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Calibration of Pressure Gauges

Edition 03/2014, Revision 3

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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. Moreover, 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 present guideline was prepared by the Technical Committee *Pressure and Vacuum* and approved by the Board of the DKD.

Revision 3 contains minor corrections to the examples as well as editorial adjustments for greater precision and better comprehensibility.

Table of contents Page

1 Purpose and scope of application

This guideline serves to establish minimum requirements for the calibration procedure and the evaluation of the measurement uncertainty in the calibration of pressure gauges. It applies to Bourdon tube pressure gauges, electric pressure gauges and pressure transmitters with electrical output for absolute pressure, differential pressure and excess pressure with negative and positive values.

2 Symbols and designations

The symbols are subject-related meaning that, as a rule, they are listed in the order in which they appear in the text.

2.1 Variables

M1 ... M6	Measurement series
EW	Highest value (of the calibration range)
Y	Output quantity in a measurement model VIM 2.51 [9]
X	Input quantity in a measurement model VIM 2.50 [9]
δX	Influence quantity VIM 2.52 [9]
K	Correction factor
x	Best estimate of the input quantity
y	Best estimate of the output quantity
c	Sensitivity coefficient
k	Coverage factor VIM 2.38 [9]
a	Half-width of a distribution
$g_{X_i}(\xi_i)$	Probability
$\mathrm{E}[...]$	Expected value
u	Standard measurement uncertainty VIM 2.30 [9]
U	Expanded measurement uncertainty VIM 2.35 [9]
w	Relative standard measurement uncertainty VIM 2.32 [9]
W	Relative expanded measurement uncertainty
p	Pressure
Δp	Systematic measurement deviation of the quantity of pressure
δp	Influence quantity in the dimension of pressure
S	Transmission coefficient (of the pressure transducer)
ΔS	Systematic deviation of the transmission coefficient from the single-figure indication
$U\ldots$	Voltage with different indices (Sections 8.2.3, 8.5.1, 8.5.2 and Appendix D)
G	Amplification factor
r	Resolution
f_0	Zero deviation
b'	Measurement repeatability VIM 2.21 [9]
b	Intermediate measurement precision VIM 2.23 [9]
h	Hysteresis

U'	Error span
W'	Relative error span
S'	Slope of a linear regression function
p_e	Excess pressure
m_i	Mass of the load mass i
g	Acceleration due to gravity
ρ	Density
A_0	Effective cross-sectional area of the piston-cylinder system at zero pressure and reference temperature t_0
λ	Deformation coefficient of the piston-cylinder system
α	Linear thermal expansion coefficient of the piston
β	Linear thermal expansion coefficient of the cylinder
$\alpha + \beta$	Thermal surface expansion coefficient of the piston-cylinder system
t	Temperature of the piston-cylinder system
Δh	Height difference between the reference planes

2.2 Indices

Sp	Supply voltage
j	Number of the measurement point
l	Number of measurement series
m	Number of the measurement series
n	Number of measurement cycles
a	Air
abs	Pressure type absolute pressure with regard to variable p
amb	Surrounding area (ambient conditions)
e	Pressure type excess pressure with regard to variable p
Fl	Pressure-transmitting medium
m_i	Load body/load mass i
Std	Standard conditions
corr	Correction (of the measurement value)

3 Reference and working standards

The calibration is carried out by direct comparison of the measurement values of the calibration item with those of the reference or working standard, which has been directly or indirectly traced back to a national standard.

The reference standards used are pressure gauges of long-time stability as, for example, pressure balances and liquid-level manometers, or less long-term stable electrical pressure gauges (see Annex F, p. 52). They are calibrated at regular intervals and provided with a calibration certificate stating the expanded measurement uncertainty under standard conditions (among other things, standard or local acceleration due to gravity, 20°C, 1 bar). The reference standard is subject to surveillance and documentation by the laboratory. If the calibration is not carried out under standard conditions, all relevant corrections must be made in the pressure calculation.

The long-term stability of the reference standard as well as all relevant input and influence quantities are to be included as contributions in the measurement uncertainty budget. This also includes those quantities that enter into the corrections.

In case of indicating pressure gauges that are used as standards, the resolution has to be considered a second time when calculating the measurement uncertainty.

The working standards documented in the quality manual of the laboratory are calibrated in an accredited calibration laboratory and provided with a calibration certificate stating the expanded uncertainty at the time of calibration. The working standards are subject to surveillance by the laboratory. Depending on their type, the working standards may vary considerably.

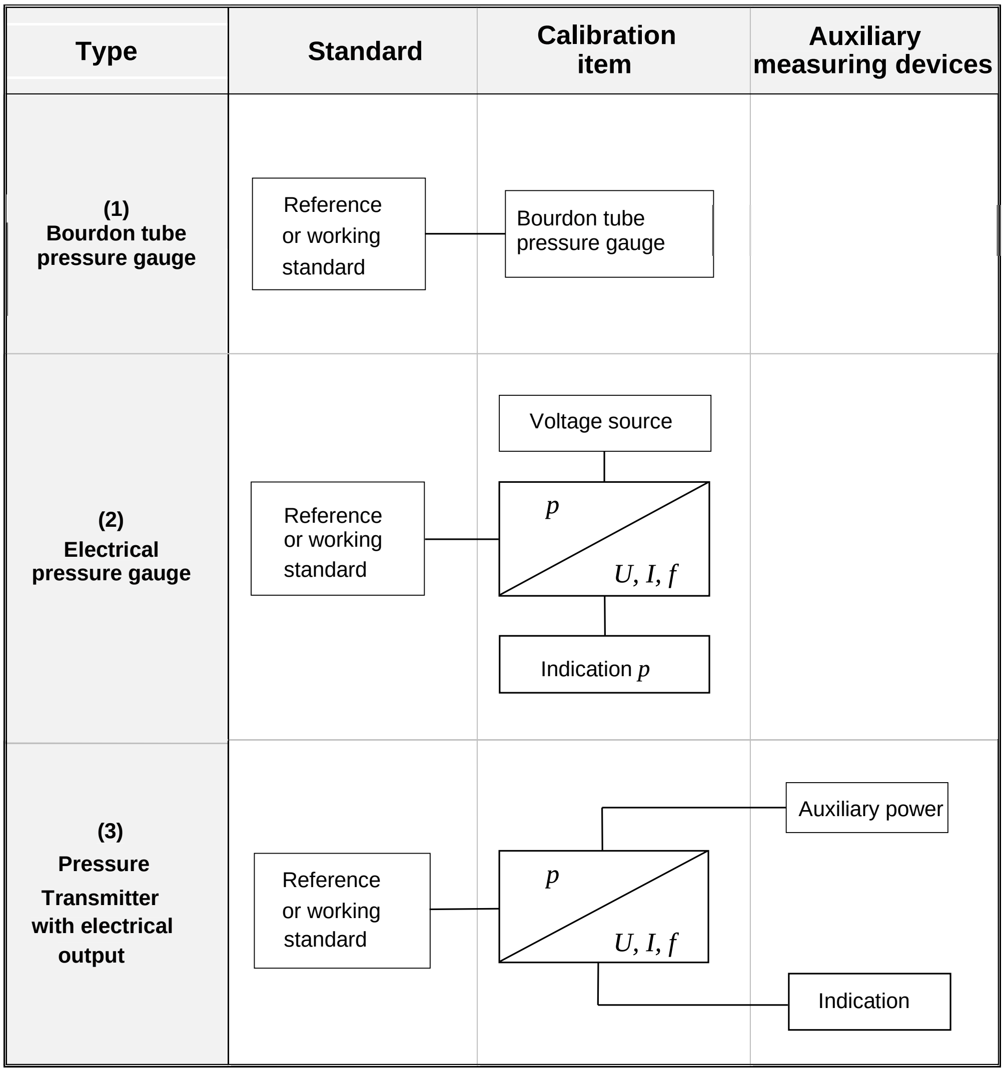
Recommendation:
The measurement uncertainty attributed to the measurement values of the reference or working standard should not exceed 1/3 of the aspired uncertainty[1] which will presumably be attributed to the measurement values of the calibration item.

[1] The measurement uncertainty aimed at is the uncertainty that can be achieved when specified calibration efforts are made (uncertainty of the values of the standard, number of measurement series, etc.). It may be equal to or greater than the best measurement capability.

4 Calibration item

The calibration items are pressure gauges of the three types represented in Figure 1.

Figure 1: Types of pressure gauges



For the calibration of pressure transmitters with electrical output (3) auxiliary measuring devices of the accredited laboratory have to be used – as opposed to electrical pressure gauges (2) which only require the provision of a voltage or current source. These auxiliary devices serve to convert the electrical signal into a readable indication. The measurement uncertainty attributed to the measurement values of the auxiliary measuring devices is to be taken into account in the uncertainty budget. To ensure traceability, the auxiliary measuring devices must have been calibrated and a statement on the measurement uncertainty to be attributed to the measurement values must be available.

When choosing the auxiliary measuring devices, it must be ensured that their uncertainty contributions do not significantly affect the aspired measurement uncertainty of the calibration item.

In the case of calibration items with a digital interface (e.g. RS232, RS485 IEEE488, etc.), this interface can be used instead of the display. It has to be ensured that the data that are read out are unequivocally interpreted and processed.

5 Calibration capability

The handling of a calibration order requires the calibration capability (suitability) of the calibration item, i.e. the current status of the calibration item should meet the generally recognized rules of technology as well as the specifications according to the manufacturer's instructions. The calibration capability has to be ascertained by means of external inspections and functional tests.

External inspections cover, for example:

- visual inspection for damage (pointer, threads, sealing surface, pressure channel)
- contamination and cleanness
- visual inspections regarding labelling, readability of indications
- checking whether the documents required for calibration (technical data, operating instructions) are available

Functional tests cover, for example:

- leak tightness of the calibration item’s line system
- electrical operational capability
- proper function of the control elements (e.g. zero adjustability)
- adjusting elements in defined position
- error-free execution of self-test and/or self-adjustment functions; if necessary, internal reference values are to be read out via the EDP interface
- torque dependence (zero signal) due to mounting

Note:
If repair work or adjustments are required to ensure the calibration capability, this work has to be agreed upon between customer and calibration laboratory. Relevant device parameters are to be documented, as far as possible, before and after the adjustments.

6 Ambient conditions

The calibration is to be carried out after temperature equalisation between calibration item and environment within the permissible temperature range. The warm-up time of the calibration item or a possible warming of the calibration item by the supply voltage must be considered. The warm-up time depends on personal experience or specifications provided by the manufacturer.

Calibration is to be carried out at a stable ambient temperature which is to be recorded. The recommended temperature variation during calibration is limited to ±1 K. When using the maximum tolerance limits, an additional measurement uncertainty contribution may have to be taken into account.

The permissible temperature range is 18 °C to 28 °C.

Note:
When using piston pressure gauges, the air density may have a significant impact on the calibration result (air buoyancy of the mass and hydrostatic pressure) and must therefore be taken into account. Therefore, in addition to the ambient temperature, the atmospheric pressure must also be recorded. The relative humidity must either be measured and recorded or, in cases where the relative humidity does not represent a significant influence on the uncertainty analysis of the pressure value, reasonably estimated (e.g. 50 % with an expanded measurement uncertainty of 50 %). This information must be stated in the calibration certificate (see DAkkS-DKD-5 [12] and DAkkS 71 SD 0 025 [13] in conjunction with DIN EN ISO/IEC 17025:2018 [7] section 7.8).

7 Calibration method

- The pressure gauge is to be calibrated as a whole (measuring chain), if possible.
- The required mounting position is to be considered.
- The calibration is to be carried out at equally distributed measurement points across the calibration range.
- Depending on the desired measurement uncertainty, one or more measurement series are necessary (see Table 1 or Figure 2, respectively).
- If the calibration item's behaviour regarding the influence of the torque is not sufficiently known during mounting, the reproducibility must be determined by additional clamping. In this case, the value of the torque is to be documented.
- The height difference between the reference heights of the standard and the calibration item is to be minimised; otherwise, the correction is to be calculated.

Upon request, further influence quantities (e.g. temperature influence from further measurement series at different temperatures) can be determined.

The comparison of the measured value between calibration item and reference or working standard is feasible in two ways:

- adjustment of the pressure according to the indication of the calibration item
- adjustment of the pressure according to the indication of the standard

The preloading time at the highest value and the time between two preloadings should at least be 30 seconds. After preloading and after steady conditions have been reached, the indication of the calibration item is set to zero – provided that this is supported by the calibration item. The zero reading is carried out immediately afterwards. As to the pressure step variation of a measurement series, the time between two successive load steps should be the same and not shorter than 30 seconds, and the reading should be performed no earlier than 30 seconds after the start of the pressure change. Especially Bourdon tube pressure gauges have to be slightly tapped to minimize any frictional effect of the pointer system. The measured value for the upper limit of the calibration range is to be registered before and after the waiting time. The zero reading at the end of a measurement series is carried out at the earliest 30 seconds after the complete relief.

The calibration effort in dependence on the desired measurement uncertainty (cf. footnote 1 in section 3) is illustrated in Figure 2, which shows the sequence of the calibration.

Table 1: Calibration sequences

Se-quence	Desired measure-ment uncertainty in % of the measure-ment span *	Minimum number of measure-ment points with zero point up/down	Number of pre-loadings	Load change + waiting time ** seconds	Waiting time at upper limit of the measure-ment range *** minutes	Number of measurement series upward	downward
A	< 0.1	9	3	> 30	2	2	2
B	0.1 ... 0.6	9	2	> 30	2	2	1
C	> 0.6	5	1	> 30	2	1	1

* The reference to the measurement span was chosen in order to allow the selection of the sequence (necessary calibration effort) from the table, since the accuracy specifications provided by the manufacturers are usually related to the measurement span. For measuring instruments whose accuracy specifications are specified proportional to the measured value or whose specifications are specified by its various components, Table 1 is to be applied using the accuracy specification at the upper range value (related to the measuring span).

** In any case, one has to wait until steady state conditions (sufficiently stable indication of the standard and the calibration item) are reached.

*** For Bourdon tube pressure gauges, a waiting time of 5 minutes is to be observed.

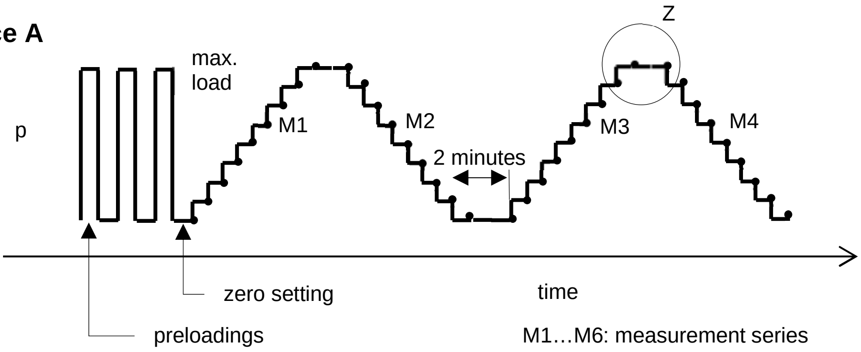
Notes:
The calibration of items with a measurement range greater than 2500 bar basically requires the application of calibration sequence A. If clamping effects are observed, the calibration is to be repeated with a second clamping.

Calibration items that are calibrated with positive and negative gauge pressure should at least be calibrated at two points in the negative range (e.g. at -1 bar and -0.5 bar); the remaining measurement points should be calibrated in the positive range.

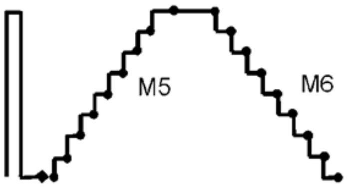
If several references are required to carry out a calibration, the pressure at the calibration item must be kept constant when changing the reference. If this is not practicable (e.g. change of the mounting position, second clamping), a complete, new calibration sequence has to be carried out.

Figure 2: Visualisation of the calibration sequences

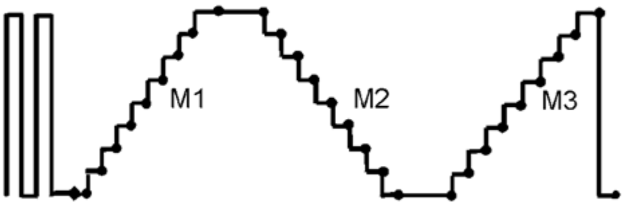
Sequence A



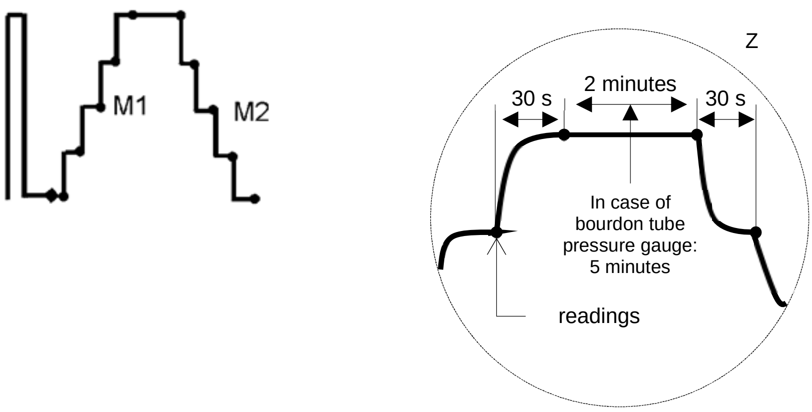
Additional repeat measurement in the case of 2nd clamping



Sequence B



Sequence C



8 Measurement uncertainty

8.1 Definition VIM 2.26 [9]

The measurement uncertainty is a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used“.

8.2 Procedure

8.2.1 Model of measurement VIM 2.48 [9]

The measurement model is defined as “mathematical relation among all quantities known to be involved in a measurement”.
Basically, the measurement uncertainty is determined according to the procedure described in EA-4/02 M:2013 [18]. The following terms and calculation rules are used provided that no correlations between the input quantities are to be taken into account:

Model function			$y = f(x_1, x_2, ..., x_N)$
Standard measurement uncertainty	$u(x_i)$	Standard uncertainty attributed to the input/influence quantity	
	c_i	Sensitivity coefficient	$c_i \equiv \frac{\partial f}{\partial x_i}$
	$u_i(y)$	Contribution to the standard uncertainty attributed to the output quantity due to the standard uncertainty $u(x_i)$ of the input/influence quantity x_i	$u_i(y) \equiv \lvert c_i \rvert \cdot u(x_i)$
	$u(y)$	Standard uncertainty attributed to the output quantity	$u^2(y) = \sum_{i=1}^{N} u_i^2(y)$ $u(y) = \sqrt{\sum_{i=1}^{N} u_i^2(y)}$
Expanded measurement uncertainty	$U(y)$	Expanded uncertainty	$U(y) = k \cdot u(y)$
	k	Coverage factor	$k = 2$ *for a measurand of largely normal distribution and a coverage probability of approximately 95 %*

If relative measurement uncertainties are used, the variables u, U are replaced by the variables w, W.

With complex models, the calculation rule quickly leads to an analytical determination of the sensitivity coefficients which is no longer manageable. As a result, there will be a shift toward a software-based numerical determination of the sensitivity coefficients.

Besides this general calculation rule, there are two particular rules which lead to sensitivity coefficients $c_i = \pm 1$ or $c_i x_i y^{-1} = \pm 1$, and thus to the simple quadratic addition of the uncertainties of the input/influence quantities. This enables the simple determination of the measurement uncertainty without software support.

Note:
Also the “simple” model must of course correctly reflect the physical process of measurement/calibration. If necessary, more complex relations have to be represented by means of a suitable model (no special case) in a separate uncertainty budget (see Annex A Determination of the measurement uncertainty to be attributed to the values of the pressure balance under conditions of use).

8.2.2 Sum/difference model

$$Y = X + \sum_{i=1}^{N} \delta X_i \quad (1)$$

Y	Output quantity
X	Input quantity (quantities)
δX_i	Influence quantity (quantities)
$\mathrm{E}[\delta X_i] = 0$	Expected value; the components do not contribute to the calculation of the output quantity, i.e. corrections are not applied, but they do contribute to the measurement uncertainty

e.g. model for determining the indication error:

$$\Delta p = p_{\text{ind}} - p_{\text{standard}} + \sum_{i=1}^{N} \delta p_i \quad (2)$$

This model is particularly suitable for calibration items with an indication of their own in units of pressure (e.g. Bourdon tube pressure gauge, electric pressure gauge). Here, the measurement uncertainties are also stated in the unit of the physical quantity of pressure (pascal, bar, etc.).

8.2.3 Product/quotient model

$$Y = X \cdot \prod_{i=1}^{N} K_i \tag{3}$$

Y	Output quantity
X	Input quantity (quantities)
$K_i = \left(1 + \frac{\delta X_i}{\lvert X_i \rvert}\right)$	Correction factor(s)
δX_i	Influence quantity (quantities)
$\mathrm{E}[\delta X_i] = 0$; $\mathrm{E}[K_i] = 1$	Expected values; the components do not contribute to the calculation of the output quantity, i.e. corrections are not applied, but they do contribute to the measurement uncertainty

e.g. model for determining the transmission coefficient of a pressure transducer (strain-gauge transducer):

$$S = \frac{X_{\text{out}}}{X_{\text{in}}} = \frac{U_{\text{ind}} / \left(G \cdot U_{\text{Sp}}\right)}{p_{\text{standard}}} \cdot \prod_{i=1}^{N} K_i \tag{4}$$

This model is particularly suitable for calibration items without an indication of their own (e.g. pressure transmitters with electrical output) using relative measurement uncertainties w of dimension 1 (dimensionless or %).

8.2.4 Input/influence quantities

As to their determination, the measurement uncertainties attributed to the input/influence quantities are divided into two categories:

Type **A**: The value and its attributed standard uncertainty are determined by means of statistical methods of analysis for measurement series under repeatability conditions ($l \geq 10$, with the variable l indicating the number of measurement series).

Type **B**: The determination of the value and its associated standard uncertainty is based on other scientific findings and can be estimated from the following information:

- data from previous measurements
- general knowledge and experience regarding the characteristics and the behaviour of measuring instruments and materials
- manufacturer's specifications
- calibration certificates or other certificates
- reference data from manuals

In many cases, only the upper and lower limits a_+ and a_- can be specified for the value of a quantity, with all values within the limits being considered equally probable. This circumstance can best be described by a rectangular probability density.

With
$$a_+ - a_- = 2a \quad (5)$$

the estimate of the input/influence quantity

$$x_i = \frac{1}{2} \cdot (a_+ + a_-) \quad (6)$$

and the attributed standard measurement uncertainty

$$u(x_i) = \frac{a}{\sqrt{3}} \quad (7)$$

are obtained.

If the values are more likely to be found in the middle or at the edge of the interval, then it is reasonable to assume a triangular or U-shaped distribution.

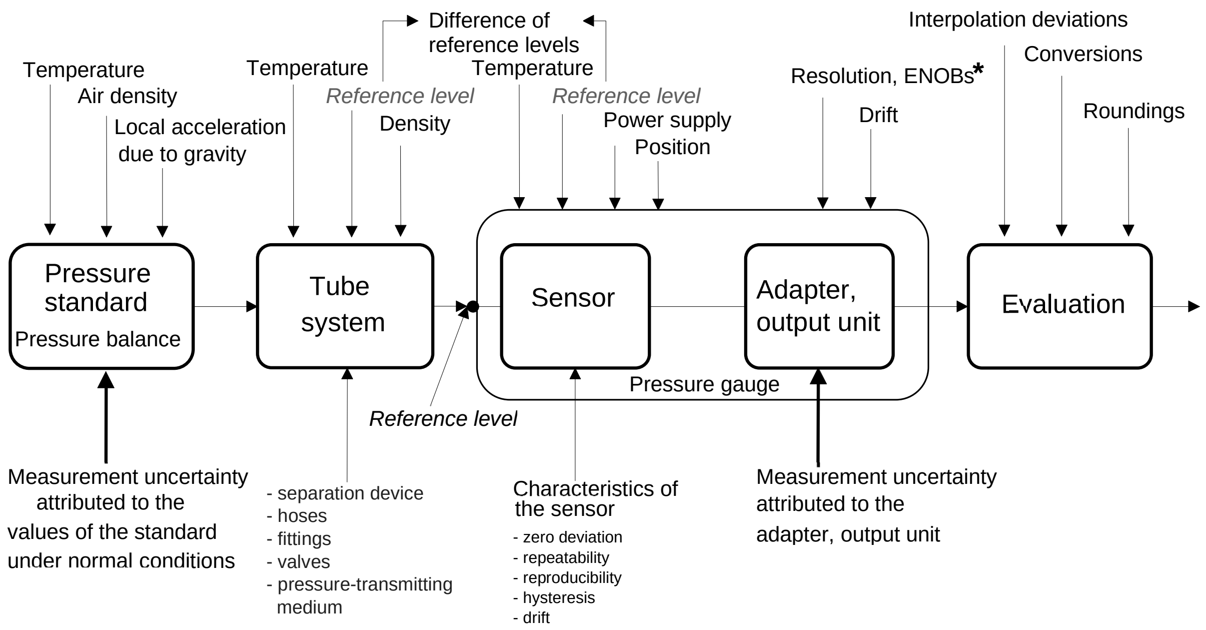
Table 2: Other type B distribution shapes

Shape of distribution	Standard measurement uncertainty
normal	$u = \frac{U}{k}$
triangular	$u = \frac{a}{\sqrt{6}}$
U-shaped	$u = \frac{a}{\sqrt{2}}$
etc.	

8.2.5 Potential influence quantities, example

To set up the model of the measurement uncertainty, a graphical representation of the influencing variables is recommended. As an example, the following illustration shows the possible influencing quantities when calibrating a pressure gauge with a piston manometer. Figure 3 shows the block diagram of the pressure gauge type (3) from section 4, Figure 1.

Figure 3: Influence quantities in the calibration of a pressure gauge



* ENOB : Effective Number of Bits
(Characteristic value of A/D converters which characterizes their actual accuracy and performance better than the resolution.)

Note:
For a first approach, it may sometimes be helpful to assign the influencing quantities to the following blocks:
- standard
- procedure (method)
- calibration.

The measurement uncertainties which are attributed to the values of the standard, the adapter and the output unit are taken from calibration certificates (usually with a normal distribution, k = 2). The long-term stability is to be evaluated as a measurement uncertainty contribution and taken into account if necessary. When using electrical pressure gauges, this also applies to their resolution and temperature dependence.

8.3 Calibration of Bourdon tube pressure gauges

8.3.1 Model of measurement

For example, a simple sum/difference model is suitable for determining the measurement deviation of the indication – separately for the measurement values in the direction of increasing pressure and for the measurement values in the direction of decreasing pressure – according to the calibration procedures (see Section 7, Table 1 and Figure 2):

$$\Delta p_{\text{up/down}} = p_{\text{ind,up/down}} - p_{\text{standard}} + \sum_{i=1}^{2} \delta p_i = p_{\text{ind,up/down}} - p_{\text{standard}} + \delta p_{\text{zero deviation}} + \delta p_{\text{repeatability}} \qquad (8)$$

$Y = \Delta p_{...}$	Output quantity; deviation of the indication (indication error) Index ... stands for up/down or mean, see equations (8) and (9)	[2]	
$X_1 = p_{\text{ind},...}$	Indication of the pressure gauge Index ... stands for up/down or mean, see equations (8) and (9)	[3]	[4]
$X_2 = p_{\text{standard}}$	Value of the reference standard[5]		
$X_3 = \delta p_{\text{zero deviation}}$	Influence quantity “zero deviation”	[6]	
$X_4 = \delta p_{\text{repeatability}}$	Influence quantity “repeatability”		

and for the mean values from the upward and downward measurement values:

$$\Delta p_{\text{mean}} = p_{\text{ind,mean}} - p_{\text{standard}} + \sum_{i=1}^{3} \delta p_i = p_{\text{ind,mean}} - p_{\text{standard}} + \delta p_{\text{zero deviation}} + \delta p_{\text{repeatability}} + \delta p_{\text{hysteresis}} \qquad (9)$$

$$p_{\text{ind,mean}} = \frac{p_{\text{ind, up}} + p_{\text{ind, down}}}{2} \qquad (10)$$

additionally, with:

$X_5 = \delta p_{\text{hysteresis}}$	Influence quantity “hysteresis”	[7]	[5]

[2] Output quantity
[3] Input quantities
[4] Quantities for determining the measurement uncertainty
[5] The value of the reference standard takes into account the use of the piston pressure gauge under conditions of use (application of corrections). Therefore, the uncertainty budget, too, contains uncertainty contributions from the piston pressure gauge both under standard conditions and under conditions of use. The latter contribution is determined in uncertainty budgets (see Appendix A “Estimate of the measurement uncertainty which is to be attributed to the values of the piston pressure gauge under conditions of use”) for the influences of the temperature, the thermal linear expansion coefficient, the acceleration due to gravity, the air density, the deformation coefficient (piston pressure gauge) or for the influence of density, acceleration due to gravity and height difference. In addition, the long-term stability of the reference standard must be taken into account.
[6] Influence quantities

When considering the increasing and decreasing series separately, the expanded measurement uncertainty ($k = 2$) is:

$$U_{\text{up/down}} = k \cdot u_{\text{up/down}}$$
$$U_{\text{up/down}} = k \cdot \sqrt{u^2_{\text{standard}} + u^2_{\text{resolution}} + u^2_{\text{zero deviation}} + u^2_{\text{repeatability}}} \qquad (11)$$

and a so-called error span [7] allowing for the systematic deviation is:

$$U'_{\text{up/down}} = U_{\text{up/down}} + \left|\Delta p_{\text{up/down}}\right| \qquad (12)$$

When using the mean values from the increasing and decreasing series, the expanded measurement uncertainty ($k = 2$) is calculated as follows:

$$U_{\text{mean}} = k \cdot \sqrt{u^2_{\text{up/down}} + u^2_{\text{hysteresis}}} \qquad (13)$$

using the larger value of the repeatability for the calculation of the measurement uncertainty $u_{\text{up/down}}$.

The associated error span is determined as follows:

$$U'_{\text{mean}} = U_{\text{mean}} + \left|\Delta p_{\text{mean}}\right| \qquad (14)$$

[7] The maximum expected difference between the measured value and the correct value of the measurand is called error span. The error span can be used to characterize the accuracy.

8.3.2 Measurement uncertainty budget

The knowledge of the input/influence quantities is preferably summarised in tabular form.

Table 3: Measurement uncertainty for the calibration of a Bourdon tube pressure gauge

No.	Quantity	Best estimate	Width of the distribution	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Unit[8]
	X_i	x_i	$2a$	$g_{X_i}(\xi_i)$		$u(x_i)$	c_i	$u_i(y)$	
1	$p_{\text{ind},...}$	$p_{i,\text{ ind},...}$	$2r$	rectangular	$2\sqrt{3}$	$u(r)=\sqrt{\frac{1}{3}\cdot\left(\frac{2r}{2}\right)^2}$	1	u_r	bar
2	p_{standard}	$p_{i,\text{ standard}}$		normal		$u(\text{standard})$	-1	u_{standard}	bar
3	$\delta p_{\text{zero deviation}}$	0	f_0	rectangular	$2\sqrt{3}$	$u(f_0)=\sqrt{\frac{1}{3}\cdot\left(\frac{f_0}{2}\right)^2}$	1	u_{f_0}	bar
4	$\delta p_{\text{repeatability}}$	0	b'	rectangular	$2\sqrt{3}$	$u(b')=\sqrt{\frac{1}{3}\cdot\left(\frac{b'}{2}\right)^2}$	1	$u_{b'}$	bar
5	$\delta p_{\text{hysteresis}}$	0	h	rectangular	$2\sqrt{3}$	$u(h)=\sqrt{\frac{1}{3}\cdot\left(\frac{h}{2}\right)^2}$	1	u_h	bar
	Y	$\Delta p_{...}$						$u(y)$	bar

[8] It is recommended to indicate the unit of the uncertainty contributions (unit of the physical quantity, indication unit, etc.)

8.3.3 Load step-related measurement uncertainty budget

The estimate of the measurement uncertainty has to be carried out for each calibration value, i.e. for each load step. For a clear representation, the following table is recommended – for the ascending, descending and mean values respectively:

Table 4: Measurement uncertainty budget

Pressure	**Measure-ment deviation**	**Standard measurement uncertainty** u			**Expanded measurement uncertainty** U $(k=2)$	**Error span** U'
		Contribution 1	...	Contribution n'		
bar	bar	bar			bar	bar
min.						
...						
max.						

8.3.4 Single-figure indication

In addition to the error span for each load step, the customer can be informed of the maximum error span in the range for which the calibration is valid (in the unit of the pressure related to the measurement value or the measurement span). Similarly, the conformity can be confirmed (see page 32).

8.4 Calibration of electric pressure gauges

The model of the measurement and the measurement uncertainty budget for the calibration of a Bourdon tube pressure gauge can also be used for calibrating an electric pressure gauge (numerically correct indication in units of pressure). If necessary, a portion of "reproducibility b with repeated mounting" is to be taken into account.

$X_6 = \delta p_{\text{reproducibility}}$	Influence quantity "reproducibility"	7	5

Table 5: Additional component in determining the measurement uncertainty for the calibration of an electric pressure gauge

No.	Quantity	Best esti-mate	Width of the distri-bution	Probability distribution	Divisor	Standard uncertainty	Sensi-tivity coef-ficient	Uncer-tainty contribu-tion	Unit
	X_i	x_i	$2a$	$g_{X_i}(\xi_i)$		$u(x_i)$	c_i	$u_i(y)$	
6	$\delta p_{\text{reproducibility}}$	0	b	rectangular	$2\sqrt{3}$	$u(b)=\sqrt{\frac{1}{3}\cdot\left(\frac{b}{2}\right)^2}$	1	u_b	bar

The expanded measurement uncertainty ($k = 2$) for the increasing and decreasing series is determined as follows:

$$U_{\text{up/down}} = k \cdot u_{\text{up/down}}$$
$$U_{\text{up/down}} = k \cdot \sqrt{u^2_{\text{standard}} + u^2_{\text{resolution}} + u^2_{\text{zero deviation}} + u^2_{\text{repeatabillity}} + u^2_{\text{reproducibility}}} \quad (15)$$

The determination of the associated error span for the increasing and decreasing series and for the expanded uncertainty as well as for the error span of the mean value is carried out in the same way as with the Bourdon tube pressure gauge.

8.5 Calibration of pressure transducers and pressure transmitters with electrical output

8.5.1 Model of measurement

For example, a simple product/quotient model is suitable for determining the transmission coefficient – separately for the measurement values in the direction of increasing pressure and those in the direction of decreasing pressure:

$$S_{\text{up/down}} = \frac{X_{\text{out,up/down}}}{X_{\text{in}}} = \frac{U_{\text{ind,up/down}} / (G \cdot U_{\text{Sp}})}{p_{\text{standard}}} \prod_{i=1}^{3} K_i = \frac{U_{\text{ind,up/down}} / (G \cdot U_{\text{Sp}})}{p_{\text{standard}}} K_{\text{zero deviation}} K_{\text{repeatability}} K_{\text{reproducibility}} \qquad (16)$$

$Y = S_{...}$	Output quantity; transmission coefficient Index ... stands for up/down or mean, see equations (16) and (17)	3	
$X_1 = U_{\text{ind},...}$	Indication of the output unit (voltmeter) Index ... stands for up/down or mean, see equations (16) and (17)	4	5
$X_2 = G$	Transmission coefficient of the adapter (added amplifier)		
$X_3 = U_{\text{Sp}}$	Value of the supply voltage (auxiliary device)		
$X_4 = p_{\text{standard}}$	Value of the reference standard		
$X_5 = K_{\text{zero deviation}}$	Correction factor due to the influence quantity “zero deviation”	7	
$X_6 = K_{\text{repeatability}}$	Correction factor due to the influence quantity “repeatability”		
$X_7 = K_{\text{reproducibility}}$	If applicable, correction factor due to the influence quantity “reproducibility”		

For the mean values the following is valid:

$$S_{\text{mean}} = \frac{X_{\text{out,mean}}}{X_{\text{in}}} = \frac{U_{\text{ind,mean}} / (G \cdot U_{\text{Sp}})}{p_{\text{standard}}} \prod_{i=1}^{4} K_i = \frac{U_{\text{ind,mean}} / (G \cdot U_{\text{Sp}})}{p_{\text{standard}}} K_{\text{zero deviation}} K_{\text{repeatability}} K_{\text{reproducibility}} K_{\text{hysteresis}} \qquad (17)$$

additionally, with:

$X_8 = K_{\text{hysteresis}}$	Correction factor due to the influence quantity “hysteresis”	7	5

When considering the increasing and decreasing series separately, the relative expanded measurement uncertainty ($k = 2$) is determined as follows:

$$W_{\text{up/down}} = k \cdot w_{\text{up/down}}$$

$$W_{\text{up/down}} = k \cdot \sqrt{w_{\text{standard}}^2 + w_{\text{output unit}}^2 + w_{\text{adapter}}^2 + w_{\text{auxiliary device}}^2 + w_{\text{zero deviation}}^2 + w_{\text{repeatability}}^2 + w_{\text{reproducibility}}^2} \tag{18}$$

and the associated error spans as:

$$W'_{\text{up/down}} = W_{\text{up/down}} + \left| \frac{\Delta S_{\text{up/down}}}{S'} \right| \tag{19}$$

with the systematic deviation

$$\Delta S_{\text{up/down}} = S_{\text{up/down}} - S' \tag{20}$$

with S' preferably representing the slope of the regression line through all measurement values and through the zero point of the output signal of the pressure transmitter.

When using the mean value from increasing and decreasing series, the relative expanded measurement uncertainty ($k = 2$) is calculated as follows:

$$W_{\text{mean}} = k \cdot \sqrt{w_{\text{up/down}}^2 + w_{\text{hysteresis}}^2} \tag{21}$$

where for the calculation of the measurement uncertainty $w_{\text{up/down}}$ the larger value of the repeatability is to be inserted.

The associated error span is determined as follows:

$$W'_{\text{mean}} = W_{\text{mean}} + \left| \frac{\Delta S_{\text{mean}}}{S'} \right| \tag{22}$$

with

$$\Delta S_{\text{mean}} = S_{\text{mean}} - S' \tag{23}$$

(for S' see above)

8.5.2 Measurement uncertainty budget

The knowledge of the input/influence quantities is preferably given in tabular form.

Table 6: Measurement uncertainty budget for the calibration of a pressure transmitter with electrical output

No.	Quantity	Best estimate	Width of the distribution	Probability distribution	Divisor	Standard uncertainty	Exponent of X_i	Uncertainty contribution	Unit
	X_i	x_i	$2a$	$g_{X_i}(\xi_i)$		$w(x_i)$	$c_i x_i y^{-1}$	$w_i(y)$	
1	$U_{\text{ind},...}$	$U_{i,\text{ind},...}$		normal		$w(\text{output unit})$	1	$w_{\text{output unit}}$	#
2	G	G		normal		$w(\text{adapter})$	-1	w_{adapter}	#
3	U_{Sp}	U_{Sp}		normal		$w(\text{aux. device})$	-1	$w_{\text{aux. device}}$	#
4	p_{standard}	$p_{i,\text{ standard}}$		normal		$w(\text{standard})$	-1	w_{standard}	#
5	$K_{\text{zero deviation}}$	1	f_0 [9]	rectangular	$2\sqrt{3}$	$w(f_0)=\sqrt{\frac{1}{3}\cdot\left(\frac{f_0}{2}\right)^2}$	1	w_{f_0}	#
6	$K_{\text{repeatability}}$	1	b'	rectangular	$2\sqrt{3}$	$w(b')=\sqrt{\frac{1}{3}\cdot\left(\frac{b'}{2}\right)^2}$	1	$w_{b'}$	#
7	$K_{\text{reproducibility}}$	1	b	rectangular	$2\sqrt{3}$	$w(b)=\sqrt{\frac{1}{3}\cdot\left(\frac{b}{2}\right)^2}$	1	w_b	#
8	$K_{\text{hysteresis}}$	1	h	rectangular	$2\sqrt{3}$	$w(h)=\sqrt{\frac{1}{3}\cdot\left(\frac{h}{2}\right)^2}$	1	w_h	#
	Y	$S...$						$w(y)$	#

[9] Here, the characteristic quantities f_0, b', b and h are relative quantities, i.e. quantities related to the measurement value (indication) which are not defined at the zero pressure.

8.5.3 Load step-related measurement uncertainty budget

The estimation of the measurement uncertainty has to be carried out for each calibration value, i.e. for each load step. To provide a clear representation, the following table is recommended – one each for the ascending, descending and mean values:

Table 7: Uncertainty budget

Pressure	Relative standard measurement uncertainty w			Relative expanded uncertainty W (k=2)
	Contribution 1	...	Contribution n'	
bar	#			#
min.				
...				
max.				

8.5.4 Single-figure indication

Transmission coefficient as slope of a linear regression function

When using a pressure transducer, it is common practice not to apply different transmission coefficients for the individual load steps (i.e. calibration pressures) but one single transmission coefficient for the whole range for which the calibration is valid. This is preferably the slope of the regression line through all measurement values and through the zero point of the output signal of the pressure transducer (fitting without absolute term).

When using this characteristic quantity of the pressure transducer, a statement of conformity replaces the measurement uncertainties attributed to the individual measurement values of the transmission coefficient (cf. 9.1.3).

For this purpose, the specification limits are to be defined. This can be done on the basis of the calibration results by calculating the error span according to 8.5.1 (“self-determined conformity”, definition based on the manufacturer’s instructions, cf. below).
In doing so,

- the measurement uncertainties attributed to the individual measurement values of the transmission coefficient and
- the deviations of these values from the single-figure indication of the transmission coefficient

are to be taken into account.

As a rule, this results in error spans whose magnitudes decrease with increasing pressure. As specification limit

- it is possible to select the maximum calculated error span (in this case, the specification limits are shown in the calibration diagram as straight lines parallel to the pressure axis; cf. 9.2.2, Pressure transmitters with electrical output signal, Figure 5, upper charts)

or

- to specify a suitable curve (e.g. hyperbola or polynomial) (cf. 9.2.2, Pressure transmitters with electrical output signal, Figure 5, lower charts).

Note:
It is not common practice to use pressure-dependent specification limits. But in case of pressure measurements with the calibrated device, it does allow the specification of smaller measurement uncertainties in the upper part of the measuring range.

For calibration items with a nominal characteristic value that has been checked by the manufacturer (e.g. 2 mV/V), the specification limits can alternatively also be determined from the associated tolerance of the characteristic value. In this case, however, it always has to be checked whether the values of the transmission coefficients determined during calibration – including their associated measurement uncertainties and their systematic deviations from the single-figure indication of the characteristic value – do not exceed the specification limits.

8.6 Influence quantities of the calibration item for the uncertainty budget

8.6.1 Resolution *r*

8.6.1.1 Analogue indicating devices

The resolution of the indicating device is obtained from the ratio of the pointer width to the centre distance of two adjacent graduation lines (scale interval). 1/2, 1/5 or 1/10 is recommended as ratio. If the ratio shall be 1/10 (i.e. the estimable fraction of a scale interval), the scale spacing must be 2.5 mm or greater (cf. also DIN 43790).

Note:
The best estimate of an analogue indicating device is determined by visual interpolation. The smallest estimable fraction of a scale interval is the interpolation component *r* by which the measurement values can be distinguished. The variation interval for the best estimate x thus is $a_+ = x + r$ and $a_- = x - r$ with the width of the rectangular distribution $2a = 2 \cdot r$.

8.6.1.2 Digital indicating devices

The resolution corresponds to the digital step, provided that the indication does not vary by more than one digital step when there is no load on the pressure gauge.

Note:
For the determination of the uncertainty contribution, half the value of the resolution $a = r/2$ is assigned to the half-width of the rectangular distribution.

8.6.1.3 Fluctuations of reading

If the indication fluctuates by more than the previously determined value of the resolution with unloaded pressure measuring device, the resolution *r* is to be taken to be half the span of the fluctuation – plus one digital step.

8.6.2 Zero deviation f_0

The zero point (unloaded pressure gauge usually at atmospheric pressure) can be set prior to each measurement cycle consisting of an increasing and a decreasing series; it has to be recorded prior to and after each measurement cycle. The reading is to be carried out with the instrument being completely relieved.

In the case of pressure gauges for excess pressure whose initial measuring range is different from the atmospheric pressure (e.g. –1 bar to 9 bar), the drift has to be determined at the zero point.

The determination of the zero-point deviation is omitted in case of absolute pressure gauges, where the zero point is not included in the calibration range, e.g. barometers.

The zero deviation is calculated as follows:

$$f_0 = \max\left\{\left|x_{2,0} - x_{1,0}\right|, \left|x_{4,0} - x_{3,0}\right|, \left|x_{6,0} - x_{5,0}\right|\right\} \tag{24}$$

The indices number the measured values x read at the zero points of the measurement series M1 to M6.

8.6.3 Repeatability b'

The repeatability with the mounting not being changed is determined from the difference of the zero signal-corrected measurement values of corresponding measurement series.

$$\begin{aligned}
b'_{\mathrm{up},j} &= \left|\left(x_{3,j} - x_{3,0}\right) - \left(x_{1,j} - x_{1,0}\right)\right| \\
b'_{\mathrm{down},j} &= \left|\left(x_{4,j} - x_{3,0}\right) - \left(x_{2,j} - x_{1,0}\right)\right| \\
b'_{\mathrm{mean},j} &= \max\left\{b'_{\mathrm{up},j}, b'_{\mathrm{down},j}\right\}
\end{aligned} \tag{25}$$

The index j numbers the nominal values of the pressure ($j = 0$: zero point).

8.6.4 Reproducibility b

The reproducibility with the instrument being mounted repeatedly and the conditions not being changed is determined from the difference of the zero signal-corrected measurement values of corresponding measurement series:

$$\begin{aligned}
b_{\mathrm{up},j} &= \left|\left(x_{5,j} - x_{5,0}\right) - \left(x_{1,j} - x_{1,0}\right)\right| \\
b_{\mathrm{down},j} &= \left|\left(x_{6,j} - x_{5,0}\right) - \left(x_{2,j} - x_{1,0}\right)\right| \\
b_{\mathrm{mean},j} &= \max\left\{b_{\mathrm{up},j}, b_{\mathrm{down},j}\right\}
\end{aligned} \tag{26}$$

For index j see above.

8.6.5 Hysteresis h

When indicating mean values, the hysteresis is determined from the difference of the zero point-corrected measurement values of the increasing and decreasing series as follows:

$$h_{\mathrm{mean},j} = \frac{1}{n}\cdot\left\{\left|\left(x_{2,j} - x_{1,0}\right) - \left(x_{1,j} - x_{1,0}\right)\right| + \left|\left(x_{4,j} - x_{3,0}\right) - \left(x_{3,j} - x_{3,0}\right)\right| + \left|\left(x_{6,j} - x_{5,0}\right) - \left(x_{5,j} - x_{5,0}\right)\right|\right\} \tag{27}$$

For index j, see above. The variable n stands for the number of the complete measurement cycles (consisting of an increasing and decreasing series).

9 Evaluation of measurement results and statements in the calibration certificate

All main components of the pressure measuring device receive a calibration mark; in the case of measuring chains, each instrument receives a calibration mark.

In addition to the requirements in DAkkS-DKD-5 [12], the calibration certificate must state the following information [10]:

- calibration method (DKD-R 6-1 sequence A, B or C)
- measurement deviation of the indication
- pressure-transmitting medium
- pressure reference plane on the calibration item
- mounting position of the calibration item during calibration
- selected settings on the calibration item

The calibration certificate should contain a table of all measurement values, e.g.:

Table 8: Measurement values

<table>
<tr><td rowspan="5">Pressure at the level of the reference plane of the calibration item

p</td><td colspan="6">Indicated value X_{ind}</td></tr>
<tr><td colspan="4">Calibration sequence A</td><td colspan="2">Measurement with 2nd clamping</td></tr>
<tr><td colspan="3">Calibration sequence B</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Calibration sequence C</td><td></td><td></td><td></td><td></td></tr>
<tr><td>M1 (up)</td><td>M2 (down)</td><td>M3 (up)</td><td>M4 (down)</td><td>M5 (up)</td><td>M6 (down)</td></tr>
<tr><td>bar, Pa, ...</td><td colspan="6">bar, Pa, A, V, mV/V, Hz, ...</td></tr>
<tr><td>min.</td><td>min.</td><td>min.</td><td>min.</td><td>min.</td><td>min.</td><td>min.</td></tr>
<tr><td>↓</td><td>↓</td><td>↑</td><td>↓</td><td>↑</td><td>↓</td><td>↑</td></tr>
<tr><td>max.</td><td>max.</td><td>max.</td><td>max.</td><td>max.</td><td>max.</td><td>max.</td></tr>
</table>

Column 1 contains the measured pressure values of the standard. Columns 2 to 7 contain the corresponding measured values indicated by the calibration items according to Figure 1 (Bourdon tube pressure gauge, electric pressure gauge, pressure transmitter with electrical output) in units of pressure or those given in other physical quantities (current, voltage, voltage ratio, frequency, ...) or already converted into the quantity of pressure.

The further evaluation of the measured values may contain the following characteristics:

- mean values
- zero deviation
- repeatability
- reproducibility, if applicable
- hysteresis
- error span

[10] These requirements are in accordance with DIN EN ISO/IEC 17025: 2018 [7] section 7.8.

- single-figure indication
- conformity

9.1 Determination of other parameters

9.1.1 Mean values $\overline{x}$

The mean values $\overline{x_{i,j}}$ with i = up/down, mean, are calculated as follows:

$$\overline{x_{\text{up},j}} = \frac{1}{l} \cdot \sum_m \left(x_{m,j} - x_{m,0} \right) \qquad \text{for } m = 1,3,5$$

$$\overline{x_{\text{down},j}} = \frac{1}{l} \cdot \sum_m \left(x_{m,j} - x_{(m-1),0} \right) \qquad \text{for } m = 2,4,6 \tag{28}$$

$$\overline{x_{\text{mean},j}} = \frac{\overline{x_{\text{up},j}} + \overline{x_{\text{down},j}}}{2}$$

with the variable l indicating the number of measurement series.

For pressure gauges, where the zero point is not included in the calibration range (e.g. 800 mbar to 1200 mbar), the zero-point correction is omitted when calculating the mean values.

9.1.2 Error span U'

The error span is the sum of the expanded measurement uncertainty ($k = 2$) and the absolute value of the systematic deviation. Due to the systematic component, the error span is assigned the rectangular distribution as distribution shape. The error span is to be determined according to the requirements for the mean values of the increasing and decreasing series and the mean value:

e.g.: $$U' = U + \left| \Delta p \right| \tag{29}$$

The relative error span W' is formed accordingly.

e.g.: $$W' = W + \left| \frac{\Delta S}{S'} \right| \tag{30}$$

Note:
See footnote 7 on p. 21.

9.1.3 Conformity

If the error spans and the transmission coefficients with attributed measurement uncertainty lie within the indicated specification limits, the conformity according to DAkkS-DKD-5 [12] can be confirmed. Their validity range (scope) has to be indicated. When assessing the compliance with the required specification limits, their origin has to be indicated, e.g. manufacturer-specific specifications according to data sheet, customer demands, inter alia.

9.2 Visualisation of the calibration result

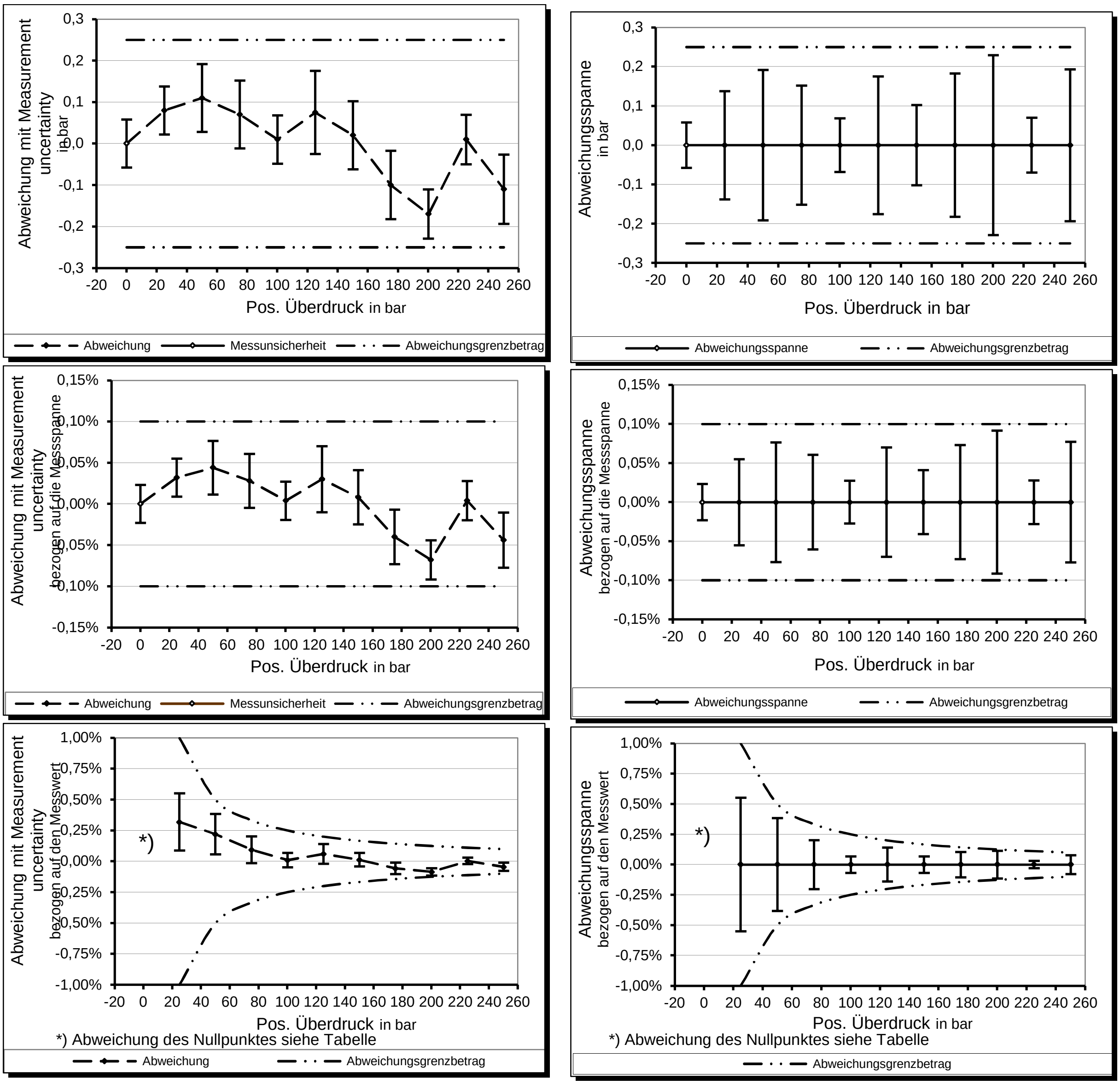
For better comprehensibility and a quick overview, the calibration result can also be given in graphical form.

9.2.1 Bourdon tube pressure gauges, electric pressure gauge

The systematic deviation with the expanded measurement uncertainty or the resulting error span are to be represented with reference (in comparison) to the specification limit (i.e. error limit) – in the unit of the physical quantity and/or as a related quantity.

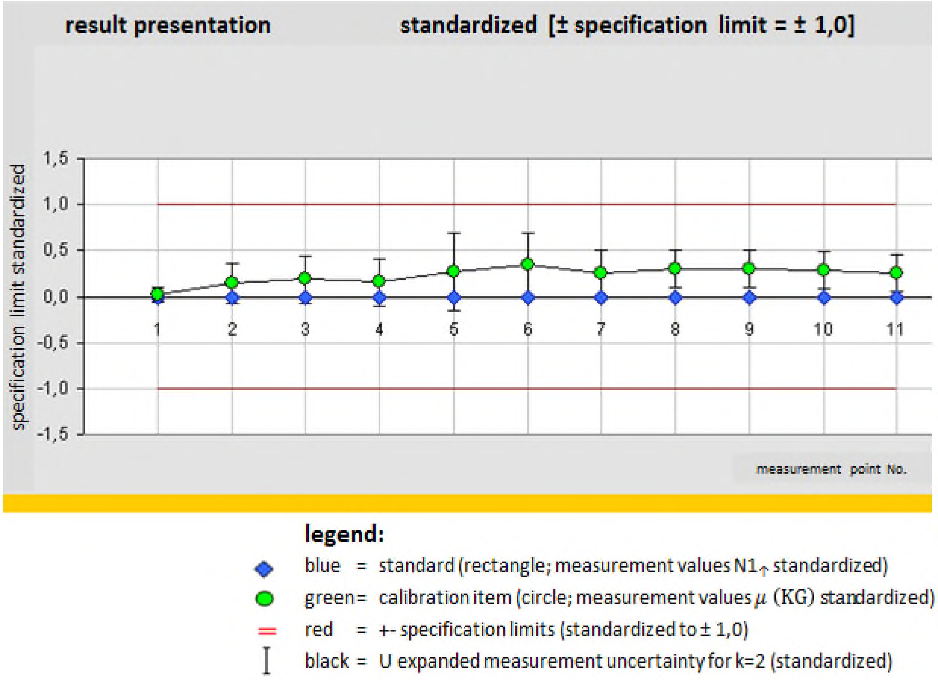
The representation of related parameters can be carried out in a form typical for the type of equipment (related to the measurement span, related to the measurement value).

Figure 4: Visualisation of the calibration result for a Bourdon tube pressure gauge and an electric pressure gauge



Abweichung mit Messunsicherheit (bezogen auf die Messspanne) / (bezogen auf den Messwert)	Deviation with measurement uncertainty (related to the measurement span) / (related to the measurement value)
Positiver Überdruck in bar	Positive excess pressure
Abweichung / Messunsicherheit / Abweichungsgrenzbetrag	Deviation / measurement uncertainty / upper/ lower limit of deviation (deviation limit)
Abweichungsspanne	Error span
Abweichung des Nullpunktes siehe Tabelle	Zero-point deviation, see table

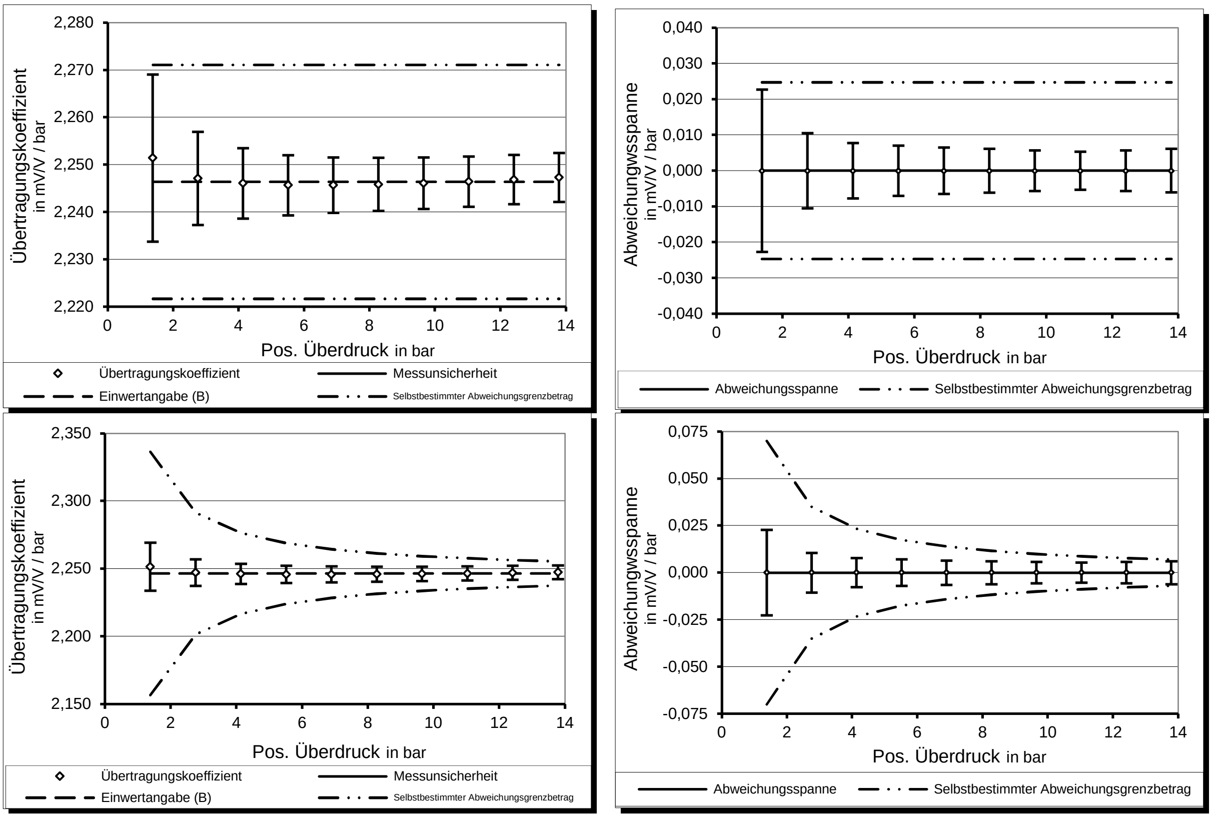
To support a statement of conformity, the results can also be represented in standardized form (specification limit = 100 %). The specification limit can either be specified by the customer, or the one provided by the manufacturer can be adopted.



9.2.2 Pressure transmitters with electrical output

The transmission coefficients and the attributed measurement uncertainties are represented with reference to the specification limits (error limits according to the manufacturer's specifications or self-determined limits).

Figure 5: Visualisation of the calibration result for a pressure transmitter with electrical output



Übertragungskoeffizient	Transmission coefficient
Positiver Überdruck in bar	Positive excess pressure
Abweichungsspanne	Error span
Messunsicherheit	Measurement uncertainty
Selbstbestimmter Abweichungsgrenzbetrag	Self-determined deviation limit

9.3 Limiting values for stating the measurement uncertainty

The measurement uncertainty and the error span are calculated according to section 8. This is valid for all the calibration sequences (A, B and C).

Regardless of the result of the calibration, however, the measurement uncertainty is stated

for	cal. sequence B	not smaller than	0.04 %	of the measurement span
and for	cal. sequence C	not smaller than	0.30 %	of the measurement span.

For the indication of an error span in a conformity statement according to DAkkS-DKD-5 [12], the value given

for	cal. sequence B	must not be smaller than	0.06 %	of the measurement span
and for	cal. sequence C	must not be smaller than	0.60 %	of the measurement span.

The measurement uncertainty and the error span for the calibration sequence A remain unaffected by these limiting values. They are indicated as actually calculated.

10 Additional rules and standards

If appropriate, the following rules are to be taken into account for the calibration of pressure gauges. It may also be agreed to carry out the calibration in accordance with individual sections of some of these rules.

[1] DIN EN 837-1 — Druckmessgeräte mit Rohrfedern
Maße, Messtechnik, Anforderungen und Prüfung
Edition: February 1997
(English title: Pressure gauges – Part 1: Bourdon tube pressure gauges; dimensions, metrology, requirements and testing)

[2] DIN EN 837-3 — Druckmessgeräte mit Platten- und Kapselfedern
Maße, Messtechnik, Anforderungen und Prüfung
Edition: February 1997
(English title: Pressure gauges – Part 3: Diaphragm and capsule pressure gauges; dimensions, metrology, requirements and testing)

[3] DIN 16086 — Elektrische Druckmessgeräte
Druckaufnehmer, Druckmessumformer, Druckmessgeräte
Begriffe und Angaben in Datenblättern
Edition: January 2006
(English title: Electrical pressure measuring instruments – Pressure transmitters, pressure measuring instruments – Concepts, specifications on data sheets)

[4] DIN 43790 — Grundregeln für die Gestaltung von Strichskalen und Zeigern
Edition: January 1991
(English title: Basic principles for the design of line scales and pointers)

[5] EURAMET cg-3 — Calibration of Pressure Balances
Version 1.0 (03/2011)

[6] EURAMET cg-17 — Guidelines on the Calibration of Electromechanical and Mechanical Manometers, EURAMET Calibration Guide No. 17
Version 4.0 (04/2019)

General

[7] DIN EN ISO/IEC 17025: 2018-03 — General requirements for the competence of testing and calibration laboratories (ISO/IEC 17025:2017); German and English version EN ISO/IEC 17025:2017.

[8] JCGM 200:2008 — International vocabulary of metrology – Basic and general concepts and associated terms (VIM) (identical to ISO/IEC Guide 99:2007)
JCGM 200:2008 Corrigendum (2010)
https://www.bipm.org/en/publications/guides/vim.html

[9] VIM — Internationales Wörterbuch der Metrologie – Grundlegende und allgemeine Begriffe und zugeordnete Benennungen (VIM) – Deutsch-Englische Fassung ISO/IEC-Leitfaden 99:2007.
4th revised edition 2012, Editor: DIN Deutsches Institut für Normung e. V.
[English title: International vocabulary of metrology – Basic and general concepts and associated terms (VIM)]

[10] DIN 1319-1: 1996 — Grundlagen der Messtechnik
Teil 1: Grundbegriffe
(English title: Fundamentals of metrology – Part 1: Basic terminology)

[11] DIN 1319-2: 1999 — Grundlagen der Messtechnik
Teil 2: Begriffe für die Anwendung von Messgeräten
(English title: Fundamentals of metrology – Part 2: Terminology related to measuring equipment)

[12] DAkkS-DKD-5: 2010 — Anleitung zum Erstellen eines Kalibrierscheins
DAkkS, 1. Neuauflage
valid until: 30.06.2021
(English title: How to create a calibration certificate; not available in English)

[13] 71 SD 0 025 — Darstellung von Kalibrierergebnissen und die Verwendung der DAkkS-Kalibriermarke, Revision 1.1, 19. September 2019
(English title: Presentation of calibration results and the use of the calibration marks)

[14] ILAC-P14:09/2020 — ILAC Policy for Measurement Uncertainty in Calibration

Measurement uncertainty

[15] JCGM 100:2008 — Evaluation of measurement data –
Guide to the Expression of Uncertainty in Measurement (GUM)
(identical to ISO/IEC Guide 98-3:2008)
https://www.bipm.org/en/publications/guides/gum.html

[16] JCGM 101:2008 — Evaluation of measurement data –
Supplement 1 to the “Guide to the expression of uncertainty in measurement” – Propagation of distributions using a Monte Carlo method (identical to ISO/IEC Guide 98-3:2008/Suppl 1:2008)
https://www.bipm.org/en/publications/guides/gum.html

[17] JCGM 104:2009 — Evaluation of measurement data –
An introduction to the “Guide to the expression of uncertainty in measurement” and related documents
(identical to ISO/IEC Guide 98-1:2009)
https://www.bipm.org/en/publications/guides/gum.html

[18] EA-4/02 M:2013 — Evaluation of the Uncertainty of Measurement in Calibration – including supplement 1 and 2
European co-operation for Accreditation
http://www.european-accreditation.org/publications

A German version is offered by DAkkS:
https://www.dakks.de/doc_kalibrier

[19] DIN V ENV 13005:1999 — Leitfaden zur Angabe der Unsicherheit beim Messen
Beuth Verlag Berlin
(English title: Guide to the expression of uncertainty in measurement)

[20] DIN 1319-3:1996 — Grundlagen der Messtechnik
Teil 3: Auswertung von Messungen einer einzelnen Messgröße, Messunsicherheit
Beuth Verlag Berlin
(English title: Fundamentals of metrology – Part 3: Evaluation of measurements of a single measurand, measurement uncertainty)

[21] DIN 1319-4:1999 Grundlagen der Messtechnik
Teil 4: Auswertung von Messungen, Measurement uncertainty
Beuth Verlag Berlin
(English title: Fundamentals of metrology – Part 4: Evaluation of measurements, measurement uncertainty)

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[22] Weise, K.; Wöger, W.: Messunsicherheit und Messdatenauswertung, VCH, Weinheim, 1999, ISBN 3-527-29610-7
(Measurement uncertainty and evaluation of measurement data)

[23] Adunka, F.: Messunsicherheiten – Theorie und Praxis, Vulkan-Verlag, Essen 2007, ISBN 978-3-8027-2205-9

[24] Themenschwerpunkt Messunsicherheit, Sonderdruck aus Heft 3 und Heft 4 der PTB-Mitteilungen 111 (2001)

[25] VDI-Berichte (VDI reports) 1805, 1867, 1947 u. Tagungsband (conference proceedings) 2008: Messunsicherheit praxisgerecht bestimmen, VDI/VDE-Gesellschaft für Mess- und Automatisierungstechnik,
Conferences:
20.-21.11.2003 and 30.11.-01.12.2004 in Oberhof/Thüringen
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VDI Verlag GmbH, Düsseldorf 2003/2004/2006 and VDI Wissensforum 2008

[26] Themenhefte Messunsicherheit: tm Technisches Messen, 2/2004 und 5/2005
(Special publication series on the subject of ‘measurement uncertainty’)

Appendix A Determination of the measurement uncertainty to be assigned to the pressure values of the piston pressure gauge under conditions of use[11]

The pressure values of the piston pressure gauge are determined based on the information stated in the current calibration certificate (e.g. by PTB). The associated expanded uncertainty $U_{\text{standard,Std}}$ is determined by combining the data from the calibration certificate with the long-term behaviour derived from the history. When being operated under conditions of use, corrections must be applied to the values with regard to the relevant influencing quantities, to which in turn a measurement uncertainty is to be assigned

Model of measurement[12]:

$$p_e = \frac{g \cdot \sum_i m_i \cdot \left(1 - \frac{\rho_a}{\rho_{m_i}}\right)}{A_0 \cdot (1 + \lambda \cdot p) \cdot \left[1 + (\alpha + \beta) \cdot (t - t_0)\right]} + \Delta\rho \cdot g \cdot \Delta h \qquad (31)$$

$$\Delta\rho = \rho_{Fl} - \rho_a \qquad (32)$$

Measurement uncertainty budget

with the influencing quantities essential for the pressure value of the standard: temperature, thermal surface expansion coefficient of the piston-cylinder system, acceleration due to gravity and deformation coefficient. The sensitivity coefficients have been calculated with the approximations that are generally used for practical applications and for the most common case $\alpha = \beta$.

Table A1: Partial measurement uncertainty budget for the correction of the pressure values of the piston pressure gauge

Quantity	Best estimate	Half-width	Probability distribution	Divisor	Standard measurement uncertainty	Sensitivity coefficient	Uncertainty contribution	Unit
X_i	x_i	a	$g_{X_i}(\xi_i)$		$u(x_i)$	c_i	$u_i(y)$	
Temperature	t	a_t	rectangular	$\sqrt{3}$	$u(t) = \sqrt{\frac{1}{3} \cdot a_t^2}$	$c_t = -2 \cdot \alpha \cdot p$	$u_t = c_t \cdot u(t)$	bar
Thermal linear expansion coefficient	$\alpha + \beta$	a_α	rectangular	$\sqrt{3}$	$u(\alpha) = \sqrt{\frac{1}{3} \cdot a_\alpha^2}$	$c_\alpha = -2 \cdot (t - t_0) \cdot p$	$u_\alpha = c_\alpha \cdot u(\alpha)$	bar
Acceleration due to gravity	g	a_g	rectangular	$\sqrt{3}$	$u(g) = \sqrt{\frac{1}{3} \cdot a_g^2}$	$c_g = \frac{p}{g}$	$u_g = c_g \cdot u(g)$	bar
Deformation coefficient	λ	a_λ	rectangular	$\sqrt{3}$	$u(\lambda) = \sqrt{\frac{1}{3} \cdot a_\lambda^2}$	$c_\lambda = -p^2$	$u_\lambda = c_\lambda \cdot u(\lambda)$	bar
Y	y						$u_{\text{corr1}} = \sqrt{u_t^2 + u_\alpha^2 + u_g^2 + u_\lambda^2}$	bar

[11] See footnote [6] on p. 19

[12] See also EURAMET cg-3, Appendix C [5]

Notes:

1. In PTB calibration certificates for piston pressure gauges, the contribution of the uncertainty of the numerical value of the deformation coefficient to the uncertainty of the pressure measurement at reference temperature is generally already taken into account.
2. By using portable measuring devices, it is possible to measure the local acceleration due to gravity in a particular place with a relative uncertainty of a few ppm. If such an exact measurement value is available, and in view of the usually much larger relative uncertainty of the value of the cross-sectional area, it may be acceptable to neglect the uncertainty contribution of the acceleration due to gravity.
3. In relation to the force of inertia $g \cdot \Sigma m_i$ acting in the vacuum, the buoyancy correction is of the order $1.5 \cdot 10^{-4}$. Changes in the air density at a particular location due to the weather normally do not exceed 2 %, corresponding to a relative contribution to the measurement uncertainty of 3 ppm ($3 \cdot 10^{-6}$). In relation to the uncertainty of the cross-sectional area of 50 ppm ($50 \cdot 10^{-6}$) that is usually indicated in calibration certificates, this contribution is negligible and, in general, does not justify the metrological effort necessary for its determination (compare with note in section 6 'Ambient conditions').

Measurement uncertainty budget

with the essential influencing variables in the determination of the hydrostatic pressure due to a difference in height

Table A2: Partial uncertainty budget with the relevant influence quantities for determining the hydrostatic pressure due to a difference in height

Quantity	Best esti-mate	Half-width	Probability distribution	Divisor	Standard measurement uncertainty	Sensitivity coefficient	Uncertainty contribution	Unit
X_i	x_i	a	$g_{X_i}(\xi_i)$		$u(x_i)$	c_i	$u_i(y)$	
Density difference	$\Delta\rho$	$a_{\rho_{\mathrm{Fl}}}$ $a_{\rho_{\mathrm{a}}}$	rectangular	$\sqrt{3}$	$u(\Delta\rho)=\sqrt{\frac{1}{3}\cdot\left(a_{\rho_{\mathrm{Fl}}}^2+a_{\rho_{\mathrm{a}}}^2\right)}$	$c_{\Delta\rho} = g \cdot \Delta h$	$u_{\Delta\rho} = c_{\Delta\rho} \cdot u(\Delta\rho)$	bar
Acceleration due to gravity	g	a_g	rectangular	$\sqrt{3}$	$u(g)=\sqrt{\frac{1}{3}\cdot a_g^2}$	$c_g = \Delta\rho \cdot \Delta h$	$u_g = c_g \cdot u(g)$	bar
Height difference	Δh	$a_{\Delta h}$	rectangular	$\sqrt{3}$	$u(\Delta h)=\sqrt{\frac{1}{3}\cdot a_{\Delta h}^2}$	$c_{\Delta h} = \Delta\rho \cdot g$	$u_{\Delta h} = c_{\Delta h} \cdot u(\Delta h)$	bar
Y	y					$u_{\mathrm{corr2}} = \sqrt{u_{\Delta\rho}^2 + u_g^2 + u_{\Delta h}^2}$		bar

Expanded measurement uncertainty ($k = 2$) for the values realized by a pressure balance under conditions of use:

$$U_{\mathrm{standard}} = k \cdot \sqrt{u_{\mathrm{standard,\,Std}}^2 + u_{\mathrm{corr1}}^2 + u_{\mathrm{corr2}}^2} \tag{33}$$

For illustrative purposes, the uncertainty contributions listed in Appendix A are calculated individually in the uncertainty budgets of the examples in Appendices B and C.

Note:

In addition to the corrections given here as an example, further corrections and associated contributions to the measurement uncertainty may have to be considered, e.g. the uncertainty of the residual gas pressure measurement for absolute pressure piston pressure gauges, or the pressure dependence of the density of the pressure-transmitting medium.

Appendix B Example
Uncertainty budget for the calibration of a Bourdon tube pressure gauge

Calibration effort for calibration sequence C
Indication of the mean value $\overline{p}$ with measurement deviation Δp and hysteresis h

Calibration item

Gauge pressure measuring device with sensing element (Bourdon tube pressure gauge)

Measuring range	: 0 bar … 60 bar
Accuracy stated by the manufacturer	: DIN Kl. (class) 1.0
Scale interval	: 0.5 bar (with fifth estimate)

Standard device

Piston pressure gauge

Expanded uncertainty	: $1.0 \cdot 10^{-4} \cdot p$, but not smaller than 0.40 mbar (data provided in the calibration certificate under standard conditions including long-term behaviour from the history)

For the correction of the pressures displayed by the standard device, the following data have been used (calculation according to Appendix A):

t	: 21.6 °C; ±1.0 °C [13]
t_0	: 20 °C
$\alpha+\beta$	: $22.0 \cdot 10^{-6}$ K^{-1}; $\pm 1.1 \cdot 10^{-6}$ K^{-1} [14]
g	: 9.812533 m/s^2; ±0.000020 m/s^2 [14]
λ	: $2.00 \cdot 10^{-7}$ bar^{-1}; $\pm 0.70 \cdot 10^{-7}$ bar^{-1} [14]

Calibration conditions

Pressure-transmitting medium	: purified nitrogen
$\rho_{\mathrm{Fl}(20\ °\mathrm{C},\ 1\ \mathrm{bar})}$	: 1.15 kg/m³
$\rho_{\mathrm{a}(20\ °\mathrm{C},\ 1\ \mathrm{bar},\ 35\ \%\ \mathrm{relative\ humidity})}$	: 1.19 kg/m³
Δh	: 0.0000 m; ±0.0050 m [14]
t_{amb}	: 21.6 °C; ±1.0 °C [14]
p_{amb}	: 990.0 mbar; ±1.0 mbar [14]

[13] Data after the semicolon: half-width a of the distribution to upper and lower limit a_+ and a_- according to 8.2.4

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Tabelle B1: Result

Pressure at the level of the reference plane of the calibration item $p_{standard}$	**Reading from calibration item (indication)** p_{ind} M1 (up)	M2 (down)	**Mean value** $\bar{p}$ (M1+M2)/2	**Measure-ment deviation** Δp $\bar{p} - p_{standard}$	**Hysteresis** h |M2-M1|	**Expanded uncertainty** (k = 2) U *
bar	bar	bar	bar	bar	bar	bar
0.00	0.0	0.0	0.00	0.00	0.00	0.12
12.02	12.1	12.2	12.15	0.13	0.10	0.13
24.03	24.2	24.2	24.20	0.17	0.00	0.12
36.04	36.1	36.2	36.15	0.11	0.10	0.13
48.04	48.1	48.1	48.10	0.06	0.00	0.12
60.05	60.0	60.1	60.05	0.00	0.10	0.13

* The stated expanded uncertainties correspond to the values calculated according to Table B2. In the calibration certificate, however, an expanded uncertainty not being smaller than 0.30 % of the measuring span has to be stated due to having used calibration sequence C, i.e. U = 0.30 % · 60 bar = 0.18 bar.

Table B2: Measurement uncertainty budget for load step p = 60.05 bar

Quantity	Best estimate	Width of distribution	Divisor	Standard measurement uncertainty	Sensitivity coefficient	Uncer-tainty contri-bution	Variance
X_i	x_i	$2a$		$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$
						bar	bar²
p_{standard}	60.05 bar			$3.00 \cdot 10^{-3}$ bar *	-1	$3.00 \cdot 10^{-3}$	$9.02 \cdot 10^{-6}$
t	21.6 °C	2 K	$2\sqrt{3}$	$5.77 \cdot 10^{-1}$ K	$-1.32 \cdot 10^{-3}$ bar/K	$7.63 \cdot 10^{-4}$	$5.82 \cdot 10^{-7}$
$\alpha+\beta$	$22 \cdot 10^{-6}$ / K	$2.2 \cdot 10^{-6}$ / K	$2\sqrt{3}$	$6.35 \cdot 10^{-7}$ / K	-192 K·bar	$1.22 \cdot 10^{-4}$	$1.49 \cdot 10^{-8}$
g	9.812533 m/s²	0.000040 m/s²	$2\sqrt{3}$	$1.15 \cdot 10^{-5}$ m/s²	6.12 bar·s²/m	$7.07 \cdot 10^{-5}$	$4.99 \cdot 10^{-9}$
λ	$2.0 \cdot 10^{-7}$ / bar	$1.4 \cdot 10^{-7}$ / bar	$2\sqrt{3}$	$4.04 \cdot 10^{-8}$ / bar	$-3.61 \cdot 10^{3}$ bar²	$1.46 \cdot 10^{-4}$	$2.12 \cdot 10^{-8}$
Δh **	0	$1.0 \cdot 10^{-2}$ m	$2\sqrt{3}$	$2.89 \cdot 10^{-3}$ m	$6.74 \cdot 10^{-3}$ bar/m	$1.94 \cdot 10^{-5}$	$3.78 \cdot 10^{-10}$
p_{ind}	60.05 bar	0.20 bar	$2\sqrt{3}$	$5.77 \cdot 10^{-2}$ bar	1	$5.77 \cdot 10^{-2}$	$3.33 \cdot 10^{-3}$
$\delta p_{\text{zero deviation}}$	0	0.00 bar	$2\sqrt{3}$	0	1	0	0
$\delta p_{\text{repeatability}}$	0	0.00 bar	$2\sqrt{3}$	0	1	0	0
$\delta p_{\text{hysteresis}}$	0	0.10 bar	$2\sqrt{3}$	$2.89 \cdot 10^{-2}$ bar	1	$2.89 \cdot 10^{-2}$	$8.33 \cdot 10^{-4}$
Δp	0.00 bar	Standard measurement uncertainty u or variance u^2				$6.46 \cdot 10^{-2}$	$\sum u_i^2 =$ $4.18 \cdot 10^{-3}$
Δp	0.00 bar	Expanded measurement uncertainty $U = k \cdot u \quad (k = 2)$				**0.13 bar** ***	

* Here, the indicated standard measurement uncertainty is $u_{\text{standard,Std}}$. The other uncertainty contributions according to Appendix A are listed separately.

** Taking into account the pressure-dependent gas density (approximation)

$$\rho_{p,t} = \rho_{20\,°\text{C},\,1\,\text{bar}} \cdot \left[\frac{p_{\text{abs}} \cdot (T + 20\,°C)}{1\,\text{bar} \cdot (T + t)} \right] \qquad \text{with } T = 273.15\text{ K}$$

*** According to Section 9.3 “Limiting values for stating the measurement uncertainty”, the value stated in the calibration certificate for a calibration according to sequence C (repeatability and reproducibility cannot be determined) must not be smaller than 0.30 % of the measuring span; this corresponds to an expanded uncertainty of U = 0.30 % · 60 bar = 0.18 bar.

Appendix C Example
Uncertainty budget for the calibration of a digital electric pressure gauge

Calibration effort for calibration sequence B
Indication of the mean value $\overline{p}$ with measurement deviation Δp, repeatability b' and hysteresis h

Calibration item

Electric absolute pressure gauge with suppressed zero point

Measuring range	: 50 mbar … 1550 mbar
Accuracy stated by the manufacturer	: 0.03 % of the mean value
Resolution	: 0.001 mbar

Standard device

Absolute pressure piston gauge

Expanded uncertainty	: $1.0 \cdot 10^{-4} \cdot p$, but not smaller than 0.0050 mbar (data provided in the calibration certificate under standard conditions including long-term behaviour from the history)

For the correction of the pressures displayed by the standard device, the following data have been used (calculation according to Appendix A):

t	: 21.6 °C; ±1.0 °C [14]
t_0	: 20 °C
g	: 9.812533 m/s^2; ±0.000020 m/s^2 [14]
$\alpha+\beta$	: $22.0 \cdot 10^{-6}$ K^{-1}; $\pm 1.1 \cdot 10^{-6}$ K^{-1} [14]
λ	: 0
$p_{\text{standard,residual gas}}$	: (0.010 ± 0.020) mbar

Calibration conditions

Pressure-transmitting medium	: dry air
$\rho_{\text{Fl}(20\,°\text{C},\,1\,\text{bar})}$	: 1.19 kg/m^3
Δh	: 0.0000 m; ±0.0050 m [14]
t_{amb}	: 21.6 °C; ±1.0 °C [14]
p_{amb}	: 990.0 mbar; ±1.0 mbar [14]

Table C1: Result

Pressure at the level of the reference plane of the calibration item $p_{standard}$	**Reading from calibration item (indication)** p_{ind}			**Mean value** $\overline{p}$	**Measure-ment deviation** Δp	**Re-peatability** b'	**Hyster-esis** h	**Ex-panded uncer-tainty** (k = 2) U *
	M1 (up)	M2 (down)	M3 (up)	((M1+M3) /2+M2)/2	$\overline{p} - p_{standard}$	(M3-M1)	(M2-M1)	
mbar	mbar	mbar	mbar	mbar	mbar	mbar	mbar	mbar
50.085	49.850	49.861	49.834	49.852	-0.233	0.016	0.011	0.024
130.191	129.984	130.007	129.967	129.991	-0.200	0.017	0.023	0.029
330.460	330.301	330.335	330.284	330.314	-0.146	0.017	0.034	0.045
530.731	530.616	530.654	530.600	530.631	-0.100	0.016	0.038	0.063
730.990	730.892	730.933	730.879	730.909	-0.081	0.013	0.041	0.082
931.272	931.184	931.226	931.172	931.202	-0.070	0.012	0.042	0.10
1131.138	1131.050	1131.094	1131.046	1131.071	-0.067	0.004	0.044	0.12
1331.413	1331.330	1331.359	1331.337	1331.346	-0.067	0.007	0.029	0.14
1531.673	1531.630	1531.656	1531.629	1531.643	-0.030	0.001	0.026	0.16

* In the calibration certificate, however, an expanded uncertainty not being smaller than 0.04 % of the measuring span has to be stated due to having used calibration sequence B, i.e. U = 0.04 % · 1500 mbar = 0.60 bar.

Table C2: Measurement uncertainty budget for load step p = 1531.673 mbar

Quantity X_i	**Best estimate** x_i	**Width of distribution** $2a$	**Divisor**	**Standard uncertainty** $u(x_i)$	**Sensitivity coefficient** c_i	**Uncertainty contribution** $u_i(y)$	**Variance** $u_i^2(y)$
						mbar	mbar²
p_{standard}	1531.673 mbar			$7.66\cdot10^{-2}$ mbar*	-1	$7.66\cdot10^{-2}$	$5.87\cdot10^{-3}$
$p_{\text{standard,residual gas}}$	0**			$1.00\cdot10^{-2}$ mbar	1	$1.00\cdot10^{-2}$	$1.00\cdot10^{-4}$
t	21.6 °C	2 K	$2\sqrt{3}$	$5.77\cdot10^{-1}$ K	$-3.37\cdot10^{-2}$ mbar/K	$1.95\cdot10^{-2}$	$3.78\cdot10^{-4}$
$\alpha+\beta$	$22.0\cdot10^{-6}$ K^{-1}	$2.2\cdot10^{-6}$ K^{-1}	$2\sqrt{3}$	$6.35\cdot10^{-7}$ / K	$-4.90\cdot10^{3}$ K·mbar	$3.11\cdot10^{-3}$	$9.69\cdot10^{-6}$
g	9.812533 m/s²	0.000040 m/s²	$2\sqrt{3}$	$1.15\cdot10^{-5}$ m/s²	156 mbar·s²/m	$1.80\cdot10^{-3}$	$3.25\cdot10^{-6}$
Δh ***	0	$1.0\cdot10^{-2}$ m	$2\sqrt{3}$	$2.89\cdot10^{-3}$ m	$1.78\cdot10^{-1}$ mbar/m	$5.13\cdot10^{-4}$	$2.64\cdot10^{-7}$
p_{ind}	1531.643 mbar	0.001 mbar	$2\sqrt{3}$	$2.89\cdot10^{-4}$ mbar	1	$2.89\cdot10^{-4}$	$8.33\cdot10^{-8}$
$\delta p_{\text{repeatability}}$	0	0.001 mbar	$2\sqrt{3}$	$2.89\cdot10^{-4}$ mbar	1	$2.89\cdot10^{-4}$	$8.33\cdot10^{-8}$
$\delta p_{\text{hysteresis}}$	0	0.026 mbar	$2\sqrt{3}$	$7.51\cdot10^{-3}$ mbar	1	$7.51\cdot10^{-3}$	$5.63\cdot10^{-5}$
Δp	-0.030 mbar	Standard measurement uncertainty u or variance u^2				$8.01\cdot10^{-2}$	$\sum u_i^2 = 6.41\cdot10^{-3}$
Δp	-0.030 mbar	Expanded measurement uncertainty $U = k\cdot u \quad (k=2)$				**0.16 mbar** ****	

* Here, the indicated standard uncertainty is $u_{\text{standard, Std}}$. The other uncertainty contributions according to Appendix A are listed separately.

** The residual gas pressure $p_{\text{standard,residual gas}}$ is already included in p_{standard} .

*** Taking into account the pressure-dependent gas density (approximation)

$$\rho_{p,t} = \rho_{20\,°\text{C},\,1\,\text{bar}} \cdot \left[\frac{p_{\text{abs}} \cdot (T + 20\,°\text{C})}{1\,\text{bar} \cdot (T+t)} \right] \qquad \text{with } T = 273.15\ \text{K}$$

**** According to Section 9.3 “Limiting values for stating the measurement uncertainty”, the value stated in the calibration certificate for a calibration according to sequence B must not be smaller than 0.04 % of the measuring span; this corresponds to an expanded uncertainty of U = 0.04 % · 1500 mbar = 0.60 mbar.

Appendix D Example
Uncertainty budget for the calibration of a pressure transmitter with electrical output [14]

Calibration effort for calibration sequence A with second clamping

Indication of the mean value $\overline{A}_{\text{ind}}$ from increasing and decreasing series, repeatability b', der reproducibility b, hysteresis h, transmission coefficient S and deviation ΔS .

Calibration item

Pressure transmitter with electrical output

Measuring range	: 0 bar … 200 bar
Accuracy stated by the manufacturer	: 0.01 % of the upper measuring range value

Standard device

Piston pressure gauge

Expanded uncertainty	: $1.0{\cdot}10^{-4}{\cdot}p$, but not smaller than 1.0 mbar (under conditions of use as defined in Appendix A)

Auxiliary measuring device

Digital compensator

Indication in mV/V	: $A_{\text{ind}} \equiv U_{\text{ind}}/(G{\cdot}U_{\text{Sp}})$ with $G = 1$ und $U(G) = 0$
Expanded uncertainty $U(A_{\text{ind}})$	: 0.000050 mV/V (data provided in the calibration certificate under standard conditions including long-term behaviour from the history)

Calibration conditions

Pressure-transmitting medium	: white oil
$\rho_{\text{Fl(20°C)}}$	: (855 ± 40) kg/m³ in the measurement range up to 200 bar
Δh	: 0.0000 m; ±0.0050 m [14]
t_{amb}	: 20.0 °C; ±1.0 °C [14]
p_{amb}	: 990.0 mbar; ±1.0 mbar [14]

[14] In the following example, the measurement uncertainty is determined with related values according to the product/quotient model according to equation (16). Alternatively, the sum/difference model according to equation (8) can be selected if the measurement deviations of the output signal of the pressure transducer from the values calculated according to the nominal characteristic curve are considered. In this case, quantitative agreement is found in the results of the measurement uncertainty determinations.

Table D1: Measurement data

Pressure at the level of the reference plane of the calibration item $p_{standard}$	**Indication of the digital compensator** A_{ind} M1 (up)	M2 (down)	M3 (up)	M4 (down)	M5 (up)	M6 (down)
bar	mV/V	mV/V	mV/V	mV/V	mV/V	mV/V
0.000	0.00000	-0.00003	0.00000	0.00002	0.00000	-0.00002
20.010	0.20009	0.20026	0.20019	0.20033	0.20021	0.20032
40.022	0.40026	0.40063	0.40032	0.40067	0.40033	0.40064
60.033	0.60041	0.60094	0.60049	0.60097	0.60049	0.60092
80.045	0.80053	0.80118	0.80062	0.80120	0.80062	0.80110
100.056	1.00063	1.00139	1.00072	1.00135	1.00075	1.00125
120.068	1.20074	1.20149	1.20080	1.20141	1.20082	1.20132
140.079	1.40080	1.40158	1.40089	1.40150	1.40090	1.40133
160.091	1.60082	1.60157	1.60091	1.60148	1.60091	1.60126
180.102	1.80084	1.80148	1.80097	1.80135	1.80091	1.80111
200.113	2.00079	2.00100	2.00088	2.00114	2.00086	2.00087

Table D2: Evaluation

Pressure at the level of the reference plane of the calibration item $p_{standard}$	**Output signal mean value** $\overline{A_{ind}}$ $\Sigma M_i/6$	**Zero deviation** $f_{0,rel}$ $f_0 / \overline{A_{ind}}$	**Repeatability** b'_{rel} $b'_{mean} / \overline{A_{ind}}$	**Reproducibility** b_{rel} $b_{mean} / \overline{A_{ind}}$	**Hysteresis** h_{rel} $h_{mean} / \overline{A_{ind}}$	**Relative expanded measurement uncertainty** $W(p_{standard})$ *
bar	mV/V	#	#	#	#	#
0.000	-0.00001	#	#	#	#	#
20.010	0.20023	$1.5 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
40.022	0.40048	$7.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$8.6 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
60.033	0.60070	$5.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
80.045	0.80088	$3.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
100.056	1.00102	$3.0 \cdot 10^{-5}$	$9.0 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
120.068	1.20110	$2.5 \cdot 10^{-5}$	$6.7 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
140.079	1.40117	$2.1 \cdot 10^{-5}$	$6.4 \cdot 10^{-5}$	$1.8 \cdot 10^{-4}$	$4.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
160.091	1.60116	$1.9 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
180.102	1.80111	$1.7 \cdot 10^{-5}$	$7.2 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
200.113	2.00092	$1.5 \cdot 10^{-5}$	$7.0 \cdot 10^{-5}$	$6.5 \cdot 10^{-5}$	$8.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$

* In the pressure reference plane of the calibration item

Table D3: Result

Pressure at the level of the reference plane of the calibration item p_{standard}	**Transmission coefficient** S $= \overline{A_{\text{ind}}} / p_{\text{standard}}$	**Deviation** ΔS $= S - S'$	**Relative expanded uncertainty** $W(S)$ $= 2\sqrt{w_i^2(S)}$	**Expanded uncertainty** $U(S)$ $= W(S) \cdot S$	**Error span** $U'(S)$ $= U(S) + \Delta S$
bar	(mV/V)/bar	(mV/V)/bar	#	(mV/V)/bar	(mV/V)/bar
0.000	#	#	#	#	#
20.010	0.0100067	$5.2 \cdot 10^{-6}$	$6.7 \cdot 10^{-4}$	$6.7 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
40.022	0.0100064	$4.9 \cdot 10^{-6}$	$5.4 \cdot 10^{-4}$	$5.4 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$
60.033	0.0100062	$4.7 \cdot 10^{-6}$	$4.9 \cdot 10^{-4}$	$4.9 \cdot 10^{-6}$	$9.6 \cdot 10^{-6}$
80.045	0.0100053	$3.8 \cdot 10^{-6}$	$4.4 \cdot 10^{-4}$	$4.4 \cdot 10^{-6}$	$8.2 \cdot 10^{-6}$
100.056	0.0100045	$3.0 \cdot 10^{-6}$	$3.9 \cdot 10^{-4}$	$3.9 \cdot 10^{-6}$	$7.0 \cdot 10^{-6}$
120.068	0.0100035	$2.0 \cdot 10^{-6}$	$3.3 \cdot 10^{-4}$	$3.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-6}$
140.079	0.0100027	$1.2 \cdot 10^{-6}$	$2.9 \cdot 10^{-4}$	$2.9 \cdot 10^{-6}$	$4.1 \cdot 10^{-6}$
160.091	0.0100016	$4.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-4}$	$2.5 \cdot 10^{-6}$	$2.6 \cdot 10^{-6}$
180.102	0.0100005	$-1.0 \cdot 10^{-6}$	$2.1 \cdot 10^{-4}$	$2.1 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$
200.113	0.0099990	$-2.5 \cdot 10^{-6}$	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-6}$	$3.8 \cdot 10^{-6}$

Single-figure indication:	S' = 0.0100015 (mV/V)/bar

Table D4: Measurement uncertainty budget for load step p = 100.056 bar

Quantity X_i	**Best estimate** x_i	**Width of distribution** $2a$	**Divisor**	**Standard uncertainty** $w(x_i)$	**Exponent of** ***Xi*** $c_i x_i y^{-1}$	**Uncer-tainty contribu-tion** $w_i(y)$	**Variance** $w_i^2(y)$
p_{standard}	100.056 bar			$5.00 \cdot 10^{-5}$	-1	$5.00 \cdot 10^{-5}$	$2.50 \cdot 10^{-9}$
A_{ind}	1.00102 mV/V			$2.50 \cdot 10^{-5}$	1	$2.50 \cdot 10^{-5}$	$6.24 \cdot 10^{-10}$
$K_{\text{zero deviation}}$	1	$3.0 \cdot 10^{-5}$	$2\sqrt{3}$	$8.65 \cdot 10^{-6}$	1	$8.65 \cdot 10^{-6}$	$7.50 \cdot 10^{-11}$
$K_{\text{repeatability}}$	1	$9.0 \cdot 10^{-5}$	$2\sqrt{3}$	$2.60 \cdot 10^{-5}$	1	$2.60 \cdot 10^{-5}$	$6.75 \cdot 10^{-10}$
$K_{\text{reproducibility}}$	1	$1.4 \cdot 10^{-4}$	$2\sqrt{3}$	$4.04 \cdot 10^{-5}$	1	$4.04 \cdot 10^{-5}$	$1.63 \cdot 10^{-9}$
$K_{\text{hysteresis}}$	1	$6.3 \cdot 10^{-4}$	$2\sqrt{3}$	$1.82 \cdot 10^{-4}$	1	$1.82 \cdot 10^{-4}$	$3.31 \cdot 10^{-8}$
S	0.0100045 (mV/V)/bar	Relative standard measurement uncertainty w or variance w^2				$1.96 \cdot 10^{-4}$	$3.86 \cdot 10^{-8}$
S	0.0100045 (mV/V)/bar	Relative expanded Measurement uncertainty $W = k \cdot w \quad (k = 2)$				**$3.9 \cdot 10^{-4}$**	

The pressure dependence of the oil density has been neglected.

For load step p = 100.056 bar the expanded uncertainty of the determination of the transmission coefficient is calculated as follows:

$\mathbf{U(S)|_{100\ bar}} = W(S) \cdot S = 3.9 \cdot 10^{-4} \cdot 0.0100045$ (mV/V)/bar = **$3.9 \cdot 10^{-6}$ (mV/V)/bar**

The specification limit is, for example, ±0.13 % of the transmission coefficient.

Figure D1: Visualisation of the transmission coefficients

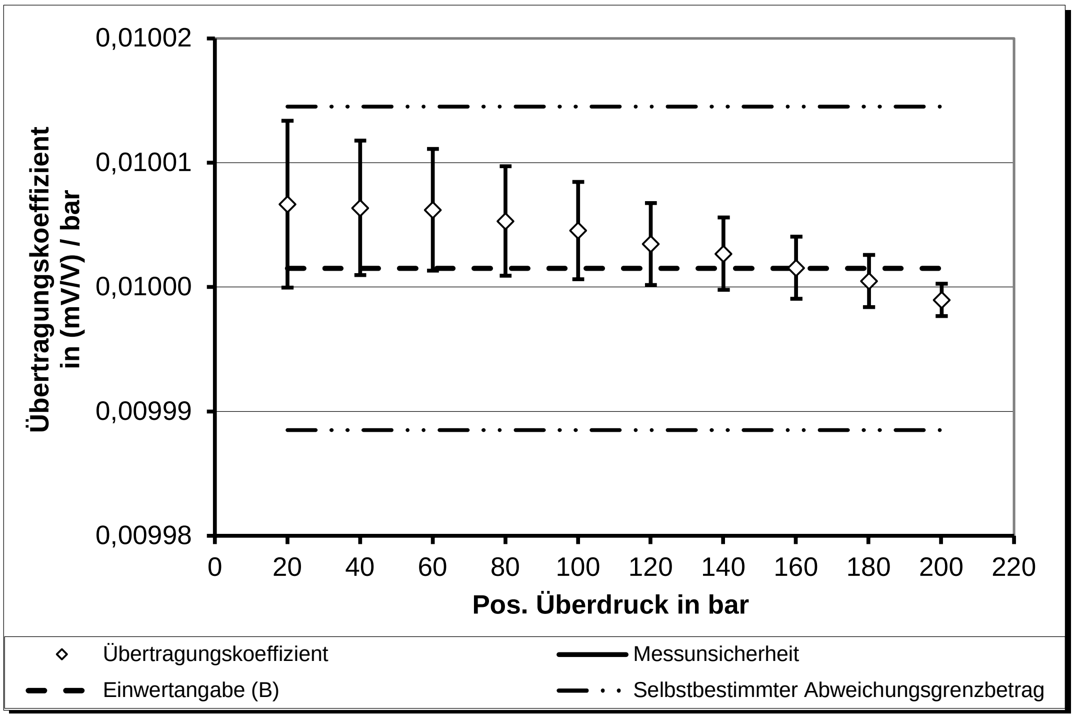
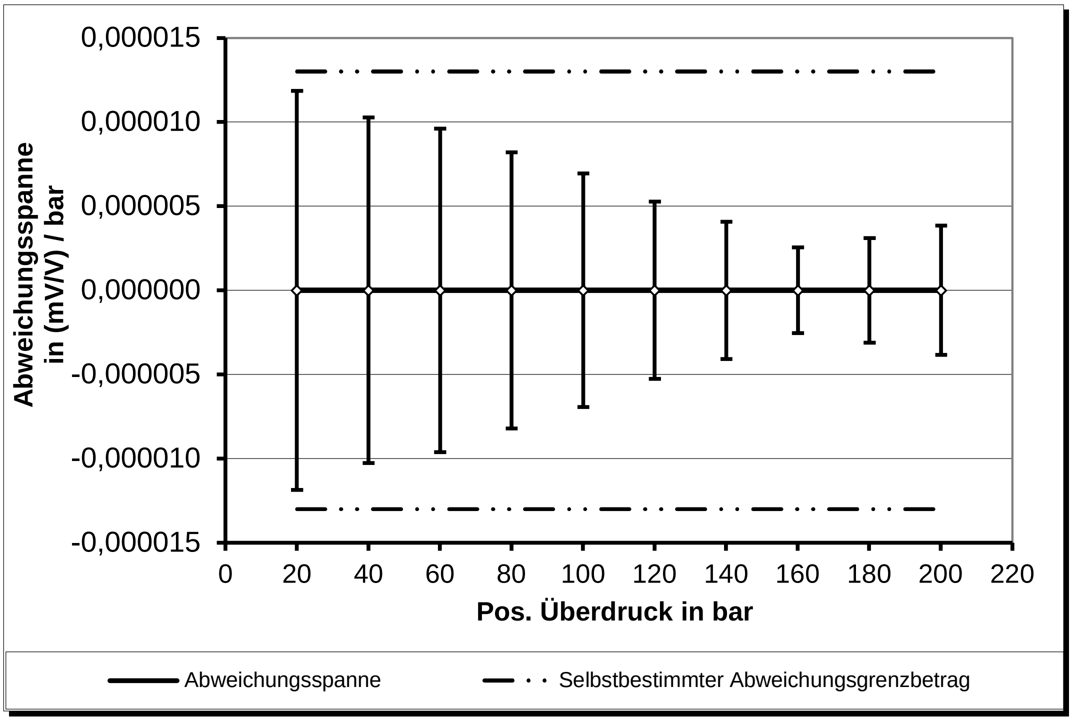


Figure D2: Visualisation of the error spans



Übertragungskoeffizient	Transmission coefficient
Abweichungsspanne	Error span
Positiver Überdruck	Positive excess pressure
Messunsicherheit	Measurement uncertainty
Einwertangabe	Single-figure indication
Selbstbestimmter Abweichungsgrenzbetrag	Self-determined deviation limit

Appendix E (informative) Measurement uncertainties of reference and working standards

Table E1: Typical measurement uncertainties which can be attributed to the values of the reference standard.

Pressure scale	**typical value of the expanded uncertainty** $U\ (k = 2)$ related to the measurement value
10^{-9} mbar ... 10^{-6} mbar	10 % ... 6 %
10^{-6} mbar ... 10^{-2} mbar	4 % ... 1 %
10^{-2} mbar ... 10 mbar	0.5 % ... 0.3 %
10 mbar ... 50 mbar	0.03 %
50 mbar ... 1 bar	0.01 %
1 bar ... 700 bar	0.008 %
700 bar ... 2000 bar	0.012 %
2000 bar ... 10000 bar	0.07 %

Tabelle E2: Typical measurement uncertainties which can be attributed to the values of the working standards.

Working standard	**typical value of the expanded uncertainty** $U\ (k = 2)$ related to the measurement span
quartz sensors, quartz spiral gauges	0.01 %
piezoresistive pressure transmitters	0.03 %
thin-film pressure transducers, pressure strain gauges)	0.05 %
capacitive pressure transducers, Bourdon tube pressure gauges Kl. (class) 0.1	0.10 %

Appendix F Recalibration intervals (recommendation)

It is the user's responsibility to determine and observe a reasonable period of time before repeating the calibration. Under normal conditions of use, the following recalibration periods are recommended:

Piston pressure gauges	**5 years**
Bourdon tube pressure gauges, class > 0.6	**2 years**
Electric pressure gauges > 0.5 % of measurement span	**2 years**
Pressure transmitters with electrical output > 0.5 % of measurement span	**2 years**
Bourdon tube pressure gauges, class ≤ 0.6	**1 year**
Electric pressure gauges ≤ 0.5 % of measurement span	**1 year**
Pressure transmitters with electrical output ≤ 0.5 % of measurement span	**1 year**

Regardless of these periods, the calibration item is to be recalibrated, among other things, if it has been subjected to overloading outside its permissible overload limit, after a repair, after improper handling which might affect the measurement uncertainty, or if other reasons exist.

Herausgeber:

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