DEUTSCHER KALIBRIERDIENST DKD

Guideline DKD-R 6-1

Calibration of Pressure Gauges

Published by the Accreditation Body of the Deutscher Kalibrierdienst (DKD) at the Physikalisch-Technische Bundesanstalt in co-operation with its Technical Committee "Pressure and Vacuum."

Deutscher Kalibrierdienst (DKD)

The DKD comprises calibration laboratories in industrial enterprises, research institutes, technical authorities, inspection and testing institutes. They are accredited and supervised by the DKD. They calibrate measuring instruments and material measures for measurands and measurement ranges specified within the scope of accreditation. The DKD calibration certificates issued by these laboratories prove traceability to national standards as required in the ISO 9000 family and ISO/IEC 17025.

Calibrations carried out by DKD laboratories ensure that the user may rely on measurement results. They increase the customers' confidence and competitiveness on the national and international markets and serve as a metrological basis for the inspection of measuring and test equipment within the framework of quality assurance measures.

Calibrations offered by the DKD cover electrical measurands, length, angles and other geometrical quantities, roughness, coordinate and form measuring techniques, time and frequency, force, torque, acceleration, pressure, flowrate, temperature, humidity, medical measurands, acoustic measurands, optical measurands, ionizing radiation and other measurands.

Publications: see Internet

Address:

Deutscher Kalibrierdienst at the
Physikalisch-Technische Bundesanstalt

Bundesallee 100	D-38116 Braunschweig
P.O. Box 33 45	D-38023 Braunschweig
Office telephone	+49 531 592 1901
Fax	+49 531 592 1905
E-Mail	dkd@ptb.de
Internet	www.dkd.info

Foreword

DKD Guidelines are application documents for the general criteria and procedures which are laid down in DIN EN ISO/IEC 17025 and DKD publications. The DKD Guidelines describe technical and organizational processes serving the calibration laboratories as a model for laying down internal procedures and regulations. DKD Guidelines can become an integral part of quality manuals of calibration laboratories. The application of the Guidelines supports equal treatment of the devices to be calibrated at the different calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories.

The DKD Guidelines will not impede the further development of calibration procedures and sequences. Deviations from guidelines and new methods are permitted in agreement with the Accreditation Body if they are justified by technical aspects.

The present Guideline was prepared by the Technical Committee "Pressure and Vacuum" in co-operation with the PTB and adopted by the Advisory Board of the DKD. With its publication it is binding for all DKD calibration laboratories unless separate procedural instructions approved by the Accreditation Body are available.

Contents

1 Purpose and scope of application

This Guideline serves to establish minimum requirements for the calibration method and the estimate of the measurement uncertainty in the calibration of pressure gauges. It applies to Bourdon tube pressure gauges, electrical pressure gauges and pressure transmitters with electrical output for absolute pressure, differential pressure and overpressure with negative and positive values.

2 Symbols and designations

The symbols are subject-related, i.e. as a rule, they are given in the order in which they appear in the text.

2.1 Variables

M1 ... M6	Measurement series
max. load	Highest value (of calibration range)
Y	Output quantity
X	Value-determining input quantity
δX	Unknown measurement deviation
K	Correction factor
x	Estimate of input quantity
y	Estimate of output quantity
c	Sensitivity coefficient
k	Expansion factor
a	Half-width of a distribution
P	Probability
E[...]	Expected value
u	Standard uncertainty
U	Expanded uncertainty
w	Relative standard uncertainty
W	Relative expanded uncertainty

p	Pressure
Δp	Systematic measurement deviation of the quantity of pressure
δp	Unknown measurement deviation of the quantity of pressure
S	Transmission coefficient (of pressure transducer)
ΔS	Systematic deviation of transmission coefficient from single-number rating ($\Delta S = S - S'$)
V	Voltage
G	Amplification factor
r	Resolution
f_0	Zero deviation
b'	Repeatability
b	Reproducibility
h	Hysteresis
U'	Error span
W'	Relative error span
S'	Slope of a linear regression function
p_e	Excess pressure
m	Mass of load masses
g	Acceleration due to gravity
ρ	Density
A	Effective cross section of piston-cylinder system
λ	Deformation coefficient of piston-cylinder system
α	Linear thermal expansion coefficient of piston
β	Linear thermal expansion coefficient of cylinder
t	Temperature of piston-cylinder system
h	Difference of pressure reference levels of reference instrument and the instrument tobe calibrated

2.2 Indices

Supply	Supply voltage
j	Number of measurement point
m	Number of measurement series
n	Number of measurement cycles
a	Air
Fl	Medium
m	Load mass
0	Reference conditions t = 20°C
ref	Reference conditions
cond. of use	Conditions of use
corr	Correction (of measurement value)

3 Reference and working standards

The calibration takes place by direct comparison of the measurement values for 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 such as pressure balances and liquid-level manometers. They are calibrated at the PTB at regular intervals and a calibration certificate is issued for them stating the expanded uncertainty under reference conditions (standard acceleration due to gravity, 20°C).

When a calibration is carried out outside the reference conditions, corrections are to be applied to the pressure calculation. The measurement uncertainties to be attributed to these corrections due to influence quantities are to be taken into account as further contributions in the uncertainty budget.

The working standards documented in the quality manual of the DKD laboratory are calibrated in an accredited laboratory and a calibration certificate is issued for them stating the expanded uncertainty under reference conditions. The working standard is subject to approval by the PTB. The working standards can be different as regards their type.

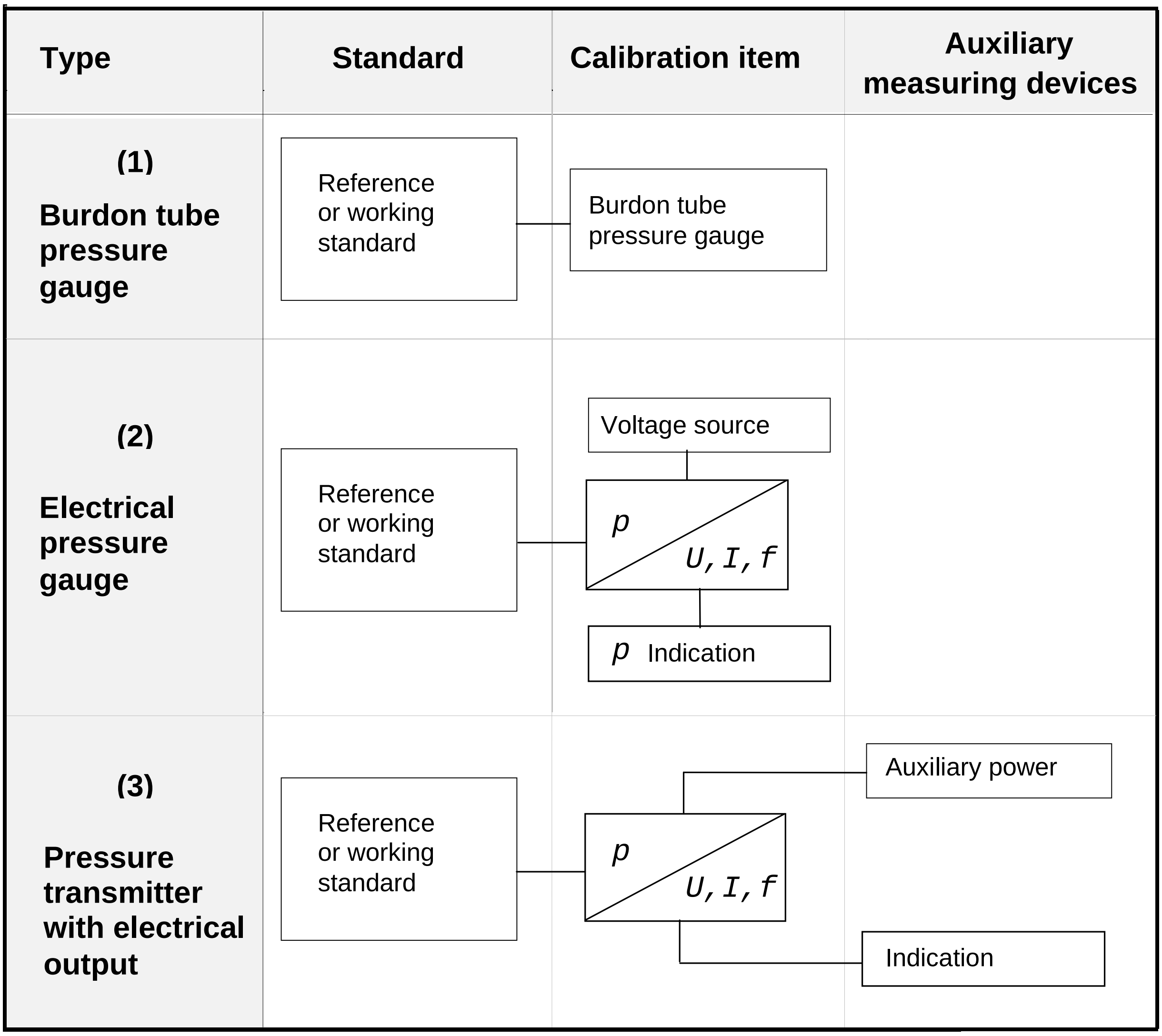
Recommendation:
The measurement uncertainty which is attributed to the measurement values of the reference or working standard should not exceed 1/3 of the uncertainty aimed at[1], which will probably be attributed to the measurement values of the calibration item.

[1] The measurement uncertainty aimed at is the uncertainty which can be achieved when specified calibration efforts are made (uncertainty of the values of the standard, number of measurement series, etc.). It is normally greater than the smallest uncertainty which can be stated.

4 Calibration item

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

Figure 1: Types of pressure gauges



In contrast to electrical pressure gauges (2) for which only auxiliary power needs to be provided, auxiliary measuring devices of the DKD laboratory must be used for the calibration of pressure transmitters with electrical output (3). These 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 analysis. 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 selecting the test equipment it is to be ensured that the measurement uncertainty attributed to the measurement values of the auxiliary measuring devices can be stated according to the measurement uncertainty aimed at for the calibration item.

If the calibration item has a digital interface (e.g. RS232, RS485, IEEE488, etc.), this interface can be used in the place of the indication. It is to be ensured that the data read out are unequivocally interpreted and processed.

5 Calibratability

Handling of a calibration task presupposes calibratability (suitability of the calibration item), i.e. the state of the calibration item at the time of calibration should comply with the generally accepted rules of technology and with the particular specifications of the manufacturer's documentation. The calibratability is to be ascertained by external inspections and function tests.

External inspections cover for example:

- visual inspection for damage (pointer, threads, sealing surface, pressure channel)
- contamination and cleanness
- visual inspections of inscriptions, readability of indications
- test whether the documents necessary for calibration (technical data, operating instructions) have been submitted.

Function tests cover for example:

- tightness of tube system of calibration item
- electrical function
- perfect function of actuators (e.g. zero adjustability)
- setting elements in defined position
- faultless execution of self-checking and/or self-setting functions; if needed, internal reference values are to be read out via the EDP interface
- torque dependence (zero signal) during mounting

Note:
If repair or adjustment work has to be carried out to ensure calibratability, this work has to be agreed upon between customer and calibration laboratory.

6 Ambient conditions

The calibration is to be carried out after temperature equalization between calibration item and environment. A period for warming up the calibration item or potential warming-up of the calibration item due to the supply voltage is to be taken into account.

The calibration is to be performed at an ambient temperature stable to within ±1 K; this temperature must lie between 18°C and 28°C and is to be recorded.

Note:
If the air density has an effect on the calibration result, not only the ambient temperature but also the atmospheric pressure and the relative humidity are to be recorded.

7 Calibration methods

- The pressure gauge is to be calibrated as a whole (measuring chain), if possible.
- The specified mounting position is to be taken into consideration
- The calibration is to be carried out in measurement points uniformly distributed over the calibration range.
- Depending on the measurement uncertainty aimed at, one or several measurement series are necessary.
- If the behaviour of the calibration item as regards the influence of the torque during mounting is not sufficiently known, the calibration item has to be clamped once again to determine the reproducibility. In this case, the torque is to be measured and documented.

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

The comparison between the measurement values for calibration item and reference or working standard can be performed by two different methods:

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

The time for preloading at the highest value and the time between two preloadings should be at least 30 seconds. After preloading and after steady-state conditions have been reached – and the calibration item permitting -, the indication of the calibration item is set to zero. The zero reading is carried out immediately afterwards. For the pressure step variation in a measurement series, the time between two successive load steps should be the same and not be shorter than 30 seconds and the reading should be made 30 seconds after the start of the pressure change at the earliest. Especially Bourdon tube pressure gauges have to be slightly tapped to minimize any frictional effect of the pointer system. The measurement value for the upper limit of the calibration range is to be recorded prior to and after the waiting time. The zero reading at the end of a measurement series is made 30 seconds after complete relief at the earliest.

The calibration effort is shown in table 1 and figure 2 in dependence on the measurement uncertainty aimed at (see [1] on page 7). Figure 2 shows the sequence of the calibration.

Table 1: Calibration sequences

Calibration sequence	Measurement uncertainty aimed at, in % of the measurement span (*)	Number of measurement points with zero up/down	Number of preloadings	Load change + waiting time (**) seconds	Waiting time at upper limit of measurement range (***) minutes	Number of measurement series up	Number of measurement series down
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

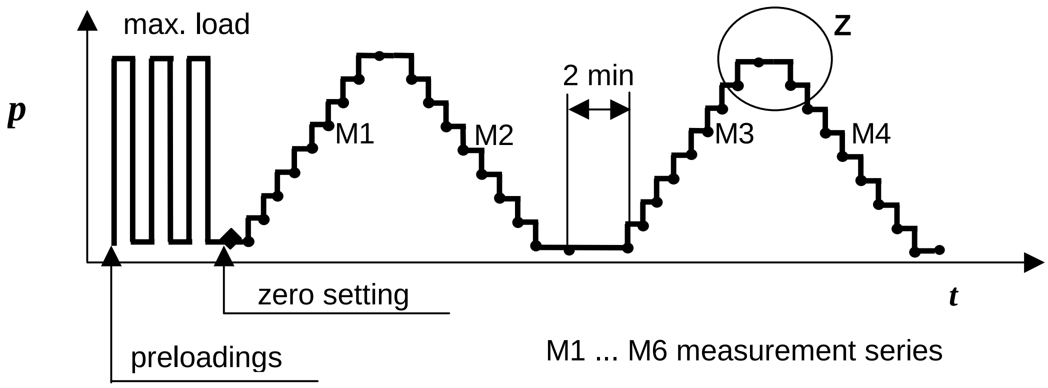
(*) Reference to the span was used to allow the sequence (necessary calibration effort) to be selected from the table, as the accuracy specifications of the manufacturers are usually related to the measurement span.

(**) One has in any case to wait until steady-state conditions (sufficiently stable indication of standard and calibration item) are reached.

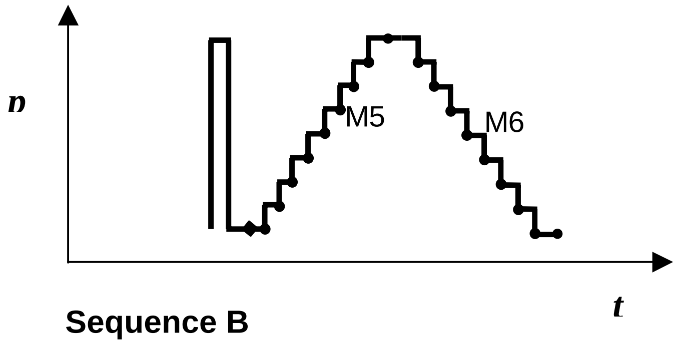
(***) For Bourdon tube pressure gauges, a waiting time of five minutes is to be observed. For quasi-static calibrations (piezoelectric sensor principle), the waiting times can be reduced.

Note:
For the calibration of items with a range of measurement greater than 2500 bar, calibration sequence A is in principle to be used. If clamping effects are observed, the calibration is to be repeated clamping the calibration item anew.

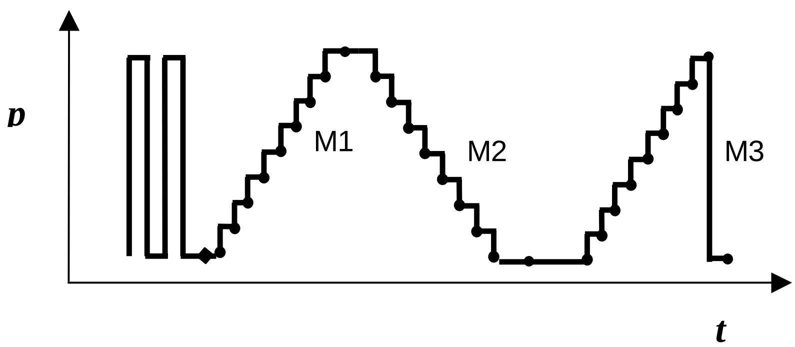
Figure 2: Visualization of the calibration sequences



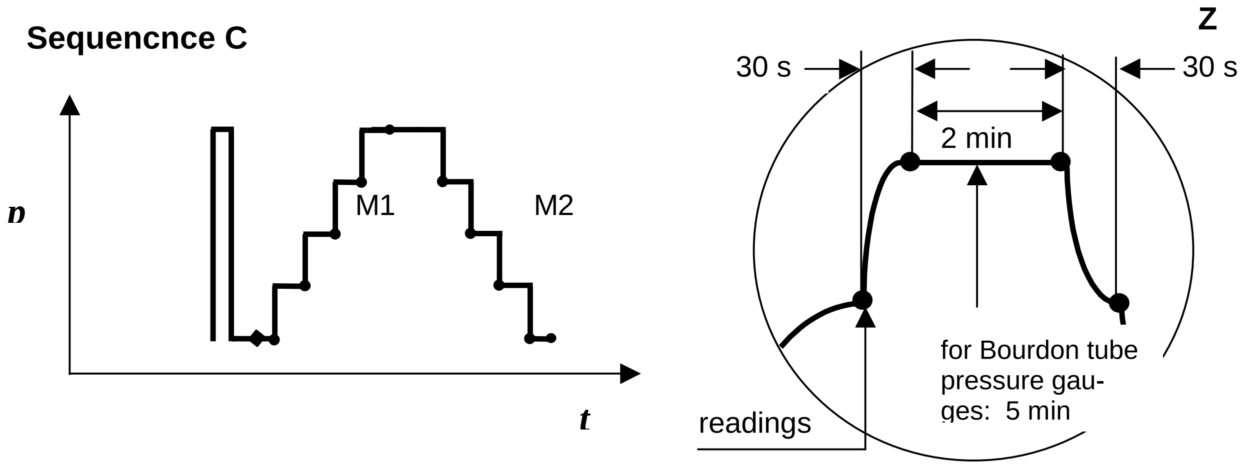
Additional reproducibility measurement with 2nd clamping
(e.g. if the effect of torque is estimated during the calibration)



Sequence B



Sequencnce C



8 Measurement uncertainty[2]

8.1 Definition

Parameter which is stated jointly with the measurement result, i.e. which is attributed by the measurement to the measurement result and characterizes the interval of values which can be reasonably assigned to the measurand on the basis of the measurement.

8.2 Procedure

8.2.1 Evaluation model

For the uncertainty analysis the sequence described in Publication DKD-3 is on principle followed. This publication uses the following terms and calculation rules on condition that no correlations between the input quantities are to be allowed for:

Model function			$y = f(x_1, x_2, ..., x_N)$
Standard uncertainty	$u(x_i)$	standard uncertainty attributed to the input quantity	
	c_i	sensitivity coefficient	$c_i = \frac{\partial f}{\partial x_i}$
	$u_i(y)$	contribution to the standard uncertainty attributed to the result, due to the standard uncertainty $u(x_i)$ of the input quantity x_i	$u_i(y) = c_i \cdot u(x_i)$
	$u(y)$	standard uncertainty attributed to the result	$u^2(y) = \sum_{i=1}^{N} u_i^2(y)$ $u(y) = \sqrt{\sum_{i=1}^{N} u_i^2(y)}$
Expanded 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 95%

[2] For the terminology, see DIN V ENV 13005.

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

With complex models, the calculation rule rapidly leads to an analytical determination of the sensitivity coefficient which is no longer manageable. As a result, the sensitivity coefficients will have to be determined numerically with the aid of a computer.

Besides this general calculation rule, two particular rules are available which lead to sensitivity coefficients $c_i = \pm 1$ and thus to the simple quadratic addition of the uncertainties of the input quantities. This simplifies the uncertainty analysis and makes EDP program support unnecessary.

Note:
The "simple" model, too, must of course correctly reflect the physical measurement/calibration process. If appropriate, complex relations must be represented in a suitable model (no special case) in a separate uncertainty budget (see Annex A: Estimate of measurement uncertainty to be attributed to the values of the pressure balance under conditions of use)

8.2.2 Sum/difference model

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

Y	measurand or output quantity
X	input quantity/quantities according to the functional relationship $Y = f(X_1, X_2, \ldots X_n)$
δX_i	unknown measurement deviation(s)
$E[\delta X_i] = 0$	expected value [the components do not contribute to the determination of the output quantity (corrections are not applied) but they make a contribution to the measurement uncertainty]

e.g. model for determining the measurement deviation of the indication:

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

This model is most suitable for calibration items with an indication of their own in pressure units (e.g. Bourdon tube pressure gauge, electrical 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

$$Y = X \cdot \prod_{i=1}^{N} K_i \qquad (3)$$

Y	output quantity
X	value-determining input quantity/quantities
$K_i = (1 + \delta X_i)$	correction factor(s)
δX_i	unknown deviation(s)

$\mathrm{E}\,[\delta X_\mathrm{i}] = 0$; $\mathrm{E}\,[K_\mathrm{i}] = 1$ expected values
[the components do not contribute to the determination of the output quantity (corrections are not applied) but they make a contribution to the measurement uncertainty]

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

$$S = \frac{X_\mathrm{out}}{X_\mathrm{in}} = \frac{V_\mathrm{ind} / (G \cdot V_\mathrm{supply})}{p_\mathrm{standard}} \cdot \prod_{\mathrm{i}=1}^{\mathrm{N}} K_\mathrm{i} \qquad (4)$$

This model is most suitable for calibration items without an indication of their own (e.g. pressure transmitter with electrical output) using related measurement uncertainties (dimensionless).

8.2.4 Input quantities

The measurement uncertainties attributed to the input quantities are subdivided into two categories as regards their determination:

Type **A**: For the determination of the value and the standard uncertainty attributed to it, analysis methods from statistics for measurement series under repeatability conditions ($\mathrm{n} \geq 10$) are applied.

Type **B**: The determination of the value and of the standard uncertainty attributed to it 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 and other certificates,
- reference data from manuals.

In many cases, only the upper and lower bounds a_+ and a_- can be stated for the value of a quantity, whereby all values within the bounds can be considered equally probable. This situation can best be described by a rectangular probability density.

With

$$a_+ - a_- = 2\,a \qquad (5)$$

the estimate of the input quantity

$$x_\mathrm{i} = \frac{1}{2} \cdot (a_+ + a_-) \qquad (6)$$

and the attributed standard uncertainty

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

are obtained.

If the values more likely lie in the centre or at the border of the interval, it is reasonable to assume a triangular or U-shaped distribution.

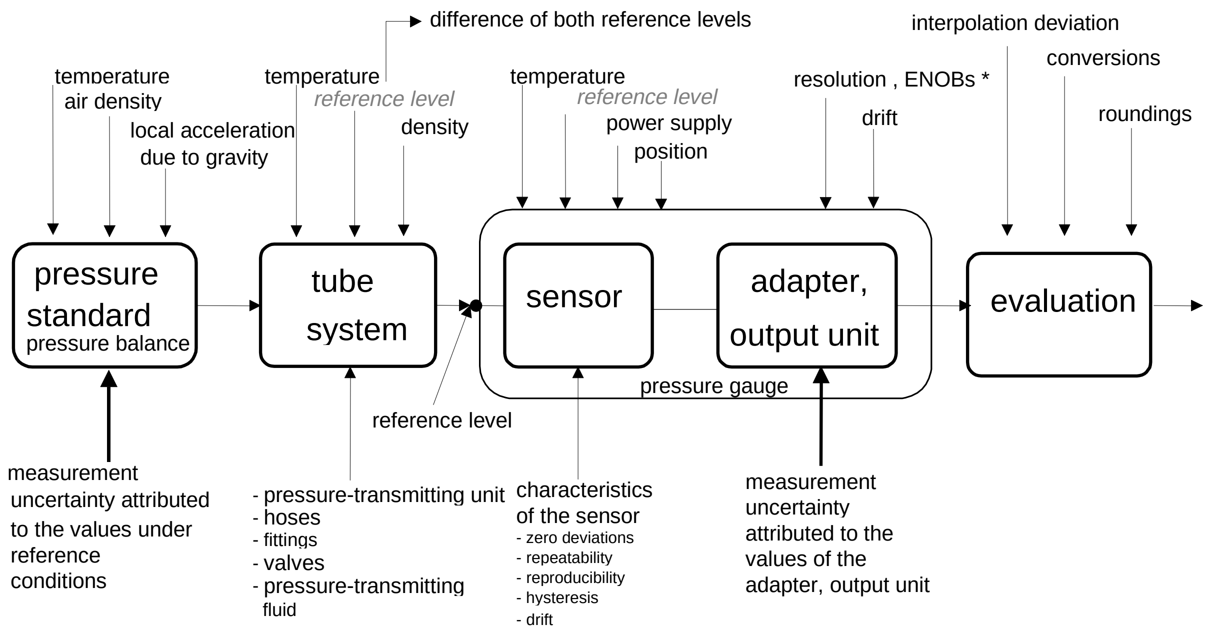
Table 2: Other type B distribution shapes

Distribution	Standard uncertainty
triangular	$u = \frac{a}{\sqrt{6}}$
U-shaped	$u = \frac{a}{\sqrt{2}}$
etc.	

8.2.5 Potential influence quantities, example

For establishing the evaluation model it is advisable to set up a block diagram showing the cause-effect development. The example of the representation below shows the potential influence quantities for the calibration of a pressure gauge against a pressure balance.

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



* Effective Number of Bits; see IEEE 1057-1994 „IEEE Standard for Digitizing Waveform Recorders“

Note:
It sometimes is helpful for the initial approach to subdivide the influence quantities according to whether they are associated with the standard, the procedure or the calibration item.

The measurement uncertainties which are attributed to the values of the standard, the adapter and the output unit are taken from calibration certificates (generally normally distributed, $k = 2$).

8.3 Calibration of Bourdon tube pressure gauges

8.3.1 Evaluation model

A simple sum/difference model is suitable for determining the measurement deviation of the indication – separate for the measurement values in the direction of increasing pressure and for the measurement values in the direction of decreasing pressure.

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

$Y = \Delta p_{...}$	measurand; measurement deviation of indication Index ... stands for up/down or mean (cf. eqs. 8 and 9)
$X_1 = p_{\mathrm{ind,\ ...}}$	indication of pressure gauge Index ... stands for up/down or mean (cf. eqs. 8 and 9)
$X_2 = p_{\mathrm{standard}}$	value of reference standard[3]
$X_3 = \delta\, p_{\mathrm{zero\ deviation}}$	unknown measurement deviation due to zero deviation
$X_4 = \delta\, p_{\mathrm{repeatability}}$	unknown measurement deviation due to repeatability

and for the mean values:

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

$$\Delta p_{\mathrm{mean}} = \frac{p_{\mathrm{ind,\ up}} + p_{\mathrm{ind,\ down}}}{2} \quad (10)$$

$X_5 = \delta\, p_{\mathrm{hysteresis}}$	unknown measurement deviation due to hysteresis

When the increasing and decreasing series are taken separately, the expanded uncertainty U with k=2 is:

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

[3] The value of the reference standard allows for the use of the pressure balance under conditions of use (application of corrections). Therefore the uncertainty analysis, too, contains uncertainty contributions from the pressure balance both under reference conditions and conditions of use. The latter contribution is determined in uncertainty budgets (see Annex A: Estimate of measurement uncertainty to be attributed to the values of the pressure balance under conditions of use) for the effects of temperature, of the thermal linear expansion coefficient, acceleration due to gravity, air density, deformation coefficient (pressure balance) or for density, acceleration due to gravity, altitude (difference in altitude).

and a so-called error span[4] allowing for the systematic deviation:

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

When the mean values from increasing and decreasing series are used, the expanded uncertainty U with k=2 is calculated at:

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

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

The associated error span is determined at:

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

8.3.2 Uncertainty analysis

The knowledge of the input quantities is preferably given in a table.

[4] As error span the maximum difference to be expected between the measured value and the conventional true value of the measurand is referred to. The error span can be used to characterize the accuracy.

Table 3: Uncertainty analysis for the calibration of a Bourdon tube pressure gauge

Cont. No.	Quantity X_i	Estimate x_i	Width of distrib-ution $2a$	Probability distribution $P(x_i)$	Divisor	Standard uncertainty $u(x_i)$	Sensiti-vity coef-ficient c_i	Uncer-tainty con-tribution $u_i(y)$	Unit[5]
1	$p_{\text{ind},...}$	$p_{\text{i, ind},...}$	$2r$	rectangle	$\sqrt{3}$	$u(r)=\sqrt{\frac{1}{3}\cdot\left(\frac{2r}{2}\right)^2}$	1	u_r	bar
2	p_{standard}	$p_{\text{i, standard}}$		normal	2	u(standard)	-1	u_{standard}	bar
3	$\delta p_{\text{zero deviation}}$	0	f_0	rectangle	$\sqrt{3}$	$u(f_0)=\sqrt{\frac{1}{3}\cdot\left(\frac{f_0}{2}\right)^2}$	1	u_{f_0}	bar
4	$\delta p_{\text{repeatability}}$	0	b'	rectangle	$\sqrt{3}$	$u(b')=\sqrt{\frac{1}{3}\cdot\left(\frac{b'}{2}\right)^2}$	1	$u_{b'}$	bar
5	$\delta p_{\text{hysteresis}}$	0	h	rectangle	$\sqrt{3}$	$u(h)=\sqrt{\frac{1}{3}\cdot\left(\frac{h}{2}\right)^2}$	1	u_h	bar
	Y	Δp ...						$u(y)$	bar

8.3.3 Load step-related uncertainty budget

The estimate of the measurement uncertainty has to be made for each calibration value, i.e. for each load step. For reasons of clearness, the following tabular representation is recommended for increasing, decreasing and mean values:

Table 3: Uncertainty budget

Pressure	**Measure-ment de-viation**	**Standard uncertainty** u			**Expanded uncertainty** U **(**k **= 2)**	**Error span** U'
		Contrib-ution 1	...	Contrib-ution n		
bar	bar	bar			bar	bar
min.						
...						
max.						

[5] It is advisable to carry over the unit of the uncertainty contributions (unit of physical quantity, unit of indication, related (dimensionless) quantity, etc.)

8.3.4 Single-number rating

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). Also, the conformity can be confirmed (cf. 9.1.3).

8.4 Calibration of electrical pressure gauges

The evaluation model and the uncertainty budget for the calibration of Bourdon tube pressure gauges can also be used for the calibration of an electrical pressure gauge (numerically correct indication in units of pressure). If necessary, a component for "reproducibility *b* when repeatedly mounted“ is to be taken into account.

$X_6 = \delta p_{\text{reproducibility}}$	unknown measurement deviation due to reproducibility

Table 5: Additional component of uncertainty analysis for calibration of an electrical pressure gauge

Cont. No.	Quantity	Estimate	Width of distribution	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Unit
	X_i	x_i	$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$	
6	$\delta p_{reproducibility}$	0	b	rectangle	$\sqrt{3}$	$u(b)=\sqrt{\frac{1}{3}\cdot\left(\frac{b}{2}\right)^2}$	1	u_b	bar

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

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

The determination of the associated error span for the increasing and decreasing series and of the expanded uncertainty and the error span for the mean value is made in analogy to the procedure for the Bourdon tube pressure gauge.

8.5 Calibration of pressure transducers and pressure transmitters with electrical output

8.5.1 Evaluation model

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

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

$Y = S_{...}$	measurand, transmission coefficient Index ... stands for up/down or mean value (cf. eqs. 16 and 17)
$X_1 = V_{\text{ind}, ...}$	indication of output unit (U, I, f) Index ... stands for up/down or mean value (cf. eqs. 16 and 17)
$X_2 = G$	transmission coefficient of adapter (amplifier made available)
$X_3 = V_{\text{supply}}$	value of supply voltage (auxiliary device)
$X_4 = p_{\text{standard}}$	value of reference standard
$X_5 = K_{\text{zero deviation}}$	correction factor due to zero deviation
$X_6 = K_{\text{repeatability}}$	correction factor due to repeatability
$X_7 = K_{\text{reproducibility}}$	if applicable, correction factor due to reproducibility

For the mean values the following is valid:

$$S_{\text{mean}} = \frac{X_{\text{out, mean}}}{X_{\text{in}}} = \frac{V_{\text{ind, mean}} / (G \cdot V_{\text{supply}})}{p_{\text{standard}}} \prod_{i=1}^{4} K_i$$

$$S_{\text{mean}} = \frac{V_{\text{ind, mean}} / (G \cdot V_{\text{supply}})}{p_{\text{standard}}} K_{\text{zero deviation}} \cdot K_{\text{repeatability}} \cdot K_{\text{reproducibility}} \cdot K_{\text{hysteresis}} \tag{17}$$

$X_8 = K_{\text{hysteresis}}$	correction factor due to hysteresis

When the increasing and decreasing series are taken separately, the relative expanded uncertainty (k=2) is determined at:

$$W_{\text{up/down}} = k \cdot w_{\text{up/down}}$$
$$W_{\text{up/down}} = k \cdot \sqrt{w_{\text{standard}}^2 + w_{\text{ind}}^2 + w_{\text{amplifier}}^2 + w_{\text{supply}}^2 + u_{\text{zero deviation}}^2 + u_{\text{repeatability}}^2 + (u_{\text{reproducibility}}^2)} \tag{18}$$

and the associated error spans at:

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

with the systematic deviation

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

S' preferably representing the slope of the regression line through all measurement values and through the zero point of the output signal of the measuring transmitter.
When the mean value from increasing and decreasing series is used, the relative expanded uncertainty (k=2) is calculated at:

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

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 at:

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

with

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

For S', cf. above.

8.5.2 Uncertainty analysis

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

Table 6: Uncertainty analysis for the calibration of a pressure transmitter with electrical output

Cont. No.	Quantity X_i	Estimate x_i	Width of distribution $2a$	Probability distribution $P(x_i)$	Divisor	Standard uncertainty $w(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $w_i(y)$	Unit
1	$V_{\text{ind, ...}}$	$V_{\text{i, ind}}$		normal	2	w(indicator)	1	w_{ind}	#
2	G	G		normal	2	w(amplifier)	-1	$w_{\text{amplifier}}$	#
3	V_{supply}	V_{supply}		normal	2	w(supply)	-1	w_{supply}	#
4	p_{standard}	$p_{\text{i, standard}}$		normal	2	w(standard)	-1	w_{standard}	#
5	$K_{\text{zero deviation}}$	1	f_0 [6)]	rectangle	$\sqrt{3}$	$w(f_0)=\sqrt{\frac{1}{3}\cdot\left(\frac{f_0}{2}\right)^2}$	1	w_{f_0}	#
6	$K_{\text{repeatability}}$	1	b'	rectangle	$\sqrt{3}$	$w(b')=\sqrt{\frac{1}{3}\cdot\left(\frac{b'}{2}\right)^2}$	1	$w_{b'}$	#
7	$K_{\text{reproducibility}}$	1	b	rectangle	$\sqrt{3}$	$w(b)=\sqrt{\frac{1}{3}\cdot\left(\frac{b}{2}\right)^2}$	1	w_b	#
8	$K_{\text{hysteresis}}$	1	h	rectangle	$\sqrt{3}$	$w(h)=\sqrt{\frac{1}{3}\cdot\left(\frac{h}{2}\right)^2}$	1	w_h	#
	Y	$S_{\text{...}}$						$w(y)$	#

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

8.5.3 Load step-related uncertainty budget

The estimate of the measurement uncertainty has to be made for each calibration value, i.e. for each load step. For reasons of clearness, the following tabular representation is recommended for increasing, decreasing and mean values:

Table 7: Uncertainty budget

Pressure	**Rel. standard uncertainty** *w*			**Rel. expanded uncertainty** *W* (k=2)
	Contribution 1	...	Contribution n	
bar	#			#
min.				
...				
max.				

8.5.4 Single-number rating

Transmission coefficient as slope of a linear regression function

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

When this characteristic of the pressure transducer is used, a statement of conformity is substituted for the measurement uncertainties attributed to the individual values measured for the transmission coefficient (cf. 9.1.3).

For this purpose, the upper limiting amounts of the deviation are to be defined. This can be made on the basis of the calibration results by calculation of the error spans according to 8.5.1 ("self-determined conformity," definition on the basis of manufacturer's statements, cf. below). In this operation,

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

are to be taken into account.

As a rule, error spans result whose magnitudes decrease with increasing pressure. As the upper limiting amounts of the deviation

- the maximum calculated error span can be selected (in this case, the upper limiting amounts of the deviation are represented in the calibration diagram as straight lines parallel to the pressure axis, cf. 9.2, pressure transmitters with electrical output signal, figure 5, upper details) or
- the upper limiting amounts of the deviation are described by suitable curves such as hyperbolas or polynomials (cf. 9.2, pressure transmitters with electrical output signal, figure 5, lower details).

Note:
The use of pressure-dependent upper limiting amounts of the deviation is not common practice. In pressure measurements with the calibrated device in the upper part of the measurement range, it allows, however, smaller measurement uncertainties to be stated.

For calibration items whose nominal parameter (e.g. 2 mV/V) has been balanced by the manufacturer, the upper limiting amounts of the deviation can alternatively be determined from the associated parameter tolerance. In this case, it is, however, always to be checked whether the values of the transmission coefficients determined in the calibration, including their attributed measurement uncertainties and systematic deviations from the single-number rating of the parameter do not exceed the upper limiting amounts of the deviation.

8.6 Determination of relevant parameters for uncertainty analysis

8.6.1 Resolution r

8.6.1.1 Analog indicating devices

The resolution of the indicating device is obtained from the ratio of the pointer width to the centre distance of two neighbouring graduation lines (scale interval). 1/2, 1/5 or 1/10 is recommended as ratio. If 1/10 is chosen as the ratio (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 for an analog 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 being $2a = 2r$.

8.6.1.2 Digital indicating devices

If the indication varies by one digital step at most when the pressure gauge is not loaded, the resolution corresponds to the digital step.

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. This uncertainty contribution does not explicitly appear in section 8.5 as it is contained in the measurement uncertainty of the output unit (display) (statement in calibration certificate).

8.6.1.3 Fluctuation of readings

If the readings fluctuate by more than the value previously determined for the resolution with the pressure gauge not being loaded, the resolution r is to be taken as half the span of the fluctuation, additionally added with a digital step.

8.6.2 Zero deviation f_0

The zero point can be set prior to every measurement cycle consisting of an increasing and a decreasing series and must be recorded prior to and after every measurement cycle. The reading is to be made with the instrument being completely relieved.

The zero deviation is calculated as follows:

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

The indices number the measurement values x read in 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.

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

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.

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

For index j, see above.

8.6.5 Hysteresis h

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

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

For index j, see above. The variable n stands for the number of the complete measurement cycles.

9. Evaluation of measurement results and statements in the calibration certificate

The main components of the pressure gauge are each provided with a calibration mark; devices belonging to a measuring chain are each provided with a calibration mark.

In addition to the requirements in DKD-5, the following information is to be stated in the calibration certificate:

- calibration method (DKD-R 6-1 sequence A, B, C or EN 837 parts 1 and 3)
- pressure-transmitting medium
- pressure reference plane on calibration item
- position of calibration item for calibration
- selected settings on calibration item

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

Table 8: Measurement values

<table>
<tr><th rowspan="4">Pressure
$p_{standard}$</th><th colspan="6">Value displayed p_{ind}</th></tr>
<tr><th colspan="4">Calibration sequence A</th><th colspan="2">Measurement with 2nd clamping</th></tr>
<tr><th colspan="3">Calibration sequence B</th><th></th><th></th><th></th></tr>
<tr><th colspan="2">Calibration sequence C</th><th></th><th></th><th></th><th></th></tr>
<tr><td></td><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, Pascal, ...</td><td colspan="6">bar, Pascal, 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 pressure values measured for the standard. Columns 2 to 7 contain the corresponding measurement values displayed by the calibration items according to figure 1 (Bourdon tube pressure gauge, electrical pressure gauge, pressure transmitter with electrical output) in units of pressure or output in other physical quantities (current, voltage, voltage ratio, frequency, ...) or already converted into the quantity of pressure.

The further evaluation of the measurement values can encompass the following characteristics:

- mean values
- measurement deviation of display
- zero deviation
- repeatability
- reproducibility, if applicable
- hysteresis
- error span
- single-number rating
- conformity

9.1 Determination of other parameters

9.1.1 Mean values $\bar{x}$

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

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

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

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

where variable l gives the number of measurement series.

9.1.2 Error span U'

The error span is the sum of the expanded uncertainty (k=2) and the amount of the systematic deviation. Due to the systematic component, the error span is assigned 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.: $$U' = U + |\Delta p| \tag{29}$$

The relative error span W' is formed accordingly.

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

<u>Note:</u>
cf. also [4] on page 18.

9.1.3 Conformity

If the error span and the transmission coefficients with attributed measurement uncertainty lie within the error limit stated by the manufacturer, the conformity according to DKD-5 can be confirmed. The range for which it is valid is also to be stated.

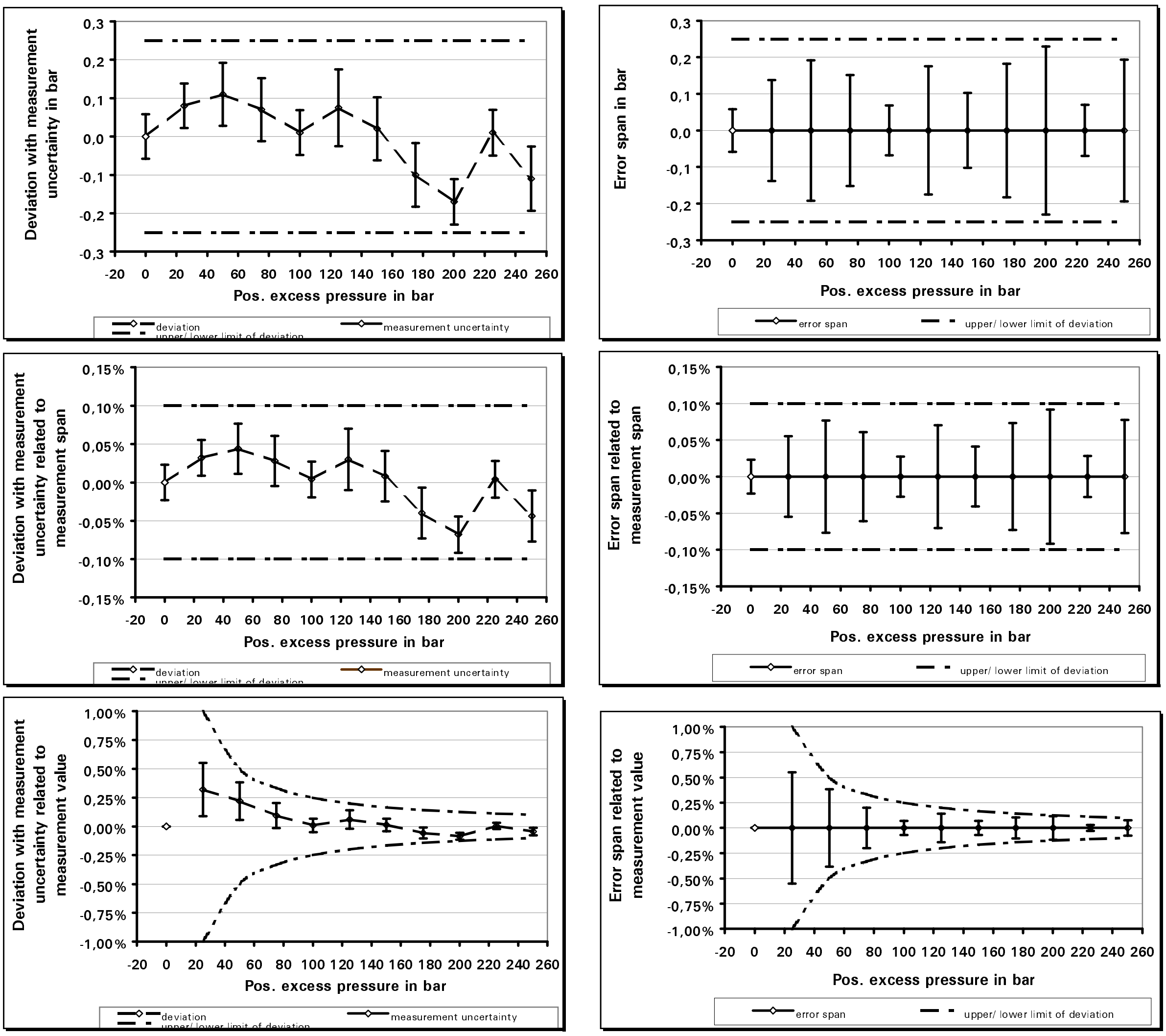
9.2 Visualization of calibration result

For better understanding and ease of overview, the calibration result can also be given in a graphical form.

9.2.1 Bourdon tube pressure gauges, electrical pressure gauges

The systematic deviation with the expanded measurement uncertainty or the resulting error span, respectively, are to be represented with reference to the upper limiting amount of the deviation (error limit), in the unit of the physical quantity and/or as a related quantity. The representation of related parameters can be made in a form which is typical of the kind of device (related to the measurement span, related to the measurement value).

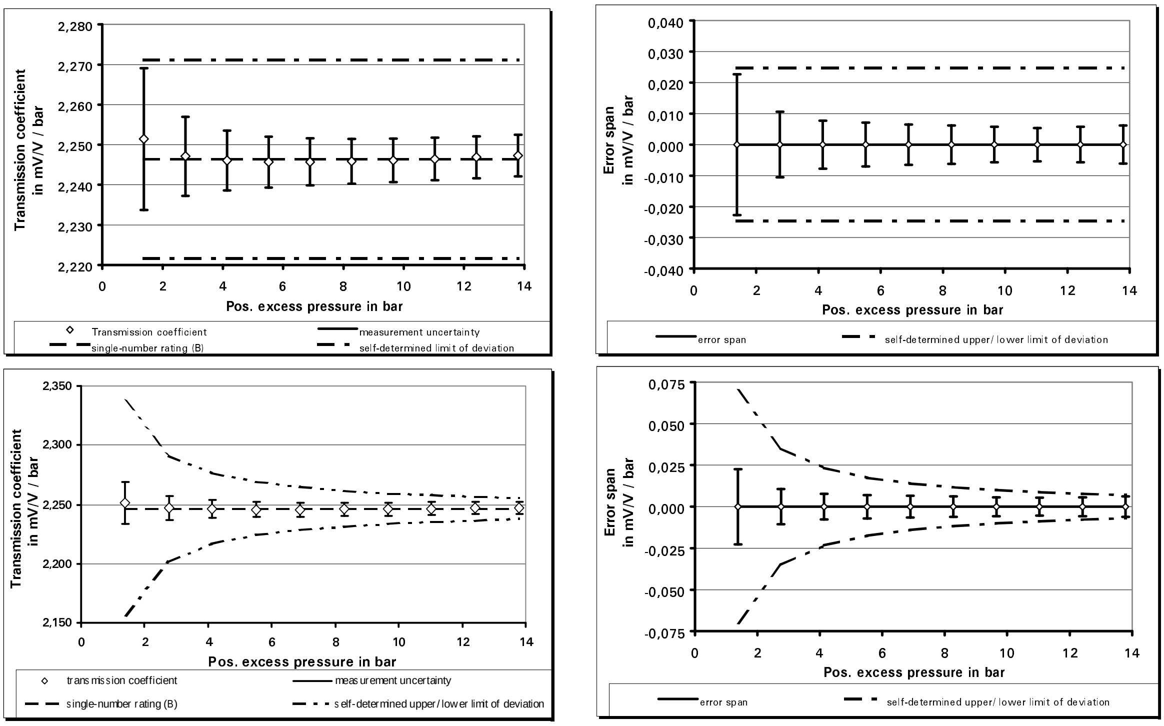
Figure 4: Visualization of the calibration result for a Bourdon tube pressure gauge or an electrical pressure gauge



9.2.2 Pressure transmitters with electrical output

The transmission coefficients and the attributed measurement uncertainties are represented with reference to the upper limiting amounts of the deviation (error limits according to manufacturer's specification or self-determined limit).

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



9.3 Limiting values for uncertainty statements[7]

For all calibration sequences (A, B, C) the measurement uncertainty is calculated in accordance with section 8. Independently of the result of the calibration, the measurement uncertainty is stated

for	cal. sequence B	not smaller than	0,04% of measurement span
and for	cal. sequence C	not smaller than	0,30% of measurement span.

For the statement of the error span in a conformity statement according to DKD-5, the value must be given

for	cal. sequence B	not smaller than	0,06% of measurement span
and for	cal. sequence C	not smaller than	0,60% of measurement span.

[7] for the present not valid for measuring transmitters

10. Other 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.

EN 837 part 1	Druckmeßgeräte mit Rohrfedern Maße, Meßtechnik, Anforderungen und Prüfung (Pressure gauges with Bourdon tubes; measures, measuring technique, requirements and test) February 1997 edition
EN 837 part 3	Druckmeßgeräte mit Platten- und Kapselfedern Maße, Meßtechnik, Anforderungen und Prüfung (Pressure gauges with diaphragm and capsule elements; measures, measuring technique, requirements and test) February 1997 edition
DIN 16086	Elektrische Druckmeßgeräte Druckaufnehmer, Druckmeßumformer, Druckmeßgeräte Begriffe und Angaben in Datenblättern (Electrical pressure gauges; pressure transducers, pressure transmitters, pressure gauges; terms and statements in data sheets) May 1992 edition
DIN 43790	Grundregeln für die Gestaltung von Strichskalen und Zeigern (Basic rules for the design of line scales and pointers) January 1991 edition
EA-10/03	Calibration of Pressure Balances Edition 1, July 1997
DKD-R 3-6	Richtlinie zur Auswahl und Kalibrierung von elektrischen Referenzdruckmeßgeräten für die Anwendung in DKD-Laboratorien (Guideline for the selection and calibration of electrical reference pressure gauges for use in DKD laboratories) November 1993 edition
EA – 10/17	EA Guidelines on the Calibration of Electromechanical Manometers (rev. 00) July 2002

Annex A Estimate of measurement uncertainty to be attributed to the values of the pressure balance under conditions of use[8]

The values and the attributed expanded uncertainty $U_{\text{standard, ref}}$ for a pressure balance under reference conditions are to be taken from the calibration certificate (issued, for example, by the PTB). When the instrument is used under conditions of use, corrections for the relevant influence quantities are to be applied to the values and to these values, too, an uncertainty has to be attributed.

Evaluation model[9]:

$$p_e = \frac{\sum_{i=1}^{n} m_i \cdot g \cdot \left(1 - \frac{\rho_a}{\rho_{m,i}}\right)}{A_0 \cdot (1 + \lambda \cdot p) \cdot \left[1 + (\alpha + \beta) \cdot (t - 20\,°\text{C})\right]} + \Delta\rho \cdot g \cdot h \qquad (31)$$

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

Uncertainty analysis

with the influence quantities relevant to the pressure value of the standard: temperature, thermal linear expansion coefficient of piston and cylinder, acceleration due to gravity and deformation coefficient. The sensitivity coefficients were calculated with the approximations usual for practical applications and for the most common case $\alpha = \beta$.

Table 9

Quantity X_i	Estimate x_i	Half-width a	Probability distribution $P(x_i)$	Divisor	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$	Unit
Temperature	t_K	a_t	rectangle	$\sqrt{3}$	$u(t) = \sqrt{\frac{1}{3} \cdot a_t^2}$	$c_t = -2 \cdot \alpha \cdot p$	$u_t = c_t \cdot u(t)$	bar
Thermal linear expansion coefficient	$\alpha + \beta$	a_α	rectangle	$\sqrt{3}$	$u(\alpha) = \sqrt{\frac{1}{3} \cdot a_\alpha^2}$	$c_\alpha = -2 \cdot (t - 20°\text{C}) \cdot p$	$u_\alpha = c_\alpha \cdot u(\alpha)$	bar
Acceleration due to gravity	g	a_g	rectangle	$\sqrt{3}$	$u(g) = \sqrt{\frac{1}{3} \cdot a_g^2}$	$c_g = p / g$	$u_g = c_g \cdot u(g)$	bar
Deformation coefficient	λ	a_λ	rectangle	$\sqrt{3}$	$u(\lambda) = \sqrt{\frac{1}{3} \cdot a_\lambda^2}$	$c_\lambda = -p^2$	$u_\lambda = c_\lambda \cdot u(\lambda)$	bar
Y	y					$u_{\text{corr}1} = \sqrt{u_t^2 + u_\alpha^2 + u_g^2 + u_\lambda^2}$		bar

[8] cf. [3] on page 17
[9] cf. also EA-10/03 Annex B

Note:
1. In calibration certificates issued by the PTB for pressure balances, the contribution of the uncertainty of the numerical value of the deformation coefficient to the uncertainty of the pressure measurement at reference temperature generally has already been taken into account.
2. Portable measuring instruments allow the local acceleration due to gravity at a certain location to be measured with a relative uncertainty of a few ppm. If such an exact measurement value is available, it may be permissible to neglect the uncertainty contribution of the acceleration due to gravity as the relative uncertainty of the value of the cross sectional area is in most cases substantially higher.
3. Related to the force of inertia $g \cdot m$ acting in the vacuum, the buoyancy correction is of the order of $1{,}5 \cdot 10^{-4}$. 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. In relation to the uncertainty of the cross sectional area of 50 ppm usually given in calibration certificates, this contribution is negligible and generally does not justify the metrological efforts made to determine it (cf. 6 Ambient conditions, Note).

Uncertainty analysis
with the influence quantities relevant to the determination of the hydrostatic pressure due to a difference between the reference level of the standard instrument and the instrument to be calibrated.

Table 10

Quantity X_i	Estimate x_i	Half-width a	Probability distribution $P(x_i)$	Divisor	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$	Unit
Determination of density difference	$\Delta\rho$	a_{ρ_a} $a_{\rho_{Fl}}$	rectangle	$\sqrt{3}$	$u(\Delta\rho)=\sqrt{\frac{1}{3}\left(a_{\rho_a}^2+a_{\rho_{Fl}}^2\right)}$	$c_{\Delta\rho}=g\cdot h$	$u_{\Delta\rho}=c_{\Delta\rho}\cdot u(\Delta\rho)$	bar
Determination of acceleration due to gravity	g	a_g	rectangle	$\sqrt{3}$	$u(g)=\sqrt{\frac{1}{3}\cdot a_g^2}$	$c_g=\Delta\rho\cdot h$	$u_g=c_g\cdot u(g)$	bar
Determination of difference in altitude	h	a_h	rectangle	$\sqrt{3}$	$u(h)=\sqrt{\frac{1}{3}\cdot a_h^2}$	$c_h=\Delta\rho\cdot g$	$u_h=c_h\cdot u(h)$	bar
Y	y					$u_{\text{corr 2}}=\sqrt{u_{\Delta\rho}^2+u_g^2+u_h^2}$		bar

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

$$U_{\text{standard, cond. of use}}=k\cdot\sqrt{u_{\text{standard, ref}}^2+u_{\text{corr 1}}^2+u_{\text{corr 2}}^2} \qquad (33)$$

Note:
Besides the corrections given here as an example, further corrections and associated contributions to the measurement uncertainty are to be taken into account, for example the uncertainty of the residual gas pressure measurement for pressure balances for absolute pressure or the pressure dependence of the density of the pressure-transmitting medium in the measurement of major hydraulic pressures.

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

Calibration effort for calibration sequence C
Statement of mean value (*Miw*) with measurement deviation (Δp) and hysteresis (h)

<u>Calibration item</u>

Gauge pressure measuring equipment with elastic sensing element (Bourdon tube pressure gauge)
Accuracy stated by manufacturer : DIN cl. 1,0
Scale interval : 0,5 bar (with fifth estimate)

<u>Standard device</u>

Designation : xxx
Expanded uncertainty : $1 \cdot 10^{-4} \cdot p$ but not smaller than 0,4 mbar

<u>Calibration conditions</u>

Pressure-transmitting medium : purified nitrogen
ρ_{Fl}(20°C,1bar) : 1,15 kg/m³
Δh : (0 m ± 0,005) m
t_{amb} : (21,6 ± 1) °C
p_{amb} : (990 ± 1) mbar

Table 11: Result

Pressure	**Reading from calibration item (indication)**		**Mean value**	**Measure-ment devia-tion**	**Hysteresis**	**Expanded uncertainty**
$p_{standard}$	p_{ind}		*Miw*	Δp	h	U
	M1	M2	(M1+M2)/2	$Miw - p_e$	|M2-M1|	
bar	bar	bar	bar	bar	bar	bar
0,00	0,0	0,0	0,0	0,0	0,0	0,12
12,02	12,1	12,2	12,2	0,2	0,1	0,12
24,03	24,2	24,2	24,2	0,2	0,0	0,12
36,04	36,1	36,2	36,2	0,2	0,1	0,13
48,04	48,1	48,1	48,1	0,1	0,0	0,12
60,05	60,0	60,1	60,1	0,0	0,1	0,13

Table 12: Uncertainty budget for load step p=60,05 bar

Quantity	Esti-mate	Width of distribu-tion	Divisor	Uncer-tainty	Sensitivity coefficient	Uncer-tainty contrib.	Variance
X_i	x_i	$2a$		$u(x_i)$	c_i	$u(y)$	u^2
						bar	bar²
$p_{standard}$	60,05 bar		2	3,00*10^{-3} bar	-1	3,00*10^{-3}	9,02*10^{-6}
$p_{standard, t}$	0,999997	2 K	$\sqrt{3}$	5,77*10^{-1} K	-1,32*10^{-3} bar/K	7,63*10^{-4}	5,82*10^{-7}
$p_{standard, h}$ *	0	1,0*10^{-2} m	$\sqrt{3}$	2,89*10^{-3} m	-6,74*10^{-3} bar/m	1,95*10^{-5}	3,79*10^{-10}
p_{ind}	60,05 bar	0,1 bar	$\sqrt{3}$	5,77*10^{-2} bar	1	5,77*10^{-2}	3,33*10^{-3}
$\delta p_{zero\ deviation}$	0	0,0 bar	$\sqrt{3}$	0	1	0	0
$\delta p_{repeatability}$	0	0,0 bar	$\sqrt{3}$	0	1	0	0
$\delta p_{hysteresis}$	0	0,1 bar	$\sqrt{3}$	2,89*10^{-2} bar	1	2,89*10^{-2}	8,33*10^{-4}
Δp	0,00 bar	u =				6,46*10^{-2}	$\sum u_i^2 = 4{,}17 \cdot 10^{-3}$
Δp	0,00 bar	$U = k \cdot u$ (k = 2)				**0,13 bar**	

*allowing for the pressure-dependent gas density (approximation)

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

with T=273,15K

For the correction of the pressures realized by the standard device, the following data were used (calculation in accordance with Annex A):

t_K : (21,6 ± 1) °C
g : (9,812533 ± 0,000020)*10^{-6} m·s^{-2}
$\alpha+\beta$: (11 ± 1,1)*10^{-6} K^{-1}

Note:
The calculated expanded measurement uncertainty of U = 0,13 bar for the load step p = 60,05 bar corresponds to a relative expanded uncertainty of W = 0,22%. According to section 10.3: Limiting values for uncertainty statements, 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 a value of W = 0,30%, corresponding to an expanded uncertainty of ***U* = 0,18 bar**.

Annex C Example Uncertainty budget for the calibration of a digital electrical pressure gauge

Calibration effort for calibration sequence B
Statement of mean value (Miw) with measurement deviation (Δp), repeatability (b') and hysteresis (h)
Electrical pressure gauge with suppressed zero

Calibration item

Electrical pressure gauge with suppressed zero
Accuracy stated by manufacturer : 0,03 % of mean value
Resolution : 0,001 mbar

Standard device

Designation : xxx
Expanded uncertainty (standard) : $1 \cdot 10^{-4} \cdot p$ but not smaller than 0,005 mbar

Calibration conditions

Pressure-transmitting medium : air
$\rho_{\mathrm{Fl}\,(20°\mathrm{C},1\mathrm{bar})}$: 1,19 kg/m³
Δh : (0 ± 0,005) m
t_{amb} : (2 ± 1) °C
p_{amb} : (990 ± 1) mbar

Table 13: Result

Pressure p_{standard}	**Reading from calibration item (indication)** p_{ind}			**Mean value** Miw	**Deviation** Δp	**Repeat-ability** b'	**Hyste-resis** h	**Expanded uncer-tainty** U
	M1	M2	M3	((M1+M3)/2+M2)/2	$Miw-p_{\mathrm{e}}$	(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	0,101
1131,138	1131,050	1131,094	1131,046	1131,071	-0,067	0,004	0,044	0,121
1331,413	1331,330	1331,359	1331,337	1331,346	-0,067	0,007	0,029	0,140
1531,673	1531,630	1531,656	1531,629	1531,643	-0,030	0,001	0,026	0,160

Table 14: Uncertainty budget for load step p=1531,673 mbar

Quantity	Estimate	Width of distribution	Divisor	Uncertainty	Sensitivity coefficient	Uncertainty contribution	Variance
X	x_i	$2a$		$u(x_i)$	c_i	$u(y)$	u^2
						mbar	mbar²
$p_{standard}$	1531,673 mbar		2	7,66*10^{-2} mbar	-1	7,66*10^{-2}	5,87*10^{-3}
$p_{standard, t}$	0,999997	2 K	$\sqrt{3}$	5,77*10^{-1} K	-3,37*10^{-2} mbar/K	1,95*10^{-2}	3,78*10^{-4}
$p_{standard,residual}$	0		2	1,00*10^{-2} mbar	1	1,00*10^{-2}	1,00*10^{-4}
$p_{standard, h}$*	0	1,0*10^{-2} m	$\sqrt{3}$	2,89*10^{-3} m	-1,78*10^{-1} mbar/m	5,14*10^{-4}	2,64*10^{-7}
p_{ind}	1531,643 mbar	0,001 mbar	$\sqrt{3}$	2,89*10^{-4} mbar	1	2,89*10^{-4}	8,33*10^{-8}
$\delta p_{zero\ deviation}$	0	0,000 mbar	$\sqrt{3}$	0	1	0	0
$\delta p_{repeatability}$	0	0,001 mbar	$\sqrt{3}$	2,89*10^{-4} mbar	1	2,89*10^{-4}	8,33*10^{-8}
$\delta p_{hysteresis}$	0	0,026 mbar	$\sqrt{3}$	7,51*10^{-3} mbar	1	7,51*10^{-3}	5,63*10^{-5}
Δp	-0,030 mbar	$u =$				8,00*10^{-2}	$\sum u_i^2 = 6,40*10^{-3}$
Δp	-0,030 mbar	$U = k \cdot u$ $(k = 2)$				**0,160 mbar**	

* allowing for the pressure-dependent gas density (approximation)

$$\rho_{p,t} = \rho_{20°C,1bar} \cdot \left[\frac{p_{abs} \cdot (T + 20K)}{1bar \cdot (T + t)} \right]$$ with T=273,15K

For the correction of the pressures realized by the standard device, the following data were used (calculation according to Annex A):

t_K : 21,6 ± 1) ℃
g : (9,812533 ± 0,000020))·10^{-6} m·s⁻²
$\alpha+\beta$: (11 ± 1,1)·10^{-6} K^{-1}

Note:
The calculated expanded uncertainty of U = 0,160 mbar for the load step p = 1531,673 mbar corresponds to a relative expanded uncertainty of W = 0,01%. According to section 10.3: Limiting values for uncertainty statements, the value stated in the calibration certificate for a calibration according to sequence B must not be smaller than a value of W = 0,04%, corresponding to an expanded uncertainty of ***U* = 0,613 mbar**.

Annex D Example Uncertainty budget for the calibration of a pressure transmitter with electrical output[10]

Calibration effort for calibration sequence A with second clamping
Statement of mean value (*Miw*) from increasing and decreasing series,
of repeatability (b'), reproducibility (b), hysteresis (h), transmission coefficient S
and deviation (ΔS)

Calibration item

Pressure transmitter with electrical output
Accuracy stated by manufacturer : 0,01 % of EW

Standard device

Designation : xxx
Expanded uncertainty : $1 \cdot 10^{-4} \cdot p$ but not smaller than 1 mbar
in the measuring temperature range
in the pressure reference plane of the calibration item
at the place of installation ($g = g_{\mathrm{local}}$)

Auxiliary measuring device

Digital compensator : xxx
Expanded uncertainty $U(A)$: 0,00005 mV/V
[A: display in mV/V ≡ $V_{\mathrm{ind}}/G \cdot V_{\mathrm{supply}}$ with G = 1 and $U(G)$ = 0]

Calibration conditions

Pressure-transmitting medium : white oil
$\rho_{\mathrm{Fl(20°C)}}$: (855 ± 40) kg/m³ in meas. range up to 200 bar
Δh : (0 ± 0,005) m
t_{amb} : (20 ± 1)°C
p_{amb} : (990 ± 1) mbar

[10] In the following example, the measurement uncertainty is estimated with related values according to the product/quotient model (eq. 16). Alternatively, the sum/difference model (eq. 8) can be selected when the measurement deviations of the output signal of the pressure transducer from the values calculated according to the desired characteristic curve are considered. There is quantitative agreement between the results of the uncertainty estimates.

Table 15: Measurement data

Pressure $p_{standard}$	**Display** $A_{digital\ compensator}$					
	M1	M2	M3	M4	M5	M6
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 16: Evaluation

Pressure	**Output signal *A*: mean value**	**Zero deviation**	**Repeatability**	**Repro-ducibility**	**Hysteresis**	**Relative uncertainty**
$p_{standard}$	Miw $\Sigma M_i/6$	$f_{0\ rel}$ $\lvert max \rvert / Miw$	b'_{rel} $\lvert max \rvert / Miw$	b_{rel} $\lvert max \rvert / Miw$	h_{rel} $(1/3Miw)*\Sigma\lvert h_i \rvert$	$W(p_{standard})$ *)
bar	mV/V	#	#	#	#	#
0,000	-0,000005	#	#	#	#	#
20,010	0,200233	1,5E-04	5,0E-04	6,0E-04	7,0E-04	1,0E-04
40,022	0,400475	7,5E-05	1,5E-04	1,7E-04	8,6E-04	1,0E-04
60,033	0,600703	5,0E-05	1,3E-04	1,3E-04	8,0E-04	1,0E-04
80,045	0,800875	3,7E-05	1,1E-04	1,1E-04	7,1E-04	1,0E-04
100,056	1,001015	3,0E-05	9,0E-05	1,5E-04	6,3E-04	1,0E-04
120,068	1,201097	2,5E-05	1,1E-04	1,5E-04	5,2E-04	1,0E-04
140,079	1,401167	2,1E-05	9,3E-05	1,9E-04	4,3E-04	1,0E-04
160,091	1,601158	1,9E-05	8,7E-05	2,0E-04	3,5E-04	1,0E-04
180,102	1,801110	1,7E-05	1,0E-04	2,1E-04	2,3E-04	1,0E-04
200,113	2,000923	1,5E-05	4,5E-05	7,0E-05	8,0E-05	1,0E-04

*) in the pressure reference plane of the calibration item

Table 17: Result

Pressure $p_{standard}$	Transmission coefficient S Miw/p	Deviation ΔS $S - S'$	Rel. expanded uncertainty $W(S)$ $2[\Sigma w_i^2(S)]^{0,5}$	Expanded uncertainty $U(S)$ $W \cdot S$	Error span $U'(S)$ $U + \Delta S$
bar	(mV/V)/bar	(mV/V)/bar	#	(mV/V)/bar	(mV/V)/bar
0,000	#	#	#	#	#
20,010	0,01000666	0,00000515	6,7E-04	0,00000668	0,00001183
40,022	0,01000637	0,00000486	5,4E-04	0,00000539	0,00001025
60,033	0,01000622	0,00000471	4,9E-04	0,00000493	0,00000964
80,045	0,01000531	0,00000380	4,4E-04	0,00000438	0,00000818
100,056	0,01000455	0,00000304	3,9E-04	0,00000394	0,00000698
120,068	0,01000347	0,00000196	3,3E-04	0,00000335	0,00000531
140,079	0,01000269	0,00000118	3,0E-04	0,00000297	0,00000415
160,091	0,01000155	0,00000004	2,6E-04	0,00000259	0,00000263
180,102	0,01000050	-0,00000101	2,1E-04	0,00000215	0,00000316
200,113	0,00999897	-0,00000254	1,2E-04	0,00000123	0,00000377
	Single-number rating: S' = 0,01000151 (mV/V) / bar				

Table 18: Uncertainty budget for load step p=100,056 bar

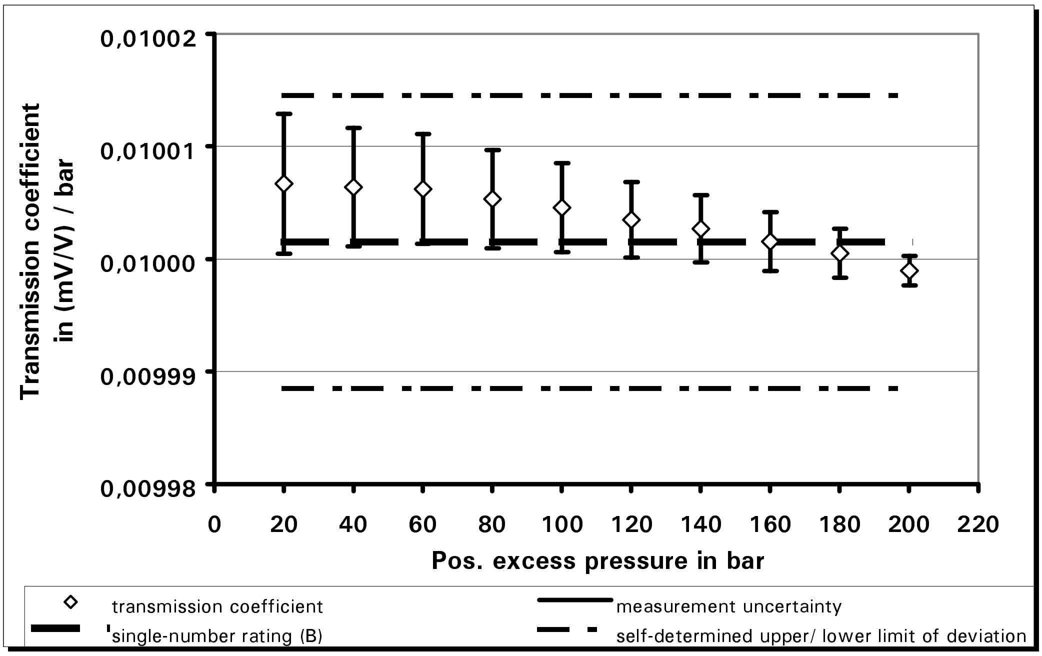
Quantity X_i	Estimate x_i	Width of distribu-tion $2a$	Divisor	Uncer-tainty $w(x_i)$	Sensitiv-ity coeffi-cient c_i	Uncertainty contrib-ution $w_i(y)$	Variance w_i^2
$p_{standard}$	100,056 bar	20 mbar	2	5,00*10^{-5}	-1	5,00*10^{-5}	2,50*10^{-9}
V_{ind}	1,001015 mV/V	0,00010 mV/V	2	2,50*10^{-5}	1	2,50*10^{-5}	6,25*10^{-10}
$K_{zero\ deviation}$	1	3,0*10^{-5}	$\sqrt{3}$	8,66*10^{-6}	1	8,66*10^{-6}	7,50*10^{-11}
$K_{repeatability}$	1	9,0*10^{-5}	$\sqrt{3}$	2,60*10^{-5}	1	2,60*10^{-5}	6,76*10^{-10}
$K_{reproducibility}$	1	1,5*10^{-4}	$\sqrt{3}$	4,33*10^{-5}	1	4,33*10^{-5}	1,87*10^{-9}
$K_{hysteresis}$	1	6,3*10^{-4}	$\sqrt{3}$	1,82*10^{-4}	1	1,82*10^{-4}	3,31*10^{-8}
S	0,01000455	w =				1,97·10^{-4}	Σw_i^2 = 3,88·10^{-8}
S	0,01000455	$W = k \cdot w \quad (k=2)$				**3,9*10^{-4}**	

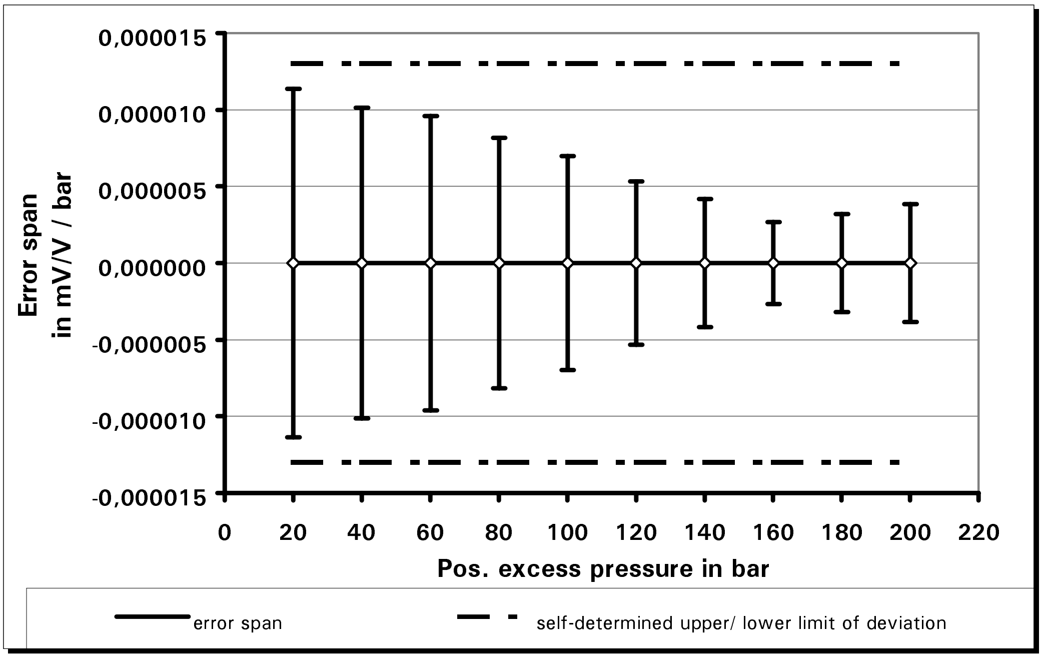
The pressure dependence of the oil density has been neglected.

For load step p = 100,056 bar, the expanded uncertainty of the measurement of the transmission coefficient is calculated as follows:

$$U(S)|_{100\ \mathrm{bar}} = W \cdot S = 3{,}9 \cdot 10^{-4} \cdot 0{,}01000455\ (\mathrm{mV/V})/\ \mathrm{bar} = \mathbf{3{,}9 \cdot 10^{-6} \cdot (mV/V)/\ bar}$$

The self-determined upper limiting amount of the deviation is, for example, **±0,13 %** of the transmission coefficient.





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

Table 19: Typical measurement uncertainties which can be attributed to the values of the reference standards

Pressure scale	**Typical value of the expanded uncertainty** U 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%

Table 20: Typical measurement uncertainties which can be attributed to the values of working standards

Working standard	**Typical value of the expanded uncertainty** U 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 cl. 0,1	0,10%

Annex F Period of validity (recommended)

It is the user who is responsible for fixing, and complying with, an appropriate period for repeating the calibration. For the usual conditions of use, the following recalibration periods are recommended:

Pressure balances	**5 years**
Bourdon tube pressure gauges, class >0,6	**2 years**
Electrical 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**
Electrical pressure gauges ≤ 0,5% of measurement span	**1 year**
Pressure transmitters with electrical output ≤ 0,5% of measurement span	**1 year**

Independently of these periods, the calibration item is to be recalibrated, among other things, if it has been subjected to an overload outside its overload limits, after a repair, after improper handling which might have an effect on the measurement uncertainty or for other reasons.

References

DIN:
Internationales Wörterbuch der Metrologie
German version of International Vocabulary of Basic and General Terms in Metrology, 2nd edition 1994, Beuth-Verlag, ISBN 3-410-13086-1

DIN 1319-1:
Grundlagen der Meßtechnik, Teil 1: Grundbegriffe
Fundamentals of Metrology, part 1: Basic terms, 1996

DIN 1319-2:
Grundlagen der Meßtechnik, Teil 2: Begriffe für die Anwendung von Meßgeräten
Fundamentals of Metrology, part 2: Terms for the use of measuring instruments, 1999

DKD-5:
Anleitung zum Erstellen eines DKD-Kalibrierscheins
Instructions for drawing up a DKD calibration certificate,
DKD, edition 2002

The uncertainty analysis is based on the following documents:

ISO:
Guide to the Expression of Uncertainty in Measurement
1st edition 1993, ISO, Geneva, ISBN 92-67-10188-9

DIN V ENV 13005
Leitfaden zur Angabe der Unsicherheit beim Messen
German version of ENV 13005:1999

EA-4/02:
Expression of the Uncertainty of Measurement in Calibration
December 1999

EA-10/03:
Calibration of Pressure Balances, Annex B
Edition 1, July 1997

DKD-3:
Angabe der Meßunsicherheiten bei Kalibrierungen
DKD 1998, German version of publication EA-4/02: *Expression of the Uncertainty of Measurement in Calibration*

DKD-3-E1: Supplement 1
Angabe der Meßunsicherheiten bei Kalibrierungen, Beispiele
DKD 1998, German version of publication EA-4/02-S1: *Expression of the Uncertainty of Measurement in Calibration*, *Examples*

DIN 1319-3:
Grundlagen der Meßtechnik, Teil 3: Auswertung von Messungen einer einzelnen Meßgröße, Meßunsicherheit

Fundamentals of Metrology, part 3: Evaluation of measurements of a single measurand, measurement uncertainty, 1996

DIN 1319-4:
Grundlagen der Meßtechnik, Teil 4: Auswertung von Messungen, Meßunsicherheit

Fundamentals of Metrology, part 4: Evaluation of measurements, measurement uncertainty, 1999