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Calibration of Pressure Balances

PURPOSE

This document has been produced by EAL to improve the harmonisation in pressure measurement. It provides guidance to national accreditation bodies to set up minimum requirements for the calibration of pressure balances and gives advice to calibration laboratories to establish practical procedures.

The document contains a detailed example of the estimation of the uncertainty contribution of a pressure balance when used for the calibration of another measuring instrument.

Authorship

This publication has been prepared by EAL Committee 2 (Calibration and Testing Activities).

Official language

The text may be translated into other languages as required. The English language version remains the definitive version.

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Guidance Publications

This document represents a consensus of EAL member opinion and preferred practice on how the relevant clauses of the accreditation standards might be applied in the context of the subject matter of this document. The approaches taken are not mandatory and are for the guidance of accreditation bodies and their client laboratories. Nevertheless, the document has been produced as a means of promoting a consistent approach to laboratory accreditation amongst EAL member bodies, particularly those participating in the EAL Multilateral Agreement.

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Contents

1 Scope

1.1 This guideline describes calibration methods for pressure balances including an example of uncertainty estimation for the use of a pressure balance. It applies to both the gas operated and the liquid operated pressure balances. In any case the method is a comparative one. When the reference standard is also a pressure balance, the comparison is carried out using the cross-floating method described in this document.

1.2 Two calibration methods are described:

- a first method where the calibration determines the pressure generated by a piston-cylinder assembly under specified conditions.
- a second method where the calibration determines the mass of the piston and of the weights of the balance, and determines the effective area of the piston cylinder assembly.

1.3 The document does not cover other methods such as the determination of the effective area from dimensional measurement, but does not preclude their use when applicable.

1.4 This document is a guideline to write a procedure which applies to pressure balances comprising a piston-cylinder assembly, or a floating ball. It applies to industrial pressure balances using direct loading of the piston or the ball, excluding dividing or multiplying devices, and digital piston manometers. The involved types of pressure balances cover typically the ranges:

- for gas medium, 1,5 kPa to 7 MPa in absolute mode and 1,5 kPa to 100 MPa in gauge mode;
- for liquid medium, 0,1 MPa to 500 MPa.

2 Range of application

2.1 The document applies to the pressure balances the expanded uncertainty of which is presupposed to be within $5 \times 10^{-4} \times p$ and $5 \times 10^{-5} \times p$ (where p is the measured pressure).

2.2 The balances may be used for the calibration of any type of instrument used for pressure measurements. They can also be used for calibrating other pressure balances by the cross-floating method.

3 Principle of the pressure balance

3.1 The pressure balance consists of a vertical piston freely rotating within a cylinder. The two elements of good machined quality define a surface called 'effective area'. The pressure to be measured is applied to the base of the piston, creating an upward vertical force. This force is equilibrated by the gravitational downward force due to masses submitted to the local gravity and placed on the top of the piston. The piston is a part of the load.

3.2 Sometimes, for practical reasons, and essentially at low pressure, the cylinder is rotating instead of the piston. The principle and the tests methods are exactly the same in this case.

3.3 The pressure is transmitted to the movable element by a fluid which can be a gas (usually dry nitrogen) or liquid (usually oil).

3.4 Sometimes the measuring element is not a piston-cylinder assembly: it is the case of the floating-ball balance which combines a ball to receive the load and a hemispheric base to support the ball. In this case a flow regulator controls the flow rate of gas in the clearance of the system. This type of pressure balance is used only for gas in gauge mode measurement.

3.5 When the masses are submitted to vacuum, the balance measures an absolute pressure. The residual pressure in the belljar around the masses creates a force in opposition to the measured pressure. The residual pressure has to be measured and added to the measured pressure.

3.6 When the overall masses are submitted to the atmosphere which also applies to the top of the piston, the balance measures a gauge pressure. In some cases, an adaptor allows to reverse the piston-cylinder mounting: the balance then measures negative gauge pressure (below atmospheric pressure) and generates an upward force opposed to the gravitational one.

3.7 The general definition of the pressure measured by the balance is obtained by analysing the different components of the forces applied to the system. For the gas operated balance in gauge mode, the pressure definition is as follows:

$$p_{\mathrm{e}} = \frac{\sum_i m_i g\left(1 - r_{\mathrm{a}} / r_{mi}\right)}{A_{\mathrm{p}}\left[1 + \left(a_{\mathrm{p}} + a_{\mathrm{c}}\right)\left(t - t_{\mathrm{r}}\right)\right]}$$

where:

p_{e} is the gauge pressure measured at the bottom of the piston,

m_i is the individual mass value of each weight applied on the piston, including all floating elements,

g is the local gravity,

r_{a} is the density of air,

r_{mi} is the density of each weight

A_{p} is the effective area of the piston-cylinder assembly at a reference temperature t_{r} (usually 20 °C) and at pressure p_{e}. Depending on the type and range of the balance, A_{p} can be expressed:

(a) as a constant A_{o} equal to the mean value of all the determinations

(b) from the effective area at null pressure A_{o} and the first-order pressure distortion coefficient:

$$A_p = A_0 . \left(1 + l . p\right)$$

p is an approximate value of the measured pressure p_{e}. It can be the nominal value.

(c) eventually, from a second-order polynomial, l' being the second-order pressure distortion coefficient:

$$A_p = A_0.(1 + l.p + l'.p^2)$$

a_p is the linear thermal expansion coefficient of the piston,

a_c is the linear thermal expansion coefficient of the cylinder,

t is the measured temperature of the piston-cylinder assembly during its use.

If for all quantities SI units are used without prefixes, p_e will emerge in pascals.

3.8 For liquid operated pressure balance, a similar expression could be considered, and the force due to the surface tension of the liquid has to be added to the gravitational force:

$$p_e = \frac{\sum_i m_i.g(1 - \rho_a / \rho_{mi}) + \sigma.c}{A_p[1 + (\alpha_p + \alpha_c)(t - 20)]}$$

where

s is the surface tension of the liquid,

c is the circumference of the piston or its extension in the level where it emerges from oil.

Note: In some types of pressure balances, such as the dual-range ones, a correction has to be applied to take into account the fluid buoyancy on the piston. The value of this correction can often be higher than that due to the surface tension.

3.9 For gas operated absolute mode pressure balances, the measured pressure is expressed as:

$$p_{abs} = \frac{\sum_i M_i.g}{A_p[1 + (\alpha_p + \alpha_c)(t - 20)]} + \mu$$

where

p_{abs} is the absolute pressure measured at the bottom of the piston,

m is the residual pressure surrounding the weights,

m_i is the individual mass value of the weights applied to the unit, referred to the mass-density and not to any conventional density.

3.10 The bottom of the piston when the balance is in equilibrium is considered to be the reference level of the balance. In some cases, for practical reasons, the initial weight is adjusted by the manufacturer to refer the reference level to the output connection of the balance. Special attention will be paid to the method used for the calibration of this type of instrument.

3.11 When the pressure p_m is expressed at a level different from the reference level, a corrective term (the head correction) has to be added to the pressure expressed above:

in gauge mode, $p_m = p_e + (r_f - r_a).g.\Delta h$

in absolute mode, $p_m = p_{abs} + r_f.g.\Delta h$

where

r_f is the density of the measuring fluid,

r_a is the density of the surrounding air,

Δh is the difference between the altitude h_1 of the balance reference level and the altitude h_2 of the point where the pressure has to be measured:

$$\Delta h = h_1 - h_2$$

4 Preparation for calibration

4.1 The calibration should only be carried out when the pressure balance is in good working order. The operation of the pressure balance under calibration and the pressure reference standard should be carried out according to the laboratory's calibration procedure prepared from this guideline, and the manufacturer's technical manual.

4.1 Calibration room

4.1.1 The following parameters shall be controlled according to the uncertainty regime. Typically:

- Ambient temperature within 15 °C and 25 °C, stabilised within ± 2 °C. For lower uncertainty, typically 0,01 %, the temperature of the piston-cylinder assembly should preferably be measured.
- Relative humidity between 40 % and 65 %, or measured.
- Control opening of doors and the movement of operators to keep a stable atmosphere, and control ventilation in order to prevent intense air flow above or below the piston balances.

4.2 Devices installation

4.2.1
- Install the devices out of the air disturbances such as ventilation and air-conditioning.
- Install the balance to be calibrated as near the standard instrument as possible.
- Use a rigid, stable table supporting the full load, checked in with a spirit level.
- Minimise the height difference between the reference levels of the two instruments to be compared.
- Respect the verticality of the piston as recommended by the manufacturer: use the built-in spirit level, or a laboratory spirit level on the top of the piston to minimise the tilt. This should be checked also at full mass load.
- Use short, wide bore pipework. This is more critical at low pressure.
- Insure the cleanliness and the tightness of the tubings.
- Install appropriate drain to control the nature of the fluid in the tubings.
- Attach a suitable temperature measurement system.

4.3 Pressure generation

4.3.1 For gas pressure:

(a) Use a clean and dry gas (nitrogen for example), at a temperature near ambient.

(b) Adjust the pressure input to the range of the intercompared instruments.

(c) Clean the tubings of any liquid (for the oil-lubricated type).

4.3.2 For absolute pressure:

(a) Use a clean pump, or, when using mechanical rotational pumps, use an appropriate trap.

(b) Use an appropriate vacuum pump to ensure that the residual pressure over the mass-piston set is less than typically 2 Pa or 10^{-5} of the measured pressure, whichever is the higher, unless otherwise recommended by the manufacturer.

(c) Measure the residual pressure with a vacuum gauge calibrated and connected directly to the belljar.

4.3.3 For liquid pressure:

(a) Use the liquid recommended by the manufacturer.

(b) If the liquid is not the same in the balance under calibration as in the standard, use appropriate interface/separator to avoid any mixture of the two liquids.

(c) Clean the tubings of any other liquid.

(d) Clean the fluid in the tubings of any possible internal gas.

4.4 Pressure reference

4.4.1 The pressure reference instrument in general use for the calibration of a pressure balance is another pressure balance. For the ranges lower than 300 kPa, the standard instrument may be a mercury column manometer. Other instruments may be used as an alternative for specific cases (low gauge pressure for example).

4.4.2 The calibration of an absolute pressure balance may be carried out in gauge mode, with an added uncertainty in A_o.

4.4.3 In all cases, the reference instrument used for the calibration has to meet the following conditions:

(a) to be traceable to a National Standard with a recognised calibration certificate.

(b) to have an uncertainty better than the presupposed uncertainty of the balance to be calibrated. Complete the uncertainty budget on the reference standard pressure balance to check this condition.

4.5 Preparation of the pressure balance

4.5.1 The pressure balance under calibration shall be placed in the laboratory at least 12 hours before the calibration is started, to reach thermal equilibrium.

(a) Check that the oil is free from impurities. If not, drain all the tubings and replace the oil in the tank.

(b) With the pressure circuit closed and half the set of weights placed on the piston, the piston shall be moved upwards and downwards by means of the spindle pump. Thus, the mobility of the piston is examined over the total range of displacement.

(c) If necessary, and using the technical manual, remove the piston-cylinder assembly, and clean the surfaces of the two pieces with a suitable solvent or pure soap, and with dry soft cloth according to the manufacturer’s recommendations. Inspect the piston and the cylinder for surface scratches and corrosion. Relubricate the piston with clean liquid if the piston-cylinder operates in liquid, or if the balance operates in gas but with an oil-lubricated piston-cylinder assembly.

(d) Examine the free rotation time (for the hand-rotating pressure balances only). Weights corresponding to 2/10 of maximum pressure are placed upon the piston. The initial rotation rate should be approximately 30 rpm. Measure the elapsed time until the piston is stationary. This time should be at least 3 min.

(e) Examine the descent rate of the piston. The piston descent rate is observed at maximum pressure when the piston is rotating. Measure the time interval in which the piston drops from top to bottom position. This time should be at least 3 min.

Note: For these two last parameters, the stated values should be related to the technical instructions of the manufacturer.

(f) Connect the pressure balance to the standard instrument.

(g) Identify the reference level for both pressure balances. The reference level should be defined by the manufacturer at the bottom surface of the piston when the balance is in equilibrium. In the absence of this, and when the bottom surface of the piston is not accessible, the reference level is generally defined at the outlet pipe connection level. The difference in height between the reference level of the standard and the reference level of the balance to be calibrated shall be reduced as much as possible and measured. In any case the difference in height between the reference levels of both standard and balance under calibration will need to be measured in order to apply the appropriate head correction (see paragraph 3).

(h) For absolute pressure, pump for 30 min. at the beginning of the calibration to eliminate the water vapor in the belljar. Use dry nitrogen as working gas.

(j) Rotate the piston or cylinder while respecting the manufacturer's recommendation.

(k) For hand rotating balances, check the clockwise and anticlockwise direction influence (if any), or indicate the rotation direction in the certificate.

5 Example of calibration procedure

5.1 Methods to apply

5.1.1 Both methods that follow are comparative ones, consisting of comparing the balance to be calibrated and the standard instrument when both are submitted to the same pressure and the same environmental conditions.

5.1.2 However, dependent on the presupposed accuracy of the balance to be calibrated, and according to customer requirement alternative methods may be used:

5.1.3 Method A - Generated pressure method

The scope of this method is to determine the bias error and the repeatability of the calibrated pressure balance. This is done by determining the generated pressure corresponding to well identified weights. In that method the weighing of the masses of the instrument under calibration is optional.

5.1.4 Method B - Effective area determination method

The scope of this method is to determine:

(a) the value of the mass of all the weights, including piston of the pressure balance if removable.

(b) the effective area A_p referred to 20 °C of the piston-cylinder assembly of the pressure balance as a function of pressure. At high pressure, this area can be expressed from the effective area at null pressure A_0 and the pressure distortion coefficient .

(c) the repeatability as a function of the measured pressure.

The elements relating to the determination of the effective area are given in section 6. The equations to be used for the calculation of the effective area are given in Appendix A.

5.1.5 Method A is usually not employed where the smallest uncertainty is required.

5.2 Method A procedure

5.2.1 Three measuring series are carried out, each of them with at least five pressure points regularly spaced over the whole range of the pressure balance. For twin range balances, at least five pressure points should be carried out for each range. The pressure points should be selected evenly spaced across the range of the instrument under test.

5.3 Method B procedure

5.3.1 Determination of the mass

(a) The value of the mass of each weight (including the floating elements when removable) of the pressure balance shall be determined by a laboratory accredited for such mass measurements. The relative uncer-tainty of the mass determination should not usually exceed 20 % of the likely total measurement uncertainty of the pressure balance to be calibrated. For example, if the supposed expanded uncertainty of the pressure balance is $5\times10^{-5} \times p$, the relative uncertainty of mass determination should be within $1\times10^{-5} \times m$.

(b) If the floatbase weight cannot be determined by weighing, the corres-ponding base pressure may be determined from the results of the pressure comparison measurements by using a least-squares analysis: in this case a tare value in pressure units should be given. The Δp-method mentioned in paragraph 6.3.3(c) allows the determination of this initial value.

5.3.2 Determination of the effective area

(a) For pressure balances which are equipped with both low pressure and high pressure piston-cylinder assemblies or with removable piston-cylinder assemblies, the complete calibration process should be carried out for each piston-cylinder assembly.

(b) The effective area shall be determined by carrying out three to five measuring series, each of them with at least six pressure points. The first point shall be chosen at the minimum value of the pressure range (manufacturer indicated value, or the lower value corresponding to a satisfactory functioning, see paragraph 4.5). The other pressure points should be spaced over the whole range, typically between 1/10 and 10/10 of the maximum pressure range.

(c) The repeatability of the measured pressure is estimated from the experimental standard deviation calculated from the successive determinations operated for each pressure point.

Note (valid for both methods): Ascending measuring series can be considered to be identical to descending measuring series, as the balances used for pressure measurements usually have no significant hysteresis effect.

5.4 Cross-floating procedure

5.4.1 Gauge pressure mode

(a) When using a pressure balance as standard instrument, the cross-floating method is carried out at each measuring point:

(b) Place the weights on the pressure balance to be calibrated, so that the masses correspond to the fixed pressure point.

(c) Adjust the pressure to equilibrate the balance under calibration.

(d) Perform an adjustment with small weights on one of both instruments (usually the one which is the more sensitive to a change in mass), until the equilibrium condition of both balances has been found. The equilibrium should be considered as reached when the proper falling rate of both pistons is found (no flow of fluid in the tubing between the two pressure balances). Both pistons have to rotate during the adjustment. In the case of hand rotating units, the influence of the clockwise/anticlockwise rotation, and of the spin rate will be checked.

(e) Note the reference number of each of the weights applied on both balances.

(f) Note the temperature of the piston-cylinder assembly of both balances. If the balance is not equipped with a temperature probe, note the surrounding air temperature using an electronic thermometer attached to some suitable point of the balance. This information shall be included in the certificate.

5.4.2 Absolute pressure mode

(a) When using a pressure balance as standard instrument, the crossfloating method cannot be used. In this case a differential pressure transducer equipped with a by-pass is used to measure the difference between the pressures measured by both balances. For each pressure point:

(b) Place the corresponding weights on both pressure balances.

(c) Adjust the pressure to equilibrate the standard balance.

(d) Read the zero of the transducer.

(e) Close the by-pass.

(f) Adjust the pressure on both sides to equilibrate both balances.

(g) Record the reading of the transducer. If the differential pressure is so high that the needed uncertainty cannot be reached from the calibration of the transducer, adjust the mass on the reference balance and repeat the three last operations.

(h) Note the reference number of each of the weights applied on both balances.

(j) Note the temperature of the piston-cylinder assembly of both balances. If the balance is not equipped with a temperature probe, note the surrounding air temperature.

(k) Note the residual pressure in the belljar of both balances.

6 Data evaluation and calibration certificate

6.1 General points

6.1.1 The Calibration Certificates shall be established in conformity with the EAL document EAL-R1.

6.1.2 Preferably a separate Calibration Certificate shall be established for the determination of the mass of the weights. The number of this mass Certificate will be recalled in the one related to the calibration of the pressure balance.

6.2 Method A procedure

6.2.1 The following technical data shall be included in the Certificate:

(a) type of the working fluid;

(b) linear thermal expansion coefficients of the piston-cylinder assembly under calibration (if not determined experimentally, e.g. using literature data, this shall be stated);

(c) pressure distortion coefficient (if obtained by a theoretical method);

(d) position of the pressure reference level;

(e) information about how to convert the pressure values to the measurement temperature and to the local acceleration due to gravity.

6.2.2 Usually the results will be presented for the standard value of the gravity 9,80665 m s^{-2} (unless customer requests his own local gravity) and the reference temperature 20 °C in the form of the table suggested in paragraph 6.2.3 as an example. It will include:

(a) the pressure indicated by the balance under calibration (p_m);

(b) the reference pressure measured by the standard instrument (mean of the three determinations), in Pa and in the unit of the pressure delivered by the balance if different (p_r);

(c) the standard deviation of the reference pressure p_r;

(d) the difference between the indicated pressure and the reference pressure ($p_m - p_r$);

(e) the uncertainty of this difference, in the conditions of the calibration. The method used to estimate this uncertainty shall be reported in the Certificate.

6.2.3 A table that lists all weights applied on the unit to be calibrated for each pressure point of the calibration shall be included in the Calibration Certificate.

Indicated pressure uncertainty of	**Mean reference**	**Mean reference**	**Experimental standard pressure**	**Difference pressure**	**Relative deviation**	**Expanded difference**
p_m in X(a)	p_r in Pa(b)	p_r in X	**of** p_r in X	$p_m - p_r$ in X	$(p_m - p_r)/p_r$ in %	$p_m - p_r$ in X(c)

Notes

(a) X = Unit indicated by the pressure balance under calibration.

(b) This column may be replaced by a conversion factor in the certificate.

(c) The method of calculation of the uncertainty is described in section 7.

6.3 Method B procedure

6.3.1 The following technical data shall be included in the Certificate:

(a) type of the working fluid

(b) equation according to which the pressures reported in the certificate have been calculated

(c) linear thermal expansion coefficients of the piston-cylinder assembly under calibration (if not determined experimentally, e.g. by using literature data, this shall be stated)

(d) position of the pressure reference level

6.3.2 The results of the calibration, after analysis (see below):

(a) effective area and its combined uncertainty

(b) if relevant, the pressure distortion coefficient(s) and the corresponding combined uncertainty

6.3.3 Calculation of the effective area

(a) The computing method in more general use, described in details in Appendix A, can be used to calculate step by step the effective area of the pressure balance to be calibrated from the mass applied on its piston and the pressure delivered by the standard instrument.

(b) From this method, the effective area is calculated by reversing the equation of definition of the pressure presented in section 3.

(c) The use of other methods, such as differential method (Δp-method) to eliminate potential zero-errors is not excluded, but requires some experience in the analysis of the results. Particularly, the Δp-method may be the only one available if method B is used for the determination of effective area of pressure balances with an unknown initial weight that cannot be determined by weighing.

(d) The step-by-step determination of the effective area as a function of pressure allows a modelling of effective area. In any case all the experimental data and the residuals of the modelling shall be reported in the certificate to make apparent the validity of the used method.

(e) The results may be presented in the form of the table below, suggested as a comprehensive example, and including:

(i) the reference pressure measured by the reference standard instrument in each pressure point, in Pa and in the unit of the pressure delivered by the balance if different;

(ii) the corresponding mass applied on the floating element of the balance to be calibrated;

(iii) the corresponding temperature of the measuring assembly during the calibration;

(iv) the individual value of the effective area A_p calculated at the reference temperature and at reference pressure, as described in Appendix A;

(v) the mean value of the effective area A_p;

(vi) the experimental standard deviation of the mean.

Reference standard the mean kPa	Mass pressure p_r kg	Temperature applied on the piston °C	Effective of the mm²	Mean area assembly mm²	Experimental effective (t_r, p_r) mm²	deviation of area (n = 5)
400,096	6,162 52	21,28	156,931			
400,083	6,162 52	20,86	156,937			
400,083	6,162 52	20,88	156,938	156,940	0,003	
400,063	6,162 52	20,86	156,948			
400,078	6,162 52	20,80	156,944			
			.....			

(f) Then, the effective area as a function of pressure is analysed using a least-squares method. Three cases can be observed:

(i) the dependence upon pressure is not significant relating to the standard deviation (this is always the case for the low-range pressure balances). The effective area at null pressure A_o is calculated as the mean value of all the determinations. If the theoretical pressure distortion coefficient is known, it shall be used for calculating the effective area. The type A standard uncertainty is estimated from the experimental standard deviation of the mean A_o.

(ii) the dependence upon pressure can be considered to be linear. The effective area at null pressure A_o and the pressure distortion coefficient l are calculated by analogy with the best least-squares straight line. The type A combined standard uncertainty is estimated using the standard uncertainties of A_o and l.

(iii) the dependence upon pressure cannot be considered to be linear. The effective area at null pressure A_o and the pressure distortion coefficient l (first order) and l' (second order) are calculated by analogy with the least-squares second-order best fit. The type A combined standard uncertainty is estimated using the standard uncertainties of A_o, l and l'.

(g) The standard uncertainties of each of the parameters shall be estimated using literature on statistics.

(h) The certificate shall report:

(i) the calculated value of the effective area under reference conditions A_0 and the corresponding uncertainty, estimated from the standard deviation of A_0, and the contribution of the standard, the measurement of the mass applied to the moving element and the temperature.

(ii) when relevant, the pressure distortion coefficient(s) and the corresponding uncertainty estimated from the standard deviation of l and the uncertainty of the pressure distortion coefficient of the standard.

6.3.4 Calculation of the measured pressure

(a) The pressure measured by the pressure balance to be calibrated can be calculated using the equation presented in section 3. It is useful to the user to have this measured pressure compared to the reference pressure delivered by the standard, under the conditions of the calibration.

(b) The results shall be presented in the form of the table below suggested as an example and including:

(i) the reference pressure measured by the standard instrument, in Pa and in the unit of the pressure delivered by the balance if different

(ii) the corresponding pressure measured by the balance under calibration, and calculated from the data (effective area and pressure distortion coefficient) taken from the certificate

(iii) the difference between the measured pressure and the reference pressure for each pressure equilibrium, as residuals of the effective area modelling

(iv) the mean value of these differences

(v) the experimental standard deviation of the measured differences

(c) This table gives information on a potential residual pressure due to unknown forces and on the repeatability of the pressure balance as a function of pressure. So, the minimum information contained in this part of the certificate is the mean difference and the experimental standard deviation.

Reference pressure p_r kPa	Measured pressure p_m kPa	Difference $p_m - p_r$ kPa	Mean difference ($n = 5$) kPa	Experimental standard deviation of $p_m - p_r$ kPa
600,152	600,159	+ 0,000 6	+ 0,001 8	0,001 7
600,155	600,161	+ 0,000 6		
600,149	600,161	+ 0,001 1		
600,114	600,161	+ 0,004 6		
600,140	600,161	+ 0,002 1		
		....		

7 Estimation of the uncertainty

7.1 The combined uncertainty of the measured pressure under the conditions of the calibration shall be estimated in conformity with the EAL Document EAL-R2. The components to take into account are listed below for both recommended methods.

7.2 Method A

7.2.1 Uncertainty estimated using a type A method (u_A components):

(a) Repeatability of the balance, estimated as a function of pressure from the values of the standard deviation expressed in the table. Following the experimental data, it can be expressed in Pa, or using a term proportional to the pressure, or both terms.

7.2.2 Uncertainty estimated using a type B method (u_B components):

(a) Uncertainty of the mass;

(b) Uncertainty of the pressure reference standard;

(c) Uncertainty of the local gravity;

(d) Uncertainty due to temperature;

(e) Uncertainty due to the head correction;

(f) Uncertainty due to tilt (negligible if perpendicularity was duly checked);

(g) Uncertainty due to air buoyancy, if significant;

(h) Uncertainty due to spin rate and/or direction, eventually;

(j) Uncertainty of the residual pressure (absolute mode only).

7.2.3 When the standard uncertainty is estimated for each component, the combined standard uncertainty, then the expanded uncertainty are calculated in conformity with the EAL-R2 publication.

7.3 Method B

7.3.1 Uncertainty estimated using a type A method (u_A components):

(a) Repeatability of the balance, estimated as a function of pressure from the values of the standard deviation expressed in the table. Following the experimental data, it can be expressed in Pa, or using a term proportional to the pressure, or both terms.

7.3.2 Uncertainty estimated using a type B method (u_B components):

(a) Uncertainty of the masses;

(b) Uncertainty of the measured effective area, including the uncertainty estimated using a type-A method;

(c) Uncertainty due to the pressure distortion coefficient, when relevant, including the uncertainty estimated using a type-A method;

(d) Uncertainty of the local gravity;

(e) Uncertainty due to the temperature of the balance;

(f) Uncertainty due to the air buoyancy;

(g) Uncertainty due to the head correction;

(h) Uncertainty due to tilt (negligible if perpendicularity was duly checked);

(j) Uncertainty due to spin rate and/or direction, eventually;

(k) Uncertainty of the residual pressure (absolute mode only).

7.3.3 When the standard uncertainty is estimated for each component, the combined standard uncertainty, then the expanded uncertainty, are calculated in compliance with the EAL-R2 publication. An example of uncertainty budget corresponding to the use of a pressure balance calibrated using method B is given in Appendix B.

8 References

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Appendix A

Computing method used to determine the effective area of the piston-cylinder assembly of a pressure balance

A1 The determination of the effective area of the piston-cylinder assembly of a pressure balance is derived from the equation used to calculate the pressure delivered by the reference balance. The pressure measured by a pressure balance at its reference level is expressed from the well-known equation, established by analysing the forces applied to the piston. The following expression is given as an example. It is corresponding to the case of a gas operated balance, in gauge mode. The calculation progress would be the same for other types of pressure balances (see section 4).

$$p_e = \frac{\sum_i m_i g \left(1 - \rho_a / \rho_{mi}\right)}{A_p\left[1 + \left(\alpha_p + \alpha_c\right)\left(t - t_r\right)\right]} \qquad \text{(A.1)}$$

where:

p_e is the gauge pressure measured at the bottom of the piston,

m_i is the individual mass value of the weights applied on the piston, including all floating elements,

g is the local gravity,

ρ_a is the density of air,

ρ_{mi} is the density of the weights. If the weights are made of different materials, it is necessary to take the different densities into account,

A_p is the effective area of the piston-cylinder assembly at the reference temperature t_r as a function of pressure,

α_p is the linear thermal expansion coefficient of the piston,

α_c is the linear thermal expansion coefficient of the cylinder,

t is the temperature of the piston-cylinder assembly.

A2 Using the cross-floating method, the two intercompared balances, in equilibrium conditions, are measuring the same pressure. So, for each calibration point, referenced by suffix j, corresponding to a known mass Σm_i, the reference pressure p_{rj} indicated by the reference instrument is calculated from the equation (A.1) above by using the known characteristics of the reference instrument. Then, from this pressure p_{rj}, the effective area A_{pj} at the reference temperature t_r (usually 20 °C) of the balance to be calibrated is determined for each pressure p_{rj}, by:

$$A_{pj} = \frac{\left[\sum_i m_i g \left(1 - \rho_a / \rho_{mi}\right)\right]_j}{p_{rj}\left[1 + \left(\alpha_p + \alpha_c\right)\left(t_j - t_r\right)\right]} \qquad \text{(A.2)}$$

In this case $\Sigma_i m_{ij}$ is the overall mass, t_j the temperature, and a_p, a_c, r_{mi} the characteristics of the balance under calibration.

From the analyses of the mean results $A_p = f(p_r)$, three cases can arise:

1 The effective area A_p is independent of pressure. In this case, the effective area under reference conditions is equal to the mean of all the determinations.

2 The effective area A_p is a linear function of the pressure; when noting A_o the effective area at null pressure and l the pressure distortion coefficient of the piston-cylinder assembly:

$$A_p = A_0 . \left(1 + l . p_r\right) \tag{A.3}$$

A_o and l are calculated from the least-squares straight line.

3 The effective area is derived from a second-order polynomial expression

$$A_p = A_0 . \left(1 + l . p_r + l' . p_r^2\right) \tag{A.4}$$

A_0, l and l' are also calculated using the least-squares method.

Note : Particular attention should be paid to the experimental data before this model is applied to be sure that the second-order form, as for example equation (A.4), is not due to an incorrect experimental data (of the difference of height between the two reference levels of the pressure balances for example).

Appendix B

Example of uncertainty estimation for the use of a pressure balance

B1 Presentation of the measurement

This example is relating to the estimation of the expanded uncertainty of the pressure generated by an industrial oil operated pressure balance when used to calibrate another measuring instrument. The estimation is based on the measurement procedure, the data included in the calibration certificate of the balance (presuming that the calibration has been done using method B) and the environmental conditions.

The estimation of the uncertainty is derived from the calculation of the generated pressure by using the values of the effective area at null pressure and the pressure distortion coefficient issued from the calibration certificate of the balance. Only the main components considered significant in the most usual cases have been kept. It is an example of an acceptable and practicable method.

B2 Definition of the pressure

The general definition of the pressure measured at the reference level of the instrument to be calibrated by an oil operated pressure balance in gauge mode may be obtained from the following expression:

$$p_e = \frac{\sum_i m_i g\left(1 - r_a / r_{mi}\right) + s c}{A_0\left(1 + l p\right)\left[1 + \left(a_p + a_c\right)\left(t - t_r\right)\right]} + r_f . g . \Delta h \qquad \text{(B.1)}$$

where:

p_e is the gauge pressure measured;

å$_i$m$_i$ is the total mass applied on the piston, including all floating elements;

g is the local gravity;

r_a is the density of air;

r_{mi} is the density of the weights;

A_0 is the effective area of the piston-cylinder assembly at reference temperature t_r and at null pressure;

l is the pressure distortion coefficient of the piston-cylinder assembly;

a_p is the linear thermal expansion coefficient of the piston;

a_c is the linear thermal expansion coefficient of the cylinder;

t is the temperature of the piston-cylinder assembly;

s is the surface tension of the oil;

c is the circumference of the piston;

r_f is the density of the measuring fluid;

Δh is the difference between the altitude h_1 of the reference level of the balance and the altitude h_2 of the reference level of the measuring instrument under calibration: $\Delta h = h_1 - h_2$. In some cases, the reference level of the pressure balance is a function of the oil buoyancy of the piston: the exact reference level is indicated in the calibration certificate.

The results reported in the calibration certificates of a pressure balance are the values of the effective area, the pressure distortion coefficient of the piston-cylinder assembly, and the individual value of the mass of each weight. The calibration certificates also give the corresponding expanded uncertainties of each parameter and an estimation of the repeatability of the balance.

B3 List of the uncertainty components

B3.1 Type A evaluation of standard uncertainty

There is no component evaluated statistically in this example. The type A evaluation would correspond to the repeatability of the measuring instrument under calibration.

B3.2 Type B evaluation of standard uncertainty

For each component:

(a) Estimate the uncertainty $U(X_i)$ of each component. For influence quantities, it is estimated from the bounds of variation.

(b) Determine the standard uncertainty $u_i(X_i)$ from the probability distrib-ution of each component.

(c) Determine the standard uncertainty $u_i(p)$ due to the quantity X_i using the sensitivity coefficient calculated as the partial derivative of the function (B.1) with respect to the quantity X_i.

Each component is analysed individually below.

B3.2.1 B1 – Repeatability of the pressure balance

This component $u_1(p)$, stated as the repeatability of the balance, was estimated in the calibration certificate. As the calibration was done at several pressure points repeated a few times, the repeatability is estimated from the experimental standard deviation $u_1(p_i)$ calculated at each pressure point. Depending on the case, $u_1(p)$ is evaluated as the maximum value of $u_1(p_i)$ or as an expression function of the pressure:

$$u_1(p) = a + b.p$$

defined as the envelope of the different values of $u_1(p_i)$.

For example: $u_1(p) = 10 \text{ Pa} + 3{,}2 \times 10^{-5} \times p$

B3.2.2 B2 – Effective area

The uncertainty of the determination of the effective area $U(A)$ is given in the calibration certificate of the pressure balance. If the result is expressed using a coverage factor $k = 2$:

$$u_2(p) = \frac{p}{A}.\frac{U(A)}{2}$$

For example: $u_2(p) = 3{,}6 \times 10^{-5} \times p$

B3.2.3 B3 – Pressure distortion coefficient

In the determination of $A_p = A_0(1 + \lambda p)$, as $\lambda p << 1$, an approximate value of p_e can be used for computing the measured pressure (for example the nominal value of p, or $p = (\Sigma m_i g)/A_0$). Only the uncertainty of λ is significant in the estimation of the combined uncertainty.

The uncertainty of the determination of the pressure distortion coefficient $U(\lambda)$ is given in the calibration certificate of the pressure balance. If the result is expressed using a coverage factor $k = 2$:

$$u_3(p) = -p^2.\frac{U(\lambda)}{2}$$

For example: $u_3(p) = 2 \times 10^{-13}\ \text{Pa}^{-1} \times p^2$

B3.2.4 B4 – Mass

The mass value of the weights determined in the calibration certificate is used to calculate the total mass applied to the piston. The uncertainty of the determination of the masses $U(m)$ is given in the calibration certificate of the masses. If the result is expressed using a coverage factor $k = 2$:

$$u_4(p) = \frac{P}{M}.\frac{U(M)}{2}$$

For example: $u_4(p) = 0{,}7 \times 10^{-5} \times p$

B 3.2.5 B5 – Temperature of the piston-cylinder assembly

The temperature of the piston-cylinder assembly is derived from the measurement of the ambient temperature. The calibration is performed in a controlled-temperature laboratory at (20 ± 1) °C. A 1 °C-uncertainty is added to take into account the gradient of temperature within the balance:

$U(t) = 2$ °C.

As the measurements are carried out in a controlled-temperature room over a long time regarding the time period of the temperature regulation, the temperature of the assembly is estimated to follow a sinusoidal distribution:

$$u_5(p) = p.(\alpha_p + \alpha_c).\frac{U(t)}{\sqrt{2}}$$

For example: $u_5(p) = 3{,}2 \times 10^{-5} \times p$ (both piston and cylinder made of steel).

B3.2.6 B6 – Thermal expansion coefficient of the piston-cylinder assembly

Another component comes from the temperature variation. It is due to the uncertainty of the thermal expansion coefficient of piston and cylinder. For our purpose, we consider that we are at a temperature near to the calibration temperature. If this is not the case, this uncertainty is higher.

$$u_6(p) = p.U(\alpha_p + \alpha_c).\frac{\Delta t}{2}$$

where Δt is the maximum difference between the observed temperature when using the balance and the reference temperature (2 °C in this example). As the values a_p and a_c are based on the measurement of the characteristics of the materials, and their uncertainties expressed at $k = 2$:

For example, if the relative uncertainty of $(a_p + a_c)$ is 10 %,

$u_6(p) = 0{,}23 \times 10^{-5} \times p$

B3.2.7 B7 – Local gravity

The local gravity has been determined by calculation from the local longitude, latitude and altitude. The uncertainty of g has been estimated from the uncertainty of the local parameters expressed at $k = 3$:

$$U(g) = \pm 1 \times 10^{-5} \times g$$

The statistical distribution may be supposed to be normal:

$$u_7(p) = \frac{p}{g} \times \frac{U(g)}{3}, \text{ so}$$

$u_7(p) = 0{,}3 \times 10^{-5} \times p$

B3.2.8 B8 – Air buoyancy

The calculation of the air buoyancy correction involves the determination of the air density. As the conventional value of the mass obtained from a calibration certificate, and based upon the conventionally assumed value of the weight's density is used for weights made of steel in gauge pressure mode, the uncertainty due to the weight's density may be considered negligible. We suppose in this example that the conventional value of the air density $\rho_a = 1{,}2\ \mathrm{kg\ m^{-3}}$ is taken for calculating the correction. So the environmental conditions (atmospheric pressure, relative humidity and ambient temperature) are not taken into account: the maximum air density variations in the laboratory have been demonstrated to be within ± 5%:

$$U(\rho_a) = \pm 5 \times 10^{-2} \times \rho_a$$

As it was demonstrated that the average of the observed values of the air density at the location of the laboratory is equal to the conventional value, and that the statistical distribution is normal:

$$u_8(p) = \frac{p}{(\rho_M - \rho_a)} \times \frac{U(\rho_a)}{3} \quad \text{, so}$$

$$u_8(p) = 0{,}25 \times 10^{-5} \times p$$

B3.2.9 B9 – Head correction

The head correction is calculated from three parameters ρ_f, g and Δh. Only the uncertainty of Δh can be considered significant in the estimation of the uncertainty due to this correction. By estimating the uncertainty of the h measurement at ± 2 mm at $k = 2$ level, and by assuming the statistical distribution as being normal, the equivalent uncertainty of p is:

$$u_9(p) = \rho_f \cdot g \cdot \frac{U(\Delta h)}{3} \text{, and}$$

if $\rho_f = 915\ \mathrm{kg\ m^{-3}}$,

$$u_9(p) = 6\ \mathrm{Pa}$$

B3.2.10 B10 – Tilt of the piston

If the piston axis is not perfectly perpendicular, the force applied to the piston has to be corrected from the angle of tilt :

$$F' = F \times \cos\theta$$

The distribution of force (or pressure) is non-symmetric. When experi-mentally treated correctly, this component is a small one. The following estimation of the standard uncertainty is a maximal one.

$$u_{10}\left(p\right) = p.\sin\theta\,.\frac{U\left(\theta\right)}{\sqrt{3}}$$

The deviation from the vertical is generally checked by using a spirit level either built in the base of the pressure balance or put on the top of the piston. In that case the contribution of the component is far less than other contributions.

In that case, with $U(q) = 5{,}8 \times 10^{-4}$ rad:

$u_{10}(p) = 0{,}2 \times 10^{-6} \times p$

B3.2.11 B11 – Discrimination threshold (cross-floating sensitivity)

The discrimination is the pressure corresponding to the largest mass that produces no detectable change in the generated pressure. It may be taken into account when there is no reliable estimation of the repeatability of the pressure balance. In this example we assume that it is included in the repeatability (component B1).

B3.2.12 B12 – Long term stability

The value of this component is obtained from the history of the instrument. It applies to the values of both the masses and the effective area of the piston-cylinder assembly. The analysis is based on successive calibrations.

A lower value of this component may be obtained from more frequent calibrations. A long history may allow determination of a law of variation with time, making it possible to anticipate the actual value by extrapolation.

B4 Determination of the combined standard uncertainty

The combined standard uncertainty $u_c(p)$ is calculated from the following equation:

$$U_c^2\left(p\right) = \sum_{i=1 to 12} U_i^2\left(p\right)$$

The result is given for the 10 first components. The two last ones are not relevant as B11 has been stated as being included in B1 and B12 needs a case-to-case analysis.

For our example:

$$\begin{aligned} u_c(p) = {} & \sqrt{\left[10^2 + 6^2\right]}\ \mathrm{Pa} + 10^{-5} \times p \\ & \times \sqrt{\left[3{,}2^3 + 3{,}6^2 + 0{,}7^2 + 3{,}2^2 + 0{,}23^2 + 0{,}3^2 + 0{,}5^2 + 0{,}6^2\right]} \\ & + 2 \times 10^{-13}\ \mathrm{Pa}^{-1} \times p^2 \end{aligned}$$

It is common practice, for making the presentation of the result easier, to sum separately the constant terms, the terms proportional to p and the terms proportional to p^2. In any case, even if that result is not so strict, it is a rising one:

$$u_c(p) = 12\ \mathrm{Pa} + 5{,}9 \times 10^{-5} \times p + 2 \times 10^{-13}\ \mathrm{Pa}^{-1} \times p^2$$

Depending on the pressure range, the third term can be calculated at the max. pressure and introduced into the second one.

B5 Determination of the expanded uncertainty

The expanded uncertainty $U(p)$ is directly derived from the combined standard uncertainty by multiplying it by a coverage factor $k = 2$:

$$U(p) = \pm\left(24\ \mathrm{Pa} + 9{,}8 \times 10^{-5} \times p + 4 \times 10^{-13}\ \mathrm{Pa}^{-1} \times p^2\right)$$

or, if $p_{\max} = 10$ MPa:

$$U(p) = \pm\left(24\ \mathrm{Pa} + 10{,}2 \times 10^{-5} \times p\right)$$