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Guideline DKD-R 5-1

Calibration of resistance thermometers

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Deutscher Kalibrierdienst (DKD) – German Calibration Service

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.
This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.
The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guidelines are application documents that meet the requirements of DIN EN ISO/IEC 17025. The guidelines contain a description of technical, process-related and organizational procedures used by accredited calibration laboratories as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. The implementation of the guidelines promotes equal treatment of the equipment to be calibrated in the various calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories. In addition, the implementation of the guidelines allows the state of the art in the respective field to be incorporated into laboratory practice.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted in agreement with the accreditation body if there are technical reasons to support this action.

Calibrations by accredited laboratories provide the user with the security of reliable measuring results, increase the confidence of customers, enhance competitiveness in the national and international markets, and serve as metrological basis for the monitoring of measuring and test equipment within the framework of quality assurance measures.

The guideline DKD-R 5-1 was created by the Technical Committee *Temperature and Humidity* in cooperation with PTB and the accredited calibration laboratories. The first edition was published in 1992 and has been revised several times since then. Edition 11/2023 replaces all previous editions.

The previous edition 09/2018 of DKD-R 5-1 may still be used up until 30 November 2026.

The present guideline has been drawn up by the DKD Technical Committee *Temperature and Humidity* and approved by the Board of the DKD.

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1 Purpose and scope of application

This guideline has been prepared to define the technical requirements necessary for the calibration of resistance thermometers in accredited calibration laboratories. In many cases, the hysteresis effect has turned out to be the largest contribution to the measurement uncertainty, so it will be discussed in more detail. There are also references to further literature and documents of a higher level.

This guideline specifically covers the calibration of

- standard platinum resistance thermometers (SPRT); temperature range: -189.3442 °C to 961.78 °C) [1], [2]
- industrial platinum resistance thermometers according to DIN EN 60751 in the temperature range from -200 °C to 850 °C [3]
- resistance thermometers made of other metallic conductors (e.g., Cu, Ni) [4]
- semiconductor resistance thermometers (thermistors: NTC, PTC) [5], [6]

Furthermore, the guideline analogously applies to:

- direct-reading electronic thermometers with resistance sensor,
- electronic thermometers with resistance sensor and digital interface,
- data loggers with a resistance sensor,
- resistance thermometers with a transmitter and an analogue output signal

For fixed-point calibrations of standard platinum resistance thermometers (SPRT) which meet the requirements for interpolation instruments of the International Temperature Scale of 1990 (ITS-90), higher-level guidelines apply [1], [2]. These are developed and updated by the Consultative Committee for Thermometry (CCT). It is also possible to calibrate standard platinum resistance thermometers using the comparison method described here. However, the user should bear in mind that calibration at the defining fixed points of the ITS-90 means that only significantly lower measurement uncertainties can be achieved.

The results of a calibration are only valid within the calibration range between the maximum and minimum calibration temperature. The only permissible exception is within the temperature range of approximately 77.3 K to 83.8058 K. If an ITS-90-compliant standard thermometer has been calibrated in the range between the water triple point (273.16 K) and the argon triple point (83.8058 K), the calibration function may be extrapolated to approx. 77.3 K (boiling point of nitrogen). The measurement uncertainty for the extrapolated range must be increased accordingly, see [7].

2 Introduction

The operating principle of contact thermometers consists of bringing a sensor to the temperature of the measured object by thermal contact and then determining the temperature of the sensor by measuring another quantity (expansion, electrical resistance, etc.) that shows a continuous and monotonic dependence on temperature.

In practice, the largest deviation (measurement error) in a temperature measurement often arises from the fact that the sensor temperature does not correspond to the temperature of the measured object. A contact thermometer "only" measures its own temperature. Calibration of a contact thermometer means the metrological determination of the correlation between the temperature of the sensor and the output quantity of the thermometer. In practice, the user of the thermometer must ensure that the temperature of the sensor corresponds to the temperature to be measured. Uncertainties due to lack of thermal coupling on the part of the user are not included in the measurement uncertainty of the thermometer calibration. However, the calibration certificate must contain all relevant information a user needs to be able to completely re-perform the calibration with comparable equipment and to achieve comparable measurement uncertainties.

3 Resistance thermometers

The operating principle of resistance thermometers relies on the fact that the electrical resistance of metal conductors and semiconductors is temperature-dependent ($R(t)$). Thus, the temperature measurement is traced back to the measurement of an electrical resistance ($t(R)$). In practice (and without considering the low-temperature range below -200 °C) the following materials are mainly used as resistance sensors.

3.1 Metal resistance thermometers

Physically, metals are characterized by the existence of freely movable electrons as carriers of the electrical current. The movement of the electrons is hampered by collisions with and scattering from the so-called phonons, the quanta of heat vibration. As the number of phonons rises with increasing temperature, the specific resistance of metals also increases with temperature.

Today, platinum is almost the only metal used as material for resistance thermometers. Below is a brief description of the different types.

3.1.1 Standard platinum resistance thermometers (SPRT)

The acronym SPRT for the English designation "standard platinum resistance thermometer" is also used in German language. The thermometers are made of high purity platinum wire, suitably fixed as to be free from mechanical stresses over the entire temperature range. In fact, this is why SPRTs provide the most accurate and reproducible temperature measurements over a wide temperature range. Hence, the SPRT is an essential part of the ITS-90 as interpolation instrument between the fixed points of the ITS-90 in the temperature range from 13.8033 K (259.3467 °C) to 1234.93 K (961.78 °C). Electrically, these thermometers are characterised by a particularly large temperature coefficient, as expressed in the ITS-90 requirement $R(29.7646\ ℃)\ /\ R(0.01\ ℃) > 1.118\,07$. In practice, however, they are employed only rarely since only certain designs can be realized, and these are not very stable when exposed to mechanical stress (e.g. vibrations and shocks).

3.1.2 Industrial platinum resistance thermometers (IPRT)

The acronym IPRT for the English designation "industrial platinum resistance thermometer" is also used in German-speaking countries. As sensor material, these thermometers use

platinum which to a minor degree contains other alloying constituents in a composition ensuring that the characteristic given in the standard DIN EN 60751 [3] is complied with. The temperature coefficient of IPRTs is smaller than that of SPRTs. IPRTs with sensor types of different designs are most widely used. Wire-wound sensors have proven to be particularly stable, but thin-film sensors are nevertheless most widely used worldwide. Thermometers with a resistance of 100 Ω at 0 °C – also referred to as Pt100 thermometers for short – are the most common types. The application range of IPRTs usually lies between -200 °C and 600 °C. The use of suitable protection tubes/materials and high-purity insulation materials aims to prevent contamination of the platinum sensor element which can occur particularly at high temperatures.
Compared to SPRTs, IPRTs are much less sensitive to vibrations or shocks. This is achieved by mechanical fixation of the platinum resistor but leads to a hysteresis with alternating thermal stress. The hysteresis strongly depends on the mechanical construction of the platinum sensor element, the configuration of the thermometer and the temperature range. Therefore, the influence of the hysteresis must be investigated or estimated when calibrating IPRTs. How this has to be done is described in detail in chapter 8.10.

3.1.3 Other types of resistance thermometers

For certain applications, Ni or Cu resistors [4] are used; however, they can only be employed in a limited temperature range.

3.2 Semiconductor resistance thermometers

Semiconductors are physically characterized by the limited availability of free electrons (and holes) as charge carriers, which arise as thermal excitation causes individual electrons to be transferred from the completely filled valence band to the empty conduction band. As the number of electron-hole pairs increases with increasing temperature, the electrical resistance decreases accordingly. This is why sensors made of semiconductors are called sensors with negative temperature coefficient (NTC). Profiting from certain parameters it is also possible to manufacture sensors with a positive temperature coefficient (PTC). In practice, NTC sensors are fabricated from a complex mixture of metal oxides; the designation “thermistors” is also used [5]. With 3 % K^{-1} to 5 % K^{-1}, the temperature coefficient is substantially higher than for metals. Therefore, the requirements for the measuring electronics used are lower than for platinum resistance thermometers. Disadvantages are the strong non-linearity of the characteristic as well as the considerably smaller operating temperature range [5], [6].

4 Fundamentals of the calibration of resistance thermometers

Prior to calibration, the thermometer is brought to a known temperature in a suitable temperature control device, and the value of the output signal (e.g. the electrical resistance) is measured. According to the kind of thermostating, a distinction is made between fixed-point method and comparison method: In the fixed-point method, the temperature of the respective fixed point is realized, whereas in the case of the comparison method the calibration item and a standard thermometer are brought as exactly as possible to the same temperature using a thermostat, and the indications are then compared with each other. Fixed point cell and/or standard thermometer must have been traceably calibrated. The temperature control used in comparison methods must be characterised with regard to its thermal properties.
To measure the resistance of the calibration item and/or the standard thermometer, suitable electrical measuring equipment must be used (resistance meter, multimeter, resistance measuring bridge, standard resistors). These electrical devices must have been traceably calibrated. In many cases, the requirements for the ambient conditions – especially the ambient temperature – are given in the specifications of the electrical devices. Here, the temperature dependence of the standard resistor – which for measurements with small measurement uncertainties must be kept at a constant temperature in a separate thermostat – is particularly critical. If the ambient conditions (in this case the ambient temperature) influence the validity of the calibration results, these must be traceably monitored and recorded in a suitable form [8].

5 Transport and initial inspection

Resistance thermometers are manufactured in various designs to suit the respective applications or installation situations. Sensors, internal structure, and the outer protection tube of the thermometers can differ greatly. Depending on the construction of the sensing element, shocks and vibrations may lead to partly irreversible changes of the electrical resistance and must therefore be avoided. Even a metal protection tube does not provide complete protection against shocks or other mechanical loads. Undesirable resistance changes, however, are rather easy to detect by measuring the resistance at the ice point or water triple point. Special precautions must therefore be taken when transporting resistance thermometers. Good packing, for example in suitable foam-padded packets is indispensable. Despite special packaging labels, it cannot always be taken for granted that commercial transport companies handle the packages with the necessary care. For particularly high-quality calibration items, such as reference standards to disseminate the temperature scale with the lowest measurement uncertainties, transport by expert personnel is essential.

The type and scope of the initial inspection depends not only on the proposed use of the thermometers but also on their design and the desired measurement uncertainty of the calibration. First, the calibration items are checked for completeness and integrity. If transport damage or other mechanical or electrical defects are detected, the customer must be informed. The customer is also to be informed if the scope of calibration has not been stated clearly and completely.
For thermometers with connected measuring transducers or thermometers with electrical evaluation units, the operating instructions and, if necessary, further technical documentation must also be available to the calibration laboratory.
The calibration item must be clearly marked to ensure clear-cut identification. This also covers details such as serial number, type designation and manufacturer. If necessary, it must also be indicated which thermometer is to be connected to which channel of the measuring electronics.
If possible (by design), the insulation resistance at room temperature must be determined before starting the calibration (see chapter 8.9). It must be ensured that neither the sensor nor the connected electronics are damaged by the test voltage.

The number of calibration points, the temperature range to be calibrated and other parameters shall be agreed between customer and calibration laboratory. Calibrations must be carried out using at least two temperatures. In case a characteristic curve is to be determined, please refer to the guideline "Determination of thermometer characteristics" (DKD-R 5-6 [9]).

6 Stability test

Shocks or vibrations during the transport of resistance thermometers may cause mechanical stresses within the platinum sensor, leading to a change in resistance. So before and after transport, the thermometer resistance is measured at a given temperature (usually at the ice point or at the water triple point).
In case significant changes (30 % of the desired uncertainty) of the thermometer resistance are detected during this stability test, the thermometer should be subjected to a heat treatment. This can be done as follows:
After measuring the resistance value at reference temperature (ice or water triple point), the temperature sensor is heated about 10 Kelvin above the maximum calibration temperature over a period of approx. 8 to 12 hours; in doing so, it must be observed that the maximum operating temperature specified by the manufacturer is not exceeded. Afterwards, the resistance of the thermometer is measured again at reference temperature. If the deviation between the two measurements at reference temperature exceeds 30 % of the desired uncertainty, the heat treatment is to be repeated. If the result of the repeat measurement deviates again by more than 30 % from the previous measurement, the calibration item is usually to be classified as not calibratable within the scope of the desired measurement uncertainty. In certain cases, it may be useful to perform several heat treatments on the thermometer.
If recalibration shows that the resistance value of the thermometer at reference temperature has not changed by more than 30 % of the desired uncertainty since the last calibration, the heat treatment may be omitted. For new thermometers, the manufacturer's specification (initial value) can be used to assess stability, provided it has been determined by an NMI or an accredited calibration laboratory with a sufficiently small measurement uncertainty.
The input value of the thermometer resistance (usually at the ice point or at the water triple point) before heat treatment or calibration must be stated separately in the calibration certificate. If the maximum calibration temperature is 150 °C and the measurement uncertainty is greater than 0.10 K, a stability test is not required.

7 Temperature control device

Resistance thermometers are calibrated either by the comparison method or at defined fixed points of the applicable temperature scale. Combination of both procedures is permissible. In the comparison method, the resistance thermometers to be calibrated are compared with reference or working standards (thermometers) in thermally stable and homogeneous temperature control devices. It must be ensured that all thermometers are within the so-called useful volume. The useful volume is an area with a homogeneous and constant temperature within the temperature control device. Within the scope of the validation of a calibration set-up, the temperature stability and homogeneity within this specified useful volume must be determined experimentally. The use of manufacturer specifications is only admissible in exceptional cases (in this case, corresponding additions are to be made in the calculation of the measurement uncertainty). The position and geometric dimensions of the useful volume are to be specified in the working instructions. In addition, the temperature stability and homogeneity within the useable volume must be determined (characterisation) for each combination of temperature control device and fluid used and taken into account in the uncertainty budget. This must be done for the most unfavourable cases, for instance at the highest temperature difference to the ambient temperature and at the highest viscosity of the fluid (in an oil bath, for example, these would be the highest and lowest operating temperatures). Should a counter cooler be activated for certain temperature ranges, temperature stability and/or homogeneity may increase. Characterisation is also required in these cases. In the event of changes to the temperature control device (for example, changes to the internal structure, change of components), the characterisation is to be repeated.
Furthermore, the loading influence must be quantified (see also DKD-R 5-4 [10]) and adequately taken into account in the measurement uncertainty budget.
To determine the time-related stability and homogeneity, thermometers of identical type are positioned on the boundaries of the useful volume (horizontally, vertically) of the temperature control device. The tests do not necessarily require the thermometers to be calibrated. Adequate accuracy in the measurement of temperature differences can also be ensured by other means. After thermal stabilisation, the temperatures measured with the thermometers are continuously recorded over an appropriate period (> 20 minutes). The maximum resulting temperature difference between the measuring positions and the amplitude of the time-related temperature variation are to be considered in the uncertainty budget.
Temperature gradients in temperature-stabilised baths or furnaces can be reduced by installing a metal equalising block with drilled holes to accommodate the standards and calibration items.
For temperature control devices with air as the working medium, the influence of radiation must also be determined and taken into account in the measurement uncertainty. This can be done by measuring the temperature using a thermometer with an emissivity as high as possible ($\varepsilon > 0.6$) and a thermometer with an emissivity as low as possible ($\varepsilon < 0.15$). The use of a thermometer with a gold-plated surface (low emissivity) and a thermometer with a Teflon or blackened surface (high emissivity) would be a recommended measurement set-up. The emissivity of both thermometer surfaces must be known with sufficient accuracy (in the infrared wavelength range). The thermometer with low emissivity approximately indicates the air temperature. The air temperature is obtained by extrapolation to the emissivity $\varepsilon = 0$. The difference between the two thermometers indicates the influence of radiation. For temperature control devices with air as the working fluid, the uncertainty component based on the temperature gradient can be reduced by specifying a smaller useful volume. Where appropriate, the instructions of DKD-R 5-7 [11] should also be observed for measurements in air.

The calibration of a thermometer takes place after both the temperature control device and the thermometer itself have reached thermal equilibrium. The influence of the remaining temperature fluctuations can be reduced if the standard and the calibration item are measured quasi-simultaneously or if mean values over the same observation period are used instead of instantaneous values of the readings. If due to technical reasons this should not be possible, a comparable effect can be achieved by precise determination of the drift behaviour (for example, when measuring the standard before and after measurement of the calibration item with linear drift behaviour). Since the time constants of the standard and the calibration item usually differ, the influence of the time-related stability of the temperature can only be partially reduced.

8 Influencing factors

The measurement uncertainty in the calibration of a thermometer is determined by different influencing factors. These are not only the measurement uncertainty in the realisation of the temperature but also influences emanating from the calibration item itself. They can in part amount to many times the measurement uncertainty in the temperature realisation. The measurement uncertainty must therefore necessarily take into account the contributions of the calibration method, the standards used and the calibration item. For the latter, a minimum value – which can be achieved with an actual calibration item – must be taken into account. In the following, these influencing factors will be described in detail.

8.1 Short-term behaviour during calibration

Instabilities of resistance thermometers can have very different causes. As described in chapter 6, changes in resistance can occur, for example, due to shocks during transport. In many cases, it is possible to stabilise the resistance value by suitable heat treatment, in other words, to reduce the time-related change in resistance. In this case, a distinction is made between the long-term behaviour (drift) and the short-term behaviour. When investigating the short-term behaviour, all changes that are detected during the duration of a calibration (a few hours up to a few days) are taken into account. Possible causes are, for example, reversible changes in the oxidation state of the sensor element (platinum). This contribution must be taken into account in the measurement uncertainty budget (calibration certificate).

8.2 Long-term behaviour due to thermal load (drift)

In addition to short-term instabilities, there are also long-term effects the magnitude of which depends, among other things, on thermal load during use. An evaluation of the resulting measurement uncertainty is the task of the thermometer user. The evaluation is carried out using the results of previous calibrations (calibration history). The statement of the measurement uncertainty in the calibration certificate does not include a contribution for the long-time stability of the thermometer.

8.3 Thermal coupling

Carrying out calibrations with insufficient thermal coupling or insufficient immersion depth of the thermometer may lead to considerable measuring errors.
For calibrations carried out with a temperature control device, the maximum possible immersion depth or optimum thermal coupling is aimed at for the thermometer to be calibrated. The required immersion depth depends on the desired measurement uncertainty, the design and thermal conductivity of the materials of the thermometer, the heat transfer coefficient between the thermometer and the surrounding fluid and other variables. Usually, the diameter of the thermometer is used as a reference to obtain an initial estimate of the required immersion depth.
To estimate the required immersion depth, it can generally be assumed that the immersion depth must be at least ten times the thermometer diameter when trying to achieve a relative

measurement error of less than 1 % of the difference between the calibration temperature and the ambient temperature [12]. Increasing the immersion depth again by ten times the thermometer diameter reduces the measurement error by a factor of 10. It is important to remember that the zero point for determining the immersion depth does not refer to the lower edge of the thermometer protection tube, but to the upper edge of the sensor element.
For calibrations with air as medium (in a temperature cabinet, for example), the complete calibration item, including connecting cable (at least 1 m, if available) should be installed in the calibration device and exposed to the calibration temperature to avoid heat dissipation.
Any further measures that may be necessary as well as the immersion depth during calibration are to be listed in the calibration certificate. This is to ensure that the calibration results are reproducible and, in the case of recalibration, comparable.
To check whether a sufficient immersion depth was selected during calibration, the maximum possible immersion depth is reduced by 10 %. The resulting change in the temperature indication due to heat dissipation must not exceed 10 % of the desired measurement uncertainty, otherwise the corresponding measurement uncertainty contribution must be increased.

8.4 Electrical measurement procedures

In the measurement of the electrical resistance, effects influencing the measurement result must be taken into account and included when determining the measurement uncertainty. The resistance measurement is carried out either with an alternating or a (usually varying) direct current. Some measuring instruments allow or operate exclusively in pulsed mode.
The measured thermometer resistance must be independent of the type of resistance measurement (alternating or direct current (AC/DC)) and the integration time. If AC/DC-related deviations are detected, this may be an indication of dielectric effects. One possible cause is the penetration of water (vapour) into the sensing element.
Kind and choice of the measuring instruments depend on the desired measurement uncertainty for the calibration.

8.5 Connection system

False measurements can also arise due to the resistance of the incoming leads. Distinction between the resistance of the incoming leads and the resistance of the sensor must be made. In electrical resistance measurements, a distinction is made between three methods of connection: two-wire, three-wire, and four-wire circuits.

8.5.1 Two-wire circuit

In the two-wire circuit, the connection between sensor element and measuring instrument is ensured by a two-wire cable. As is the case with all other electrical conductors, this cable also has a resistance which is connected in series with the sensor element. The two resistances thus add, leading to a systematically higher resistance value which is reflected in the calibration data. What is not taken into account, however, is the fact that during use the electrical resistance of the lead also changes due to external temperature influence. If the thermometer to be calibrated is provided with a two-wire cable, the user must take into account additional measurement errors which depend on the temperature of the lead.
The calibration certificate also states the length and temperature of the lead during calibration.

Example:
Platinum resistance thermometer Pt100 with 2.5 m lead (copper, cross section: 0.25 mm^2)
Resistance of lead at room temperature: 410 mΩ
If the lead has a temperature of 70 °C, the loop resistance of the lead rises to 492 mΩ.
This corresponds to a temperature indication higher by +0.2 K.

This must be taken into account when determining the measurement uncertainty during calibration of the thermometer. As a matter of principle, a higher measurement uncertainty is obtained when calibrating resistance thermometers in a two-wire circuit.

8.5.2 Three-wire circuit

To minimize the influences of the line resistance and their temperature-dependent fluctuations, the three-wire circuit is used in industrial metrology. By using this circuit technique, both the contribution and the temperature dependence of the line resistance are compensated. However, additional uncertainties must be expected because the compensation only works correctly if the respective line resistances are identical, and their temperature dependencies show the same behaviour. Since the measuring instruments used for calibration operate in the four-wire technique, the loop resistance must be measured separately and compensated for by calculation.

8.5.3 Four-wire circuit

The preferred type of connection is the four-wire circuit. Thanks to the separate supply of current and voltage path to the sensor, the measurement result is neither affected by the line resistance itself nor by its temperature dependence. It must be ensured (e.g. by the manufacturer's specifications) that the four-wire circuit is realised up to the sensor element. However, if the sensor element inside the thermometer uses a two-wire circuit, there will be an additional (temperature profile-dependent) line resistance. With many measuring instruments, the possible line resistance is limited even with the four-wire circuit; this may also affect the line inductance and capacitance. In practice, this will only occur with very long supply lines. In this case, stronger influences from electromagnetic fields are to be expected.

8.6 Electromagnetic compatibility (EMC) - influences

Electromagnetic alternating fields – such as those generated by mains lines, electric motors or heating coils – may cause interference voltages and/or currents to couple capacitively and/or inductively into the measuring lines. In the case of very strong fields and a moving measuring line, DC fields can also have a comparable effect.
For this reason, measuring lines and mains power lines should be installed at a distance from each other and never in parallel.
An effective reduction of this influence can be achieved by twisting the wires of the measuring line in pairs. In the four-wire circuit, the wires of the voltage and current paths are twisted separately. The effectiveness of this measure also depends on the quality of the common mode rejection (CMR) of the measuring device.
Shielding of the measuring cable is also effective. Preferably, the shield should not be part of the four-wire circuit, but an independent conductor, with low impedance to earth potential or guard. Since the shielding dimension is finite, twisting and shielding should be combined to enhance the effect. It should also be remembered that shielding only reduces the capacitive

coupling of interference. For measurements at a very high metrological level, the twisted voltage and current paths should each be shielded separately.
Depending on the design of the thermometer, the EMC shielding may be insufficient. This can be noticed, for example, especially in furnaces due to coupling of the electromagnetic fields of the heating coils. In this case, an attempt should be made to reduce the influence by using an earthed and electrically well-conducting protection tube.
EMC influences can also be reduced by using suitable measuring equipment. In some cases, analogue filters (in measuring devices) can effectively reduce interferences; however, it must be ensured that the measurement result is not falsified by this (for instance, offset and amplification may change due to analogue filters).
The integration time for multimeters or DC measuring bridges should usually be an integer multiple of the period of the mains frequency. Non-periodic disturbances can usually be reduced by increasing the integration time.

8.7 Parasitic thermoelectric voltage

As a rule, the measuring circuit of a thermometer does not consist of a single material. Therefore, a temperature gradient along the measuring circuit can lead to the formation of a thermoelectric voltage superimposed on the voltage drop at the resistor. According to the direction of current, this voltage adds or subtracts, resulting in a systematically higher or lower thermometer resistance. By reversing the polarity of the current direction during calibration, the magnitude of the thermoelectric voltage (with known intensity of the measurement current) can be determined from the difference of the two indicated values.
With alternating current and varying direct current, this effect compensates itself automatically.

Example:
Resistance thermometer: Pt100
Measurement current: 1 mA
Thermoelectric voltage: 25 µV

Resulting offset from thermoelectric voltage: $\frac{U}{I} = R = \frac{25\,\mu\text{V}}{1\,\text{mA}} = 25\,\text{m}\Omega$

This corresponds to a deviation of approximately 63 mK.

8.8 Self-heating

Since resistance thermometers are passive components, a measurement current must be fed through the corresponding sensor to determine the electrical resistance. The measuring current causes a heating of the sensor (self-heating), thus leading to a falsification of the measuring result. This effect is not only dependent on the intensity of the measuring current, but also on the measurement conditions (thermal coupling) and the sensor design. When calibrating resistance thermometers, the self-heating behaviour must be investigated, or its influence must be estimated.
Usually, the sensor resistance is measured with two different measuring currents and extrapolated to the measuring current I of 0 mA (or the electrical power P to 0 mW).
If, for example, it is not possible to change the intensity of the measurement current, another possibility is to vary the thermal coupling of the thermometer to its environment. A proven way of implementing this is to place a tube with a large diameter (compared to the diameter of the sensor) in a temperature-homogeneous and time-stable environment (e.g. ice point or calibration bath). Subsequently, the significantly smaller sensor is used to take a measurement in the lower part of the tube. The sensor is completely surrounded by air and must not touch the wall of the tube. The tube is then filled with a contact medium of good thermal conductivity (e.g. aluminium oxide) to such an extent that the entire sensor is surrounded by it. After a

sufficiently long stabilisation time, a new measurement is carried out. Now the influence of self-heating can be estimated from the difference between the two measurement results. For the measurements, the tube must always be sealed below the transition from the temperature control medium to the environment (e.g. with cotton wool) so that an undisturbed, stationary and homogeneous temperature distribution can form inside. Attention must be paid to possible heat dissipation.

The results of the self-heating investigation must be stated in the calibration certificate. This must be done in such a way that the user has all the necessary information to make an appropriate correction or to estimate the uncertainty for his conditions. If the self-heating is not determined experimentally (due to the measurement current), its contribution is to be taken into account in the measurement uncertainty budget with 30 mK (rectangular distribution) for all types of resistance thermometers, including their use in measuring chains. Assuming a rectangular distribution with a half-width a of 30 mK, we get a standard uncertainty of

$$u = \sqrt{\frac{1}{3} \cdot a^2} \approx 17\ \mathrm{mK} \tag{1}$$

In case a certain type of thermometer is calibrated at regular intervals, the determined maximum values for its self-heating can be used after a sufficiently large number of thermometer calibrations (at least 10 thermometers of the same type). The thus determined typical self-heating of a thermometer type is to be verified at regular intervals. The calibration certificate must then state that the value was not explicitly determined for the thermometer to be calibrated.

8.9 Insulation resistance

The insulation resistance of the thermometer is already measured at room temperature during the initial inspection, provided that the design allows for it (see also chapter 5). According to DIN EN 60751 [3], it has to be measured between each measuring circuit and the fitting, applying a DC voltage of at least 100 V. At room temperature, the resistance must not be less than 100 MΩ. It must be ensured that neither the sensor nor the connected electronics are damaged by the test voltage. During calibration, the insulation resistance must be measured at the highest calibration temperature with a DC voltage of at least 10 V (DIN EN 60751 [3]) and taken into account accordingly when determining the measurement uncertainty. If necessary, the thermometer is to be rejected as not suitable for calibration.

Example:
Resistance thermometer: Pt100 according to DIN EN 60751
Temperature: 400 °C (correspond to 247.092 Ω)
Insulation resistance: 1 MΩ
Assuming a parallel connection:

$$R_{\mathrm{ges}} = \frac{R_{\mathrm{PRT}} \cdot R_{\mathrm{iso}}}{R_{\mathrm{PRT}} + R_{\mathrm{iso}}} = \frac{247.092\ \Omega \cdot 1\ \mathrm{M}\Omega}{247.092\ \Omega + 1\ \mathrm{M}\Omega} = 247.031\ \Omega$$

This corresponds to a temperature value of 399.823 °C and thus a rectangular contribution to the measurement uncertainty (half-width) of 0.177 K.

8.10 Hysteresis

In general, it has to be borne in mind that industrial platinum resistance thermometers show a hysteresis effect, i.e. the relation between temperature and resistance depends on the thermal "history" of the thermometer. This effect arises, for example if the platinum sensor is closely bonded with a glass or ceramic carrier and the difference in thermal expansion leads to mechanical stresses. For IPRTs, this may result in a considerable difference in the measured temperature [13], [14], depending on whether the thermometer was previously used at higher or lower temperatures. The hysteresis effect depends on the design of the sensor element. Experience shows that it is particularly strong with glass-encapsulated IPRTs and thin-film sensors; it's only for SPRTs that it is negligible. The difference between maximum and minimum value is usually greatest in the middle of the temperature range (Fig. 1).

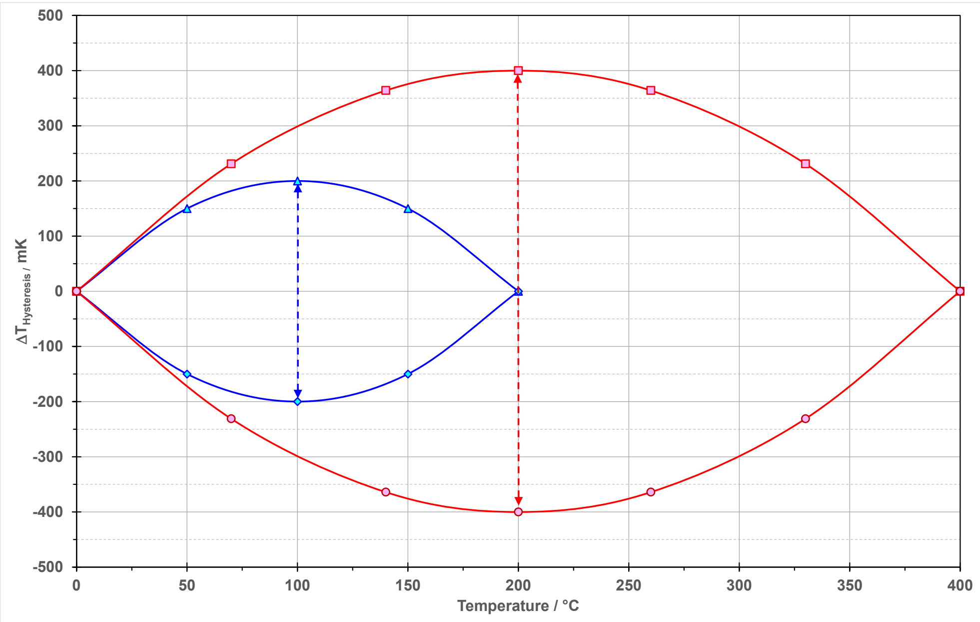

Figure 1: Example of a hysteresis-related deviation of the characteristic curve of an industrial resistance thermometer in different temperature ranges

The calibration certificate for IPRTs must therefore contain information regarding the influence of the hysteresis and the calibration conditions (calibration with ascending/descending temperatures).

The influence of the hysteresis is to be determined experimentally according to DIN EN 60751 [3] (Fig. 1). This is done by starting the calibration with steadily increasing temperatures, beginning with the lowest temperature T_{Min}. The most important measuring point T_{H} is located in the middle of the temperature range: $T_{\mathrm{Min}} < T_{\mathrm{H}} < T_{\mathrm{Max}}$. After having completed the measurement at the highest temperature T_{Max}, the temperature T_{H} is then directly re-set in the middle of the temperature range and another measurement is carried out.

Simplified measurement scheme without further calibration points of a direct-reading thermometer at the measured temperatures T_n:

(1) lowest temperature ($T_1 = T_{Min}$)
(2) mean temperature ($T_2 = T_H$)
(3) highest temperature ($T_3 = T_{Max}$)
(4) directly to the mean temperature ($T_4 = T_H$)

$$\Delta T_{\text{Hysterese}} = T_4 - T_2 \tag{2}$$

If the hysteresis-related temperature deviation is not determined, the effect is assumed to be 0.2 % of the total measuring range of the thermometer in Kelvin. The determined value must either be taken into account in the uncertainty budget or stated separately in the calibration certificate.

Possible entry in the calibration certificate in case the influence has not been measured (example):

> *The calibration has been carried out in the temperature range from 0 °C to 400 °C using a programme with ascending temperature steps. The influence of the hysteresis has not been experimentally determined. It is to be assumed that the influence in the above-mentioned temperature range can be up to 0.8 K, if the measurements are not carried out continuously at rising temperatures. In this case, the strongest influence is to be expected in the middle of the temperature range.*

When calibrating several thermometers of the same type, individual determination of the hysteresis can only be omitted if maximum values for their hysteresis have been determined by previous investigations covering an adequate number of thermometers (at least 10).

However, the procedure described here reaches its limits when it becomes necessary to change the temperature control device between the lowest and the highest temperature.
Especially with thin/fast sensors, it may be possible that the sensor temperature returns to almost room temperature when changing from one device to the other.
In this case, the determination of the hysteresis in the above-mentioned way is not useful.
Should one or more changes of the temperature control devices be necessary to calibrate the resistance thermometer in order to cover the required calibration range, the specified procedure must be modified:

1) The described procedure for determining the hysteresis is carried out separately for each of the n temperature control units and its corresponding temperature interval. As a result, a hysteresis $\Delta T_{\text{Hysterese},\,k}(\text{temperature control device}\ _k)$ is determined for each temperature control device according to equation (2) for the corresponding temperature range $T_{k,\,\text{Min}}$ to $T_{k,\,\text{Max}}$.
2) From the n hystereses $\Delta T_{\text{Hysterese},\,k}$ for the temperature ranges $T_{k,\,\text{Min}}$ to $T_{k,\,\text{Max}}$ of the individual temperature control devices, the relative hysteresis $\Delta T^{\text{rel}}_{\text{Hysterese},k}$ according to equation (3) is calculated.

$$\Delta T^{\text{rel}}_{\text{Hysterese},k} = \frac{\Delta T_{\text{Hysterese},k}}{\left(T_{k,\,\text{Max}} - T_{k,\,\text{Min}}\right)} \quad \forall\, k = 1 \dots n \tag{3}$$

3) The relative hysteresis for the entire temperature calibration range T_{Min} to T_{Max} of all temperature control devices used is then the maximum of the individual relative hystereses.

$$\Delta T_{\text{Hysterese}}^{\text{rel}} = \max_{k=1\dots n}\left(\Delta T_{\text{Hysterese},k}^{\text{rel}}\right) \tag{4}$$

4) The hysteresis for the entire temperature calibration range T_{Min} to T_{Max} can then be estimated to be:

$$\Delta T_{\text{Hysterese}} = \Delta T_{\text{Hysterese}}^{\text{rel}} \cdot (T_{\text{Max}} - T_{\text{Min}}) \tag{5}$$

5) The sum of the partial temperature ranges

$$\sum_{k=1}^{n} \Delta T_k = \sum_{k=1}^{n}\left(T_{k,\,\text{Max}} - T_{k,\,\text{Min}}\right) \tag{6}$$

must be at least 90% of the total range $(T_{\text{Max}} - T_{\text{Min}})$.

For the calibration of a resistance thermometer in the temperature range from -100 °C to 600 °C we obtain the following result analogous to Figure 1:

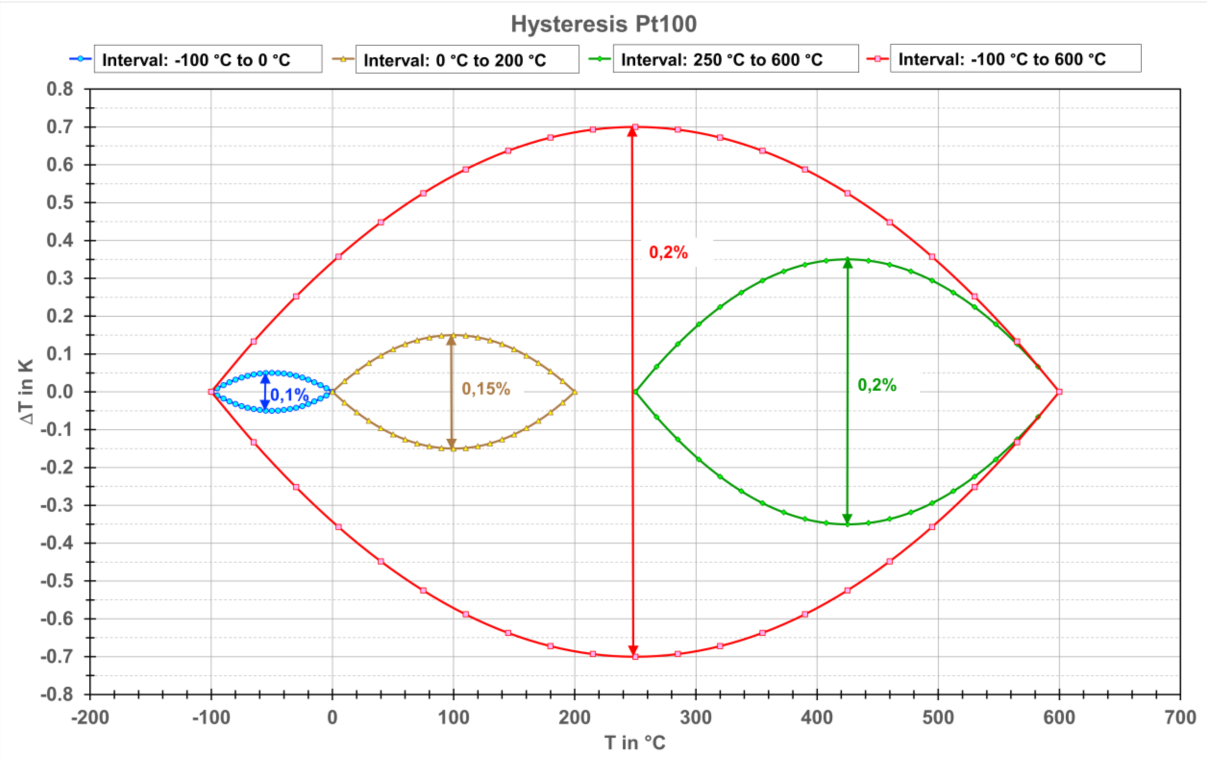

Figure 2: Example for the determination of the hysteresis of an industrial resistance thermometer during calibration in several temperature control devices and different temperature ranges

In the example, the calibration was carried out in three different temperature control devices covering the following ranges:

- In a cryo bath, in the range from -100 °C to 0 °C, the relative hysteresis was 0.1 %.
- In an oil bath, in the range from 0 °C to 200 °C, the relative hysteresis was determined to be 0.15 %.
- In a calibration furnace, the hysteresis in the range from 250 °C to 600 °C was measured at 0.2 %.
- The relative hysteresis for the entire calibration range from -100 °C to 600 °C was thus estimated at 0.2 %, resulting in a hysteresis for the total calibration range of 1.4 K.
- There was no calibration point in the temperature range between 200 °C and 250 °C, so the relative hysteresis was not determined. The sum of the temperature subranges is 650 K. This is more than 90 % of the total calibration interval of 700 K, so that the three examined ranges are sufficient.

9 Requirements for reference standards and measuring equipment

For the following reasons, it is necessary for calibration laboratories to have at least two reference standards available for each temperature range:

- Resistance thermometers exhibit a drift. Vibrations or mechanical shocks can lead to changes in the electrical resistance of the sensor. This usually results in shifts of the characteristic curve, which means that there is a temperature-independent change of the thermometer resistance. In certain cases, however, there may also be a change in the rise of the characteristic curve. This is usually caused by contamination of the platinum sensor element. Changes in the characteristic curve can only be detected and corrected by comparison measurements at at least two temperatures with another resistance thermometer, or by recalibration (or intermediate tests) using thermometric fixed points (ITS-90 fixed points, ice point).
- To carry out intermediate tests (requirement of DIN EN ISO/IEC 17025 [8]), either a second reference standard (resistance thermometer) or at least two thermometric fixed points are needed. The interval for the intermediate tests is to be chosen appropriately from a technical point of view. If changes in the characteristic curve can be excluded (e.g. maximum operating temperature less than 250 °C), an intermediate test at one temperature (e.g. ice point) is sufficient.
- Since the calibration of a resistance thermometer is time-consuming, the second reference standard ensures the calibration laboratory's ability to carry on working during the calibration of the other standard. Therefore, it makes sense to carry out the calibrations of the reference standards with a time delay.

The above-mentioned requirements can be fulfilled either by two resistance thermometers or by one resistance thermometer with at least two fixed temperature points.
The recalibration intervals depend on the desired measurement uncertainty and the stability of the reference standards; the following recommendations apply:

Measuring device/reference standard	**Maximum recalibration interval**	**Note**
Standard platinum resistance thermometer (SPRT)	2 to 3 years	depending on the history
Industrial resistance thermometer (IPRT)	1 to 2 years	depending on the history
Fixed-point cell	5 years	
Standard resistance	2 to 5 years	depending on the history
Resistance meter	2 years	
AC measuring bridge for resistance ratios	3 to 5 years	linearity test, depending on the history
DC measuring bridge for resistance ratios	1 to 3 years	linearity test, depending on the history; for an internal reference resistor (1 year)

Table 1: Recommended recalibration intervals

The long-term behaviour of all reference and working standards must be documented and evaluated in a suitable manner to be able to determine or extrapolate the influence of drift or other instabilities. If necessary, recalibration intervals have to be shortened.

10 Results

As a result of the calibration, a calibration certificate is issued.
The calibration certificate must meet the requirements of the currently valid standards (DIN EN ISO/IEC 17025 [8]) as well as the additional specifications of the respective accreditation body or regional metrology organisations. Within the scope of this guideline, the following is to be referred to:

- reference to the specifications or procedures used,
- measured values and the associated measurement uncertainties,
- interpolated or extrapolated "results" for certain (e.g. integer) values do not form part of the calibration certificate but may be additionally indicated in the appendix. The additional uncertainty component must be taken into account here.
- Statements regarding conformity with a defined metrological specification or standard are permissible at the customer's request.
- If a characteristic curve approximation is carried out, the uncertainty of this characteristic curve must be stated in addition to the calculated coefficients. [9]
- Specification of hysteresis behaviour (see chapter 8.10) and self-heating (see chapter 8.8),
- selected intensity of the measuring current used (if AC: frequency, DC: alternating / unipolar), current (continuous / pulsed).
- If a device to be calibrated has been adjusted or repaired, the calibration results, if available, must be given before and after the adjustment or repair. This will be the case especially for direct-reading thermometers.

11 Bibliography

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Appendix A – Measurement uncertainty budgets – Examples

The measurement uncertainty in the calibration of a thermometer depends on the calibration method used, the uncertainty contributions of the temperature control device (fixed-point cell, furnace, bath, block calibrator, ...), the uncertainty from the calibration of the standards, the characteristics of the measuring equipment used and the properties of the resistance thermometer to be calibrated (including the corresponding measuring equipment such as transmitter or digital measuring device). Hence, there can be no general specification regarding the measurement uncertainty of certain types of thermometers. The examples of calculation of the measurement uncertainty in calibration dealt with in this section therefore cannot be directly transferred to any calibration actually carried out; for each individual case, the contributions to the measurement uncertainty are to be thoroughly determined.

For accredited calibration laboratories, the Accreditation Body has established so-called “best measurement capabilities” within the scope of the respective accreditation procedure To achieve these values, calibration laboratories must use the best available measuring equipment and the calibration item must behave almost ideally. The “almost ideal calibration item” used to determine the smallest measurable uncertainty must exist in reality to ensure that no assumptions or “zero values” but proven contributions can be used for its contributions in the uncertainty budget. Accredited calibration laboratories are not allowed to state measurement uncertainties in calibration certificates that are smaller than the (accredited) smallest measurable uncertainty.

There are four examples of the calibration of different types of thermometers given below:

- calibration of a precision resistance thermometer with an AC measuring bridge,
- calibration of an IPRT with a resistance meter,
- calibration of a direct-reading electrical thermometer,
- calibration of a thermometer with measuring transducer and analogue output.

The following examples only consider the calibration at one single temperature. Usually, thermometers are calibrated at several temperatures and a characteristic curve is calculated from these values, the uncertainty of which is greater than the measurement uncertainty at the individual calibration temperatures. For the determination of this characteristic curve and for the determination of the uncertainty that can be achieved with the thermometer in the calibration range on the basis of this characteristic curve, reference is made to DKD-R 5-6 [9].

A.1: Calibration of a resistance thermometer with a measuring bridge

The calibration of the precision resistance thermometer is carried out by comparison with two SPRTs (25 Ω), using the comparison method at a nominal temperature of 180 °C. The measurements are carried out in a stirred liquid bath, with oil as the fluid and without an equalising block. The resistance of the standard thermometers (SPRTs) is determined by means of a resistance bridge with direct temperature indication or direct resistance indication and a 100 Ω standard resistor. The standard thermometers, the measuring bridge and the standard resistor were calibrated by an NMI or an accredited laboratory.
After a stabilisation time of two hours, the arithmetic mean value was calculated over a period of 10 minutes from 60 individual values each. The measurement uncertainty budget comprises two steps.

1. Determination of the reference temperature in the oil bath.
2. Determination of the associated resistance of the precision resistance thermometer (calibration item), the associated measurement error with respect to the standard characteristic curve according to DIN EN 60751 [3] as well as the associated expanded measurement uncertainty.

Step 1: Determination of the reference temperature in the oil bath:

The reference temperature is determined from the mean value of the temperature of the bath measured with both standard thermometers. The resistances of both standards are measured using a measuring bridge and a reference resistor. The coefficients of the characteristics of both SPRTs can be stored in the measuring bridge – this enables direct conversion to temperatures which are also indicated by the bridge.

Model equation:

$$\begin{aligned} T_\mathrm{S} = T_\mathrm{m,S} &+ \tfrac{1}{2}\cdot\delta T_\mathrm{cal,S1} + \tfrac{1}{2}\cdot\delta T_\mathrm{Int,S1} + \tfrac{1}{2}\cdot\delta T_\mathrm{Drift,S1} + \tfrac{1}{2}\cdot\delta T_\mathrm{EEw,S1} + \tfrac{1}{2}\cdot\delta T_\mathrm{Hyst,S1} \\ &+ \tfrac{1}{2}\cdot\delta T_\mathrm{cal,S2} + \tfrac{1}{2}\cdot\delta T_\mathrm{Int,S2} + \tfrac{1}{2}\cdot\delta T_\mathrm{Drift,S2} + \tfrac{1}{2}\cdot\delta T_\mathrm{EEw,S2} + \tfrac{1}{2}\cdot\delta T_\mathrm{Hyst,S2} \\ &+ \delta T_\mathrm{i,S1-S2} + \delta T_\mathrm{Res,S} + c_\mathrm{T}\cdot\delta R_\mathrm{Par,S} + \delta T_\mathrm{Wa} + \delta T_\mathrm{axial} + \delta T_\mathrm{radial} + \delta T_\mathrm{Instab} \\ &+ c_\mathrm{T}\cdot N\cdot\left(\delta R_\mathrm{Ref,Cal} + \delta R_\mathrm{Ref,Drift} + \delta R_\mathrm{Ref,T}\right) + c_\mathrm{T}\cdot R_{Ref}\cdot\left(\delta N_\mathrm{Br,Cal} + \delta N_\mathrm{Br,Drift}\right) \end{aligned} \quad (7)$$

The sensitivity coefficient c_T results from the characteristic of the SPRTs at 180 °C
$c_\mathrm{T} = 10.4\ {}^{K}/_{\Omega}$.
The bridge ratio N is the ratio of the resistance of the standard thermometers R_S at 180 °C to the resistance of the reference resistor $R_\mathrm{Ref} = 100\ \Omega$.
The following applies: $N = {}^{R_\mathrm{S}}/_{R_\mathrm{Ref}} = 0.421$,
yielding: $c_\mathrm{T}\cdot N = 4.38\ {}^{\mathrm{K}}/_{\Omega}$ and for $c_\mathrm{T}\cdot R_\mathrm{Ref} = 1040\ \mathrm{K}$.

This model equation applies if the contributions (calibration, interpolation, drift, self-heating and hysteresis) of the two standard thermometers can be assumed to be uncorrelated.
This is approximately the case, for example, if the two standard thermometers have not been calibrated at the same time by the same calibration laboratory using the same standards. Ideally, the dates of calibration of both standards differ from each other by half the calibration period.
Especially when using different types of standards or SPRTs from different manufacturers, the drift, self-heating and hysteresis are not or only slightly correlated.

Another possibility would be to avoid constant use of the two standards in the same calibrations, thus ensuring that they are not constantly exposed to the same influences.[1]
If the contributions of both standards are considered to be correlated due to non-fulfilment of these conditions, the respective contributions should be combined to an associated uncertainty contribution of the mean value, taking into account the correlation. This combined value should then be used in the measurement uncertainty budget instead of the two individual contributions (for an estimation of a maximum value for this combined uncertainty contribution, see also EA-4/02 M: 2022, Annex D [15]).

The following contributions result for the individual components of the model equation:

$T_{\mathrm{m,S}}$:

The mean value of the relative temperature indications of the two SPRTs corrected by the associated indication corrections is determined from all individual measurements of the standard thermometers (60 readings each). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the standard thermometers. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022 [15]). In the example, the result is a mean value of 180.079 °C and 0.001 K for the standard deviation of the mean value.

$\delta T_{\mathrm{cal,S1}}$, $\delta T_{\mathrm{cal,S2}}$:

Correction of the temperature of the standard thermometers due to their calibration. The standard thermometers are calibrated at fixed points of the ITS-90 (WTP, Sn, Zn). The coefficients for the range WTP - Zn (0.01 °C to 419.527 °C) for the measuring current of 1 mA – extrapolated to 0 mA – and the associated measurement uncertainty for the range from 0 °C to 419 °C are stated in the corresponding calibration certificates. The coefficients for the measuring current intensity of 1 mA were stored for each thermometer in the measuring bridge. The indication of the temperature of each standard thermometer is calculated by the measuring bridge using the individual coefficients for the measuring current intensity of 1 mA from the respective calibration certificate. This means that a calibration correction has already been taken into account and does not need to be considered further. The expanded uncertainty U of the temperature in the range from 0 °C to 419 °C is taken from the respective calibration certificate ($U_{(\mathrm{S1})}$ = 4 mK and $U_{(\mathrm{S2})}$ = 5 mK normal distribution, k = 2). The associated standard uncertainties are thus: $u_{(\mathrm{S1})}$ = 2 mK and $u_{(\mathrm{S2})}$ = 2.5 mK. The uncertainty component δT_{EEw} due to self-heating is described further below.

$\delta T_{\mathrm{Int,S1}}$, $\delta T_{\mathrm{Int,S2}}$:

Correction of the temperature indication of the standard thermometers due to the interpolation between the calibration points. The uncertainty stated in the respective calibration certificates for the range from 0 °C to 419 °C already includes this contribution – so it does not need to be taken into account here.

In case the calibration certificate should only state the uncertainty at the calibration points but not the uncertainty for the range, then this contribution is to be determined according to

[1] It is therefore recommended
- to keep available more than two standard thermometers (diversity recommended)
- to take a different combination of standard thermometers from the pool for each subsequent calibration
- to have all standard thermometers recalibrated individually (maybe even at different laboratories)

DKD-R 5-6 [9] and applied accordingly. In this case, a rectangular contribution with the half-width of the distribution according to Table 6.1 or Table 6.2, DKD R 5 6 [9] is applied.

$\delta T_{\mathrm{Drift,S1}}$, $\delta T_{\mathrm{Drift,S2}}$:

Correction of the mean temperature of the standard thermometers due to drift since their last recalibration. The last calibrations of the standards showed a maximum drift of the standard thermometers of less than 3 mK per year. This drift represents a rectangular contribution with a half-width of 3 mK for each standard. The associated standard uncertainty is then 1.7 mK.

$\delta T_{\mathrm{EEw,S1}}$, $\delta T_{\mathrm{EEw,S2}}$:

Correction of the mean temperature of the standard thermometers due to their self-heating. During measurement, the resistances of the standard thermometers are measured by the measuring bridge with a measuring current of 1 mA. The (possibly different) self-heating of the two standard thermometers is usually taken into account by approximation, using the coefficients for the measuring current of 1 mA from the corresponding calibration certificates for the conversion of the thermometer resistances into the temperature values. However, there remains an uncertainty due to self-heating which is caused by the different thermal couplings of the thermometer sensors to the surrounding temperature field. This contribution is estimated based on the self-heating specified for the SPRTs in the calibration certificate.

The last calibration certificates of the standards showed a maximum self-heating of the standard thermometers of less than 2 mK. The contribution of self-heating represents a rectangular contribution with a half-width of 2 mK for each standard. The associated standard uncertainty is then 1.2 mK.

$\delta T_{\mathrm{Hyst,S1}}$, $\delta T_{\mathrm{Hyst,S2}}$:

Correction of the temperature of the standard thermometers due to a possible hysteresis. In the case of SPRTs, the hysteresis is very small and is checked by repeating the fixed points several times during calibration, in particular the water triple point. The expanded measurement uncertainty specified in the calibration certificates of the SPRTs already takes into account a minor instability or hysteresis contribution that may have been found.

A rectangular contribution with the half-width of 0.0 K is assumed. The associated standard uncertainty is then 0.0 K.

When dealing with IPRTs instead of SPRTs as standard thermometers, the hysteresis must be determined separately (see chapter 8.10) and taken into account as half-width of a rectangular distribution.

$\delta T_{\mathrm{i,S1\text{-}S2}}$:

Correction of the mean temperature of the standard thermometers due to the different indications of the two temperatures of the two SPRTs. The difference in measured temperature observed between the two SPRTs must not be greater than ±3.5 mK ($\triangleq 0.7 \cdot U_{\mathrm{cal,S}}$). If the difference is not within these limits, the observations are to be repeated and/or the reasons for the differences observed must be investigated further.

The difference between the indications of the two thermometers is 3 mK. The criterion is thus fulfilled, and the mean value of the indications is used as reference value.

As long as the difference between the indications of the two standard thermometers is significantly smaller than the uncertainty of the calibration of the standard thermometers, there is no need to apply an additional measurement uncertainty for the mean value. Therefore, a rectangular contribution with a half-width of 0.0 K is applied. The associated standard uncertainty is then 0.0 K.[2]

$\delta T_{\mathrm{Res,S}}$:

Correction due to the resolution of the temperatures of the standard thermometers indicated by the measuring bridge. The resolution of the temperature indication is 1 mK. Therefore, a rectangular contribution with a half-width of 0.5 mK is applied. The associated standard uncertainty is then 0.29 mK.

$\delta R_{\mathrm{Par,S}}$:

Correction of the resistance of the standard thermometers due to the parasitic thermoelectric voltages in the measuring circuit of the standard thermometers. Since the measuring bridge operates with alternating direct current and each displayed measured value represents an average of both current directions, any measurement errors due to parasitic thermoelectric voltages in the measuring circuit neutralise each other approximately. Therefore, a rectangular contribution with a distribution of 0.0 Ω is applied. The associated standard uncertainty is then 0.0 Ω.

δT_{Wa} :

Correction of the temperature of the standard thermometers due to heat dissipation of the standard thermometers. Both standard thermometers have an outer diameter of 7 mm. The immersion depth in the bath is 200 mm. The standard thermometers are thus immersed in the bath at least 20 times their diameter plus the sensor length. This means that the estimated heat dissipation error is less than 0.1 mK (estimate according to Traceable Temperatures – An Introduction to Temperature Measurement and Calibration [16]) and cannot be measured directly due to the instability and inhomogeneity of the bath.

A rectangular contribution with a half-width of 0.1 mK is assumed. The associated standard uncertainty is then 0.06 mK.

If the immersion depth is less than 15 times the diameter plus sensor length, the heat dissipation error must be determined by pulling out the standards by at least twice their diameter and taken into account.

[2] If the deviation of the indications of both standards is greater than 0.7 times the expanded calibration uncertainty of the standards and if there is no investigation of the causes and the measurements are not repeated, then the difference of the indications of both standards is assumed to be half the width of the rectangular distribution of $\delta T_{\mathrm{i,S1\text{-}S2}}$.

δT_{axial} :

Correction of the local temperature in the calibration bath due to the axial inhomogeneity of the temperature in the measuring volume. An examination of the bath has shown that the maximum deviation of the temperature in axial direction in the measuring volume is ±10 mK.

Therefore, a rectangular contribution with a half-width of 10 mK is assumed. The associated standard uncertainty is then 5.8 mK.

δT_{radial} :

Correction of the local temperature in the calibration bath due to the radial inhomogeneity of the temperature in the measuring volume. An examination of the bath has shown that the maximum deviation of the temperature in the radial direction in the measuring volume is ±8 mK.

Therefore, a rectangular contribution with a half-width of 8 mK is assumed. The associated standard uncertainty is then 4.6 mK.

δT_{Instab} :

Temperature correction due to instability of the temperature in the calibration volume. The examination of the calibration volume revealed a maximum deviation of the temperature from the mean value over 30 minutes of ±6 mK. Therefore, a rectangular contribution with a half-width of 6 mK is assumed. The associated standard uncertainty is then 3.5 mK.

$\delta R_{\text{Ref,Cal}}$:

Correction of the reference resistance due to the calibration of the reference resistor. The expanded relative uncertainty of the calibration of the 100 Ω reference resistor is given in the calibration certificate as $1 \cdot 10^{-6}$. The expanded uncertainty of the resistance due to calibration is thus 0.1 mΩ. The associated standard uncertainty is then 0.05 mΩ.

$\delta R_{\text{Ref,Drift}}$:

Correction of the reference resistance due to the drift of the reference resistor since its last calibration. The recalibration interval is 1 year. According to the manufacturer's specification, the maximum drift within one year is within the limits $\pm 6 \cdot 10^{-6}$. The uncertainty contribution is therefore assumed to be rectangular with the half-width of 0.6 mΩ. The associated standard uncertainty is then 0.35 mΩ.

$\delta R_{\text{Ref,T}}$:

Correction of the reference resistance due to the dependence of the reference resistor on the temperature. The reference resistor is calibrated at 23 °C. This is also the target temperature of the environment during use. The manufacturer specifies a temperature dependence of $3 \cdot 10^{-6}$ / 5 K = $0.6 \cdot 10^{-6}$/K. With a permissible change in ambient temperature ±3 K, this yields a rectangularly distributed uncertainty of the resistance value of $\pm 1.8 \cdot 10^{-6} \triangleq 0.18$ mΩ. The associated standard uncertainty is then 0.10 mΩ.

$\delta N_{\mathrm{Br,Cal}}$:

Correction of the indication of the measuring bridge due to the calibration of the measuring bridge. In the calibration certificate, the expanded relative uncertainty of the calibration of the measuring bridge is given as $2 \cdot 10^{-6}$. The associated standard uncertainty is then $1 \cdot 10^{-6}$.

$\delta N_{\mathrm{Br,Drift}}$:

Correction of the indication of the measuring bridge due to the drift of the measuring bridge since its last calibration. The recalibration interval is 1 year. According to the manufacturer's specification, the maximum drift within one year is within the limits of $\pm 1 \cdot 10^{-6}$. The uncertainty contribution is therefore assumed to be rectangular with a half-width of $\pm 1 \cdot 10^{-6}$. The associated standard uncertainty is then $0.58 \cdot 10^{-6}$.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
$T_{\mathrm{m,S}}$	Mean value of the corrected readings of the standards	180.079 °C	0.0010 K	0.0010 K	normal	1	1.0	0.00100 K
$\delta T_{\mathrm{cal,S1}}$	Calibration of Standard 1	0.000 K	0.0040 K	0.0020 K	normal	2	0.5	0.00100 K
$\delta T_{\mathrm{Int,S1}}$	Interpolation between the calibration points Standard 1	0.000 K	0.0000 K	0.0000 K	rectangular	√3	0.5	0.00000 K
$\delta T_{\mathrm{Drift,S1}}$	Drift of Standard 1	0.000 K	0.0030 K	0.00173 K	rectangular	√3	0.5	8.660E-04 K
$\delta T_{\mathrm{EEw,S1}}$	Self-heating of Standard 1	0.000 K	0.0020 K	0.00115 K	rectangular	√3	0.5	5.774E-04 K
$\delta T_{\mathrm{Hyst,S1}}$	Hysteresis Standard 1	0.000 K	0.0000 K	0.00000 K	rectangular	√3	0.5	0.00000 K
$\delta T_{\mathrm{cal,S2}}$	Calibration Standard 2	0.000 K	0.0050 K	0.00250 K	normal	2	0.5	0.00125 K
$\delta T_{\mathrm{Int,S2}}$	Interpolation between the calibration points Standard 2	0.000 K	0.0000 K	0.00000 K	rectangular	√3	0.5	0.000E+00 K
$\delta T_{\mathrm{Drift,S2}}$	Drift of Standard 2	0.000 K	0.0030 K	0.00173 K	rectangular	√3	0.5	8.660E-04 K
$\delta T_{\mathrm{EEw,S2}}$	Self-heating Standard 2	0.000 K	0.0020 K	0.00115 K	rectangular	√3	0.5	5.774E-04 K
$\delta T_{\mathrm{Hyst,S2}}$	Hysteresis Standard 2	0.000 K	0.0000 K	0.00000 K	rectangular	√3	0.5	0.00000 K
$\delta T_{\mathrm{i,S1\text{-}S2}}$	Difference between the reference standards	0.000 K	0.0000 K	0.00000 K	rectangular	√3	1.0	0.00000 K
$\delta T_{\mathrm{Res,S}}$	Resolution of the measuring bridge	0.000 K	0.0005 K	2.89E-04 K	rectangular	√3	1.0	2.887E-04 K
$\delta R_{\mathrm{Par,S}}$	Parasitic thermoelectric voltages	0.000 Ω	0.0000 Ω	0.00000 Ω	rectangular	√3	10.4 K/Ω	0.000E+00 K
δT_{Wa}	Heat dissipation	0.000 K	0.0001 K	5.77E-05 K	rectangular	√3	1.0	5.774E-05 K
$\delta T_{\mathrm{axial}}$	Axial inhomogeneity in the bath	0.000 K	0.0100 K	0.00577 K	rectangular	√3	1.0	5.774E-03 K
$\delta T_{\mathrm{radial}}$	Radial inhomogeneity in the bath	0.000 K	0.0080 K	0.00462 K	rectangular	√3	1.0	4.619E-03 K
$\delta T_{\mathrm{Instab}}$	Time-dependent instability in the bath	0.000 K	0.0060 K	0.00346 K	rectangular	√3	1.0	3.464E-03 K
$\delta R_{\mathrm{Ref,Cal}}$	Calibration of the reference resistor	0.000 Ω	0.0001 Ω	0.00005 Ω	normal	2	4.40 K/Ω	2.200E-04 K
$\delta R_{\mathrm{Ref,Drift}}$	Drift of the reference resistance	0.000 Ω	0.0006 Ω	3.46E-04 Ω	rectangular	√3	4.40 K/Ω	1.524E-03 K
$\delta R_{\mathrm{Ref,T}}$	Temperature dependence of the reference resistor	0.000 Ω	0.00018 Ω	1.04E-04 Ω	rectangular	√3	4.40 K/Ω	4.573E-04 K
$\delta N_{\mathrm{Br,Cal}}$	Calibration of the measuring bridge	0.000	1.00E-06	1.00E-06	normal	1	1040 K	1.040E-03 K
$\delta N_{\mathrm{Br,Drift}}$	Drift of the measuring bridge	0.000	1.00E-06	5.77E-07	rectangular	√3	1040 K	6.004E-04 K
T_{S}	**Temperature**	**180.07900 °C**					***u* =**	**0.00875 K**

Table 2: Uncertainty budget of the temperature in the oil bath (measured with the standard thermometers)[3]

[3] The column "Uncertainty or half-width" contains the standard measurement uncertainty or the expanded measurement uncertainty for a normal distribution and the half-width for a rectangular distribution.

Step 2: Calibration result

The deviation of the temperature indicated by the calibration item from the temperature measured in the oil bath represents the calibration result.

The resistance of the calibration item (Pt100 precision thermometer) is measured at the temperature T_X. The measurement is carried out using a resistance bridge and a standard resistor – identical in type to those used for the measurement with the standard thermometers. In this case, however, it is the direct resistance measurement with the measuring bridge that is used.

The model for this measurement reads

$$\Delta R(T_\mathrm{X}) = R_\mathrm{S}^\mathrm{EN60751}(T_\mathrm{S}) - R_\mathrm{Br} + c_\mathrm{R} \cdot \delta T_\mathrm{S} + \delta R_\mathrm{Res} + \delta R_\mathrm{Par} + \delta R_\mathrm{EEw} + \delta R_\mathrm{Wa} + \delta R_\mathrm{Hyst} + N \cdot \left(\delta R_\mathrm{Ref,Cal} + \delta R_\mathrm{Ref,Drift} + \delta R_\mathrm{Ref,T}\right) + R_\mathrm{Ref} \cdot \left(\delta N_\mathrm{Br,Cal} + \delta N_\mathrm{Br,Drift}\right) \quad (8)$$

For a Pt100 at 180 °C, the sensitivity coefficient c_R is: $c_\mathrm{R} = 0.37\ ^{\Omega}/_{\mathrm{K}}$ or

$c_\mathrm{T} = 2.70\ ^{\mathrm{K}}/_{\Omega}$

For the contributions δR_Par, $\delta R_\mathrm{Ref,Cal}$, $\delta R_\mathrm{Ref,Drift}$, $\delta R_\mathrm{Ref,T}$, $\delta N_\mathrm{Br,Cal}$ and $\delta N_\mathrm{Br,Drift}$ the same considerations apply as for the determination of the temperature in the oil bath. Hence, they will not be repeated here. The other contributions are as follows:

$R_\mathrm{S}^\mathrm{EN60751}(T_\mathrm{S})$:

In the first step, the temperature of the oil bath was determined to be 180.079 °C by means of the two standard thermometers. The corresponding resistance of a Pt100 according to EN 60751 [3] is 168.5075 Ω.

The bridge ratio N is the ratio of the resistance $R_\mathrm{S}^\mathrm{EN60751}$ of the Pt100 at 180.079 °C to the resistance of the reference resistor $R_\mathrm{Ref} = 100\ \Omega$. The result is therefore $N = \frac{R_\mathrm{S}^\mathrm{EN60751}}{R_\mathrm{Ref}} = 1.68$.

R_{Br}, δR_{Br} :

The measuring bridge internally determines the ratio of the thermometer resistance to the external reference resistor and calculates the resistance of the thermometer with the calibration value of the reference resistance stored in the software and displays it.

The mean value of the bridge reading is determined from all individual measurements of the thermometer resistance at calibration temperature (60 readings each). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the measuring bridge. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022 [15]). In the example, this results in a mean value of 168.4783 Ω as well as 0.0006 Ω for the standard deviation of the mean value.

δT_S :

Correction due to the temperature of the oil bath. The uncertainty of the temperature in the oil bath was determined in the first step. The associated standard uncertainty is 8.8 mK.

δR_{Res} :

Correction of the thermometer resistance due to the resolution of the resistance of the thermometer indicated by the measuring bridge at calibration temperature. The resolution of the resistance indication is 1 mΩ. Therefore, a rectangular contribution with a half-width of 0.5 mΩ is applied. The associated standard uncertainty is then 0.29 mΩ.

δR_{EEw} :

Correction of the temperature of the thermometer to be calibrated due to its self-heating. During measurement, the resistance of the thermometer is measured by the measuring bridge with a measuring current intensity of 1 mA. The bridge offers the possibility to additionally measure the resistance with a measuring current of 1.41 mA (double electrical power loss ⇒ approximately double self-heating). The resistance of the thermometer thereby increases by 0.9 mΩ. This change is therefore taken as the maximum resistance uncertainty of 0.9 mΩ caused by the self-heating of the thermometer. It represents a rectangular contribution with a half-width of 0.9 mΩ. The associated standard uncertainty is then 0.52 mΩ.

With the sensitivity of the Pt100, $c_{\mathrm{T}} = {}^{1}/_{c_{\mathrm{R}}} = 2.70\ {}^{\mathrm{K}}/_{\Omega}$, this corresponds to a standard uncertainty due to self-heating of 1.4 mK.

δR_{Wa} :

Correction due to heat dissipation of the Pt100. The thermometer to be calibrated has an outer diameter of 8 mm. The immersion depth in the bath is 200 mm. As there is no information about the internal structure, the heat dissipation error is determined experimentally by pulling out the thermometer by twice its diameter (16 mm). After removal, the thermometer resistance decreases by 0.4 mΩ. A rectangular contribution with a half-width of 0.4 mΩ is assumed. The associated standard uncertainty is then 0.23 mΩ.

With the sensitivity of the Pt100, this corresponds to a standard uncertainty due to heat dissipation of 0.6 mK.

δR_{Hyst} :

Correction of the temperature of the Pt100 due to hysteresis. Depending on the design, the hysteresis of IPRTs is usually not negligible (see chapter 8.10). The thermometer is calibrated for the range from 0 °C to 400 °C. The desired calibration point (180 °C) is approximately in the middle of the range to be calibrated. Therefore, the hysteresis of the thermometer at this point is determined by measuring the resistance of the thermometer at this calibration temperature with rising (starting from 0 °C) and falling (starting from 400 °C) temperature. With both measurements, a difference in thermometer resistance of 7.0 mΩ was determined (corrected by the slope of the thermometer characteristic to equalise the temperatures). A rectangular contribution with a half-width of 7.0 mΩ is estimated. The associated standard uncertainty is then 4.04 mΩ. With the sensitivity of the Pt100, this corresponds to a standard uncertainty due to hysteresis of 11 mK.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
R_{Br}	Bridge indication for the resistance of the Pt100	168.4783 Ω	6.00E-04 Ω	6.00E-04 Ω	normal	1	1.0	6.000E-04 Ω
$R_S^{EN60751}(T_S)$	Resistance according to EN 60751 to the reference temperature in the oil bath	168.5075 Ω						
δT_S		0.0000 K	8.80E-03 K	8.80E-03 K	normal	1	0.37 Ω/K	3.256E-03 Ω
δR_{Res}	Resolution of the bridge indication	0.0000 Ω	5.00E-04 Ω	2.89E-04 Ω	rectangular	√3	1.0	2.887E-04 Ω
δR_{Par}	Parasitic thermoelectric voltages	0.0000 Ω	0.00E+00 Ω	0.00E+00 Ω	rectangular	√3	1.0	0.000E+00 Ω
δR_{EEw}	Self-heating	0.0000 Ω	9.00E-04 Ω	5.20E-04 Ω	rectangular	√3	1.0	5.196E-04 Ω
δR_{Wa}	Heat dissipation	0.0000 Ω	4.00E-04 Ω	2.31E-04 Ω	rectangular	√3	1.0	2.309E-04 Ω
δR_{Hyst}	Hysteresis	0.0000 Ω	7.00E-03 Ω	4.04E-03 Ω	rectangular	√3	1.0	4.041E-03 Ω
$\delta R_{Ref,Cal}$	Calibration of the reference resistor	0.0000 Ω	1.00E-04 Ω	5.00E-05 Ω	normal	2	1.68	8.400E-05 Ω
$\delta R_{Ref,Drift}$	Drift of the reference resistor	0.0000 Ω	6.00E-04 Ω	3.46E-04 Ω	rectangular	√3	1.68	5.820E-04 Ω
$\delta R_{Ref,T}$	Temperature dependence of the reference resistor	0.0000 Ω	1.80E-04 Ω	1.04E-04 Ω	rectangular	√3	1.68	1.746E-04 Ω
$\delta N_{Br,Cal}$	Calibration of the measuring bridge	0.0000	2.00E-06	1.00E-06	normal	2	100 Ω	1.000E-04 Ω
$\delta N_{Br,Drift}$	Drift of the measuring bridge	0.0000	1.00E-06	5.77E-07	rectangular	√3	100 Ω	5.774E-05 Ω
$\Delta R(T_X)$	**Deviation of the thermometer resistance from the standard characteristic according to EN 60751**	**-0.0292 Ω**	***U* =**	**0.011 Ω**	**(*k* =2)**		***u* =**	**0.0053 Ω**

Table 3: Uncertainty budget calibration result thermometer resistor

At 180.079 °C, the precision resistance thermometer has a resistance of 168.4783 Ω. This corresponds to a deviation from the standard characteristic according to EN 60751 [3] of -0.0292 Ω with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.011 Ω.[4]

If the deviation from the standard characteristic and the associated uncertainty are converted to temperature using the sensitivity coefficient of a Pt100 at 180 °C $c_T = 2.70\ ^{K}/_{\Omega}$, the result is a deviation from the standard characteristic of -80 mK with an expanded measurement uncertainty of 30 mK.

[4] Alternatively, the indication correction can be used instead of the indication deviation. Indication correction and indication deviation differ only by sign. In the above example, the calibration result would then read:
"At 180.079 °C, the precision resistance thermometer has a resistance of 168.4783 Ω. This corresponds to a correction of 0.0292 Ω to the standard characteristic according to EN 60751 [3] with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.011 Ω."
Using the indication correction offers an advantage for the user of the thermometer: the best estimate for the measured temperature/resistance can be determined by adding the correction to the indicated temperature resistance of the thermometer.

A.2: Calibration of an IPRT in a block calibrator

The calibration of the IPRT is carried out by comparison with a Pt100 working standard (calibrated, for example, according to the example in A.1) in a temperature block calibrator using the comparison method at a nominal temperature of 350 °C. The resistance of the working standard thermometer (Pt100) is determined using a resistance bridge with direct temperature indication and internal standard resistor. The resistance of the IPRT is measured with a resistance meter. The resistance of the IPRT at calibration temperature as well as the associated temperature deviation from the standard characteristic according to DIN EN 60751 [3] are stated as calibration result. The working standard thermometer, the measuring bridge, and the device for measuring the resistance have been traceably calibrated by an accredited calibration laboratory.

After a stabilization time of one hour, the arithmetic mean was calculated from 20 individual values over a period of 10 minutes. The uncertainty budget is divided into two steps:

1. Determination of the reference temperature in the block calibrator.
2. Determination of the associated resistance of the IPRT, the associated measurement deviation from the standard characteristic curve according to DIN EN 60751 [3] and the associated expanded measurement uncertainty.

Step 1: Determination of the reference temperature in the block calibrator

The reference temperature is determined from the mean value of the temperature of the equalising block of the block calibrator measured with the working standard. The resistance of the working standard (Pt100) is measured with a measuring bridge with internal reference resistor and indicated in temperature by the measuring bridge with the coefficients determined on the basis of the calibration of the working standard.

Model equation:

$$T_{\mathrm{S}} = T_{\mathrm{m,S}} + \delta T_{\mathrm{cal,S}} + \delta T_{\mathrm{Int,S}} + \delta T_{\mathrm{Drift,S}} + \delta T_{\mathrm{EEw,S}} + \delta T_{\mathrm{Hyst,S}} + \delta T_{\mathrm{Res,S}} + c_{\mathrm{T}} \cdot \left(\delta R_{\mathrm{Par,S}} + \delta R_{\mathrm{Br,Cal}} + \delta R_{\mathrm{Br,Drift}}\right) + \delta T_{\mathrm{Wa}} + \delta T_{\mathrm{axial}} + \delta T_{\mathrm{radial}} + \delta T_{\mathrm{Instab}} \quad (9)$$

The sensitivity coefficient c_{T} results from the characteristic of a Pt100 according to DIN EN 60751 [3] at 350 °C to $c_{\mathrm{T}} = 2.85\ ^{\mathrm{K}}/_{\Omega}$.

The following contributions result for the individual components of the model equation:

$T_{\mathrm{m,S}}$:

The mean value of the relative temperature indication corrected by the associated indication correction of the working standard (Pt100) is determined from all 20 individual measurements. The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the standard thermometer. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022, Annex D [15]). In the example, the result is a mean value of 350.256 °C and 0.0055 K for the standard deviation of the mean value.

$\delta T_{\mathrm{cal,S}}$:

Correction of the temperature of the standard thermometer due to calibration. The standard thermometer is calibrated in the range from 0 °C to 400 °C at a total of 6 temperature points. The corresponding calibration certificate states the resistances of the thermometer as well as the temperature deviation from the standard characteristic according to DIN EN 60751 [3] for the measuring current of 1 mA as well as the associated measurement uncertainty for the range from 0 °C to 400 °C.

The coefficients for the measuring current intensity of 1 mA had been calculated from the calibration data according to DKD-R 5-6:2018 [9] and stored in the measuring bridge. The indication of the temperature of the standard thermometer is calculated by the measuring bridge using the individual coefficients. A calibration correction is thus already taken into account and does not need to be considered further. The maximum expanded uncertainty U of the temperature in the range from 0 °C to 400 °C is taken from the calibration certificate ($U_{(\mathrm{S})}$ = 25 mK; normally distributed, k = 2). The associated standard uncertainty is thus $u_{(\mathrm{S})}$ = 12.5 mK.

$\delta T_{\mathrm{Int,S}}$:

Correction of the temperature indication of the standard thermometer due to interpolation between the calibration points. This contribution is not included in the uncertainty stated in the calibration certificate of the standard thermometer, because the calibration certificate does not specify coefficients for an interpolation function for the entire range and thus no range uncertainty. This contribution must therefore be considered separately.

The coefficients of an interpolation function for the range from 0 °C to 400 °C are determined by the laboratory itself from the 6 calibration points of the standard thermometer according to DKD-R 5-6:2018 [9]. A characteristic according to DIN EN 60751 [3] is approximated in the form of a Callendar-Van-Dusen equation. The coefficients are used in the measuring bridge to convert the measured thermometer resistance into temperature. According to DKD-R 5-6:2018 Table 6.1 [9], a rectangular uncertainty contribution of 25 mK (half-width) is therefore to be assumed for the approximation of the characteristic. The associated standard uncertainty is then 14.4 mK.

$\delta T_{\mathrm{Drift,S}}$:

Correction of the mean temperature of the standard thermometer due to the drift since its last recalibration. From the last calibrations of the working standard, a maximum drift of < 10 mK per year was obtained. This drift represents a rectangular contribution with a half-width of 10 mK. The associated standard uncertainty is then 5.8 mK.

$\delta T_{\mathrm{EEw,S}}$:

Correction of the temperature of the standard thermometer due to its self-heating. During measurement, the resistance of the standard thermometer is measured by the measuring bridge using a measuring current of 1 mA. Generally, the self-heating of the standard thermometer is taken into account by approximation, using the coefficients for the measuring current intensity of 1 mA from the associated calibration certificate for the conversion of the thermometer resistance into temperature. However, there still remains an uncertainty due to self-heating caused by the different thermal couplings of the thermometer sensor to the surrounding temperature field under calibration conditions or in the equalising block of the block calibrator. Since this contribution is already included in the calibration uncertainty of the standard thermometer, it does not need to be considered further. A rectangular distributed residual contribution with a half width of 3 mK is assumed. The associated standard uncertainty is then 1.7 mK.

If the self-heating is not stated in the calibration certificate of the standard thermometer, it must be assumed to be rectangularly distributed with a half-width of 30 mK according to chapter 8.8. The associated standard uncertainty is then 17 mK.

$\delta T_{\mathrm{Hyst,S}}$:

Correction of the temperature of the standard thermometer due to a possible hysteresis. During calibration, the hysteresis was determined to be ±3.5 mΩ ≙ ±10 mK for the calibration range from 0 °C to 400 °C. It is included in the measurement uncertainty stated in the calibration certificate and must therefore not be taken into account again here.

A rectangular contribution with a half-width of the distribution of 0.0 K is therefore assumed. The assigned standard uncertainty is then 0.0 K.

If the hysteresis was not determined during the calibration of the standard thermometers or was not taken into account in the combined measurement uncertainty of the calibration, it must be determined separately (see chapter 8.10) and taken into account as the half-width of a rectangular distribution.

$\delta T_{\mathrm{Res,S}}$:

Correction due to the resolution of the temperature of the standard thermometers indicated by the measuring bridge. The resolution of the temperature indication is 1 mK. Therefore, a rectangular contribution with a half-width of 0.5 mK is assumed. The associated standard uncertainty is then 0.29 mK.

$\delta R_{\mathrm{Par,S}}$:

Correction due to parasitic thermoelectric voltages in the measuring circuit of the standard thermometer. Since the measuring bridge operates with alternating direct current and each indicated measured value represents an average of both current directions, any measurement deviations due to parasitic thermoelectric voltages in the measuring circuit approximately compensate each other. Therefore, a rectangular contribution with a half-width of 0.0 Ω is assumed. The associated standard uncertainty is then 0.0 Ω.

$\delta R_{\mathrm{Br,Cal}}$:

Correction due to calibration of the measuring bridge. The expanded uncertainty of the calibration of the measuring bridge is given in the calibration certificate as $2 \cdot 10^{-6}$ (expanded measurement uncertainty; $k = 2$). With the resistance of the standard thermometer at a calibration temperature of 229.8 Ω, this results in an uncertainty of the thermometer resistance due to calibration of the measuring bridge of 0.5 mΩ (normally distributed; $k = 2$). The associated standard uncertainty is then 0.25 mΩ.

$\delta R_{\mathrm{Br,Drift}}$:

Correction due to drift of the measuring bridge since its last calibration. The recalibration interval is 1 year. According to the manufacturer's specification, the maximum drift within one year is within the limits of 0.4 mΩ. The uncertainty contribution is therefore assumed to be rectangular distributed with a half-width of ±0.4 mΩ. The associated standard uncertainty is then 0.23 mΩ.

δT_{Wa} :

Correction due to heat dissipation of the standard thermometer in the equalising block of the block calibrator. The working standard thermometer is immersed to the maximum in a suitable hole in the equalising block (difference between the outer diameter of the thermometer and the hole diameter is less than 1 mm, i.e. the gap is less than 0.5 mm, see also DKD-R 5-4 [10]). The immersion depth in the block is 120 mm. The thermometer diameter is 8 mm. The internal structure of the thermometer is not known. The standard thermometer is thus immersed in the block less than 15 times its diameter plus the sensor length. With the worst-case assumption of a sensor length of max. 40 mm, the "effective" immersion depth is 10 times the thermometer diameter. The estimated heat dissipation error is thus less than $5 \cdot 10^{-5} \cdot (T - T_{\mathrm{amb}}) = 5 \cdot 10^{-5} \cdot 320\ \mathrm{K} = 16\ \mathrm{mK}$ (estimate according to Traceable Temperatures – An Introduction to Temperature Measurement and Calibration [16]).

A rectangular contribution with a half-width of 16 mK is assumed. The associated standard uncertainty is then 9.2 mK.

Alternatively, the heat dissipation error could also be determined by pulling out the standard by at least twice its diameter and taken into account.

$\delta T_{\mathrm{axial}}$:

Correction due to axial inhomogeneity of the temperature in the equalising block of the block calibrator. An examination of the block calibrator according to DKD-R 5-4 [10] has shown that the maximum deviation of the temperature in the axial direction in the equalising block is ±30 mK.

Therefore, a rectangular contribution with a half-width of 30 mK is assumed. The associated standard uncertainty is then 17.3 mK.

$\delta T_{\mathrm{radial}}$:

Correction due to radial inhomogeneity of the temperature in the equalising block of the block calibrator. An examination of the block calibrator according to DKD-R 5-4 [10] has shown that the maximum deviation of the temperature in radial direction in the measuring volume is ±8 mK.

Therefore, a rectangular contribution with a half-width of 8 mK is assumed. The associated standard uncertainty is then 4.6 mK.

$\delta T_{\mathrm{Instab}}$:

Correction due to instability of the temperature in the equalising block of the block calibrator. The examination of the block calibrator according to DKD-R 5-4 [10] has shown a maximum deviation of the temperature from the mean value over 30 minutes of ±25 mK. Therefore, a rectangular contribution with a half-width of 25.0 mK is assumed. The associated standard uncertainty is then 14.4 mK.[5]

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
$T_{\text{m,S}}$	Mean value of the corrected readings of the working standard	350.2560 °C	0.0055 K	5.50E-03 K	normal	1	1.0	5.50E-03 K
$\delta T_{\text{cal,S}}$	Calibration of the working standard	0.0000 K	0.0250 K	1.25E-02 K	normal	2	1.0	1.25E-02 K
$\delta T_{\text{Int,S}}$	Interpolation between the calibration points of the working standard	0.0000 K	0.0250 K	1.44E-02 K	rectangular	√3	1.0	1.44E-02 K
$\delta T_{\text{Drift,S}}$	Drift of the working standard	0.0000 K	0.0100 K	5.77E-03 K	rectangular	√3	1.0	5.77E-03 K
$\delta T_{\text{EEw,S}}$	Self-heating of the working standard	0.0000 K	0.0030 K	1.73E-03 K	rectangular	√3	1.0	1.73E-03 K
$\delta T_{\text{Hyst,S}}$	Hysteresis of the working standard	0.0000 K	0.0000 K	0.00E+00 K	rectangular	√3	1.0	0.00E+00 K
$\delta T_{\text{Res,S}}$	Resolution of the measuring bridge	0.0000 K	0.0005 K	2.89E-04 K	rectangular	√3	1.0	2.89E-04 K
$\delta R_{\text{Par,S}}$	Parasitic thermoelectric voltages	0.0000 Ω	0.0000 Ω	0.00E+00 Ω	rectangular	√3	2.85 K/Ω	0.00E+00 K
$\delta R_{\text{Br,Cal}}$	Calibration of the measuring bridge	0.0000 Ω	0.0005 Ω	2.50E-04 Ω	normal	2	2.85 K/Ω	7.13E-04 K
$\delta R_{\text{Br,Drift}}$	Drift of the measuring bridge	0.0000 Ω	0.0004 Ω	2.31E-04 Ω	rectangular	√3	2.85 K/Ω	6.582E-04 K
δT_{Wa}	Heat dissipation	0.0000 K	0.0160 K	9.24E-03 K	rectangular	√3	1.0	9.238E-03 K
δT_{axial}	Axial inhomogeneity in the block calibrator	0.0000 K	0.0300 K	1.73E-02 K	rectangular	√3	1.0	1.73E-02 K
δT_{radial}	Radial inhomogeneity in the block calibrator	0.0000 K	0.0080 K	4.62E-03 K	rectangular	√3	1.0	4.62E-03 K
δT_{Instab}	Time-related instability in the block calibrator	0.0000 K	0.0250 K	1.44E-02 K	rectangular	√3	1.0	1.44E-02 K
$\boldsymbol{T_{\text{S}}}$	**Temperature in the block calibrator**	**350.2560 °C**					***u*** =	**0.0324 K**

Table 4: Measurement uncertainty budget of the temperature in the equalising block of the block calibrator (measured by means of the working standard thermometer)

Step 2: Calibration result

The deviation of the temperature indicated by the calibration item from the temperature measured in the equalisation block of the block calibrator represents the calibration result.

The resistance of the calibration item (Pt100-IPRT) is measured at temperature T_{X}. A resistance meter is used for measurement. The resistance meter is used in the 1 kΩ measuring range with a measuring current of 1 mA in “true ohm mode” (that means measurement is carried out with both current directions and then averaged internally).

The model for this measurement reads

$$\Delta R(T_{\text{X}}) = R_{\text{S}}^{\text{EN60751}}(T_{\text{S}}) - R_{\text{DVM}} + c_{\text{R}} \cdot (\delta T_{\text{S}} + \delta T_{\text{EEw}}) + \delta R_{\text{Res}} + \delta R_{\text{Par}} + \delta R_{\text{Wa}} + \delta R_{\text{Hyst}} + \delta R_{\text{Cal,DVM}} + \delta R_{\text{Drift,DVM}} \quad (10)$$

[5] As an alternative to the investigation of the contributions of instability and axial and radial inhomogeneity of the block calibrator, the data from a calibration of the block calibrator according to DKD-R 5-4 [10] can also be used.

For a Pt100 at 350 °C, the sensitivity coefficient c_{R} is: $c_{\mathrm{R}} = 0.35\ ^{\Omega}/_{K}$.

The individual contributions are as follows:

$R_{\mathrm{S}}^{\mathrm{EN60751}}(T_{\mathrm{S}})$:

As first step, the temperature of the equalising block of the block calibrator has been determined to be 350.256 °C by means of the working standard thermometer. The corresponding resistance of a Pt100 according to DIN EN 60751 [3] is 229.8058 Ω.

$R_{\mathrm{DVM}}, \delta R_{\mathrm{DVM}}$:

The measuring bridge measures the resistance of the IPRT to be calibrated using a measuring current of 1 mA in "true ohm mode" (which means that the measurement is carried out with both current directions and averaged internally). The resistance is indicated by the measuring bridge.

The mean value of the reading is determined from all individual measurements of the thermometer resistance at calibration temperature (20 readings each). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the measuring bridge. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022 [15]). In the example, this results in a mean value of 229.9905 Ω, and 0.0022 Ω for the standard deviation of the mean value.

δT_{S} :

Correction of the temperature in the block calibrator. The uncertainty of the temperature in the block calibrator has been determined in the first step. The associated standard uncertainty is 32.4 mK.

δT_{EEw} :

Correction of the temperature of the thermometer to be calibrated due to its self-heating. During measurement, the resistance of the thermometer is measured by the measuring bridge with a measuring current of 1 mA. The resistance measuring device does not offer the possibility to measure the thermometer resistance with different measuring currents. The change in the thermometer resistance due to self-heating caused by the measuring current of 1 mA is therefore assumed as maximum temperature uncertainty of 30.0 mK according to chapter 8.8. It represents a rectangular contribution with a half-width of 30.0 mK. The associated standard uncertainty is then 17 mK.

δR_{Res} :

Correction based on the resolution of the resistance of the thermometer indicated by the resistance measuring device at calibration temperature. The resolution of the resistance indication is 1 mΩ. Therefore, a rectangular contribution with a half-width of 0.5 mΩ is assumed. The associated standard uncertainty is then 0.29 mΩ.

δR_{Par} :

Correction due to parasitic thermoelectric voltages in the measuring circuit of the IPRT. Since the resistance meter operates with alternating direct current and each indicated measured value represents an average of both current directions, any measurement errors due to parasitic thermoelectric voltages in the measuring circuit compensate each other approximately. Therefore, a rectangular contribution with a half-width of 0.0 Ω is assumed. The associated standard uncertainty is then 0.0 Ω.

δR_{Wa} :

Correction due to heat dissipation of the IPRT. The thermometer to be calibrated has an outer diameter of 6 mm. The immersion depth in the equalising block is 120 mm. Since there is no information about the internal structure, the heat dissipation error is determined experimentally by pulling out the thermometer by twice its diameter (12 mm). The thermometer resistance decreases by 3.4 mΩ after being pulled out. A rectangular contribution with a half-width of 3.4 mΩ is assumed. The associated standard uncertainty is then 1.96 mΩ.

Together with the sensitivity of the Pt100, this corresponds to a standard uncertainty due to heat dissipation of 5.6 mK.

δR_{Hyst} :

Correction of the temperature of the IPRT due to hysteresis. Depending on the design, the hysteresis is generally not negligible for IPRTs. The hysteresis is determined or estimated according to chapter 8.10. The thermometer is only calibrated with increasing temperatures. The hysteresis is therefore not determined and not taken into account in the measurement uncertainty of the calibration. According to chapter 8.10, the following information is therefore given in the calibration certificate:

> *The calibration was carried out in the temperature range from 0 °C to 400 °C using a programme with ascending temperature steps. The influence of the hysteresis was not determined experimentally. It can be assumed that this influence can amount to up to 0.8 K in the above-mentioned temperature range if the measurements are not carried out continuously at ascending temperatures when using the IPRT. The highest influence is to be expected in the middle of the temperature range.*

Therefore, a rectangular contribution with a full width of 0.0 mΩ or a half-width of 0.0 mΩ is assumed. The associated standard uncertainty is then 0.0 mΩ.

$\delta R_{\mathrm{Cal,DVM}}$:

Correction due to the calibration of the resistance measuring device. The expanded uncertainty of calibration of the resistance meter is stated in the calibration certificate as 5-10-6 (expanded measurement uncertainty; k = 2). For the 1 kΩ measuring range, this results in an uncertainty of the thermometer resistance due to the calibration of the resistance meter of 5.0 mΩ (normally distributed; k = 2). The associated standard uncertainty is then 2.5 mΩ.

$\delta R_{\mathrm{Drift,DVM}}$:

Correction due to the drift of the resistance measuring device since its last calibration. The recalibration interval is 1 year. According to the manufacturer's specification, the maximum drift within one year in the operating temperature range of (23±5) °C in the 1 kΩ measuring range lies within the following limits: 0.006 % of value + 0.0002 % of range. With a thermometer resistance of 230 Ω, limits of ±15.8 mΩ result. The uncertainty contribution is therefore assumed to be rectangularly distributed with a half-width of ±15.8 mΩ. The associated standard measurement uncertainty is then 9.12 mΩ.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
R_{DVM}	Indication of the resistance meter	229.9905 Ω	0.0022 Ω	2.20E-03 Ω	normal	1	-1.0	-2.200E+00 Ω
$R_S^{EN60751}(T_S)$	Resistance according to EN 60751 for reference temperature in the oil bath	229.8058 Ω						
δT_S	Correction of the temperature in the block calibrator	0.0000 K	0.0324 K	3.24E-02 K	normal	1	0.35 Ω/K	1.134E-02 Ω
δT_{EEw}	Self-heating	0.000 K	0.030 K	1.73E-02 K	rectangular	√3	0.35 Ω/K	6.062E-03 Ω
δR_{Res}	Resolution of the resistance meter	0.0000 Ω	0.0005 Ω	2.89E-04 Ω	rectangular	√3	1.0	2.887E-04 Ω
δR_{Par}	Parasitic thermoelectric voltages	0.0000 Ω	0.0000 Ω	0.00E+00 Ω	rectangular	√3	1.0	0.000E+00 Ω
δR_{Wa}	Heat dissipation	0.0000 Ω	0.0034 Ω	1.96E-03 Ω	rectangular	√3	1.0	1.963E-03 Ω
δR_{Hyst}	Hysteresis	0.0000 Ω	0.0000 Ω	0.00E+00 Ω	rectangular	√3	1.0	0.000E+00 Ω
$\delta R_{Cal,DVM}$	Calibration of the resistance meter	0.0000 Ω	0.0050 Ω	2.50E-03 Ω	normal	2	1.0	2.500E-03 Ω
$\delta R_{Drift,DVM}$	Drift of the resistance meter	0.0000 Ω	0.0158 Ω	9.12E-03 Ω	rectangular	√3	1.0	9.122E-03 Ω
$\Delta R(T_x)$	**Deviation of the thermometer resistance from the standard characteristic according to EN 60751**	**0.185 Ω**	***U* =**	**0.032 Ω**	**(*k*=2)**		***u* =**	**0.0162 Ω**

Table 5: Uncertainty budget calibration result thermometer resistance

The industrial platinum resistance thermometer (IPRT) has a resistance of 229.990 Ω at 350.256 °C. This corresponds to a deviation from the standard characteristic according to DIN EN 60751 [3] of 0.185 Ω, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.032 Ω.[6]

If the deviation from the standard characteristic and the associated uncertainty are converted to temperature using the sensitivity coefficient of a Pt100 at 350 °C $c_T = 2.85\ ^{K}/_{\Omega}$, the result is a deviation from the standard characteristic of 0.60 K with an expanded measurement uncertainty U of 0.094 K.

If calibration of the IPRT is carried out in this way in the range from 0 °C to 400 °C with at least 5 different temperatures distributed over the temperature range and the largest expanded uncertainty is 0.12 K (determined as in the example at 400 °C), then a characteristic can be

[6] Alternatively, the indication correction can be used instead of the indication deviation. The correction differs from the deviation only by sign. In the above example, the calibration result would then read:
"At 350.256 °C, the platinum resistance thermometer (IPRT) has a resistance of 229.990 Ω. This corresponds to a correction to the standard characteristic according to DIN EN 60751 [3] of -0.185 Ω, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor $k = 2$) of 0.032 Ω."
For the user of the thermometer, the use of the indication correction offers the advantage that the best estimate for the measured temperature / resistance can be determined by adding the correction to the indicated temperature / resistance of the thermometer.

approximated for the IRPT in the form of a Callendar-Van-Dusen equation (analogous to DIN EN 60751 [3]) and the associated coefficients R_0, a and b can be determined in accordance to DKD-R 5-6 [9]. The uncertainty for the entire range from 0 °C to 400 °C with this characteristic is then determined according to DKD-R 5-6 chapter 8.1.1 [9].

The model for temperature measurement by means of this characteristic curve for the calibration range (without the uncertainty of the resistance measurement by the user and without additional temperature uncertainties due to drift, hysteresis and heat dissipation etc.) results in:

$$T(R_{\mathrm{IPRT}}) = f\,(R_{\mathrm{IPRT}}, R_0, A, B) \; + \; \delta T_{\mathrm{Cal}} + \delta T_{\mathrm{Kennlinie,Typ}} + \delta T_{\mathrm{Kennlinie,Res.}} \tag{11}$$

Here, $f\,(R_{\mathrm{IPRT}}, R_0, A, B)$ is the inverse function of the Callendar-van-Dusen equation

$$R(T) = R_0 \cdot (1 + A \cdot T + B \cdot T^2 + C \cdot (T - 100\,°C) \cdot T^3) \; with\; C = 0\; für\; T \geq 0\,°C \tag{12}$$

The following contributions result for the individual components of the model equation:

δT_{cal}:

Correction of the temperature of the IPRT due to calibration. The IPRT is calibrated in the range from 0 °C to 400 °C at a total of 5 temperature points. The corresponding calibration certificate shows the resistances of the thermometer as well as the temperature deviation from the standard characteristic according to DIN EN 60751 [3] for a measuring current of 1 mA and the corresponding measurement uncertainties of the individual calibration points.

The maximum expanded measurement uncertainty U of the temperature in the range from 0 °C to 400 °C is taken from the calibration certificate (U = 0.12 K; normal distribution, k = 2). The associated standard uncertainty is thus u = 0.06 K.

$\delta T_{\mathrm{Kennlinie,\,Typ}}$:

Correction of the temperature of the IPRT due to interpolation between the calibration points by means of a characteristic according to Callendar-Van-Dusen. This contribution is not included in the uncertainty given in the calibration certificate of the standard thermometer, because the calibration certificate does not give coefficients for an interpolation function for the entire range and thus also no range uncertainty. This contribution must therefore be considered separately.

The coefficients of an interpolation function for the range from 0 °C to 400 °C are determined from the 5 calibration points of the IPRT according to DKD-R 5-6 [9]. The coefficients are used to convert the measured thermometer resistance of the IPRT into temperature. This contribution only takes into account the deviation which results from the fact that the applied characteristic curve approach does not adequately describe the behaviour of a Pt resistance thermometer in the corresponding temperature range. According to DKD-R 5-6 Table 6.1 [9], a rectangular uncertainty contribution of 25 mK (half-width) is therefore to be applied for the approximation of the characteristic. The associated standard uncertainty is then 14.4 mK (half-width).

$\delta T_{\text{Kennlinie,Res.}}$:

Correction of the temperature of the IPRT due to the interpolation between the calibration points by means of a characteristic according to Callendar-Van-Dusen. This contribution is not included in the uncertainty stated in the calibration certificate of the standard thermometer because the calibration certificate does not state coefficients for an interpolation function for the entire range and, as a consequence, does not state a range uncertainty. This contribution must therefore be considered separately.

The coefficients of an interpolation function for the range from 0 °C to 400 °C are determined from the 5 calibration points of the IPRT according to DKD-R 5-6 [9]. The coefficients are used to convert the measured thermometer resistance of the IPRT into temperature. In addition to the contribution $\delta T_{\text{Kennlinie,Typ}}$ and according to DKD-R 5-6 Kap. 2.3.2 [9], a normally distributed uncertainty contribution must be taken into account. It results from the residuals of the adjusted characteristic and the applied supporting points. This contribution can be estimated by means of the standard deviation for individual values from all residuals. This resulted in a standard deviation of the residuals of 22 mK. The associated standard uncertainty is then 22 mK.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
δT_{Cal}	Calibration of the IPRT	0.000 °C	0.120 K	0.0600 K	normal	2	1.0	0.0600 K
$\delta T_{\text{Kennlinie,Typ}}$	Approximation of the characteristic (type)	0.000 °C	0.025 K	0.0144 K	rectangular	√3	1.0	0.0144 K
$\delta T_{\text{Kennlinie,Res.}}$	Approximation of the characteristic (residue)	0.000 °C	0.022 K	0.0220 K	normal	1	1.0	0.0220 K
$T(R_{\text{IPRT}})$	**Temperature of the IPRT**		**U =**	**0.13 K**	**(k=2)**		**u =**	**0.0655 K**

Table 6: Uncertainty budget calibration result thermometer characteristic

With the given characteristic in the temperature range from 0 °C to 400 °C, an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.13 K results for the IPRT. This does not include the uncertainty of the resistance measurement by the user or additional temperature uncertainties due to drift, hysteresis and heat dissipation etc.). The influence of hysteresis has not been determined experimentally. It can be assumed that the hysteresis influence can amount to up to 0.8 K in the above-mentioned temperature range. The highest influence is to be expected in the middle of the temperature range.

If the hysteresis is not determined, but is included in the total measurement uncertainty, then an additional contribution of 0.4 K (half-width of the rectangular distributed contribution) must be taken into account for the above-mentioned temperature range.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
δT_{Cal}	Calibration of the IPRT	0.000 K	0.120 K	0.0600 K	normal	2	1.0	0.060 K
$\delta T_{\mathrm{Kennlinie,Typ}}$	Approximation of the characteristic (type)	0.000 K	0.025 K	0.0144 K	rectangular	√3	1.0	0.014 K
$\delta T_{\mathrm{Kennlinie,Res.}}$	Approximation of the characteristic (residue)	0.000 K	0.022 K	0.0220 K	normal	1	1.0	0.022 K
δT_{Hyst}	Hysteresis	0.000 K	0.400 K	0.2309 K	rectangular	√3	1.0	0.231 K
$T(R_{\mathrm{IPRT}})$	**Temperature of the IPRT**		***U* =**	**0.48 K**	**(*k* =2)**		***u* =**	**0.240 K**

Table 7: Uncertainty budget calibration result thermometer characteristic taking into account an estimated 0.2 % of the temperature range as maximum hysteresis

The expanded measurement uncertainty for the temperature range is then 0.48 K.[7]

[7] Here, it can be seen very clearly that the hysteresis of the calibration object IPRT does make a considerable contribution to the overall measurement uncertainty. Therefore, it cannot be neglected when determining the measurement uncertainty for a specific application and must be additionally taken into account by the user if it is not already included in the uncertainty of the calibration! If it is not determined experimentally, then a contribution according to chapter 8.10 must be applied. For high-quality Pt100s, however, it can also be smaller. Therefore, in the interest of the smallest possible, but realistic estimation of the measurement uncertainty for the application, it is recommended to always determine the hysteresis experimentally and to take it into account.

A.3: Calibration of a digital thermometer in the block calibrator

The calibration of a digital thermometer with connected Pt100 sensor is carried out by comparison with a working standard Pt100 (for instance, calibrated according to the example in A.1) in a temperature block calibrator using the comparison method, at a nominal temperature of 350 °C. The resistance of the working standard thermometer (Pt100) is determined by means of a resistance bridge with direct temperature indication and internal standard resistor. The temperature of the Pt100 sensor of the digital thermometer is read directly from the display. The temperature deviation of the indication of the digital thermometer from the reference temperature is given as calibration result. The working standard thermometer and the measuring bridge have been calibrated by an accredited laboratory.

After a stabilisation time of one hour, the arithmetic mean value was calculated from 20 individual values over a period of 10 minutes. The uncertainty budget is divided into 2 steps.

1. Determination of the reference temperature in the block calibrator.
2. Determination of the associated indication error of the digital thermometer as well as the associated expanded measurement uncertainty.

Step 1: Determination of the reference temperature in the block calibrator

The determination of the reference temperature with the working standard thermometer is carried out according to the same procedure as in step 1, example A.2. Therefore, the same measurement uncertainty budget applies to this step.

For the reference temperature in the equalising block of the block calibrator, this results in a temperature of 350.256 °C with an associated standard uncertainty (normal distribution) of u = 32.4 mK.

Step 2: Calibration result

The deviation of the temperature indicated by the digital thermometer from the temperature measured in the equalising block of the block calibrator represents the calibration result.

The model for this measurement is:

$$\Delta T_{\mathrm{X}} = T_{\mathrm{X}} - T_{\mathrm{S}} + \delta T_{\mathrm{Res}} + \delta T_{\mathrm{EEw}} + \delta T_{\mathrm{Wa}} + \delta T_{\mathrm{Hyst}} \qquad (13)$$

The individual contributions are as follows:

T_{S} :

In the first step, the temperature of the equalising block of the block calibrator has been determined to be 350.256 °C by means of the working standard thermometer. The associated standard measurement uncertainty u is 32.4 mK.

T_X ; δT_X :

After having reached stable conditions, the digital thermometer is read 20 times at intervals of 30 seconds within 10 minutes. The mean value of the reading is determined from all individual measurements of the thermometer display at calibration temperature (20 readings each). The type A uncertainty contribution is determined from the standard deviation of the mean value. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022 [15]). In the example, this results in a mean value of 350.49 °C, and 0.07 K for the standard deviation of the mean value.

δT_{Res} :

Correction due to the resolution of the digital thermometer at calibration temperature. The resolution of the digital thermometer is 0.1 K. Therefore, a rectangular contribution with a half-width of 0.05 K is assumed. The associated standard uncertainty is then 0.0289 K.

δT_{EEw} :

Correction of the temperature of the digital thermometer due to self-heating of the Pt100 sensor. The digital thermometer does not offer the possibility to measure the sensor resistance with different measuring currents. The change in the thermometer resistance due to self-heating by the measuring current is therefore assumed to be a maximum temperature uncertainty of 30 mK according to Chapter 8.8. It represents a rectangular contribution with a half-width of 30 mK. The associated standard uncertainty is then 17 mK.

δR_{Wa} :

Correction due to heat dissipation of the Pt100 sensor. The sensor of the thermometer to be calibrated has an outer diameter of 6 mm. The immersion depth in the equalising block is 120 mm. Since there is no information about the internal structure, the heat dissipation error is determined experimentally by pulling out the thermometer by twice its diameter (12 mm). After pulling out the thermometer, the temperature indication decreases by less than one resolution step. A rectangular contribution with a half-width of 0.05 K is assumed. The associated standard uncertainty is then 0.029 K.

δT_{Hyst} :

Correction of the temperature of the digital thermometer due to the hysteresis of the Pt100 sensor. The hysteresis of the Pt100 sensor is determined according to chapter 8.10 by calibrating the mean temperature of 200 °C of the calibration range from 0 °C to 400 °C, using an increasing and a decreasing temperature profile. The difference of both calibrations at 200 °C was 0.3 K. Therefore, a rectangular contribution with a full width of 0.3 K or a half width of 0.15 K is assumed. The associated standard uncertainty is then 0.087 K.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
T_X	Indication of the digital thermometer	350.49 °C	0.07 K	0.0700 K	normal	1	1.0	0.0700 K
T_S	Reference temperature in the block calibrator	350.256 °C	0.0324 K	0.0324 K	normal	1	-1.0	-0.0324 K
δT_{Res}	Resolution of the digital thermometer	0.000 K	0.050 K	0.0289 K	rectangular	√3	1.0	0.0289 K
δT_{EEw}	Self-heating	0.000 K	0.030 K	0.0173 K	rectangular	√3	1.0	0.0173 K
δT_{Wa}	Heat dissipation	0.000 K	0.050 K	0.0289 K	rectangular	√3	1.0	0.0289 K
δT_{Hyst}	Hysteresis	0.000 K	0.150 K	0.0866 K	rectangular	√3	1.0	0.0866 K
ΔT_X	**Indication error of the digital thermometer**	**0.23 K**	***U* =**	**0.25 K**	**(*k* =2)**		***u* =**	**0.124 K**

Table 8: Uncertainty budget calibration result digital thermometer

The digital thermometer has an indication deviation of 0.23 K at 350.256 °C, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.25 K.[8]

[8] Alternatively, the indication correction can be used instead of the indication deviation. The correction differs from the deviation only by sign. In the above example, the calibration result would then read:
"The digital thermometer has a display correction of -0.23 K at 350.256 °C, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.25 K".
The use of the indication correction offers the user of the thermometer the advantage that the best estimate for the measured temperature can be determined by adding the correction to the indicated temperature of the thermometer.

A.4: Calibration of a transmitter with resistance sensor

Calibration of the resistance thermometer with transmitter is carried out by comparison with a working standard of the Pt100 type (e.g. calibrated according to the example in A.1) in a temperature block calibrator using the comparison method at a nominal temperature of 350 °C. The resistance of the working standard thermometer (Pt100) is determined with a resistance bridge with direct temperature indication and internal standard resistor. The temperature of the Pt100 sensor with transmitter is determined by measuring the output current of the transmitter with a digital multimeter. As calibration result, the intensity of the output current of the transmitter in relation to the reference temperature as well as the temperature deviation of the temperature calculated with the scaling of the transmitter from the measured intensity of the output current to the reference temperature is indicated. The working standard thermometer, the measuring bridge and the digital multimeter have previously been calibrated by an accredited laboratory.

After a stabilisation time of 1 hour, the arithmetic mean value was calculated from 20 individual values over a period of 10 minutes. The measurement uncertainty budget is divided into 2 steps.

1. Determination of the reference temperature in the block calibrator.
2. Determination of the associated output current of the transmitter and the associated measurement deviation from the transmitter scaling as well as the associated expanded measurement uncertainty.

Step 1: Determination of the reference temperature in the block calibrator

The determination of the reference temperature with the working standard thermometer is carried out according to the same procedure as in step 1, example A.2. Therefore, the same measurement uncertainty budget applies to this step.

For the reference temperature in the equalising block of the block calibrator, this results in a temperature of 350.256 °C with an associated standard measurement uncertainty (normal distribution) of u = 32.4 mK.

Step 2: Calibration result

The deviation of the temperature indicated by the digital thermometer from the temperature measured in the equalising block of the block calibrator represents the calibration result.

The model for the measurement of the transmitter output current is calculated as follows:

$$\Delta I_{\mathrm{X}}(T_{\mathrm{X}}) = I_{\mathrm{X}} - I_0 - c_{\mathrm{Trans}} \cdot (T_{\mathrm{S}} - T_0) + \delta I_{\mathrm{Cal}} + \delta I_{\mathrm{Drift}} + \delta I_{\mathrm{Amb}} + \delta I_{\mathrm{Load}} + \delta I_{\mathrm{Wa}} + \delta I_{\mathrm{Hyst}} + c_{\mathrm{Trans}} \cdot \delta T_{\mathrm{EEw}} \qquad (14)$$

with the transconductance of the transmitter c_{Trans} as well as the minimum output current I_0 and the associated minimum temperature T_0 .

To determine the temperature of the thermometer from the transmitter current, the following results:

$$\begin{aligned}\Delta T_X = {} & T_X(I_X) - T_S + \delta T_{EEw} + c_{Inv} \\ & \cdot \left(\delta I_X + \delta I_{Cal} + \delta I_{Drift} + \delta I_{Amb} + \delta I_{Load} + \delta I_{Wa} + \delta I_{Hyst}\right) \\ = {} & T_0 + c_{Inv} \cdot (I_X - I_0) - T_S + \delta T_{EEw} \\ & + c_{Inv} \cdot \left(\delta I_{Cal} + \delta I_{Drift} + \delta I_{Amb} + \delta I_{Load} + \delta I_{Wa} + \delta I_{Hyst}\right)\end{aligned} \qquad (15)$$

The transmitter is scaled in such a way that the following applies to the intensity of its output current in the temperature measurement range

$I_{min} = I_0 = 4$ mA at $T_{min} = T_0 = 0$ °C and $I_{max} = 20$ mA at $T_{max} = 400$ °C.

This results in the following values for the sensitivity coefficients:

$c_{Trans} = {}^{16\ \mathrm{mA}}/_{400\ \mathrm{K}} = 0.04\ {}^{\mathrm{mA}}/_{\mathrm{K}}$ and $c_{Inv} = {}^{400\ \mathrm{K}}/_{16\ \mathrm{mA}} = 25\ {}^{\mathrm{K}}/_{\mathrm{mA}}$

The individual contributions are as follows:

T_S :

In the first step and by means of the working standard thermometer, the temperature of the compensating block of the block calibrator was determined to be 350.256 °C. The associated standard measurement uncertainty is u = 32.4 mK.

δI_{Cal} :

Correction due to calibration of the digital multimeter (DMM). The expanded uncertainty of the calibration of the DMM is stated in the calibration certificate as 1.5 μA (expanded measurement uncertainty; k = 2). The associated standard uncertainty is then u = 0.00075 mA.

δI_{Drift} :

Correction due to the drift of the digital multimeter since its last calibration. The recalibration interval is 1 year. According to the manufacturer's specification, the maximum drift within one year, at an operating temperature range of (23±5) °C in the 100-mA measuring range lies within the following limits: 0.05 % of value + 0.005 % of range. With a transmitter current of 18.02 mA, the resulting limits are ±0.014 mA. The uncertainty contribution is therefore assumed to be rectangularly distributed with a half-width of ±0.014 mA. The associated standard uncertainty is then 0.0081 mA.

I_X :

After having reached a stable condition, the digital multimeter is read 20 times at intervals of 30 seconds within 10 minutes. The mean value of the readings is determined from all individual measurements of the transmitter current at calibration temperature (20 readings each). The type A uncertainty contribution is determined from the standard deviation of the mean value. If the number of readings is small (≤ 10), a factor corresponding to the t distribution may have to be added here to account for the low number of degrees of freedom (see EA-4/02 M: 2022 [15]). In the example, this results in a mean value of 18.02 mA, and 0.005 mA for the standard deviation of the mean value.

δI_{Amb} :

Correction due to ambient influences on the transmitter: Based on the information provided by the client, the operating temperature of the transmitter in use is between 40 °C and 60 °C. During calibration, the temperature of the transmitter was 52 °C. Based on the manufacturer's specification, the output current may change by a maximum of ±6 µA due to the expected influences. The uncertainty contribution is therefore assumed to be rectangularly distributed with a half-width of ±0.006 mA. The associated standard uncertainty is then 0.0035 mA.

δI_{Load} :

Correction due to feedback effects of the input resistance of the connected evaluation electronics (load dependence). According to the data sheet, the influence amounts to a maximum of 8 µA. The uncertainty contribution is therefore assumed to be rectangularly distributed with a half-width of ±0.008 mA. The associated standard uncertainty is then 0.0046 mA.

δT_{EEw} :

Correction of the temperature of the Pt100 with transmitter due to self-heating of the Pt100 sensor. The transmitter does not offer the possibility to measure the sensor resistance with different measuring currents. According to chapter 8.8, the change of the thermometer resistance due to self-heating by the measuring current is therefore assumed as maximum temperature uncertainty of 30 mK. It represents a rectangular contribution with a half-width of 30 mK. The associated standard uncertainty is then 17 mK.

δI_{Wa} :

Correction due to heat dissipation of the thermometer. The thermometer to be calibrated has an outer diameter of 6 mm. The immersion depth in the equalising block is 120 mm. Since there is no information regarding the internal structure, the heat dissipation error is determined experimentally by pulling out the thermometer by twice its diameter (12 mm). After pulling out the thermometer, the transmitter current is reduced by 0.002 mA. A rectangular contribution with half a half-width of 0.002 mA is assumed. The associated standard uncertainty is then 0.0012 mA.

δI_{Hyst} :

Correction of the temperature of the Pt100 with transmitter due to the hysteresis of the Pt100 sensor. The hysteresis of the Pt100 sensor is determined according to chapter 8.10 by calibrating the mean temperature (200 °C) of the calibration range (0 °C to 400 °C) with increasing and decreasing temperatures. The difference of both calibrations at 200 °C was 0.012 mA. Therefore, a rectangular contribution with a full width of 0.012 mA or a half width of 0.006 mA is applied. The associated standard uncertainty is then 0.0035 mA.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
I_X	Transmitter current	18.020 mA	0.0050 mA	0.0050 mA	normal	1	1.0	0.00500 mA
$I(Ts)$	Current at reference temperature in the block calibrator	18.010 mA	0.0324 K	0.0324 K	normal	1	-0.040 mA/K	-0.00130 mA
δI_{Cal}	Calibration of the DMM	0.000 mA	0.0015 mA	0.00075 mA	normal	2	1.0	0.00075 mA
δI_{Drift}	Drift of the DMM	0.000 mA	0.0140 mA	0.00808 mA	rectangular	√3	1.0	0.00808 mA
δI_{Amb}	Ambient influence on the transmitter	0.000 mA	0.0060 mA	0.00346 mA	rectangular	√3	1.0	0.00346 mA
δI_{Load}	Load dependence of the transmitter	0.000 mA	0.0080 mA	0.00462 mA	rectangular	√3	1.0	0.00462 mA
δI_{Wa}	Heat dissipation	0.000 mA	0.0020 mA	0.00115 mA	rectangular	√3	1.0	0.00115 mA
δI_{Hyst}	Hysteresis	0.000 mA	0.0060 mA	0.00346 mA	rectangular	√3	1.0	0.00346 mA
δT_{EEw}	Self-heating	0.000 K	0.0300 K	0.01732 K	rectangular	√3	0.040 mA/K	0.00069 mA
ΔI_X	**Deviation of the transmitter current**	**0.010 mA**	**U =**	**0.024 mA**	**(k =2)**		**u =**	**0.0118 mA**

Table 9: Uncertainty budget for the calibration result; output current of the transmitter according to model function (14)

At 350.256 °C, the deviation of the current intensity of the thermometer with transmitter is 0.010 mA with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.024 mA.[9]

Using these contributions, the uncertainty budget for the deviation of the temperature calculated from the current of the transmitter can also be specified.

[9] Instead of using the indication deviation, it is also possible to use the indication correction. The difference between them is only the sign. In the above example, the calibration result would then be:
"At 350.256 °C, the thermometer with transmitter has a current correction of -0.01 mA, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.024 mA."
For the user of the thermometer, the use of the indication correction offers the advantage that the best estimate for the measured transmitter current can be determined by adding the correction to the measured intensity of the transmitter current.

Quantity	Designation	Estimate	Uncertainty or half-width	Standard uncertainty	Distribution	Divisor	Sensitivity coefficient	Uncertainty contribution
X_i	X_i	x_i		$u(x_i)$			c_i	$u_i(y)$
I_X	Transmitter current	18.0200 mA	0.0050 mA	0.00500 mA	normal	1	25.0 K/mA	0.1250 K
T_S	Reference temperature in the block calibrator	350.256 °C	0.0324 K	0.03240 K	normal	1	-1.0	-0.0324 K
δT_{EEw}	Self-heating	0.000 K	0.0300 K	0.01732 K	rectangular	√3	1.0	0.0173 K
δI_{Cal}	Calibration of the DMM	0.000 mA	0.0015 mA	0.00075 mA	normal	2	25.0 K/mA	0.0188 K
δI_{Drift}	Drift of the DMM	0.000 mA	0.0140 mA	0.00808 mA	rectangular	√3	25.0 K/mA	0.2021 K
δI_{Amb}	Ambient influence on the transmitter	0.000 mA	0.0060 mA	0.00346 mA	rectangular	√3	25.0 K/mA	0.0866 K
δI_{Load}	Load dependence of the trasnmitter	0.000 mA	0.0080 mA	0.00462 mA	rectangular	√3	25.0 K/mA	0.1155 K
δI_{Wa}	Heat dissipation	0.000 mA	0.0020 mA	0.00115 mA	rectangular	√3	25.0 K/mA	0.0289 K
δI_{Hyst}	Hysteresis	0.000 mA	0.0060 mA	0.00346 mA	rectangular	√3	25.0 K/mA	0.0866 K
ΔT_X	**Indication error of the digital thermometer**	**0.24 K**	**U =**	**0.59 K**	**(k =2)**		**u =**	**0.296 K**

Table 10: Uncertainty budget for the calibration result; temperature variation of the Pt100 with transmitter according to model function (15)

At 350.256 °C, the Pt100 with transmitter has an indication error of 0.24 K with an expanded uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 0.59 K.[10]

[10] Alternatively, the indication correction can be used instead of the indication deviation (indication error). The only difference between them is the sign. In the above example, the calibration result would then read:
"At 350.256 °C, the Pt100 with transmitter has an indication correction of -0.24 K with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor $k = 2$) of 0.59 K."
The use of the indication correction offers the user of the thermometer the advantage that the best estimate for the measured temperature can be determined by adding the correction to the temperature of the thermometer calculated from the measured transmitter current.

Appendix B – Measurement uncertainties for measurements with a resistance thermometer

The above examples A.1 to A.4 only refer to the calibration of a thermometer at a single temperature. Usually, a thermometer is calibrated at several temperatures (temperature points), for which there are generally different measurement uncertainties. But the user also carries out temperature measurements between the calibration points. It is therefore helpful if the calibration certificate also contains information regarding the use of the thermometer over the entire temperature range. This is often done in the form of a characteristic curve (see DKD-R 5-6 and Example A.2 [9]). The uncertainty of the characteristic is naturally greater than the uncertainty of the calibration at a single point.

The use of the thermometer at the customer's site may take place under different conditions than during calibration. There might be contributions to the measurement uncertainty that were negligible during calibration. The measurement uncertainty during use can therefore be considerably higher than the measurement uncertainty during calibration. The main factors influencing the measurement uncertainty when using resistance thermometers are summarised in Table 11.

Influence quantity	**Evaluation**	**Maximum contribution to measurement uncertainty**
Temperature variation between measuring object and thermometer	Different immersion depth, flow velocity, coupling, positions, …	Up to more than 10 % of the temperature difference between measured object and environment
Time-related instabilities	Recording of measurements, control by means of thermometers with a different time constant	Up to the extent of the temperature fluctuations
Hysteresis of the thermometer	Investigation of the dependence of the history on the measurement result	Up to 0.2 % of the span between maximum and minimum temperature!
Resistance of the leads	Calculation of the line resistance	Up to several K
Parasitic thermoelectric voltage	Pole changing	Up to 0.2 K for Pt100
Drift of the thermometer, long-term stability	Control at fixed points (e.g. water triple point, ice point	Up to 0.5 K
Evaluation unit (for direct-reading instruments)	Data sheet	Up to 0.5 K

Table 11: Factors influencing the measurement uncertainty in measurements with resistance thermometers

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