete calibrated measurement system (see above for description and calculation of measurement uncertainty) is thus a viable alternative, as no additional instrument is needed to measure thermoelectric emf or resistance.

JUMO issues calibration certificates in the temperature range -80°C to +1100°C. Platinum resistance thermometers, data loggers, thermocouples, transmitters and direct-reading electronic thermometers can be calibrated.

5 Recommended literature

/1/ "Electrical Temperature Measurement
with thermocouples and resistance thermometers",
Dipl.-Phys. Matthias Nau,
JUMO GmbH & Co. KG, Fulda, Germany,
ISBN: 3-935742-07-X

/2/ "Messunsicherheiten - Theorie und Praxis",
Franz Adunka,
Vulkan-Verlag 1998,
ISBN: 3-8027-2186-1

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JUMO GmbH & Co. KG · 36039 Fulda, Germany · Phone +49 661 6003-480
Fax +49 661 6003-123 · E-Mail: gerd.scheller@jumo.net · Internet: www.jumo.net

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