DEUTSCHER KALIBRIERDIENST



# Guideline DKD-R 5-1

# Calibration of Resistance Thermometers

Published by the Accreditation Body of the Deutscher Kalibrierdienst (DKD) in cooperation with its Technical Committee "Temperature and Humidity".



**Deutscher Kalibrierdienst (DKD)**
The DKD consists of the Accreditation Body and independent calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. The laboratories are accredited and supervised by the Accreditation Body. They calibrate measuring instruments and material measures within the scope of accreditation. The DKD calibration certificates issued by them prove traceability to national standards as required in the ISO 9000 family and ISO/IEC 17025.

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## Preface

DKD Guidelines are application documents to the requirements of DIN EN ISO/IEC 17025:2005. DKD Guidelines describe technical and organizational processes serving the calibration laboratories as examples when laying down internal procedures and regulations. DKD Guidelines can become integral parts of the quality management documentation of calibration laboratories. By application of the Guidelines equal treatment of the devices to be calibrated at the various calibration laboratories is supported and the continuity and verifiability of the work of the calibration laboratories is enhanced.

The DKD Guidelines should not impede the further development of calibration procedures and sequences. Deviations from the Guidelines and new procedures are admissible in agreement with the Accreditation Body should this be advisable for technical reasons.

The Guideline was prepared by the Technical Committee "Temperature and Humidity" in cooperation with the PTB and adopted by the Advisory Board of the DKD. With its publication it will become binding for all DKD calibration laboratories unless these have compiled separate procedural instructions which have been approved by the Accreditation Body.

This DKD Calibration Guideline replaces the previous DKD Calibration Guidelines DKD-R 5-1 (1992) and DKD-R 5-2 (1992).

This document is a translation of the German Guideline DKD-R 5-1, Ausgabe 10/2003. In case of any disputes the respective German version will be binding.

## 1 Scope

This Guideline was prepared to fulfil the need for a guide in the form of a general document dealing with the calibration of resistance thermometers. It applies above all to platinum resistance thermometers complying with the requirements of the standard DIN EN 60751 and covering the temperature range from −200 °C to 850 °C.

It is also valid for all categories of resistance thermometers among which the following are of particular importance:

- resistance thermometers from spectrally pure platinum meeting the requirements of the ITS-90 (temperature range −259 °C to 962 °C)
- nickel resistance thermometers
- copper resistance thermometers
- semiconductor resistance thermometers (thermistors, NTCs, PTCs)

Furthermore, the Guideline is applicable to:

- direct-indicating electrical thermometers with resistance sensor
- resistance thermometers with measuring transducer, the output signal of the latter being either analog or digital standardized signals
- data loggers with an electrical resistance thermometer as sensor

# 2 Introduction

Almost all thermometers used in practice belong either to the group of radiation thermometers or to that of contact thermometers. The operation of the contact thermometer is based on a sensor which by thermal contact is brought to the temperature of the object to be measured and whose temperature is then determined by measurement of another quantity (expansion, electrical resistance, etc.) showing a dependence on temperature.

In practical temperature measurement, the greatest measurement deviation is frequently due to the fact that the sensor temperature and the temperature of the object to be measured are not identical. A contact thermometer always measures "only" its own temperature. In this sense, calibration of a contact thermometer means the metrological determination of the relation between the temperature of the sensor and the output quantity of the thermometer. It is the task of the user to ensure that the temperature of the sensor corresponds to the temperature to be measured. Measurement uncertainties due to poor thermal coupling at the user's are not included in the measurement uncertainty of thermometer calibration.

# 3 Resistance thermometers

The operation of resistance thermometers relies on the fact that the electrical resistance of metal conductors and semiconductors is temperature-dependent. The temperature measurement is thus traced back to the measurement of an electrical resistance. In practice (disregarding the low-temperature range with $t < -200$ °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 without 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 increases with temperature.
Today, platinum is almost the only metal used as material for resistance thermometers. The following types are distinguished:

### 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 consist of spectrally pure platinum wire which is wound free from mechanical stresses. Electrically, these thermometers excel by a particularly large temperature coefficient, expressed by the requirement of the ITS-90 for $R(29{,}7646\ °C) / R(0{,}01\ °C) \geq 1{,}118\ 07$. This requirement is more or less equivalent to the requirement $R(100\ °C) / R(0\ °C) \geq 1{,}392$. In the (antiquated) laboratory slang, such thermometers are therefore sometimes still referred to as 392-thermometers. SPRTs basically allow the most accurate temperature measurements as its inherent characteristic in the temperature range from 13,8 K to 962 °C defines the International Temperature Scale ITS-90. The characteristic is well reproducible because only pure metal without any alloying constituents is used. In practice, however, they are employed only rarely since only certain designs can be realized and these are not very stable when mechanically stressed.

### 3.1.2 Industrial platinum resistance thermometers (IPRT)

The acronym IPRT for the English designation "industrial platinum resistance thermometer" is also used in the German-speaking area. As sensor material the 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 is complied with. The temperature coefficient of IPRTs is smaller than that of SPRTs; R(100 °C) / R(0 °C) ≅ 1,385 is valid, so in laboratory slang 385-thermometers are sometimes spoken of. IPRTs with sensor types of different designs are most widely used. Wire-wound sensors have proved to be particularly stable but thin-film sensors are nevertheless most widely used worldwide. Best known are thermometers with a resistance of 100 Ω at 0 °C, briefly also called Pt-100 thermometers. The range of use of IPRTs extends from −200 °C to 600 °C.
For certain applications Ni or Cu resistors are used but they can be employed only 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. With 3% $K^{-1}$ to 5% $K^{-1}$, the temperature coefficient is substantially higher than for metals and thus enables a relatively simple design for direct-indicating thermometers even though the characteristic shows very strong non-linearity.

# 4 Fundamentals of the calibration of resistance thermometers

Prior to calibration, the thermometer is brought to a known temperature in a suitable environment, and the output parameter (e.g. the electrical resistance) is determined. According to the kind of thermostating, a distinction is made between fixed point methods and comparison methods. 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 compared with each other. Fixed point cell and/or standard thermometer must have been traceably calibrated.

For the measurement with the calibration item and/or the standard thermometer, suitable electrical measuring devices must be used (ohmmeter, resistance measuring bridge, standard resistors) which must also 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 standard resistor which for measurements with small measurement uncertainties is frequently kept at constant temperature in a separate thermostat is most critical. A calibrated thermometer is also needed for the measurement of the ambient temperature.

# 5 Transport and initial inspection

Thermometers are available in many different designs. Shocks and vibrations can have an effect (according to the design, of different magnitude) on the structure of the sensor and thus on the electrical properties and are therefore to be avoided. Neither can a metal conduit safely prevent shocks from affecting the sensor. Changes are, however, rather easy to detect by measurement at the ice point or at the triple point of water. A most critical operation is the transport of the thermometer. Good packing, e.g. in suitable foam-padded packets is indispensable. In spite of suitable marking, it unfortunately cannot always be taken for granted that commercial forwarders treat the packages with the necessary care. Very complex calibration items - such as reference standards with small measurement uncertainties - should therefore be transported under the permanent control of an employee.

The initial inspection depends not only on the proposed use of the thermometers but also on their design. First, the calibration item is checked for completeness and integrity. If transport damages or other mechanical or electrical defects are ascertained, the customer is to be advised. The customer is also to be informed if the scope of calibration has not been stated clearly and completely.
For thermometers with associated measuring transducers or thermometers with electrical evaluation units, the operating instructions and technical data sheets must be submitted.

The calibration item must be clearly marked to ensure clear-cut identification. This also covers details such as serial number, type designation and manufacturer. As a rule, clear-cut identification can also be ensured by means of the calibration mark to be applied.

Before the calibration is started, the insulation resistance is to be determined at room temperature pursuant to the requirements of DIN EN 60751 (test voltage, $R_{iso}$). It is to be ensured that neither the sensor nor the connected electronics are destroyed by the test voltage.

# 6 Aging test

Mechanical stresses which have, for example, arisen during transport can in part be eliminated by annealing (aging) at higher temperatures. To check the thermometers for adequate stability, an aging test is usually carried out at a fixed temperature value (nominal value temperature, ice point, triple point of water).

If a resistance thermometer is used, the resistance at the ice point is normally measured first. Then the temperature sensor is heated over an appropriate period of time (approx. 8 h to 12 h) to 10 K beyond the maximum calibration temperature taking into account that the maximum operating temperature as stated by the manufacturer must not be exceeded. Afterwards, the resistance of the thermometer is again measured at reference temperature (ice point). If the difference between the two measurements at the ice point exceeds 30 % of the measurement uncertainty aimed at, the aging procedure is to be repeated. If after the repeat measurement the reference value deviates again from the preceding measurement by more than 30 %, the calibration item is to be rejected as not calibratable.

If the thermometer is recalibrated and has not changed since the last calibration by more than 30 % of the measurement uncertainty aimed at, the aging test can be dispensed with.

The initial value before aging should be separately stated in the calibration certificate.

# 7 Thermostat

Platinum resistance thermometers and semiconductor sensors are calibrated either by the comparison method or in defined fixed points of the applicable temperature scale. Combination of the two methods is permissible. In the comparison method the resistance thermometers or semiconductor sensors to be calibrated are compared in temperature-stabilized baths or in suitable furnaces using reference/working thermometers. Fixed points and standard thermometers must be traceable to national measurement standards.

Within the scope of the determination of the measurement uncertainty, the spatial and temporal temperature distribution in the working space must be quantitatively determined and taken into account for the thermostat used for calibration (thermostated bath, furnace).
For the determination of the temporal and spatial distribution, calibrated thermometers of identical type are positioned on the boundaries of the working space (horizontal, vertical) of the thermostat. After thermal stabilization, the temperatures measured with the thermometers are continuously recorded (over a period longer than 20 min). The maximum resulting temperature difference between the thermometers is allowed for as uncertainty component in the uncertainty budget (rectangular distribution).

Temperature gradients in temperature-stabilized baths or furnaces can be reduced by providing a metallic compensation block with boreholes to accommodate the standards and calibration items.

For the calibration in defined fixed points of the applicable temperature scale, the preparation of the fixed point cells must take place in accordance with the "Supplementary Information for the International Temperature Scale of 1990".

The calibration of a thermometer takes place after both the thermostat and the thermometer itself have reached thermal equilibrium.

The number of calibration temperatures is to be agreed between customer and calibration laboratory. For the determination of characteristic curves, refer to the DKD Guideline "Determination of Characteristic Curves" (DKD-R 5-6).

# 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 realization 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 realization (accredited measurement uncertainty of the calibration laboratory). In the following, these influencing factors will be described in detail.

## 8.1 Thermal load

Besides short-time aging (investigation within the scope of the initial inspection, cf. chapter 6), there are also long-time effects the magnitude of which depends on the thermal load during use. An evaluation of this measurement uncertainty is the task of the thermometer user and is determined from the recalibration values. The statement of the measurement uncertainty in the calibration certificate does not include a contribution for the long-time stability of the thermometer.

## 8.2 Thermal coupling

Erroneous measurements due to inappropriate immersion depths are the cause for the greatest and most frequent measurement deviations in the calibration of resistance thermometers! It is also to be considered that any immersion pockets and protective tubes the customer uses are usually not used in the calibration. In such cases, it is advisable to inform the customer about any measurement deviations which might occur between measurements under calibration and under measurement conditions.

For the calibration, the maximum possible immersion depth and an optimum thermal coupling, respectively, is aimed at for the thermostat and the thermometer to be calibrated. Any measures which might have to be taken are to be stated in the calibration certificate. This prescription is intended to ensure that the calibration results are reproducible and - in recalibration - also comparable. This procedure can call for measurement conditions different from those in subsequent use. Any other measurement deviations must be determined and taken into account by the user.

The control of the immersion depth for the calibration is carried out by reducing the maximum possible immersion depth by 10 %. The resulting heat dissipation error must not exceed 10 % of the measurement uncertainty aimed at, otherwise the measurement uncertainty must be increased, which usually requires a new, detailed uncertainty budget.

## 8.3 Electrical measurement procedures

In the measurement of the electrical resistance, effects influencing the measurement result must be allowed for and, if need be, taken into account when determining the measurement uncertainty. The resistance measurement is made either with a constant alternating or a (varying) direct current. Kind and choice of the measuring instruments depend on the measurement uncertainty aimed at for the calibration.

In the case of thermistors, an asymmetry effect can arise which is dependent on the direction the current flows through the sensor element.

## 8.4 Connection systems

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

### 8.4.1 Two-wire connection system

In the two-wire circuit the connection between sensor element and measuring instrument is ensured by a two wire cable. As all other electrical conductors, this too has a resistance which is connected in series with the sensor element. The two resistances thus add leading to a temperature indication which is systematically higher. This is reflected in the calibration value but it is omitted from consideration that during use the electrical resistance of the lead also varies due to external temperature influences. If the thermometer to be calibrated is provided with a lead, the user must allow for additional measurement deviations which depend on the temperature of the lead.

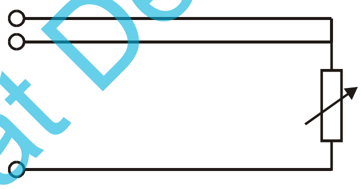
The calibration certificate also states the temperature of the lead during calibration.

**Example**:
Platinum resistance thermometer Pt-100 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.

In the determination of the measurement uncertainty in the calibration of the thermometer, this must be taken into account, and as a matter of principle, a higher value is obtained.

### 8.4.2 Three-wire connection system

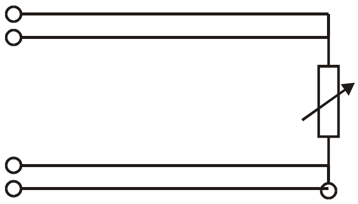
For the minimization of the influences of the line resistances and their temperature-dependent variations, the *three-wire connection* system is used in industrial metrology. Two measuring circuits are obtained, one of which is used as reference. Owing to the circuit used, the line resistance is compensated as regards both its amount and its temperature dependence.



As the measuring instruments employed for the calibration operate, however, in the four-wire technique, the loop resistance must be measured separately and be compensated by computation.

### 8.4.3 Four-wire connection system

The optimum method of connection is the four-wire circuit. As a result of the connection of a separate current and voltage path to the sensor, the measurement result is adversely affected neither by the line resistance itself nor by its temperature dependence. It must thereby be ensured (e.g. by the manufacturer's specifications) that the four-wire circuit is realized up to the sensor element. However, if the sensor element inside the thermometer uses the two-wire technique, an additional line resistance arises.



### 8.4.4 Parasitic thermovoltage

As a rule, the measuring circuit of a thermometer does not consist of a single material. Several materials are in contact with one another, therefore a temperature gradient along the measuring circuit can lead to the formation of a thermovoltage superimposed on the voltage drop at the resistor. According to the direction of current, this voltage adds or subtracts, and a calibration value results which is systematically higher or lower. By current reversal during calibration the magnitude of the thermovoltage can be determined from the difference of the two indicated values (providing the measurement current is known).

In the case of alternating current and varying direct current, this effect averages out and first remains unaccounted for. To the customer it is, however, helpful if the magnitude of the thermovoltage is determined and stated in the calibration certificate together with the measurement conditions of the calibration.

**Example**:
Resistance thermometer Pt-100
Measurement current: 1 mA
Thermovoltage: 25 µV

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

This corresponds to a temperature value of 0,063 K.

### 8.4.5 Self-heating

For the determination of the electrical resistance, an electrical measurement must be carried out for which a measurement current must be fed through the sensor. The measurement current leads to the sensor being heated (self-heating) and thus to the measurement result being falsified. This effect is dependent not only on the magnitude of the measurement current but also on the measurement conditions themselves. In the calibration, the self-heating mechanism is to be investigated or a measurement current is to be chosen at which this effect is negligible.

Should this not be possible, the calibration value is to be extrapolated to $I = 0$ A by calibration at different measurement currents.

### 8.4.6 Insulation resistance

The insulation resistance of the thermometer is already measured at room temperature during the initial inspection. During the calibration, it is yet to be measured at the highest calibration temperature.

### 8.4.7 Asymmetry deviation

In the case of semiconductor sensors in particular, it is possible that the output signal depends on the direction of current. In this case, this is to be determined during the calibration and to be stated in the calibration certificate.

### 8.4.8 Hysteresis

For accurate measurements it is further to be borne in mind that many thermometers (including platinum resistance thermometers) show a hysteresis effect, i.e. the relation between temperature and resistance is dependent on the previous history of the thermometer. This effect arises, for example, if platinum is closely bonded with a ceramic carrier and the difference in thermal expansion leads to mechanical stresses. For IPRTs this can result in a difference in the indication of up to 0,5 K according to whether the thermometer was used before at higher or at lower temperatures.

## 9 Recalibration

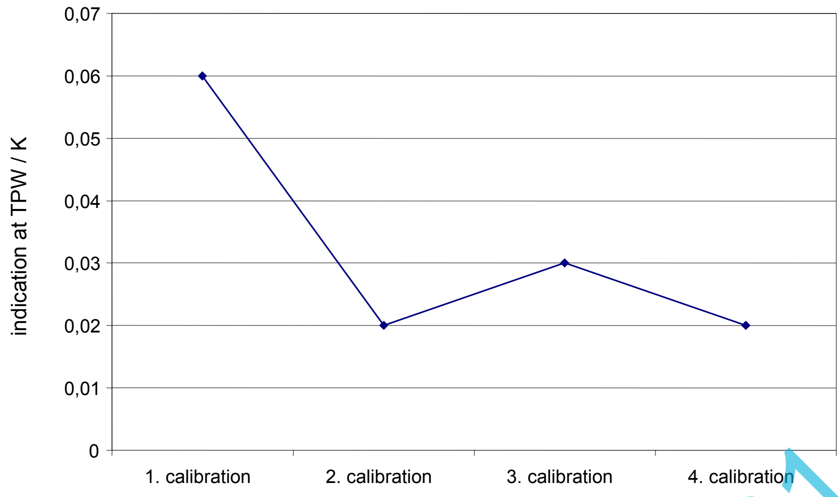
For measurements with the thermometer, the statements in a calibration certificate are not valid for an unlimited time. The various influences acting on a thermometer during its use lead to changes; the thermometer drifts. The influencing factors are:

- thermal load during the measurement
  - temperature value
  - period of use
  - fast temperature changes
- mechanical stress
  - vibration
  - shock
- chemical influences
  - diffusion of foreign matter into the resistor material
  - structural changes in the resistor material

To get an idea of the changes, it is indispensable to recalibrate the thermometer at certain intervals of time. The calibration periods cannot be laid down in the calibration certificate as they depend very strongly on the required measurement uncertainty and the load during operation. So the user is compelled to define the calibration periods himself according to the load during use.

The data from the successive calibrations in the same temperature range then allow a history to be established for the thermometer. The drift values determined from the previous calibrations are used for further evaluation. The user can himself adjust the recalibration periods to the specific requirements placed on the measurement uncertainty and the history.

Example: A Pt-100 resistance thermometer has been calibrated four times on the whole at the triple point of water. After the first calibration a drift has taken place during use, then the values are confirmed by the recalibrations, so that the recalibration period can, for example, be doubled.




## 10 Results

As a result of the calibration, a calibration certificate is issued.
The calibration certificate must meet the requirement of the publication DKD-5 "Instructions for Issuing a DKD Calibration Certificate". Within the scope of this Guideline, the following is to be referred to:

(e) reference to the specifications or procedures applied.
It is recommended to describe the calibration procedure in detail.

(h) the measurement results and the associated measurement uncertainties or a statement on the conformity with an established metrological specification.
It is recommended to state both the measurement results and the characteristic curve calculated from them, together with the assigned measurement uncertainties.

(o) if an instrument to be calibrated was adjusted or calibrated, any calibration results available for the time before and after the adjustment or repair must be stated.
This is valid also for direct-indicating thermometers in particular.

# Annex A: Measurement uncertainty in the calibration of thermometers by the comparison method

The measurement uncertainty in the calibration of a thermometer depends on the calibration method used, the uncertainty from the calibration of the standards, the characteristics of the measuring equipment used and the characteristics of the test equipment. No general instructions for the measurement uncertainty of certain thermometer types can therefore be given. 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; the contributions to the measurement uncertainty in the calibration are rather to be thoroughly determined in each individual case.

For accredited laboratories the Accreditation Body has established so-called “best measurement capabilities”. Usually, these can, however, be attained by the calibration laboratories only if the best measuring equipment available is deployed and if the calibration item behaves more or less ideally. In DKD Calibration Certificates accredited laboratories are not allowed to state measurement uncertainties which are smaller than the best measurement capabilities; frequently, the actual measurement uncertainty will, however, be higher.

In the following, examples of the calibration of four different types of thermometers will be given:

- calibration of a precision resistance thermometer with an AC measuring bridge
- calibration of an IPRT with an ohmmeter
- calibration of a direct-indicating electrical thermometer
- calibration of a thermometer with measuring transducer and analog output

All examples relate to calibration by the comparison method in a stirred liquid bath. In this method, the temperature of the calibration item is determined with the aid of a thermometer otherwise calibrated. In all cases, the mathematical model for the determination of the temperature of the calibration item is therefore basically the same and is presented here only once for reasons of space. In practice, some contributions (e.g. the correction due to heat dissipation from the calibration item) will, however, depend on the particular calibration item.

In the examples below, only the calibration at one temperature is considered. Thermometers are normally calibrated at several temperatures, the values obtained serving to calculate a characteristic whose uncertainty is greater than the measurement uncertainty at the individual test temperatures.

### A.1: Determination of the temperature of the calibration item

In all examples in this chapter the calibration of the calibration item is carried out by the comparison method at a nominal temperature of 180 °C. The measurements are performed in a stirred oil thermostat without compensation block. As standard thermometer an SPRT (25 Ω) is used which was calibrated at the internal laboratory against two reference standards calibrated by the PTB. The resistance of the SPRT is determined with a resistance measuring bridge with direct temperature indication and a 100 Ω standard resistor which were both calibrated by a DKD laboratory.
The temperature at which the calibration item is calibrated is determined by measurement with the standard thermometer and by additional corrections:

$$t_x = t_N + \delta t_{Kal} + \delta t_{Drift} + c_R\, \delta R_R + \delta t_{Br} + \delta t_{WaN} + \delta t_{EWN} + \delta t_{WAP} + \delta t_{Hom} + \delta t_{Stab}$$

with

| | |
|---|---|
| $t_x$ | temperature of the calibration item according to ITS-90 |
| $t_N$ | mean value of the temperature of the SPRT |
| $\delta t_{Kal}$ | correction due to the measurement uncertainty in the calibration of the SPRT |
| $\delta t_{Drift}$ | correction due to a possible drift of the SPRT since the last calibration |
| $\delta R_R$ | correction due to the measurement uncertainty in the calibration of the standard resistor |
| $\delta t_{Br}$ | correction due to the measurement uncertainty in the calibration of the resistance measuring bridge |
| $\delta t_{WaN}$ | correction due to a possible heat conduction by the SPRT |
| $\delta t_{EWN}$ | correction for the self-heating of the SPRT |
| $\delta t_{WAP}$ | correction due to a possible heat conduction by the calibration item |
| $\delta t_{Hom}$ | correction due to inhomogeneities in the thermostat |
| $\delta t_{Stab}$ | correction due to temporal instabilities in the bath |
| $c_R$ | sensitivity of the measuring bridge; in the range selected, $c_R \cong 10$ K/Ω is valid. |

The corrections given in this list are in most cases not known and presumably very small. As best estimate a correction of 0 K is usually assumed which is, however, affected by an uncertainty. In detail, the contributions were determined as follows:

$t_N$ mean value of the temperature of the standard thermometer (SPRT): The measuring bridge calculates the temperature from the entered coefficients of the deviation function which were determined in the calibration, and calculates the mean value of ten individual measurements and the standard deviation of this mean value. As result of the measurement a mean temperature of 180,234 °C is indicated, with a standard deviation of the mean value of 1,2 mK.

$\delta t_{Kal}$ correction due to the measurement uncertainty in the calibration of the SPRT: According to the calibration certificate, the measurement uncertainty of the SPRT at 180 °C is 15 mK ($k = 2$), so the standard uncertainty is 7,5 mK.

$\delta t_{Drift}$ correction due to a possible drift of the thermometer since the last calibration: From the known history of the thermometer it is concluded that the drift since the last calibration will not be greater than ±6 mK. From this a standard uncertainty of 6 mK / √3 = 3,5 mK follows.

$\delta R_R$ correction due to the measurement uncertainty in the calibration of the standard resistor: The relative measurement uncertainty of the standard resistor is given in the calibration certificate as $3 \cdot 10^{-6}$ ($k$ = 2). For an actual resistance of the SPRT of approx. 43 Ω, this corresponds to an uncertainty of 0,13 mΩ ($k$ = 2) and to a standard uncertainty of 0,07 mΩ. Experience has shown that the drift of the resistor since the last calibration can be neglected.

$\delta t_{Br}$ correction due to the measurement uncertainty of the resistance measuring bridge. For the measurement range used, the calibration certificate states an expanded uncertainty ($k$ = 2) of 3 mK. The indication of the bridge shows six digits but at the interface to the data acquisition seven digits are available over which temporal averaging is carried out. So measurement uncertainties due to the limited resolution can be neglected in contrast to the other contributions to the measurement uncertainty.

$\delta t_{WaN}$ correction due to a possible heat conduction by the SPRT: Pulling the SPRT 20 mm out of the bath led to a temperature change of 2 mK (which due to the temperature variations of the bath could be estimated only inaccurately). From this a standard uncertainty of 2 mK / √3 = 1,2 mK follows.

$\delta t_{EWN}$ correction for self-heating of the SPRT: The calibration certificate states that a measurement current of 1 mA in a water triple point cell has led to a heating of 2.1 mK. This contribution is neglected in the following as the thermometer is both calibrated and used now at a measurement current of 1 mA.

$\delta t_{WAP}$ correction due to a possible heat conduction by the calibration item: Pulling the calibration item 20 mm out of the bath led to a temperature change of 1 mK (which due to the temperature variations of the bath could be estimated only inaccurately), measured with the resistance bridge. This contribution is neglected. In part of the examples, it would not have been possible to detect any effect due to the low resolution of the calibration items.

$t_{Hom}$ correction due to inhomogeneities in the thermostat: It is known from previous investigations that the temperature difference between calibration item and standard thermometers due to inhomogeneities in the bath can amount to ±8 mK at most. From this a standard uncertainty of 8 mK / √3 = 4,6 mK follows.

$\delta t_{Stab}$ correction due to temporal instabilities in the bath: It is known from previous investigations that the temperature difference between calibration item and standard thermometers due to temporal instabilities in the bath can amount to ±6 mK at most. From this a standard uncertainty of 6 mK / √3 = 3,5 mK follows.

Compared with these contributions, further influences such as, for example, the short-time stability of the measuring instruments during measurement can be neglected.

The individual contributions to the uncertainty of the temperature of the calibration item are summarized in Table A.1.

| Quantity | Brief description | Estimate | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution |
|---|---|---|---|---|---|---|
| $t_N$ | Dispersion of measurement values - SPRT | 180,234 °C | 1,2 mK | normal | 1 | 1,2 mK |
| $\delta t_{Kal}$ | Calibration - SPRT | 0 K | 7,5 mK | normal | 1 | 7,5 mK |
| $\delta t_{Drift}$ | Drift - standard thermometer | 0 K | 3,5 mK | rectangular | 1 | 3,5 mK |
| $\delta R_R$ | Standard resistor | 0 Ω | 0,07 mΩ | normal | 10 K/Ω | 0,7 mK |
| $\delta t_{Br}$ | Measuring bridge | 0 K | 1,5 mK | normal | 1 | 1,5 mK |
| $\delta t_{WaN}$ | Heat dissipation - SPRT | 0 K | 1,2 mK | rectangular | 1 | 1,2 mK |
| $\delta t_{Hom}$ | Homogeneity - thermostat | 0 K | 4,6 mK | rectangular | 1 | 4,6 mK |
| $\delta t_{Stab}$ | Stability - thermostat | 0 K | 3,5 mK | rectangular | 1 | 3,5 mK |
| $t_x$ | Temperature - calibration item | 180,234 °C | 10 mK | | | |

Table A.1: Uncertainty of the temperature of the calibration item

### A.2 Calibration of a precision resistance thermometer with an AC measuring bridge

The resistance of the calibration item (Pt-100 precision thermometer) is measured at the temperature $t_x$. For the measurement the resistance measuring bridge and the standard resistor which had already been used for the measurement with the reference standard are employed; in this case, the resistance is measured directly using the measuring bridge. The model for this measurement reads

$$R(t_x) = R_{MB} + \delta R_R + \delta R_{Br} + \delta R_{Par} + c_t \cdot \delta T$$

with

$R_{MB}$ indication of the measuring bridge

$\delta R_R$ correction due to the measurement uncertainty in the calibration of the standard resistor

$\delta R_{Br}$ correction due to the measurement uncertainty in the calibration of the resistance measuring bridge

$\delta R_{Par}$ correction due to parasitic thermovoltages

$\delta T$ correction due to the uncertainty of the temperature of the calibration item

$c_t$ sensitivity of the thermometer, amounts here to 0,4 Ω / K

These contributions were in detail determined as follows:

$R_{MB}$ indication of the measuring bridge: The measuring bridge used calculates the mean value from 10 individual measurements of the resistance. A resistance of 168,432 Ω with a standard deviation of the mean value of 2,2 mΩ is read off as result.

$\delta R_R$ correction due to the measurement uncertainty in the calibration of the standard resistor: The relative uncertainty of the standard resistor is stated in the calibration certificate with $3 \cdot 10^{-6}$ ($k = 2$); with the ratio from the bridge this means for 170 Ω an uncertainty of 0,5 mΩ ($k = 2$) and a standard uncertainty of 0,25 mΩ. On account of the experience made with the resistor, the drift of the resistor since the last calibration can be neglected.

$\delta R_{Br}$ correction due to the measurement uncertainty in the calibration of the resistance measuring bridge: The relative uncertainty of the resistance measuring bridge is given in the calibration certificate with $3 \cdot 10^{-6}$ ($k$ = 2), from which a standard uncertainty of 0,15 mΩ (related to the standard resistor) results. The indication of the bridge shows six digits but at the interface to the data acquisition seven digits are available over which temporal averaging is carried out. Compared to the other contributions to the measurement uncertainty, measurement uncertainties due to the limited resolution can therefore be neglected.

$\delta R_{Par}$ correction due to parasitic thermovoltages: The influence of parasitic thermovoltages can be neglected if the measurements are carried out with an AC bridge. If the resistance thermometer is intended to be operated with a DC measuring instrument, the determination of measurement errors due to parasitic thermovoltages requires supplementary measurements (upon agreement with the customer).

$\delta T$ correction due to the uncertainty of the temperature of the calibration item: In Table A.1 it is stated that the standard uncertainty assigned to the temperature of the calibration item is 10,3 mK.

These contributions are summarized in Table A.2.

| Quantity | Brief description | Estimate | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution |
|---|---|---|---|---|---|---|
| $R_{MB}$ | Reading - measuring bridge | 168,432 Ω | 2,2 mΩ | normal | 1 | 2,2 mΩ |
| $\delta R_R$ | Standard resistor | 0 Ω | 0,25 mΩ | normal | 1 | 0,25 mΩ |
| $\delta R_{Br}$ | Measuring bridge | 0 Ω | 0,15 mΩ | normal | 1 | 0,15 mΩ |
| $\delta T$ | Temperature - calibration item | 0 K | 10,3 mK | normal | 0,4 Ω/K | 4,1 mΩ |
| $R(t_x)$ | | 168,432 Ω | 4,66 mΩ | | | |
| $R(t_x)$ | | | | | $k$ = 2 | 9,32 mΩ |

Table A.2: Uncertainty of the resistance of the calibration item

The following measurement result is stated normally[1]:
The resistance of the IPRT at the temperature of 180,234 °C is 168,432 Ω. The measurement uncertainty is 9,4 mΩ. This corresponds to an uncertainty of the temperature measurement of 24 mK.

The uncertainty stated is the expanded uncertainty obtained by multiplying the standard uncertainty by the coverage factor $k$ = 2. It has been determined in accordance with DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95 %.

[1] The case is not a normal one when the probability distribution is such that a coverage probability of 95% cannot be achieved with a coverage factor of $k$ = 2. The above note is then to be modified stating the value of the coverage factor. More detailed explanations are given in DKD-3 or can be obtained from the DKD Accreditation Body.

## A.3 Calibration of a precision resistance thermometer with an ohmmeter

At the temperature $t_x$ the resistance of the calibration item (Pt-100 precision thermometer) is measured. The measurement of the resistance of the calibration item is made with a five-digit calibrated resistance measuring instrument (ohmmeter) for which a DKD Calibration Certificate is available. The model for this measurement is obtained as follows:

$$R(t_x) = R_W + \delta R_{Ohm} + \delta R_{Drift} + \delta R_{Auf} + \delta R_{Par} + c_t \cdot \delta T + \delta R_{Hys}$$

with

$R_W$ indication of the ohmmeter

$\delta R_{Ohm}$ correction due to the measurement uncertainty in the calibration of the ohmmeter

$\delta R_{Drift}$ correction due to the drift of the ohmmeter since the last calibration

$\delta R_{Auf}$ correction due to the limited resolution of the ohmmeter

$\delta R_{Par}$ correction due to parasitic thermovoltages

$\delta T$ correction due to the uncertainty of the temperature of the calibration item

$c_t$ sensitivity of the thermometer, here: 0,4 Ω/K

$\delta R_{Hys}$ correction due to hysteresis effects

These contributions were in detail determined as follows:

$R_W$ indication of the ohmmeter: The ohmmeter displays a value of 168,43 Ω. The standard deviation of the mean value from several measurements is determined to be 0,005 Ω.

$\delta R_{Ohm}$ correction due to the measurement uncertainty in the calibration of the ohmmeter: According to the calibration certificate, the measurement uncertainty of the ohmmeter is 0,020 Ω ($k = 2$) and the standard uncertainty thus is 10 mΩ.

$\delta R_{Drift}$ correction due to the drift of the ohmmeter since the last calibration: Due to the known history of the ohmmeter it is ensured that the drift since the last calibration is ±20 mΩ at most. From this a standard uncertainty of 20 mΩ/√3 = 11,5 mΩ follows.

$\delta R_{Auf}$ correction due to the limited resolution of the ohmmeter: The limited resolution of the ohmmeter of 0,01 Ω allows a reading within ±0,005 Ω. From this a standard uncertainty of 5 mΩ / √3 = 2,9 mΩ follows.

$\delta R_{Par}$ correction due to parasitic thermovoltages. The influence of parasitic thermovoltages was determined by reversal on the ohmmeter. Due to the limited resolution of the ohmmeter, an effect could not be detected and can therefore be neglected.

$\delta T$ correction due to the uncertainty of the temperature of the calibration item: In Table A.1 it is stated that the standard uncertainty assigned to the temperature of the calibration item is 10,3 mK.

$\delta R_{Hys}$ correction due to hysteresis effects: Two measurements were carried out. For one measurement the thermometer had previously been in a salt bath at 250 °C and for the other measurement at 0 °C. The results differed by 22 mΩ. From this a contribution to the measurement uncertainty of 22 mΩ / 2√3 = 6,4 mΩ follows.

These contributions are summarized in Table A.3.

| Quantity | Brief description | Estimate | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution |
|---|---|---|---|---|---|---|
| $R_W$ | Reading - ohmmeter | 168,43 Ω | 5 mΩ | normal | 1 | 5 mΩ |
| $\delta R_{Ohm}$ | Calibration - ohmmeter | 0 Ω | 10 mΩ | normal | 1 | 10,0 mΩ |
| $\delta R_{Drift}$ | Drift - ohmmeter | 0 Ω | 11,5 mΩ | rectangular | 1 | 11,5 mΩ |
| $\delta R_{Auf}$ | Resolution - ohmmeter | 0 Ω | 2,9 mΩ | rectangular | 1 | 2,9 mΩ |
| $\delta R_{Hys}$ | Hysteresis effects | 0 Ω | 6,4 mΩ | rectangular | 1 | 6,4 mΩ |
| $\delta T$ | Temperature - calibration item | 0 K | 10,3 mK | normal | 0,4 Ω/K | 4,1 mΩ |
| $R(t_x)$ | | 168,43 Ω | 18,0 mΩ | | | |
| $R(t_x)$ | | | | | $k = 2$ | 33,6 mΩ |

Table A.3: Uncertainty of the resistance of the calibration item

The following measurement result is stated normally[1]:

The resistance of the IPRT at the temperature of 180,234 °C is 168,43 Ω. The measurement uncer-tainty is 0,04 Ω. This corresponds to an uncertainty of the temperature measurement of 0,09 °C.

The uncertainty stated is the expanded uncertainty obtained by multiplying the standard uncertainty by the coverage factor $k = 2$. It has been determined in accordance with DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95 %.

### A.4 Calibration of a direct-indicating electrical thermometer

At the temperature $t_x$ the indication $A(t_x)$ of a direct-indicating electrical thermometer is read off. It is a Pt-100 thermometer with an associated indicating device with a resolution of 0,01 K. What is searched is the correction $K(t_x)$ which must be added to the indication for the right temperature to be obtained. The model for this measurement is obtained as

$$K(t_x) = t_x + \delta t_{Auf} - A(t_x)$$

with

$K(t_x)$ correction for the thermometer

$t_x$ temperature of the thermometer

$A(t_x)$ reading of the thermometer

$\delta t_{Auf}$ correction due to the limited resolution of the thermometer

[1] The case is not a normal one when the probability distribution is such that a coverage probability of 95% cannot be achieved with a coverage factor of $k = 2$. The above note is then to be modified stating the value of the coverage factor. More detailed explanations are given in DKD-3 or can be obtained from the DKD Accreditation Body.

These contributions were in detail determined as follows:

$t_x$ temperature of the thermometer: According to Table A.1, the temperature of the thermometer is 180,234 °C with a standard uncertainty of 10,3 mK.

$A(t_x)$ reading of the thermometer: The thermometer displays a temperature of 180,25 °C. During a measurement time of 5 min, this temperature was constantly indicated; the statistical variation thus can be neglected within the resolution.

$\delta t_{Auf}$ correction due to the limited resolution of the thermometer: At a resolution of 10 mK, the reading is possible only within ±5 mK. From this a standard uncertainty of 5 mK / √3 = 2,9 mK follows.

These contributions are summarized in Table A.4.

| Quantity | Brief description | Estimate | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution |
|---|---|---|---|---|---|---|
| $t_x$ | Temperature - thermometer | 180,234 °C | 10,3 mK | normal | 1 | 10,3 mK |
| $A(t_x)$ | Reading | 180,25 °C | 0 mK | normal | 1 | 0 mK |
| $\delta t_{Auf}$ | Resolution | 0 K | 2,9 mK | rectangular | 1 | 2,9 mK |
| $K(t_x)$ | Correction | −16 mK | 10,7 mK | | | |
| $K(t_x)$ | | | | | $k = 2$ | 21 mK |

Table A.4: Uncertainty of the temperature indication of the calibration item

The following measurement result is stated normally[1]:

At the temperature of 180 °C the correction $K(t_x) = -16$ mK must be added to the indication to obtain the temperature to be measured. The measurement uncertainty of the correction is 21 mK.

The uncertainty stated is the expanded uncertainty obtained by multiplying the standard uncertainty by the coverage factor $k = 2$. It has been determined in accordance with DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95 %.



[1] The case is not a normal one when the probability distribution is such that a coverage probability of 95% cannot be achieved with a coverage factor of $k = 2$. The above note is then to be modified stating the value of the coverage factor. More detailed explanations are given in DKD-3 or can be obtained from the DKD Accreditation Body.

### A.5 Calibration of a resistance thermometer with connected transmitter

At the temperature $t_x$ the output current of the transmitter connected to the thermometer shall be measured and calibrated. The thermometer sensor is of the type Pt-100. The transmitter furnishes an analog output signal which, with the adjustment: 4 mA ≙ 0 °C, 20 mA ≙ 320 °C, rises linearly with the temperature, i.e. a variation of 20 °C leads to a variation of the signal current of 1 mA.

For the measurement of the output signal, an amperemeter with a resolution of 1µA is used for which a DKD Calibration Certificate is available.
The model for this measurement reads

$$i(t_x) = i_{Am} + \delta i_{AK} + \delta i_{AD} + \delta i_{Um} + c_i\, \delta T + \delta i_{EW}$$

with

| | |
|---|---|
| $i_{Am}$ | indication of the amperemeter |
| $\delta i_{AK}$ | correction due to the measurement uncertainty from the amperemeter |
| $\delta i_{AD}$ | correction due to the drift of the amperemeter since the last calibration |
| $\delta i_{Um}$ | correction due to ambient influences on the transmitter |
| $\delta i_{EW}$ | correction due to retroaction of the input resistance of the electronic evaluation unit |
| $\delta T$ | correction due to the measurement uncertainty of the temperature of the bath |
| $c_i$ | sensitivity of the thermometer with transmitter, here: 50 µA/K |

These contributions were in detail determined as follows:

$i_{Am}$ indication of the amperemeter: The amperemeter displays a measured value of 13,103 mA with a standard uncertainty of the mean value from several measurements of 1,7 µA.

$\delta i_{AK}$ correction due to the measurement uncertainty of the amperemeter: For a measurement current of 94 mA, the calibration certificate gives a correction of 2,2 µA with an uncertainty of 1,8 µA ($k = 2$). From this a standard uncertainty of 0,9 µA follows.

$\delta i_{AD}$ correction due to the drift of the amperemeter since the last calibration: It is concluded from the known history of the amperemeter that the drift since the last calibration will not be greater than ±2 µA. From this a standard uncertainty of 2 µA / √3 = 1,2 µA follows.

$\delta i_{Um}$ correction due to ambient influences on the transmitter: According to the customer's statements, 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. According to the manufacturer's specifications, the output current can change by ±6 µA at most under the effect of the influences to be expected. From this a standard uncertainty of 6 µA / √3 = 3,5 µA follows.

$\delta i_{EW}$ correction due to retroaction of the input resistance of the series-connected electronic evaluation unit: According to the data sheet, this influence is 8 µA at most. From this a standard uncertainty of 8 µA / √3 = 4,6 µA follows.

$\delta T$ correction due to the measurement uncertainty of the bath temperature: According to Table A.1, the temperature of the thermometer is 180,234 °C with a standard uncertainty of 10,3 mK.

These contributions are summarized in Table A.5.

| Quantity | Brief description | Estimate | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution |
|---|---|---|---|---|---|---|
| $i_{Am}$ | Indication - amperemeter | 13,103 mA | 1,7 µA | normal | 1 | 1,7 µA |
| $\delta i_{AK}$ | Calibration - amperemeter | 2,2 µA | 0,9 µA | normal | 1 | 0,9 µA |
| $\delta i_{AD}$ | Drift - amperemeter | 0 µA | 1,2 µA | rectangular | 1 | 1,2 µA |
| $\delta i_{Um}$ | Ambient temperature | 0 µA | 3,5 µA | rectangular | 1 | 3,5 µA |
| $\delta i_{EW}$ | Input resistance | 0 µA | 4,6 µA | rectangular | 1 | 4,6 µA |
| $\delta T$ | Temperature - calibration item | 0 K | 10,3 mK | normal | 50 µA/K | 0,5 µA |
| $K(t_x)$ | Signal current | 13,1052 mA | 6,2 µA | | | |
| $K(t_x)$ | | | | | $k = 2$ | 12,4 µA |

Table A.5: Uncertainty of the signal current of the transmitter

The following measurement result is stated normally[1]:

At the temperature of 180,234 °C a signal current of 13,1052 mA is output. The measurement uncertainty is 12 µA, which corresponds to an uncertainty of the temperature of 0,24 K.

The uncertainty stated is the expanded uncertainty obtained by multiplying the standard uncertainty by the coverage factor $k = 2$. It has been determined in accordance with DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95 %. The measurement uncertainty is valid for an operating temperature of the transmitter between 40 °C and 60 °C.



[1] The case is not a normal one when the probability distribution is such that a coverage probability of 95% cannot be achieved with a coverage factor of $k = 2$. The above note is then to be modified stating the value of the coverage factor. More detailed explanations are given in DKD-3 or can be obtained from the DKD Accreditation Body.

## Annex B: Uncertainty in measurements using a resistance thermometer

The above examples A.1 to A.4 relate to the calibration of a thermometer at one temperature only. Usually, a thermometer is calibrated at several temperatures (temperature points) for which, as a rule, different measurement uncertainties result. As the user also employs the thermometer to carry out temperature measurements between the calibration points, it is, however, helpful if the calibration certificate also contains statements on the use of the thermometer in the whole temperature range. This is frequently achieved by giving a characteristic curve (see DKD-R 5-6) whose uncertainty is naturally greater than that of a calibration in one point.

At the customer's, the thermometer is possibly used under conditions which are different from those under which the calibration was carried out. So contributions to the measurement uncertainty might dominate which could remain unaccounted for in the calibration. The measurement uncertainty in use can therefore considerably exceed the measurement uncertainty in calibration. The essential factors influencing the measurement uncertainty when resistance thermometers are used are summarized in Table B.1.

| Influence quantity | Evaluation | Maximum contribution to measurement uncertainty |
|---|---|---|
| Temperature difference between object measured and thermometer | Different immersion depths, flow velocities, coupling, positions, … | Up to more than 10 % of the temperature difference between object measured and environment |
| Temporal instabilities | Recording of measurements, check using thermometers with a different time constant | Up to the amount of the temperature variations |
| Hysteresis of the thermometer | Investigation of the dependence of the previous history on the measurement result | Up to 0,5 K |
| Resistance of the leads | Calculation of the line resistance | Up to some K |
| Parasitic thermovoltages | Reversal | Up to 0,2 K for Pt-100 |
| Drift of the thermometer, long-time stability | Check at fixed points (ice point) | Up to 0,5 K |
| Electronic evaluation unit (for direct-indicating thermometers) | Data sheet | Up to 0,5 K |

Table B.1: Factors influencing the uncertainty in measurements using resistance thermometers