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Vacuum technology — Vacuum gauges — Evaluation of the uncertainties of results of calibrations by direct comparison with a reference gauge

Technique du vide — Manomètres à vide — Évaluation de l'incertitude des résultats des étalonnages par comparaison directe avec un manomètre de référence

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Contents

Page

Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 27893 was prepared by Technical Committee ISO/TC 112, *Vacuum technology*.

This first edition of ISO 27893 cancels and replaces the first edition of ISO/TS 27893:2009, which has been technically revised.

Vacuum technology — Vacuum gauges — Evaluation of the uncertainties of results of calibrations by direct comparison with a reference gauge

1 Scope

This International Standard gives guidelines for the determination and reporting of measurement uncertainties arising during vacuum gauge calibration by direct comparison with a reference gauge carried out in accordance with ISO/TS 3567.

This International Standard describes methods for uniform reporting of uncertainties in vacuum gauge certificates. Uncertainties reported in accordance with the guidelines given in this International Standard are transferable in the sense that the uncertainty evaluated for one result can be used as a component in the uncertainty evaluation of another measurement or calibration in which the first result is used.

This International Standard defines two measurement models that are sufficient to cover most practical cases. However, it is possible that the models given cannot be applied to newly developed vacuum gauges.

The final uncertainty to be reported in a certificate is evaluated from the uncertainties of the input quantities and influence quantities. The principal quantities that can affect the result of a vacuum calibration are described; however, a complete list of the possible quantities that can have an influence on the final result lies outside the scope of this International Standard.

NOTE It is envisaged that future Technical Specifications will address the calibration of specific types of vacuum gauges.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TS 3567, *Vacuum gauges — Calibration by direct comparison with a reference gauge*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC Guide 99:2007, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TS 3567, ISO/IEC Guide 98-3, ISO/IEC Guide 99 and the following apply.

3.1
corrected reading
value resulting after the reading of the gauge has been corrected for systematic errors

EXAMPLE For the results given in the calibration certificate of the reference standard.

3.2
long-term instability
possible change of calibrated value after long periods of time

EXAMPLE Change resulting from transportation of the device.

NOTE Long-term instability is different from reproducibility as defined in ISO/IEC Guide 99:2007, 3.7.

3.3
model
⟨uncertainty of measurement⟩ mathematical model set out in ISO/IEC Guide 98-3

3.4
offset
⟨measuring instruments⟩ zero error
datum measurement error where the specified measured quantity value is zero

NOTE Adapted from ISO/IEC Guide 99:2007, 4.28.

EXAMPLE The reading when there is no pressure (absolute or differential) or a pressure far below the resolution limit applied to a vacuum gauge.

3.5
deviation of offset
Possible difference of an **offset** (3.4) value between the time of the measurement of the **offset** (3.4) and the time when a pressure reading is taken

3.6
reference standard
reference gauge
standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived

NOTE Adapted from ISO/IEC Guide 99:2007, 6.6.

EXAMPLE The gauge or standard that gives traceability to the SI unit in the calibration apparatus in accordance with ISO/TS 3567.

3.7
calibration pressure
⟨vacuum gauges⟩ pressure evaluated from the **corrected reading** (3.1) of the **reference standard** (3.6) and all necessary corrections at the gauge port of the unit under calibration

EXAMPLE Necessary corrections might be for known differences between gauge ports.

4 Symbols and abbreviated terms

Symbol or abbreviated term	Designation	Unit
UUC	unit under calibration (vacuum gauge)	—
e	error of reading	in relative units
k	coverage factor to expand standard uncertainty, u	1
p_{UUC}	pressure indication of a UUC corrected for known deviations	Pa[1)]
$p_{\mathrm{ind,UUC}}$	pressure indication of a UUC not corrected for any deviation	Pa
p_{std}	pressure indication of reference gauge (reference standard) corrected for known deviations	Pa
$p_{\mathrm{ind,std}}$	pressure indication of reference gauge (reference standard) not corrected for any deviation	Pa
r_{UUC}	quantity determined by a calibration in the quotient model	any unit
r_{std}	the quantity that was determined for the reference standard	any unit
S	sensitivity of the output of a vacuum gauge	any unit
u	standard uncertainty	any unit
U	expanded uncertainty	any unit
x_{UUC}	indication of a UUC	any unit
x_{std}	indication of a reference gauge	any unit
x_i	(often unknown) input quantities and corrections of gauge	any unit
X_i	(often unknown) input quantities and corrections of calibration method or condition	any unit
Δp	error of reading in absolute units	Pa
δp_i	deviations in the pressure unit (often unknown)	Pa
δx_i	(often unknown) deviations in the x	any unit
σ_{eff}	effective accommodation coefficient of a spinning rotor gauge	1

5 Basic concept and model

5.1 General

In a vacuum gauge calibration carried out in accordance with ISO/TS 3567, the corrected reading of a reference gauge gives the value of the quantity that is traceable to the SI. All vacuum gauges shall be calibrated in terms of pressure. This means that the user of the vacuum gauge calibrated in accordance with ISO/TS 3567 and this International Standard obtains a clear assignment of the output quantity of the gauge to the SI unit of pressure, the pascal.

1) 1 Pa = 0,01 mbar.

The value of pressure obtained from the corrected reading of the reference standard output can be used to determine the pressure at the entrance port of the unit under calibration (UUC). This is referred to as calibration pressure value. Often the corrected reading of the reference standard is identical to the calibration pressure value and valid for all gauge ports.

The calibration pressure value can be used to determine an error of the reading, Δp, of the unit under calibration. In this case, a sum model gives an adequate description of the measurement.

The calibration pressure value can also be used to determine a correction factor, a sensitivity coefficient, an effective accommodation coefficient or a gauge constant, in which case a quotient model gives an adequate description of the measurement.

In both models it can be assumed that all the input quantities are uncorrelated.

5.2 Sum model

In the sum model, the difference between the reading of the UUC, p_{ind}, and the "true" calibration pressure traceable to the SI units is taken as the measurand, Δp. The calibration pressure is given by the reference standard pressure value, p_{std}, and possibly by a correction term, δp_{m}, due to the calibration method considering known effects like height correction, thermal transpiration, and pressure non-uniformity. The general sum model thus becomes

$$\Delta p = p_{\mathrm{UUC}} - \left(p_{\mathrm{std}} + \delta p_{\mathrm{m}}\right) \tag{1}$$

The first term refers to the UUC, the second to the reference standard, and the third to the calibration method. The sum of the last two terms gives the calibration pressure value. All quantities shall be expressed in the SI unit of pressure, the pascal.

Each of these terms is again expressed by another model equation, which makes all necessary corrections due to offsets, temperature corrections, deviation of indication from the SI value in accordance with the calibration certificate, etc.

5.3 Quotient model

In the quotient model, the ratio of the reading of the UUC, x_{UUC}, and the standard pressure value, p_{std}, is taken as the measurand, r_{UUC}. The general quotient model thus becomes

$$r_{\mathrm{UUC}} = \frac{x_{\mathrm{UUC}}}{p_{\mathrm{std}}} \prod_i X_i \tag{2}$$

The numerator refers to the UUC, the denominator to the reference standard, and the product to the calibration method and conditions. The latter can also be defined by the vacuum gauges under study, e.g. the emission current in a hot cathode ionization gauge. It is possible to express x_{ind} in any reasonable unit, e.g. that of pressure, voltage or current. The X_i can be expressed in any meaningful physical unit or can be without dimension.

Each of these factors is expressed by another model equation, which makes all necessary corrections due to offsets, temperature corrections, deviation of indication in accordance with calibration certificate, etc.

Examples of r_{UUC} are

a) f_{c}^{-1} the reciprocal of a dimensionless correction factor, where $x_{\mathrm{UUC}} = p_{\mathrm{UUC}}$ and $X_i = 1$;

b) S a sensitivity of the analogue output, V_{UUC}, of a capacitance diaphragm gauge, where $x_{\mathrm{UUC}} = V_{\mathrm{UUC}}$;

c) S a sensitivity of the analogue output, V_{UUC}, of a thermal conductivity gauge, where $x_{\mathrm{UUC}} = V_{\mathrm{UUC}}$;

d) σ_{eff} the effective accommodation coefficient of a spinning rotor gauge, where $x_{\text{UUC}} = p_{\text{UUC}}$, when $\sigma_{\text{eff}} = 1$ was entered into the controller;

e) S a sensitivity of a Bayard-Alpert gauge with a hot cathode, where $x_{\text{UUC}} = I_{\text{UUC}}$ is the positive ion current of the collector and $X_1 = 1/I_{\text{e}}$, where I_{e} is the emission current.

5.4 Combination of the two models

It is possible to evaluate some of the input quantities in each model by either of the two models. First, for example, p_{std} as well as its uncertainty can be evaluated by the quotient model, thus

$$p_{\text{std}} = \frac{x_{\text{std}}}{r_{\text{std}}} \tag{3}$$

The result can then be used in Equation (1). This is unavoidable if r_{std} is given in the certificate applying Equation (2) (e.g. the sensitivity of an analogue output), where r_{UUC} is replaced by r_{std}.

It is, however, not recommended to combine the sum and quotient model in one equation. This task should be left to experts, since complicated sensitivity coefficients might appear that are not covered in this International Standard for reasons of clarity. The relative error of reading, e, however, is a common case, where an easy to handle combination of the two methods is possible.

The error of reading, e, can be expressed mathematically as

$$e = \frac{p_{\text{UUC}} - \left(p_{\text{std}} + \delta p_m\right)}{\left(p_{\text{std}} + \delta p_m\right)} = \frac{p_{\text{UUC}}}{p_{\text{std}} + \delta p_m} - 1 \tag{4a}$$

or, if $\delta p_{\text{m}} = 0$

$$e = \frac{p_{\text{UUC}} - p_{\text{std}}}{p_{\text{std}}} = \frac{p_{\text{UUC}}}{p_{\text{std}}} - 1 \tag{4b}$$

See Clause 4 for the designations of p_{UUC}, p_{std}, and δp_{m}. The uncertainty of e is described in Clause 8.

6 Calculation of uncertainty in the sum model

6.1 Total uncertainty — Sum model

The total uncertainty in the sum model, $u(\Delta p)$, is given by

$$u(\Delta p) = \sqrt{u(p_{\text{UUC}})^2 + u(p_{\text{std}})^2 + u(\delta p_{\text{m}})^2} \tag{5}$$

where

$u(p_{\text{UUC}})$ is the standard uncertainty of the corrected indication of vacuum gauge UUC;

$u(p_{\text{std}})$ is the standard uncertainty of the value of standard pressure;

$u(\delta p_{\text{m}})$ is the standard uncertainty of the deviations due to the calibration method.

6.2 Uncertainty contributions due to reference standard

The measurement of the standard pressure, p_{std}, is given by

$$p_{\text{std}} = p_{\text{ind,std}} - p_{\text{offs,std}} + \delta p_{\text{drft,std}} + \delta p_{\text{cal,std}} + \delta p_{t,\text{std}} + \delta p_{T,\text{std}} + \delta p_{\text{els,std}} \quad (6)$$

where

- $p_{\text{ind,std}}$ is the indication of the reference standard;
- $p_{\text{offs,std}}$ is the offset (zero deviation) of the reference standard;
- $\delta p_{\text{drft,std}}$ is the deviation of offset due to drift (in most cases, $\delta p_{\text{drft,std}} = 0$);
- $\delta p_{\text{cal,std}}$ is the correction in accordance with the calibration certificate;
- $\delta p_{t,\text{std}}$ is the deviation due to long-term instability (in most cases, $\delta p_{t,\text{std}} = 0$);
- $\delta p_{T,\text{std}}$ is the deviation due to temperature at the calibration laboratory;
- $\delta p_{\text{els,std}}$ is the deviation due to other influences, e.g. inclination of device (in most cases, $\delta p_{\text{els,std}} = 0$).

All quantities in Equation (6) refer to the reference standard gauge.

NOTE If the offset is deducted or adjusted to zero in the device itself, $p_{\text{offs,std}} = 0$.

The standard uncertainty of the standard pressure, $u(p_{\text{std}})$, is then given by

$$u(p_{\text{std}}) = \sqrt{u(p_{\text{ind,std}})^2 + u(p_{\text{offs,std}})^2 + u(\delta p_{\text{drft,std}})^2 + u(\delta p_{\text{cal,std}})^2 + u(\delta p_{t,\text{std}})^2 + u(\delta p_{T,\text{std}})^2 + u(\delta p_{\text{els,std}})^2} \quad (7)$$

where

- $u(p_{\text{ind,std}})$ is the uncertainty originating from the dispersion of measurement values, including dispersion due to digitizing, resolution scatter, etc.;
- $u(p_{\text{offs,std}})$ is the uncertainty of the offset values at measurement of the offset [without reproducibility of the offset covered by $u(\delta p_{\text{drft,std}})$];
- $u(\delta p_{\text{drft,std}})$ is the uncertainty of the offset values at time of calibration due to offset drift or other systematic dependencies, e.g. due to the frequency dependence of spinning rotor gauges;
- $u(\delta p_{\text{cal,std}})$ is the uncertainty of the standard in accordance with the calibration certificate;
- $u(\delta p_{t,\text{std}})$ is the uncertainty component allowing for the long-term instability;
- $u(\delta p_{T,\text{std}})$ is the uncertainty component due to the temperature influence under the conditions of the calibration laboratory;
- $u(\delta p_{\text{els,std}})$ is the uncertainty due to the specific conditions at the calibration laboratory, e.g. different mounting position of built-in devices.

For a $p_{\text{ind,std}}$ that has not been obtained from repeated observations, estimate $u(p_{\text{ind,std}})$ from scientific judgement based on all of the available information on the possible variability (including uncertainty component due to digitizing, repeatability, etc.).

For a temperature at calibration different from that shown in the calibration certificate, $u(\delta p_{T,\text{std}})$ should be included, if significant.

6.3 Uncertainty contributions due to unit under calibration

The measurement of the pressure of the UUC, p_{UUC}, is given by

$$p_{\text{UUC}} = p_{\text{ind,UUC}} - p_{\text{offs,UUC}} + \delta p_{\text{drft,UUC}} + \delta p_{\text{els,UUC}} \tag{8}$$

where

$p_{\text{ind,UUC}}$	is the indication of the UUC;
$p_{\text{offs,UUC}}$	is the offset (zero point deviation) of the UUC;
$\delta p_{\text{drft,UUC}}$	is the deviation of offset drift (in most cases, $\delta p_{\text{drft,UUC}} = 0$);
$\delta p_{\text{els,UUC}}$	represents the deviations due to other influences, e.g. inclination (in most cases, $\delta p_{\text{res,UUC}} = 0$).

The standard uncertainty of the measurement of the pressure with UUC, $u(p_{\text{UUC}})$, is then given by

$$u\left(p_{\text{UUC}}\right) = \sqrt{u\left(p_{\text{ind,UUC}}\right)^2 + u\left(p_{\text{offs,UUC}}\right)^2 + u\left(\delta p_{\text{drft,UUC}}\right)^2 + u\left(\delta p_{\text{els,UUC}}\right)^2} \tag{9}$$

where

$u(p_{\text{ind,UUC}})$	is the uncertainty originating from the dispersion of measurement values of UUC, including dispersion due to digitizing, resolution scatter, etc.;
$u(p_{\text{offs,UUC}})$	is the uncertainty of the offset values of the UUC at measurement of the offset (without reproducibility of the offset covered by the following quantity);
$u(\delta p_{\text{drft,UUC}})$	is the uncertainty of the offset values of the UUC due to offset drift or other systematic dependencies, e.g. due to speed dependence in the case of spinning rotor gauges;
$u(\delta p_{\text{els,UUC}})$	represents the other uncertainty components, which can also stem from the calibration item, e.g. temperature influences.

For a $p_{\text{ind,UUC}}$ that has not been obtained from repeated observations, estimate $u(p_{\text{ind,UUC}})$ from scientific judgement based on all of the available information on the possible variability (including uncertainty component due to digitizing, repeatability, etc.).

If the above-mentioned dependencies or values are not known, or cannot be estimated by the calibration laboratory, or manufacturer's specifications are not available, carry out at least two repeat measurements on different days. The uncertainty component of the values of the calibration item, $u(p_{\text{ind,UUC}})$, is then determined from

$$u(p_{\text{ind,UUC}}) = u(p_{\text{rep,UUC}}) \tag{10}$$

where $u(p_{\text{rep,UUC}})$ is the repeatability (standard deviation) of the (at least) three measurement values determined for one pressure point or over a larger range.

6.4 Uncertainty contributions due to calibration method or calibration conditions

The sum of the deviations of the pressures caused by the calibration method, δp_{m}, is given by

$$\delta p_{\mathrm{m}} = \delta p_{T,\mathrm{m}} + \delta p_{\mathrm{cf,m}} + \delta p_{t,\mathrm{m}} \tag{11}$$

where

$\delta p_{T,\mathrm{m}}$ represents the deviations of the pressures due to different temperatures at the connecting flanges;

$\delta p_{\mathrm{cf,m}}$ represents the deviations of the pressures at the connecting flanges due to height differences, desorption, leaks, conditions of flow, pumping speed, e.g. in the case of cold-cathode ion gauges;

$\delta p_{t,\mathrm{m}}$ represents the deviations due to the measuring method, e.g. variations of the calibration pressure with time when standard and calibration item are not read simultaneously.

The standard uncertainty of the calibration method, $u(\delta p_{\mathrm{m}})$, is then given by

$$u(\delta p_{\mathrm{m}}) = \sqrt{u(\delta p_{T,\mathrm{m}})^2 + u(\delta p_{\mathrm{cf,m}})^2 + u(\delta p_{t,\mathrm{m}})^2} \tag{12}$$

where

$u(\delta p_{T,\mathrm{m}})$ is the uncertainty component of the deviations of the pressures at the connecting flanges due to different temperatures;

$u(\delta p_{\mathrm{cf,m}})$ is the uncertainty component of the deviations of the pressures at the connecting flanges due to desorption, leaks, conditions of flow, pumping speed;

$u(\delta p_{t,\mathrm{m}})$ is the uncertainty component of the deviations due to the measuring procedure.

6.5 Coverage factor

The expanded uncertainty, $U(\Delta p)$, is given by

$$U(\Delta p) = k\, u(\Delta p) \tag{13}$$

where

k is the coverage factor;

$u(\Delta p)$ is the standard uncertainty.

The coverage factor is chosen based on the level of confidence needed for the application. In general, k is in the range 2 (confidence level of ≈ 95 %) to 3 (confidence level of ≈ 99 %).

If nothing else has been specified (between customer and calibration laboratory), take $k = 2$.

7 Calculation of uncertainty in the quotient model

7.1 Total uncertainty — Quotient model

The total uncertainty in the quotient model is best expressed as a relative uncertainty, $u(r_{\mathrm{UUC}})/r_{\mathrm{UUC}}$, and is given by

$$\frac{u(r_{\mathrm{UUC}})}{r_{\mathrm{UUC}}} = \sqrt{\left(\frac{u(x_{\mathrm{UUC}})}{x_{\mathrm{UUC}}}\right)^2 + \left(\frac{u(p_{\mathrm{std}})}{p_{\mathrm{std}}}\right)^2 + \sum_i \left(\frac{u(X_i)}{X_i}\right)^2} \tag{14}$$

where

x_{UUC} is the value of the output of the vacuum gauge UUC;

p_{std} is the value of standard pressure;

X_i are the values of the correction factors due to the calibration method and conditions.

7.2 Uncertainty contributions due to reference standard

The measurement of the standard pressure, p_{std}, in the sum model and its associated uncertainty is described in 6.2.

When Equation (3) is applied it is

$$\frac{u(p_{\mathrm{std}})}{p_{\mathrm{std}}} = \sqrt{\left(\frac{u(x_{\mathrm{std}})}{x_{\mathrm{std}}}\right)^2 + \left(\frac{u(r_{\mathrm{std}})}{r_{\mathrm{std}}}\right)^2} \tag{15}$$

where

x_{std} is the corrected indication of the reference standard (pressure, voltage, current, etc.);

r_{std} is the quantity for the reference standard as defined by Equation (2).

The measurement of the indication, x_{std}, of the reference standard is given by

$$x_{\mathrm{std}} = x_{\mathrm{ind,std}} - x_{\mathrm{offs,std}} + \delta x_{\mathrm{drft,std}} + \delta x_{T,\mathrm{std}} + \delta x_{\mathrm{els,std}} \tag{16}$$

where

$x_{\mathrm{ind,std}}$ is the indication of the reference standard (pressure, voltage, current, etc.);

$x_{\mathrm{offs,std}}$ is the offset of the reference standard;

$\delta x_{\mathrm{drft,std}}$ is the deviation of the offset (in most cases, $\delta x_{\mathrm{drft,std}} = 0$);

$\delta x_{T,\mathrm{std}}$ is the deviation due to temperature at the calibration laboratory;

$\delta x_{\mathrm{els,std}}$ represents the deviations due to other influences, e.g. corrections for inclination (in most cases, $\delta x_{\mathrm{els,std}} = 0$).

All quantities in Equations (15) and (16) relate to the reference standard gauge.

The standard uncertainty of the measurement of the indication of reference standard, $u(x_{\text{ind}})$, is then given by

$$u\left(x_{\text{std}}\right)=\sqrt{u\left(x_{\text{ind,std}}\right)^2+u\left(x_{\text{offs,std}}\right)^2+u\left(\delta x_{\text{drft,std}}\right)^2+u\left(\delta x_{T,\text{std}}\right)^2+u\left(\delta x_{\text{els,std}}\right)^2} \tag{17}$$

where

$u(x_{\text{ind,std}})$ is the uncertainty originating from the dispersion of measurement values of reference standard, including dispersion due to digitizing, resolution scatter, etc.;

$u(x_{\text{offs,std}})$ is the uncertainty of the offset values of the reference standard at measurement of the offset (without repeatability of the offset);

$u(\delta x_{\text{drft,std}})$ is the uncertainty of the offset values of the reference standard due to offset drift or other systematic dependencies, e.g. due to speed dependence in the case of spinning rotor gauges;

$u(\delta x_{T,\text{std}})$ is the uncertainty component due to the temperature influence under the conditions of the calibration laboratory;

$u(\delta x_{\text{els,std}})$ represents other uncertainty components, which can also stem from the calibration item, e.g. temperature influences.

The value of the reference standard, r_{std}, is calculated from the value $r_{\text{cert,std}}$ given in the certificate plus an allowance for long-term drift, $\delta r_{t,\text{std}}\, r_{\text{cert,std}}$

$$r_{\text{std}}=r_{\text{cert,std}}\left(1+\delta r_{t,\text{std}}\right) \tag{18}$$

Usually $\delta r_{t,\text{std}} = 0$, but $u(\delta r_{t,\text{std}}) \neq 0$.

The respective uncertainty, $u(r_{\text{std}})/r_{\text{std}}$, is given by

$$\frac{u\left(r_{\text{std}}\right)}{r_{\text{std}}}=\sqrt{\left(\frac{u\left(r_{\text{cert,std}}\right)}{r_{\text{cert,std}}}\right)^2+\left(\frac{u\left(\delta r_{t,\text{std}}\right)}{r_{\text{cert,std}}}\right)^2} \tag{19}$$

7.3 Uncertainty contributions due to the unit under calibration

The measurement of the indication, x_{UUC}, of the UUC is given by

$$x_{\text{UUC}}=x_{\text{ind,UUC}}-x_{\text{offs,UUC}}+\delta x_{\text{drft,UUC}}+\delta x_{\text{els,UUC}} \tag{20}$$

where

$x_{\text{ind,UUC}}$ is the indication of the UUC (pressure, voltage, current, etc.);

$x_{\text{offs,UUC}}$ is the offset;

$\delta x_{\text{drft,UUC}}$ is the deviation of offset (in most cases, $\delta x_{\text{drft,UUC}} = 0$);

$\delta x_{\text{els,UUC}}$ represents the deviations due to other influences, e.g. corrections for inclination (in most cases, $\delta x_{\text{els,UUC}} = 0$).

All quantities in Equation (20) relate to the UUC.

The standard uncertainty of the measurement of the pressure with UUC, $u(x_{\text{UUC}})$, is then given by

$$u(x_{\text{UUC}}) = \sqrt{u(x_{\text{ind,UUC}})^2 + u(x_{\text{offs,UUC}})^2 + u(\delta x_{\text{drft,UUC}})^2 + u(\delta x_{\text{els,UUC}})^2} \tag{21}$$

where

$u(x_{\text{ind,UUC}})$ is the uncertainty originating from the dispersion of measurement values of UUC, including dispersion due to digitizing, resolution scatter etc.;

$u(x_{\text{offs,UUC}})$ is the uncertainty of the offset values of the UUC at measurement of the offset (without repeatability of the offset);

$u(\delta x_{\text{drft,UUC}})$ is the uncertainty of the offset values of the UUC due to offset drift or other systematic dependencies, e.g. due to speed dependence in the case of spinning rotor gauges;

$u(\delta x_{\text{els,UUC}})$ represents other uncertainty components, which can also stem from the calibration item, e.g. temperature influences.

For a measurement value that has not been obtained from repeated observations, estimate the uncertainty from scientific judgement based on all of the available information on the possible variability (including uncertainty component due to digitizing, offset variations, etc.). If the above-mentioned dependencies or values are not known, or cannot be estimated by the calibration laboratory, or manufacturer's specifications are not available, carry out at least two repeat measurements on different days. Determine the uncertainty component of the values of the calibration item, $u(x_{\text{ind,UUC}})$, as follows:

$$u(x_{\text{ind,UUC}}) = u(x_{\text{rep,UUC}}) \tag{22}$$

where $u(x_{\text{rep,UUC}})$ is the repeatability (standard deviation) of the measurement values determined for one pressure point.

7.4 Uncertainty contributions due to calibration method or calibration conditions

7.4.1 The X_i are either due to the calibration method (e.g. a pressure ratio between the flanges) or due to the calibration condition (e.g. the emission current of an ion gauge). The latter values may be given by the manufacturer (often nominal values) or measured at the time of calibration.

It makes sense to distinguish the uncertainties of the X_i for the different cases.

7.4.2 Correction factors, X_i, for r, caused by the calibration method, can result from factors such as:

a) different temperatures at the connecting flanges;

b) different pressures at the connecting flanges due to height differences, desorption, leaks, conditions of flow, pumping speed, e.g. in the case of cold-cathode ion gauges;

c) variations of the calibration pressure with time when standard and calibration items are not read simultaneously, etc.

7.4.3 If the X_i for a measuring condition are taken from the manufacturer (e.g. a nominal value of the emission current) the uncertainty $u(X_i)$ should be given as well or, if not available, shall be estimated from scientific judgement based on all of the available information on the possible variability.

The uncertainty of the X_i due to the calibration condition, $u(X_i)$, when measured is typically given by

$$u(X_i) = \sqrt{u(X_{i,\mathrm{ind}})^2 + u(X_{i,\mathrm{cal}})^2 + u(X_{i,\mathrm{offs}})^2 + u(X_{i,\mathrm{drft}})^2 + u(X_{i,\mathrm{els}})^2} \tag{23}$$

where

$u(X_{i,\mathrm{ind}})$ is the uncertainty originating from the dispersion of measurement values of X_i, including dispersion due to digitizing, resolution scatter etc., e.g. in the case of emission current the standard deviation of the current;

$u(X_{i,\mathrm{cal}})$ is the uncertainty of X_i due to the calibration certificate and other factors such as long-term instability of the instrument measuring X_i, e.g. in the case of the emission current the uncertainty of the current meter;

$u(X_{i,\mathrm{offs}})$ is the uncertainty of the offset values of X_i at measurement of the offset without repeatability of the offset, e.g. a bias of the current meter measuring the emission current;

$u(X_{i,\mathrm{drft}})$ is the uncertainty of the offset values of X_i due to offset drift or other systematic dependencies, e.g. drifting emission current control;

$u(X_{i,\mathrm{els}})$ is other uncertainty components, e.g. temperature influences.

NOTE If $X_i = Q^{-1}$ (e.g. $Q = I_\mathrm{e}$, the emission current of an ionization gauge), the relative uncertainty is given by

$$\frac{u(X_i)}{X_i} = \frac{u(Q^{-1})}{Q^{-1}} = \frac{u(Q)}{Q}$$

The last term is easier to evaluate.

7.5 Coverage factor

The expanded uncertainty, $U(r)$, is given by

$$U(r) = k\,u(r) \tag{24}$$

where

k is the coverage factor;

$u(r)$ is the standard uncertainty.

The coverage factor is chosen based on the level of confidence needed for the application. In general, k is in the range 2 (confidence level of ≈ 95 %) to 3 (confidence level of ≈ 99 %).

If nothing else has been specified (between customer and calibration laboratory), take $k = 2$.

8 Combination of the sum and quotient model for error of reading

The error of reading, e, is defined by Equation (4a), from where it is possible to obtain the uncertainty $u(e)$ of e in accordance with ISO/IEC Guide 98-3:

$$u(e) = \frac{p_{\text{UUC}}}{p_{\text{std}} + \delta p_{\text{m}}} \sqrt{\left(\frac{u(p_{\text{UUC}})}{p_{\text{UUC}}}\right)^2 + \left(\frac{u(p_{\text{std}})}{p_{\text{std}} + \delta p_{\text{m}}}\right)^2 + \left(\frac{u(\delta p_{\text{m}})}{p_{\text{std}} + \delta p_{\text{m}}}\right)^2} \tag{25}$$

where $u(p_{\text{std}})$, $u(p_{\text{UUC}})$, and $u(\delta p_{\text{m}})$ can be evaluated in accordance with 6.2 to 6.4. If p_{std} is to be evaluated in accordance with Equation (3), $u(p_{\text{std}})$ is given by Equation (15).

If $\delta p_{\text{m}} = 0$ [Equation (4b)], but $u(\delta p_{\text{m}}) \neq 0$

$$u(e) = \frac{p_{\text{UUC}}}{p_{\text{std}}} \sqrt{\left(\frac{u(p_{\text{UUC}})}{p_{\text{UUC}}}\right)^2 + \left(\frac{u(p_{\text{std}})}{p_{\text{std}}}\right)^2 + \left(\frac{u(\delta p_{\text{m}})}{p_{\text{std}}}\right)^2} \tag{26}$$

If $\delta p_{\text{m}} = 0$ [Equation (4b)], and $u(\delta p_{\text{m}}) = 0$

$$u(e) = \frac{p_{\text{UUC}}}{p_{\text{std}}} \sqrt{\left(\frac{u(p_{\text{UUC}})}{p_{\text{UUC}}}\right)^2 + \left(\frac{u(p_{\text{std}})}{p_{\text{std}}}\right)^2} \tag{27}$$

If $0{,}95 < p_{\text{UUC}}/p_{\text{std}} < 1{,}05$, it is recommended to approximate, $p_{\text{ind}}/p_{\text{std}} \approx 1$, since uncertainty values are given by only two digits.

NOTE The uncertainty $u(e)$ is, like e itself, a relative value, with p_{std} (and not p_{UUC}) as reference value.

9 Reporting uncertainties

9.1 Uncertainty budget

In documents for quality assurance, the use of a summary table is recommended for a clear presentation of uncertainties quickly accessible to the interested reader. This summary table is called the uncertainty budget.

In the sum model, the uncertainty budget should contain rows and columns as shown in Table 1.

Table 1 — Summary table for the sum model

Quantity	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty	Relative index %
p_{UUC}	value	$u(p_{\text{UUC}})$	— [a]	1	$u(p_{\text{UUC}})$	$[u(p_{\text{UUC}})/u(\Delta p)]^2 \times 100$
p_{std}	value	$u(p_{\text{std}})$	— [a]	1	$u(p_{\text{std}})$	$[u(p_{\text{std}})/u(\Delta p)]^2 \times 100$
δp_{m}	value	$u(\delta p_{\text{m}})$	— [a]	1	$u(\delta p_{\text{m}})$	$[u(\delta p_{\text{m}})/u(\Delta p)]^2 \times 100$
Δp	value	—	—	—	$u(\Delta p)$	100 %

NOTE See Equation (5).

[a] The probability distribution depends on the special case and is defined in ISO/IEC Guide 98-3 (typical cases are normal, rectangular, triangular).

The introduction of further rows for the individual terms in Equations (6), (8), and (11) is recommended.

In the quotient model, the uncertainty budget should contain rows and columns as shown in Table 2.

Table 2 — Summary table for the quotient model

Quantity	Estimate	Standard uncertainty	Probability distribution	Relative standard uncertainty	Relative index %
x_{UUC}	value	$u(x_{UUC})$	— [a]	$u(x_{UUC})/x_{UUC}$	$\{[u(x_{UUC})/x_{UUC})]/[\ u(r_{UUC})/r_{UUC}\ ]\}^2 \times 100$
p_{std}	value	$u(p_{std})$	— [a]	$u(p_{std})/p_{std}$	$\{[u(p_{std})/p_{std}]/[\ u(r_{UUC})/r_{UUC}\ ]\}^2 \times 100$
X_1	value	$u(X_1)$	— [a]	$u(X_1)/X_1$	$\{[u(X_1)/X_1]/[\ u(r_{UUC})/r_{UUC}\ ]\}^2 \times 100$
X_2	value	$u(X_2)$	— [a]	$u(X_2)/X_2$	$\{[u(X_2)/X_2]/[\ u(r_{UUC})/r_{UUC}\ ]\}^2 \times 100$
…	value	…	— [a]	…	…
X_n	value	$u(X_n)$	— [a]	$u(X_2)/X_2$	$\{[u(X_2)/X_2]/[\ u(r_{UUC})/r_{UUC}\ ]\}^2 \times 100$
r_{UUC}	value	$u(r_{UUC})$	—	$u(r_{UUC})/\ r_{UUC}$	100 %

NOTE See Equation (14).

[a] The probability distribution depends on the special case and is defined in ISO/IEC Guide 98-3 (typical cases are normal, rectangular, triangular).

The introduction of further rows for the individual terms in Equations (15), (16), and (20) is recommended.

Several tables for a number of values covering the full range of pressures and gauges measured by the calibration laboratory should be presented in the quality documentation.

9.2 Calibration certificate

In the calibration certificate, state the model of the measurand or otherwise make clear the meaning of the measurand. The reason is that correction and sensitivity factors can easily be confused with their inverse, errors of reading with their negative.

Each calibrated value of Δp, r or e should be accompanied by its associated expanded uncertainty, U, as described in ISO/TS 3567. In cases where the measurand y (Δp, r, or e) and its uncertainty do not significantly depend on pressure, give it as a mean over a larger pressure range. A single uncertainty value of this quantity is sufficient, i.e. $[y \pm U(y)]$.

Ensure that this single value, $U(y)$, takes into account the dispersion of the results, y_i, within the considered range. This means for $k = 2$ that 95 % of the measured values, y_i, shall lie within U.

If, for simplicity, it is agreed by the customer and the calibration laboratory that only one uncertainty value is to be given for a list of data points in a whole range, this value shall represent the largest possible uncertainty value in this range.

In addition, it is strongly recommended that the user of the certificate be provided with an equation by which he or she can calculate the true pressure from the gauge output and the data given in the certificate.

The numerical value of the uncertainty of measurement should be given to two significant figures at most. The numerical value of the measurement result in the final statement should normally be rounded to the least significant figure in the value of the expanded uncertainty assigned to the measurement result.

Bibliography

[1] ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

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