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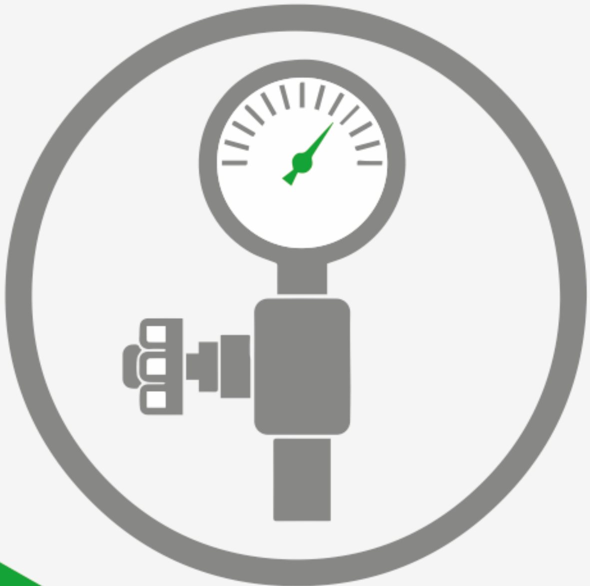

GUIDELINES ON CALIBRATION OF PRESSURE MEASURING INSTRUMENT

(GAUGES, TRANSMITTERS AND TRANSDUCERS WITH ELECTRICAL OUTPUT)

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Contents

1 SCOPE

This document presents the minimum requirements for the calibration and estimation of the uncertainty in the calibration of Pressure gauges, Pressure Transmitters and Transducers with electrical output.

2 INTRODUCTION

Pressure is generally the result of molecules, within a gas or liquid, impacting on their surroundings - usually the walls of the containing vessel. Its magnitude depends on the force of the impacts over a defined area; hence, for example, the traditional (and obsolete!) unit pounds force per square inch.

The relationship between pressure (p), force (F) and area (A) is given by:

$$P = \frac{\mathrm{F}}{\mathrm{A}}$$

and it applies whether the pressure is very small, such as in outer space - or very large, as in hydraulic systems for example. Thus the word pressure is correct when referring to the entire range of ‘force per unit area’ measurements (although it is true that at extremely low pressures the concept of molecules exerting a force becomes more abstract).

3 TERMINOLOGY

The terms and definitions conform to the international vocabulary of metrology. Basic and general concepts and associated terms (VIM) refer to current edition.

3.1 Pressure Gauge (Bourdon tube)

A pressure gauge is an instrument which measures pressure by means of mechanical movements, where the mechanical movement gets converted into the rotary motion of a pointer. The Bourdon tube dial gauge has a Bourdon tube of elliptical cross-section that is bent to form a circular arc.

Fig. 1 Bourdon Tube pressure gauge with casing

Fig. 2 Bourdon Tube pressure gauge without casing

3.1.1 How the bourdon tube pressure gauge works

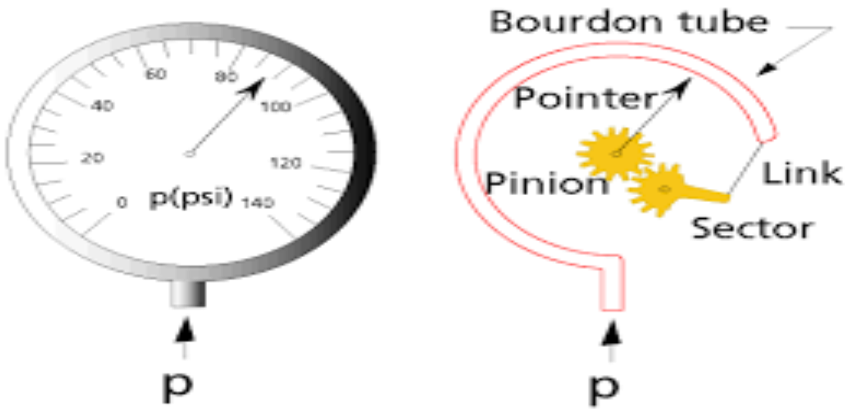

Fig 3 schematic drawing of a BT

- The media enters from socket (p) and goes into the bourdon tube (BT).
- The media can be pressurized air, water or oil.
- Pressurized media enters in the BT and tends to expand the BT.
- The end of the BT is connected to the mechanical movement.
- So that the mechanical movement of the BT converts into the rotary motion of the pinion.
- Due to that rotation, the pointer rotates and we get a reading on the scale.

3.1.2 Parts of the Bourdon Tube Pressure Gauge

- Casing or housing of a pressure gauge
- Socket (thread and holes)
- C-shape bourdon tube (brass)
- Welding of a BT and socket
- Assembly movement (brass)
- White coloured dial with letterings (fixed on assembly) (aluminium)
- Dial screws
- Pointer fixed on dial
- Toughened glass

3.2 Pressure Transducers

The pressure transducers convert the measured pressure into an analogue electrical signal that is proportional to the applied voltage.

Depending on the model, the output signal can be:

- a voltage
- a current

To ensure their function, the pressure transducers need a continuous power supply stabilized to a level in relation to the expected uncertainty of the pressure measurement.

Fig 4 Transducers

3.3 Pressure transmitters

A pressure transmitter generally is a unit that consists of a pressure transducer and a module for conditioning and amplifying the transducer signal.
Depending on the model, the output information of a pressure transmitter can be:

- a voltage (5 V; 10 V; ...),
- a current (4-20 mA; ...),
- a digital format (RS 232; ...).

For operation, pressure transmitters need a continuous electrical supply, which do not need to be specifically stabilised.

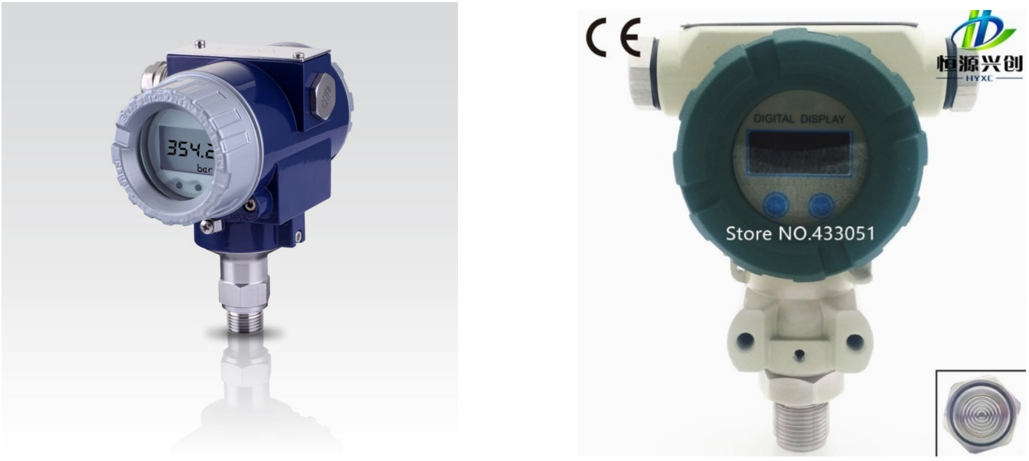

Fig 5 A Transmitter

3.4 Manometers with digital or analogue indication

This type of manometer is a complete measuring instrument that indicates units of pressure. Depending on the pattern, it may consist of the following units:

(a) Manometer with a digital indication:
- pressure transducer,
- analogue conditioning module,
- analogue-to-digital converter,
- digital processing module,
- digital indication (in the unit(s) specified by the manufacturer),
- electrical power supply unit (generally incorporated).

(b) Manometer with an analogue indication:
- pressure transducer,
- analogue conditioning module,
- analogue indicating module,
- electrical power supply unit (generally incorporated).

4 SYMBOLS AND DESCRIPTION

Table 1:

Symbol	Description
p	Pressure
Δp	Systematic measurement deviation of the quantity of pressure
Y	Output quantity
X	Value-determining input quantity
k	Correction factor
u	Standard uncertainty
U	Expanded uncertainty
w	Relative standard uncertainty
W	Relative expanded uncertainty
x	Estimate of input quantity
y	Estimate of output quantity
a	Half-width of a distribution
p_e	Effective pressure
m	Mass of load masses
$b`$	Repeatability
b	Reproducibility
$U`$	Error span
t	Temperature of piston-cylinder system
Δh	Difference reference levels of standard and calibration object
r	Resolution
g	Acceleration due to gravity
f_o	Zero deviation
h	Hysteresis
Mi	Mass of deadweight
ρ_{air}	Density of air
ρ_m	Density of mass
V	Cavity hole of piston
$\rho_{pressure\ medium}$	Density of pressure medium

σ	Surface tension of oil
C	Circumference of piston
A_o	Effective area of piston
$\alpha+\beta$	Thermal expansion coefficient of piston cylinder assembly
t	Temperature of piston
λ	Pressure coefficient

5 PRESSURE UNITS AND CONVERSION FACTORS

Table 2:

Unit	Symbol	Number Of Pascals
pascal	Pa	1
bar	bar	1×10^5 (exactly)
millibar (i)	mbar	100 (exactly)
hectopascal (i)	hPa	100 (exactly)
conventional millimetre of mercury (ii,iii)	mmHg	133.322...
conventional inch of mercury (ii,iii)	inHg	3 386.39...
inch of water (iii,iv)	inH2O	248.6... to 249.1...
torr (v)	torr	101 325/760 (exactly)
kilogram-force per square centimetre	kgf/cm2	98 066.5 (exactly)
pound-force per square inch(vi)	lbf/in2	6 894.76...

6 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. 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 accreditation body. If the calibration does not take place under standard 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.

When calculating the measurement uncertainty of the standards used, all relevant influence quantities are to be taken into account. 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 laboratory and provided with a calibration certificate stating the expanded uncertainty at the time of calibration. The working standard is subject to surveillance by the accreditation body. Depending on their type, the working standards may vary considerably.

7 CALIBRATION ITEM

The calibration items are pressure gauges of the three types: Bourdon Tube Pressure Gauge, Digital (Electrical) Pressure Gauge and Pressure Transmitter/Transducer with electrical output.

For the calibration of pressure transmitters with electrical output, auxiliary measuring devices of the accredited laboratory have to be used – as opposed to electrical pressure gauges 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 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 read out are unequivocally interpreted and processed.

8 AMBIENT CONDITION

The calibration is to be carried out after a temperature equalization between calibration item and environment within the permissible temperature range (18 °C to 28 °C). A 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 period depends on personal experience or specifications provided by the manufacturer.

The calibration is to be carried out at a steady ambient temperature. The recommended temperature variation during calibration is limited to ±1 K. It might be necessary to consider an additional uncertainty contribution when exploiting the maximum tolerance limits; this temperature must lie between 18 °C and 28 °C and has to be recorded.

9 METHODS OF CALIBRATION

9.1 Basic Calibration Method

The basic calibration procedure should be used for the desired expanded measurement uncertainty if U > 0.6. Calibration is performed once at 6 pressure points including zero in increasing and decreasing pressures. One (1) preloading is done.
Repeatability is estimated from three repeated measurements in one pressure point (preferably 50 % FS).

9.2 Standard Calibration Method

The Standard calibration procedure should be used for the expected expanded measurement uncertainty if 0.1 ≤ U ≤ 0.6. Calibration is performed once at 11 pressure points including zero in increasing and decreasing pressures. Two (2) preloadings are done. Repeatability is estimated from calibration in four pressure points (preferably 0, 20, 50, 80 % FS) that are repeated three times.

9.3 Comprehensive Calibration Method

The Comprehensive calibration procedure should be used for the expected expanded measurement uncertainty if U < 0.1.
Calibration is performed at 11 pressure points in three measuring series. Three (3) preloadings are done.

Table 3:

Exp. Uncertainty aimed at	Method of Calibration	Measurement Point	Preloading
> 0.6	B	6	1
0.1 to 0.6	S	11	2
< 0.1	C	11	3

10 CALIBRATION SEQUENCES

10.1 Preparatory work

Prior to the calibration itself, the good working condition of the instrument shall be visually checked, especially:

- good quality of the electrical contacts,
- cleanliness of the instrument.

It is recommended to perform the following operations:

- identify the reference levels,
  - of the reference standards.
  - of the instrument to be calibrated (at the level of the connection or at the reference level defined by the manufacturer).
- minimise the difference between the reference levels.
- for torque sensitive devices follow the manufacturer's instructions.

10.2 Calibration procedures

In the case of instruments with several outputs, it is sufficient to perform the calibration for the output(s) specified by the user.

Irrespective of the instrument to be calibrated and of the chosen method (refer to section 8.0), the operations are performed in three successive steps:

- check of a limited number of pressure points of the measurement range to determine the initial metrological condition of the instrument,
- adjustment of the instrument according to the manufacturer's specification,
- calibration appropriate to the instrument over its whole measurement range or span.

Each of these operations, especially adjustment of the instrument, shall be performed only with the agreement of the client and shall be reported in the calibration certificate.

10.3 Initial check

To determine the long-term drift of the instrument, it is necessary to provide the user with some information on its condition prior to any potential adjustment.

If the user does not apply for a complete calibration being carried out prior to the adjustment, it is recommended to perform the following operations:
- operate the instrument and bring it at least twice to its upper pressure limit and keep the pressure for at least one minute,
- during the first pressure rise, check out the indication obtained for conformity with the specifications,
- read the indications of the instrument at 0 %, 50 % and 100 % of its measurement span.

10.4 Adjustment

If the response of the instrument does not conform to the conventional response, i.e.:
- for a digital manometer with direct reading, if there is a difference between the indicated pressure and the applied pressure,
- for a transmitter with electrical output, if there is a deviation from the conventional signal (of, for example, 4 to 20 mA).

Perform an adjustment of the instrument according to the client’s requirements.

Depending on the capabilities of the calibration laboratory such procedure shall be performed:

- with the aid of the means normally accessible to the user (potentiometers for zero and full scale, sometimes with mid-scale)
- with the internal adjustment facilities of the instrument (potentiometers, storage of a calibration curve, etc.), in conformity with the information contained in the technical description, after agreement of the client.

Note: This operation obviously presumes a detailed knowledge of the adjustment procedures and requires specialized operators and calibration means that are more powerful than the instrument to be calibrated. If the instrument provides scale marks which are useful to the user (calibration notches, restitution of a calibration curve for example), it is recommended to determine these elements in order to report them in the calibration certificate.

10.5 Main calibration

The calibration method to be used (cf. section 8.0) is selected according to the uncertainty of measurement expected for the instrument to be calibrated.

At each calibration point at least the following data shall be recorded:

- the pressure indicated by the reference instrument or the elements necessary for calculating the pressure actually measured (values of masses and temperature for a pressure balance, for example)
- the indication of the instrument to be calibrated.

The following data shall be also recorded:

- the values of the influence quantities (temperature, atmospheric pressure),
- the identification parameters of the instrument to be calibrated,
- the identification of the instruments included in the measuring system and/or instrument used for measuring the output signal.

11 EVALUATION OF UNCERTAINTY OF MEASUREMENT OF INPUT ESTIMATES

The major uncertainty contribution to be taken into consideration for the evaluation of uncertainty associated with pressure gauges are uncertainty due to repeatability of the data, uncertainty due to hysteresis, uncertainty of the measuring instruments, uncertainty due to influencing parameters, uncertainty due to resolution of the gauge, uncertainty due to modelling, uncertainty due to reproducibility of the gauge, uncertainty due to drift in the measurement over a period of time, uncertainty due to head correction between the standard and instrument under calibration and uncertainty of reference standard.

12 DEFINITION

The uncertainty of measurement is a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand (EA-4/02 M: 2013).

13 PROCEDURE

Resolution r

- **Analog indicating devices**
  - resolution of the indication device is obtained from the ratio of the pointer width to the centre distance of two neighbouring graduation lines (scale interval); rectangular distribution.
  - 1/2, 1/5 or 1/10 is recommended as ratio $u(r) = \frac{r}{\sqrt{3}}$

- **Digital indicating devices**

  - the resolution corresponds to the digital step (if the indication varies by one digital step on unloaded pressure gauge); rectangular distribution.

$$u(r) = \frac{r}{2\sqrt{3}}$$

- **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, additional added with a digital step.

Zero deviation f_O

- The zero point can be set prior to every measurement cycle and must be recorded prior and after every measurement cycle. The reading is to be

  made with the instrument being completely relieved; rectangular distribution.

$$f_o = max\left\{\left|x_{2.0} - x_{1.0}\right|, \left|x_{4.0} - x_{3.0}\right|, \left|x_{6.0} - x_{5.0}\right|\right\}$$

Repeatability b´

- The repeatability *b´* is determined by the difference of the zero signal corrected measurement values of corresponding measurement series (the mounting not being changed); rectangular distribution.

$$b'_{up,j} = \left|\left(x_{3,j} - x_{3,o}\right) - \left(x_{1,j} - x_{1.0}\right)\right|$$

$$b'_{down,j} = \left|\left(x_{4,j} - x_{4,0}\right) - \left(x_{2,j} - x_{2,0}\right)\right|$$

$$b'_{mean,j} = max\left\{b'_{up,j}, b'_{down,j}\right\}$$

Hysteresis h

- When mean values are stated, the hysteresis h is determined by the difference of the zero point-corrected measurement values of the increasing and decreasing series; rectangular distribution.

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

Evaluation model

A simple sum/difference model is suitable for determining the measurement deviation of the indication.

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

Table 4:

$Y = \Delta p$	Measurand; measurement deviation of indication
$X_i = p_{ind}$	Indication of pressure gauge
$X_2 = p_{standard}$	Value of reference standard
$X_3 = \delta p_{zero\ deviation}$	unknown measurement deviation due to zero deviation
$X_4 = \delta p_{repeatability}$	unknown measurement deviation due to repeatability
$X_5 = \delta p_{hysteresis}$	unknown measurement deviation due to hysteresis

and for the mean values:

$$\Delta p_{mean} = \frac{p_{ind,up} + p_{ind,down}}{2}$$

The expanded uncertainty U with k=2 is:

$U = k\ u$

$$U = k\ \sqrt{u^2_{standard} + u^2_{resolution} + u^2_{zerodeviation} + u^2_{repeatability} + u^2_{hysteresis}}$$

The expanded uncertainty has to be reported in the calibration certificate. $U(y)$ is the uncertainty interval (±) of the measuring result.

Error span

The error span U' is the sum of the expanded uncertainty (k=2) and the amount of the systematic deviation.

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

Conformity

If the error span lies within the error limit stated by the manufacturer conformity can be confirmed.

Influence quantities in calibration of pressure gauges

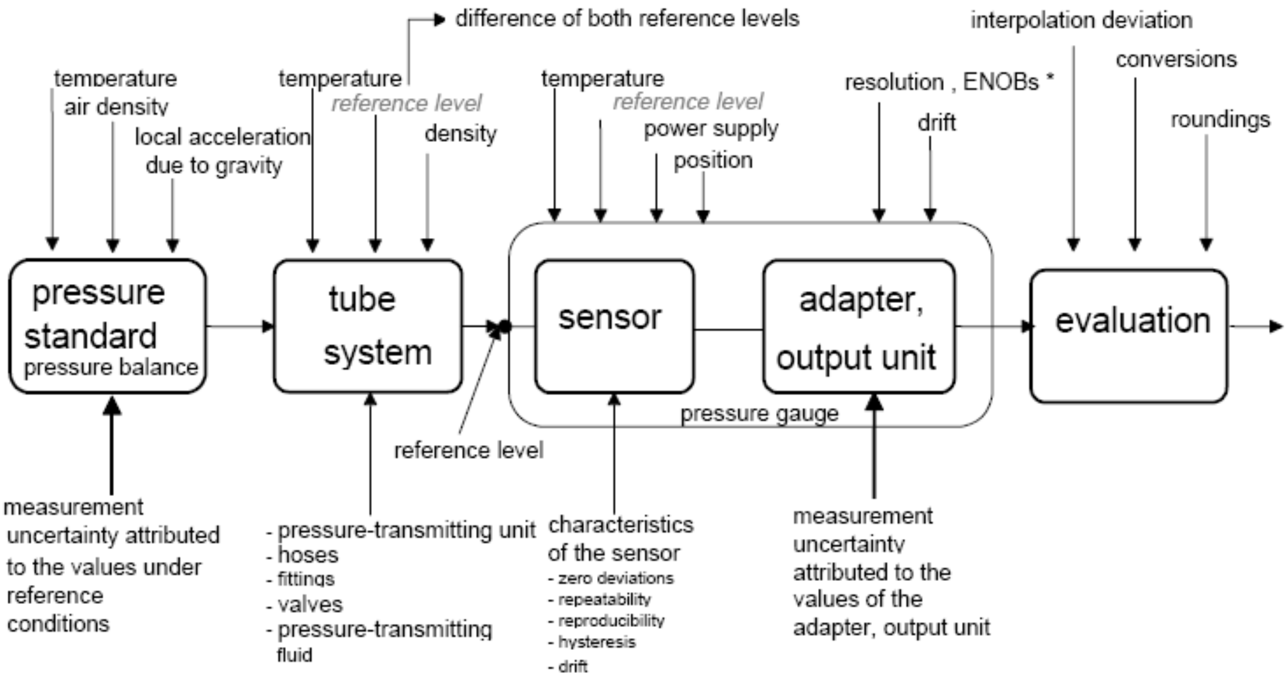

Table 5: Uncertainty budget

Cont. No.	Quantity X_i	Estimate x_i	Width of distri-bution $2a$	Probability distribution $P(x_i)$	Divisor	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncer-tainty contrib-ution $u_i(y)$	Unit *
1	$p_{ind,...}$	$p_{i,\ ind,...}$	$2r$	rectangle	$\sqrt{3}$	$u(r)=\sqrt{\frac{1}{3}.\left(\frac{2r}{2}\right)^2}$	1	u_r	bar
2	$p_{standard}$	$p_{i,\ standard}$		normal	2	u(standard)	-1	$u_{standard}$	bar
3	$\delta\ p_{zero\ deviation}$	0	f_o	rectangle	$\sqrt{3}$		1	$u_{\ fo}$	bar

						$u(f_o)=\sqrt{\frac{1}{3}\cdot\left(\frac{f_o}{2}\right)^2}$			
4	$\delta p_{repeatability}$	0	*b'*	rectangle	$\sqrt{3}$	$u(b')=\sqrt{\frac{1}{3}\cdot\left(\frac{b'}{2}\right)^2}$	1	$u_{b'}$	bar
5	$\delta p_{hysteresis}$	0	*h*	rectangle	$\sqrt{3}$	$u(h)=\sqrt{\frac{1}{3}\cdot\left(\frac{h}{2}\right)^2}$	1	u_h	bar

*It is advisable to carry over the unit of the uncertainty contributions

13.1 Uncertainty analysis for the calibration of Bourdon tube pressure gauges and electrical pressure gauges

Uncertainty budget of a 25 bar pressure gauge using Deadweight Tester

Table 6: Uncertainty budget for 25 bar

Quantity	**Estimate**	**Distribution**	**Divisor**	**Standard uncertainty**	**Sensitivity coefficient**	**uncertainty contribution**
standard	24.9390	normal	2	0.0018 bar	1	0.00177 bar
Temperature	0.0000	rectangle	1.732	0.0002 bar	1	0.00024 bar
Temperature Coefficient	0.0000	rectangle	1.732	0.0002 bar	1	0.00017 bar
Density Difference	0.0000	rectangle	1.732	0.0053 bar	1	0.00533 bar
Gravity	0.0000	rectangle	1.732	0.0000 bar	1	0.00000 bar
Difference in Altitude	0.0000	rectangle	1.732	0.0001 bar	1	0.00015 bar
resolution	25.0000	rectangle	1.732	0.0289 bar	1	0.02887 bar
Zero deviation	0	rectangle	1.732	0.0000 bar	1	0.00000 bar
hysteresis (*h*)	0	rectangle	1.732	0.0000 bar	1	0.00000 bar

***u*=**	**0.029 bar**
***U*=**	**0.059 bar**

Uncertainty budget of a 400 bar pressure gauge using Deadweight Tester

Table 7: Uncertainty budget for 400 bar

Quantity	**Estimate**	**Distribution**	**Divisor**	**Standard uncertainty**	**Sensitivity coefficient**	**uncertainty contribution**
standard	399.4941	normal	2	0.0531	1	0.05314 bar
Temperature	0.0000	rectangle	1.732	0.0033	1	0.00332 bar
Temperature Coefficient	0.0000	rectangle	1.732	0.0021	1	0.00212 bar
Density Difference	0.0000	rectangle	1.732	0.0002	1	0.00025 bar
Gravity	0.0000	rectangle	1.732	0.0000	1	0.00000 bar
Difference in Altitude	0.0000	rectangle	1.732	0.0001	1	0.00015 bar
resolution	400.0035	rectangle	1.732	0.0577	1	0.05774 bar
Zero deviation	0	rectangle	1.732	0.0000	1	0.00000 bar
hysteresis (*h*)	0	rectangle	1.732	0.0000	1	0.00000 bar
					***u*=**	**0.079 bar**
					***U*=**	**0.16 bar**

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