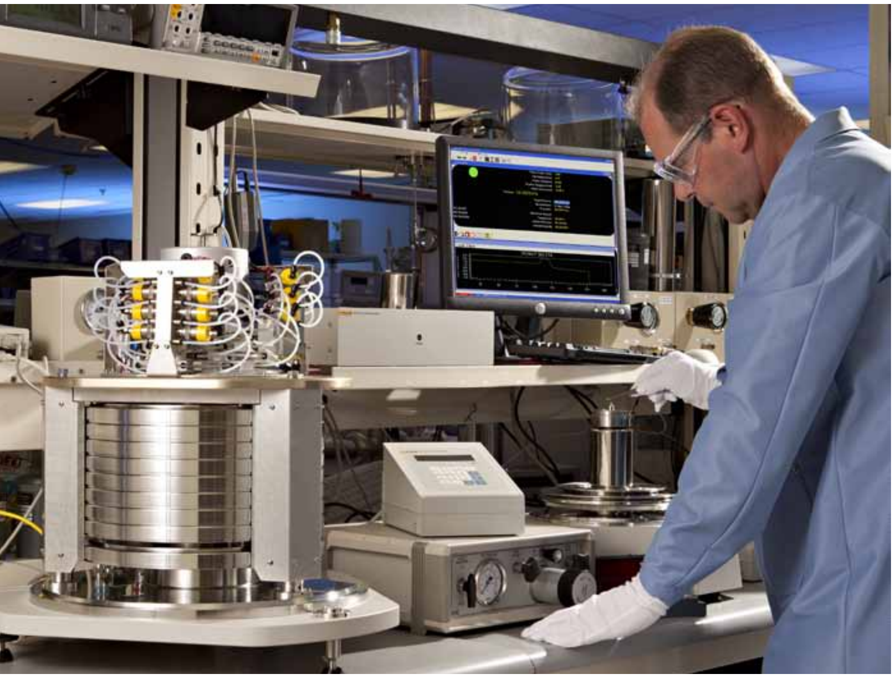
Typical pressure measurement uncertainty for a PG9607 and PG9602 Piston Gauge

Technical Note



Many users consider the single most important specification of a high performance piston gauge to be the uncertainty claimed on pressure defined by the piston gauge. At the low levels of uncertainty available today, the final uncertainty budget is highly dependent on influences that vary with conditions of operation, many of which are beyond the control of the instrument manufacturer. Therefore, uncertainty specifications provided without documenting the assumptions made in deriving them are of little use. They cannot be used to compare one instrument to another or to reliably predict the actual global uncertainty in pressure that will be obtained in the final application.

For this reason, in providing specifications for the PG9000 line of piston gauges, Fluke Calibration has developed "typical pressure measurement uncertainty" specifications. These are intended to provide easy to use figures for overall uncertainty in pressure that can be applied with confidence by the typical user under typical operating conditions. They include all significant sources of uncertainty and are intentionally rounded up to convenient values that can be used over each pressure range.

This document is intended to provide a detailed analysis of PG9000 typical uncertainty specifications for each piston-cylinder range in each of its operating modes. The PG9607 is a controlled clearance piston gauge with only one piston-cylinder as an option. This is a 5 kPa/kg (0.73 psi) large diameter piston-cylinder, 50 mm (2 in), which makes it useful for a national metrology institute or other high end pressure metrology laboratory to realize pressure fundamentally in a range of 10.5 kPa to 500 kPa (1.5 psi to 72.5 psi). This revision also includes the pressure defined by a PG9602 which can use 10, 20, 50, and 100 kPa/kg (1.5, 2.9, 7.3, and 14.5 psi) piston-cylinder ranges, defining pressure from approximately 13 kPa to 10 MPa (1.9 psi to 1 450 psi) in gauge or absolute modes.

The uncertainties described in this publication are what Fluke Calibration can support based on their accreditation. Many of these could easily be reduced to obtain a total uncertainty that is significantly lower than what is offered as a published specification. For example Fluke Calibration is only supporting ± 7 ppm, at k=2, for the uncertainty in effective area of a 5 kPa/kg (0.75 psi/oz) piston-cylinder range for a PG9607. Results from NMIs that have dimensionally characterized the 50 mm (2 in) piston-cylinder have yielded uncertainties as low as ± 3 ppm. In addition uncertainty in gravity, mass, mass density, air density, residual vacuum and piston-cylinder temperature could all be reduced.

Basis of the uncertainty analysis

All uncertainties in this analysis are calculated using the methods described in ISO "*Guide to the Expression of Uncertainty in Measurement*," June, 1992 (GUM).

The Type A component, the statistical result based on a series of observations, cannot be calculated until a set of data is acquired by the PG9000 user with a specific instrument under specific conditions. Since many unpredictable factors may affect the statistical result (i.e. air drafts, vibration, ancillary hardware), only a typical Type A uncertainty based on typical operating conditions can be provided. This prediction includes contributions of uncertainty from variations in rotation speeds and piston height.

Type B values may also be described as typical because the uncertainties are based on assumptions regarding the type of use and limits of environmental conditions typically encountered by PG9000 users. The environmental condition limits assumed in the analysis are:

- Ambient temperature: 15 °C to 25 °C (59 °F to 77 °F)
- Ambient humidity: 5 %RH to 95 %RH
- Ambient pressure: 70 kPa to 110 kPa (10 psi to 16 psi)

The uncertainties are listed in two categories:

(i) Uncertainties common in using all PG9000 piston-cylinders types and sizes such as ambient conditions, fluid heads, and piston-cylinder temperature measurement;

(ii) Uncertainties whose values are specific to piston-cylinder size such as sensitivity and effective area value.

Both uncertainties (i) and (ii) may be developed either as relative or absolute uncertainties. Some uncertainties are intrinsically relative to pressure such as effective area and gravity. Others should be expressed as constants in units of pressure such as the density of a manual mass carrying bell, piston or cylinder, vacuum pressure and the uncertainty of a barometer. Therefore, the relative uncertainties and the absolute uncertainties are combined and expanded separately and expressed as a two part uncertainty in the typical uncertainty specifications. However this does not mean they are correlated. If a PG9000 user wants to determine an uncertainty in pressure at a specific pressure point, it is acceptable to convert relative uncertainties to pressure uncertainties and root sum square (square root of the sum of the squares) all standard uncertainties that are not correlated.

For each uncertainty component, an explanation of the variable or parameter is provided along with the value of one standard uncertainty, its sensitivity with pressure and the type of distribution associated with the uncertainty. After each of the uncertainty components has been considered, they are combined to provide global uncertainty values in pressure for measurements made by all of the PG9000 piston-cylinder sizes and measurement modes.

If the PG9000 user's conditions are different from those assumed in this document or the uncertainties have been improved for a specific component, e.g. piston-cylinder effective area, it is possible to replace the typical uncertainty listed in the table with the new uncertainty. The final uncertainty can then be obtained by root sum squaring and multiplying by the appropriate coverage factor.

Pressure calculations

The following equations are used in the PG9000 for calculating the reference pressure at the test instrument's reference level. These variables are identified in the following sections during the discussion of each variable's uncertainty.

Gauge pressure

$$\frac{M\,g_l\left(1-{}^{\rho_{air}}\!/\!_{\rho_{mass}}\right)+\pi DT}{A_{20.0}\left[1+(\alpha_p+\alpha_c)(\theta-20)\right](1+\lambda P)}-(\rho_{fluid}-\rho_{air})\,g_l\,h$$

Absolute pressure by application of vacuum reference (PG7601 only)

$$\frac{M\,g_l}{A_{20.0}\left[1+(\alpha_p+\alpha_c)(\theta-20)\right](1+\lambda P)}-(\rho_{fluid}\,g_l\,h+Vac$$

Absolute pressure by addition of atmospheric pressure

$$\frac{M\,g_l\left(1-{}^{\rho_{air}}\!/\!_{\rho_{mass}}\right)+\pi\,D\,T}{A_{20.0}\left[1+(\alpha_p+\alpha_c)(\theta-20)\right](1+\lambda P)}-(\rho_{fluid}\,g_l\,h+Baro$$

Differential pressure

$$\frac{M\,g_l}{A_{20.0}\left[1+(\alpha_p+\alpha_c)(\theta-20)\right](1+\lambda P)}-(\rho_{fluid}-\rho_{fluid2})g_l\,h+Vac-P_{diff}$$

Where:

M	Total true mass load (kg)
g_l	Local acceleration due to gravity (m/s^2)
ρ_{air}	Ambient air density (kg/m^3)
ρ_{mass}	Average density of mass load (kg/m^3)
T	Surface tension (considered 0 with gas) (N/m)
D	Diameter of the piston (m) $2\sqrt{{}^{A_{(20.0)}}\!/\!_{\pi}}$
ρ_{fluid}	Density of the test medium (kg/m^3)
ρ_{fluid2}	Density of the test medium—low port in Diff Mode (kg/m^3)
h	Difference in height between PG7000 (m) reference level and test reference level
Vac	Back pressure in bell jar (absolute with vacuum) (Pa)
Baro	Atmospheric pressure read by barometer (Pa)
$A_{20.0}$	Piston-cylinder effective area at 20 °C and (m^2) 0 pressure
ap	Linear thermal expansion coefficient of piston ($°C^{-1}$)
ac	Linear thermal expansion coefficient of cylinder ($°C^{-1}$)
q	Temperature of the piston-cylinder (°C)
l	Elastic deformation coefficient of the (Pa^{-1}) piston-cylinder
P	Pressure applied to the piston-cylinder (Pa)
P_{diff}	(P_{rpm} – P_{offset}) Reference technical note 9940TN02 (Pa)

Uncertainties common to all PG9000 piston-cylinder sizes

When using a PG9000 system, the source of the values used for certain variables of the pressure equation may be chosen from a variety of sources. This document assumes that "internal" measurements, i.e. the sensors on board the PG9000 Remote Electronics Module (REM), are always used when available. These include ambient pressure, temperature and humidity, and piston-cylinder temperature. The uncertainties described for these sensors include the basic specification and any other uncertainty contributions due to position or data acquisition. Three exceptions are B7—Residual Pressure where the uncertainty is provided for a capacitance diaphragm gauge available as an option to use with a PG9000; B18—Differential Offset the uncertainty in the offset determined in differential mode; and B8—Barometric Pressure when using a low uncertainty RPM barometer in absolute by addition of atmospheric pressure mode.

B1: Mass (m)

Mass sets used with the PG9000 piston gauges are the same PG7000 mass sets used with the PG7000 piston gauge line. The true mass values that are stored in PG9000 memory are determined by Fluke Calibration using the substitution method by comparison to reference masses traceable to NIST. The PG7000 mass set consists of a main mass set comprised mostly of 5, 6.2, 10 or 10.1 kg (11, 13.7, 22 or 22.3 lb) masses, a supplementary set broken down into submultiples of the kg, or a binary set for AMH, a mass carrying bell assembly and trim mass set providing resolution to 10 mg (0.0004 oz).

Considering that all the masses used with a PG9000 are measured using the same procedure, the same references and the same comparators, the uncertainty in each individual mass is considered correlated and must be added instead of root sum squaring all or any part of the individual mass uncertainties. This gives a global true mass value uncertainty of ± 5 ppm with a coverage factor of 2 of the total mass load on the piston (excluding the piston and bell mass which are expressed as absolute uncertainties later).

The estimation of uncertainty in mass described in the previous paragraph includes changes in mass over a period of one year. Masses used with the PG9000 AMH (Automated Mass Handler) are preserved from the day to day contamination and wear to which masses loaded manually are exposed. Because of this, the uncertainty in mass when using AMH is kept at ± 5 ppm with a coverage factor of 2 of the total mass load on the piston but is considered valid for a two year period.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: 2.5 ppm

B2: Local gravity (gl)

The value of local gravity and the uncertainty in that value cannot be provided with the PG9000 since local gravity is specific to the location of use. However, it is well known that local gravity for a specific location in the United States can be obtained from the US Geodetic Survey for most locations with a typical uncertainty of ± 2 ppm with a coverage factor of 2.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: 1 ppm

B3: Air density (ρ_{air}) for gauge and absolute by addition of atmospheric pressure measurement modes

The density of air is calculated real time as PG9000 updates the calculated pressure. Air density is used with the average mass density, B4, to correct for air buoyancy as is shown in the pressure calculation equations. Air density is a function of ambient pressure, temperature and humidity.

As mentioned in the beginning of this section, it is assumed that the internal sensors on board the PG9000-REM are used to measure ambient conditions. The uncertainties shown in this section are based on the specifications of the on-board sensors.

The table to the right provides uncertainties in air density resulting from the specification of the on-board sensors used to measure ambient conditions (no uncertainty is necessary for normalized values).

Root sum squaring the standard uncertainties in air density provides a one standard uncertainty in air density equal to 0.0025 kg/m³.

The equation used for calculating air density is:

$$\frac{P}{Pn} \times \frac{Tn}{T} \times \frac{Zn}{Z_{P,T}} \times \text{Normal air density} + \text{Humidity correction}$$

Where:

P	Ambient pressure (Pa)
Pn	Normal pressure (101325 Pa)
Tn	Normal temperature (273.15 K)
T	Ambient temperature (measured in °C and added to Tn) (K)
Zn	Normal compressibility of air (0.99942)
$Z_{P,T}$	Compressibility of air at ambient pressure and temperature (-)

Normal density of air (1.2927 kg/m³)
Humidity correction (-)

Measurement	Uncertainty in measurement (1 Std Unc)	Uncertainty in air density (1 Std Unc)
Temperature	0.5 °C (32.9 °F)	0.0021 kg/m³
Pressure	0.1 kPa (0.015 psi)	0.0012 kg/m³
Compressibility of air at ambient pressure and temperature	0.01 %	0.0001 kg/m³
Relative humidity	5.0 %	0.0005 kg/m³

Type of uncertainty: Relative type B
Sensitivity: 125 ppm/kg/m³
Distribution: Considered normal
Standard uncertainty: 0.0025 kg/m³

B4: Average mass density (ρ_{mass}) for absolute by application of vacuum mode

The average mass density is calculated for each mass load on the PG9000.

PG9000 mass sets are 304L non-magnetic stainless steel and have a density of 7920 ± 40 kg/m³ at k=2. The uncertainty in the average density of the bell assembly and the piston or cylinder mass is ± 100 kg/m³ and is calculated as a pressure uncertainty in the section of this document dedicated to uncertainties specific to piston-cylinder sizes.

For both the main masses and the bell + piston mass densities they are applied only in the uncertainty for absolute by vacuum and differential modes. The reason is that if a mass is calibrated with the wrong mass density at a specific air density, and it is used at that same air density then error is nullified. It is also considered insignificant for air densities that are within the environmental limits given at the beginning of this technical note. If it is used in an air density that is different from the calibration conditions then mass value begins to be incorrect. The worse case condition in this case is with no air density, i.e. where the air is evacuated in absolute by vacuum mode.

The equation used for calculation of average density of a PG mass load is:

$$\frac{M_p + M_b + M_8}{\left(M_p/\rho_p\right) + \left(M_b/\rho_b\right) + \left(M_8/\rho_8\right)}$$

Where:

M_p	True mass of the piston assembly (kg)
ρ_p	Average density of the piston assembly (kg/m³)
M_b	True mass of the mass carrying bell (kg)
ρ_b	Average density of the bell (kg/m³)
M_8	True mass of all masses with a density of 7 920 kg/m³ (kg)
r_8	Density of main masses (7 920 kg/m³)

Type of uncertainty: Relative type B
Sensitivity: 0.02 ppm/kg/m³
Distribution: Considered normal
Standard uncertainty: 20 kg/m³

B5: Fluid head height (h)

In order to determine the contribution of uncertainty in a fluid head correction, a typical uncertainty in the height difference between the reference level of the PG9000 and a test instrument needs to be chosen.

Generally, the height can easily be measured ± 5 mm (.2 in) with a coverage factor of 2 using inexpensive apparatus available in most laboratories. This also includes the uncertainty in the piston position sensor on board the PG9000 for which the height is corrected and the uncertainty in the calculation of the reference level offset. The uncertainty in the density is based on perfect compressibility of the gas. Though the compressibility of N_2/Air and He reach 2.0 and 1.5 respectively at 100 MPa (14.5 psi), the assumption of the uncertainty calculation in perfect compressibility becomes a conservative estimate.

Type of uncertainty: Relative type B
Sensitivity: 0.12 ppm/mm
Distribution: A priori rectangular
Standard uncertainty: 2.9 mm (.1 in)

B6: Medium density (ρ_{fluid})

Referencing the table in B3, Air Density, the same equation without the humidity correction is used for calculating medium density. The pressure is known to within the specifications of the PG9000 pressure and compressibility is known to within ± 0.02 % (k=2). One standard uncertainty in N_2 gas medium then becomes dependent on the temperature of the medium. Once pressure is stable in any gas piston gauge, it is assumed the gas temperature is stable and is equal to piston-cylinder temperature, ± 1 °C (33.8 °F) (k=2).

Note that the uncertainty in piston-cylinder temperature is not used because of the possibility of temperature gradients between the PG9000 piston gauge and a device under test. One relative standard uncertainty in medium density (using N_2) becomes 0.17 % of the density calculated by the PG9000. This uncertainty is calculated using a maximum typical head correction of one meter and assuming the density changes proportionally to the pressure over the full range of the PG9000.

In the case of gauge mode the density of Air is subtracted from the media density. In this case Air is close enough to the density of N_2 that there is no need to separate the uncertainties. In the case of differential mode, the low port density is subtracted from the high port density assuming they are the same media. Differential mode can be used to measure gauge pressure where the low port is exposed to Air. There would be an equal, but still insignificant influence as with gauge mode.

Measurement	Uncertainty in measurement (1 Std Unc)	Uncertainty in N_2 medium density
Temperature	0.17 %	0.17 %
Pressure	0.01 %	0.01 %
Compressibility of air at ambient pressure and temperature	0.01 %	0.01 %

Type of uncertainty: Relative type B
Sensitivity: 1.1 ppm/% density/m
Distribution: Considered normal
Standard uncertainty: 0.17 % (of density)

B7: Residual pressure (Vac) for absolute by application of vacuum measurement mode

The residual pressure sensor available as an option for the PG9000 Piston gauge is an MKS 100 mTorr unheated CDG. Fluke Calibration expands the manufacturers uncertainty to a value of ± (0.5 % of reading + 0.05 Pa) at k=2 for one year without zeroing (must have an isolation valve to keep at vacuum). The uncertainty included will depend on the vacuum reached. With scroll and rotary vane vacuum pumps a 2 Pa residual pressure is easily achieved. At 2 Pa this uncertainty becomes ± 0.06 Pa at k=2 or 0.03 Pa for one standard uncertainty considering a normal distribution.

Type of uncertainty: Absolute type B
Sensitivity: 1 Pa/Pa
Distribution: Considered normal
Standard uncertainty: 0.03 Pa

B8: Barometric pressure (Baro) for absolute by addition of atmospheric pressure only

When using a PG9000 to measure absolute pressure by addition of atmospheric pressure, an uncertainty in the barometer used to measure atmospheric pressure must be included. This analysis assumes the use of a Fluke Calibration barometric range RPM interfaced with the PG9000. The uncertainty in this barometer output is a conservative ± 10 Pa (.001 psi). One standarduncertainty is 5 Pa (.0007 psi).

Note that if the PG9000 piston gauge is used to calibrate the RPM barometer, then there may be a correlation between the relative uncertainty and the pressure uncertainty shown in the uncertainty tables and they should not be root sum squared.

Type of uncertainty: Absolute type B
Sensitivity: 1 Pa/Pa
Distribution: Considered normal
Standard uncertainty: 5 Pa (.0007 psi)

B9: Resolution

Because PG7000 provides a digital output of pressure, the resolution must be accounted for in this uncertainty analysis. Display of pressure for all units is a minimum of seven places. This provides a worse case resolution of 1 ppm.

Note: There are exceptions to the above for some units at low pressure. For instance, the resolution for a PG9000 can be as large as 100 ppm when using a 10 kPa/kg piston-cylinder at the lowest pressure and MPa as the pressure unit of measure, or 10 ppm when using bar. To eliminate this uncertainty choose kPa instead of MPa.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Rectangular
Standard uncertainty: 0.29 ppm

B10: Piston-cylinder temperature (θ)

The uncertainty in the prediction of the change of effective area with temperature is affected by the ability of the platinum resistance thermometer (PRT) in the PG9000 mounting post to measure the piston-cylinder temperature and also uncertainty in that temperature. The combined uncertainty in both these parameters are ± 0.1 °C (32.2 °F) with a coverage factor of 2. The PG9000 piston gauge uses two PRTs located on opposite sides of the mounting post. There is some correlation between the PRTs since they are calibrated by the same reference which limits the reduction of uncertainty which is sometimes realized with redundant measurements of the same parameter. However there is significantly greater confidence that there are no gradients and that the temperature of the piston-cylinder is very close to the temperature of the mounting post.

The thermal expansion coefficient for tungsten carbide cylinders is 9×10^{-6} °C^{-1}.

Type of uncertainty: Relative type B
Sensitivity: 9 ppm/°C
Distribution: Considered normal
Standard uncertainty: 0.05 °C (32.1 °F)

B11: Verticality

The uncertainty in the pressure calculated by the PG9000 system includes the deviation of verticality of the piston-cylinder axis relative to the direction of acceleration with gravity. All PG9000 systems have a precision bubble level adjusted to the piston-cylinder mounting post with an uncertainty of ± 2 minutes with a coverage factor of 2. Two minutes of non-verticality represents ± 0.17 ppm on pressure.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Asymmetrical
Standard uncertainty: 0.08 ppm

B16: Thermal expansion ($\alpha p+\alpha c$)

The effective area of a piston-cylinder changes with temperature depending on the thermal expansion of the piston-cylinder materials. The magnitude of this change with temperature is the thermal expansion coefficient. Since all piston-cylinders available with the PG9607 and PG9602 are made of tungsten carbide they have a common value of 4.5 x 10^{-6} °C^{-1} for the piston and the cylinder. These are added (see pressure equation) to give 9.0 x 10^{-6} °C^{-1}. This coefficient has an uncertainty of ± 5% with a coverage factor of 2. The effective area is given at 20 °C (68 °F). Assuming worse case based on the ambient limits defined at the beginning of this technical note, 15 °C or 25 °C (59 °F or 77 °F), resulting in a correction of 5 °C, one standard uncertainty contributes 1.11 ppm.

Type of uncertainty: Relative type B
Sensitivity: 1.0000000/°C^{-1}
Distribution: Considered normal
Standard uncertainty: 2.25 x 10^{-7} °C^{-1}

B17: Stability (reproducibility with time)

Stability is not normally a required component of uncertainty in measurement. This is because it is not always predictable. However to help PG9000 users define initial calibration intervals and to predict contributions of uncertainty based on the natural changes of the materials, we have included known values for an interval of two years.

There are three areas to consider when identifying stability of the PG9000 system. The effective area of the piston-cylinder, the masses and all the sensors on board a PG9000 system.

The specifications for the sensors on-board a PG9000 system include stability for one year.

As long as they are inside their specifications then there is no additional uncertainty retained from drift. This includes the optional residual vacuum sensor.

Masses can change with time due to contamination or wear. Because the PG9000 systems are generally used carefully in a laboratory environment the change of mass with time is minimal. The uncertainty of ± 5 ppm or 1 mg (.00004 oz), whichever is greater includes the stability of the masses over a 1 year period for manual masses and 2 years for AMH masses.

The stability of effective area of a piston-cylinder is a function of the material, size and manufacturing. Fluke Calibration has many years of documented evidence of the stability of tungsten carbide. This clearly evidences stability better than 1 ppm for a two year period.

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: 0.5 ppm

Uncertainties specific to piston-cylinder size

The following are the piston-cylinder sizes that are covered in this uncertainty analysis technical note. It does not include the 200 kPa/kg piston-cylinder because the uncertainty would be covered under the technical note 7920TN01 (latest revision) when used with an AMH.

PG9607

- 5 kPa/kg (50 mm diameter)

PG9602

- 10 kPa/kg (35.3 mm diameter) 500 g piston
- 10 kPa/kg (35.3 mm diameter) 400 g piston
- 20 kPa/kg (25 mm diameter)
- 50 kPa/kg (15.8 mm diameter)
- 100 kPa/kg (11.2 mm diameter)

B12: Effective area ($A_{20,0}$)

Fluke Calibration maintains reference piston-cylinders that are directly traceable to PTB (Germany) and NIST (USA) and have known valid relationships to various other national metrology institutes through the Fluke Calibration DHI Piston-Cylinder Calibration Chain. Calibration chain references are used to determine the PG9000 piston-cylinder effective areas through a process called a “ratio based crossfloat”. Although the actual calculated uncertainties in the PG9000 piston-cylinder effective areas are always lower, the following tables list the worst case uncertainty in each piston-cylinder size supplied: The effective areas and their uncertainties are determined using nitrogen as the pressurized medium. They are valid for all operating modes.

As is mentioned earlier in this document, global uncertainties may be improved by determining better uncertainties in specific parameters and replacing the typical or “worst case” uncertainties with improved values.

PG9607 and PG9602 Piston-Cylinders	Uncertainty	
	k=2	1 Std Unc
5 kPa/kg	± 7 ppm	3.5 ppm
10 kPa/kg (500 g)	± 10 ppm	5 ppm
10 kPa/kg (400 g)	± 10 ppm	5 ppm
20 kPa/kg	± 11 ppm	5.5 ppm
50 kPa/kg	± 11 ppm	5.5 ppm
100 kPa/kg	± 16 ppm	8 ppm

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: See table

B13: Sensitivity

One of the intrinsic characteristics of a piston-cylinder is its sensitivity. Sensitivity is defined as the minimum change in input (mass load) that causes a detectable change in output (defined pressure). The sensitivity of a piston-cylinder is itself an uncertainty. Sensitivity is similar to resolution because it has a rectangular probability distribution.

Because sensitivity is not strictly relative to pressure it is best described by both a relative uncertainty and an absolute uncertainty.

The following tables list the uncertainty in sensitivity for both the relative and absolute component of each piston-cylinder size in both relative and absolute values. One standard uncertainty is then equal to the full width sensitivity for each piston-cylinder size divided by the square root of twelve.

PG9607 and PG9602 Piston-Cylinders	Sensitivity	1 Std Unc	Sensitivity	1 Std Unc
	ppm		Pa	
5 kPa/kg	0.5 ppm	0.14 ppm	0.01 Pa	0.0029 Pa
10 kPa/kg (500 g)	0.5 ppm	0.14 ppm	0.02 Pa	0.0058 Pa
10 kPa/kg (400 g)	0.5 ppm	0.14 ppm	0.02 Pa	0.0058 Pa
20 kPa/kg	0.5 ppm	0.14 ppm	0.04 Pa	0.0115 Pa
50 kPa/kg	0.5 ppm	0.14 ppm	0.1 Pa	0.0289 Pa
100 kPa/kg	0.5 ppm	0.14 ppm	0.2 Pa	0.0577 Pa

Type of uncertainty: Relative and absolute type B
Sensitivity: 1 ppm/ppm and 1 Pa/Pa
Distribution: Rectangular
Standard uncertainty: See table

B14: Linearity

Another intrinsic characteristic of a piston-cylinder is the degree to which the change of its effective area with pressure over its pressure range follows the mechanical theory. PG9000 piston-cylinders are characterized by a linear model with an uncertainty that depends upon range, size, type of mounting system, materials and piston-cylinder annular space. The following table lists the uncertainties attributable to the assumption of a linear model with a coverage factor of 2 and one standard uncertainty.

Though there are various sizes of mass sets available up to 100 kg (220 lb) for PG9000 systems, the uncertainty in effective area linearity for each piston-cylinder size are only given for 100 kg (220 lb) mass loads.

PG9607 and PG9602 Piston-Cylinders	**Uncertainty**	
	k=2	**1 Std Unc**
5 kPa/kg	± 1 ppm	0.5 ppm
10 kPa/kg (500 g)	± 2 ppm	1 ppm
*10 kPa/kg (400 g)	± 2 ppm	1 ppm
20 kPa/kg	± 2 ppm	1 ppm
50 kPa/kg	± 5 ppm	2.5 ppm
100 kPa/kg	± 6 ppm	3 ppm

Type of uncertainty: Relative type B
Sensitivity: 1 ppm/ppm
Distribution: Considered normal
Standard uncertainty: See table

B15: Elastic deformation (λ)

The effective area of a PG9000 piston-cylinder is a function of the applied pressure and the theoretical elastic deformation coefficient. The theoretical deformation coefficient is calculated knowing the type of mounting post in which the piston-cylinder is contained and the piston-cylinder size and materials. It is well accepted that an uncertainty in theoretical elastic deformation coefficients of the free deformation mounting post is ± 10% with a coverage factor of 2. The following tables list the elastic deformation coefficient, one standard uncertainty, the sensitivity and one standard in pressure for a 100 kg (220 lb) mass load for each piston-cylinder size.

It should be noted that the uncertainty shown in the table above is worst case considering the maximum pressure is used to determine the value shown. When the piston gauge is calibrated to a lower pressure, the uncertainty contributed by elastic deformation could be recalculated using the sensitivity coefficient.

Type of uncertainty: Relative type B
Sensitivity: See tables
Distribution: Considered normal
Standard uncertainty: See table

PG9607 and PG9602 Piston-Cylinder size	**Deformation coefficient** (λ) (MPa^{-1})	**1 Std Unc** (MPa^{-1})	**Sensitivity** (ppm/MPa)	**Maximum mass**	**Maximum pressure**	**Uncertainty**
5 kPa/kg	4.57 x 10^{-6}	2.29 x 10^{-7}	0.229	100 kg	500 KPa	0.11 ppm
10 kPa/kg (500 g)	4.20 x 10^{-6}	2.10 x 10^{-7}	0.210	100 kg	1000 KPa	0.21 ppm
10 kPa/kg (400 g)	5.19 x 10^{-6}	2.60 x 10^{-7}	0.260	100 kg	1000 KPa	0.26 ppm
20 kPa/kg	2.65 x 10^{-6}	1.32 x 10^{-7}	0.132	100 kg	2000 KPa	0.26 ppm
50 kPa/kg	-1.67 x 10^{-6}	8.3 x 10^{-8}	0.083	100 kg	5000 KPa	0.42 ppm
100 kPa/kg	-2.47 x 10^{-6}	1.23 x 10^{-7}	0.123	100 kg	10000 KPa	1.23 ppm

B1a, B1b and B1c: Manual bell, piston mass and AMH bell assembly

The mass of the mass loading bell and the mass of the pistons have uncertainty specifications that are separate from the other masses. This does not include the mass of the 5 kPa/kg cylinder. These uncertainty specifications are ± 3 mg for each piston, ± 5 mg for the tungsten-carbide 10 kPa/kg piston, ± 4 mg for the 20 kPa/kg and 400 g 10 kPa/kg and ± 16 mg for the manual mass loading bell with a coverage factor of 2.

As was mentioned in B1: Mass, the PG9000 AMH mass handling system preserves the masses from contamination and wear. Therefore the uncertainty specifications are reduced to the global mass specification of ± 5 ppm at k=2. Since the mass loading bell and piston mass are part of the global mass uncertainty, they do not need to be included a second time as a pressure constant as is the case with a manual mass set. But with an AMH B1c is an uncertainty that is added primarily due the stability of the bell assembly. The mating threads of the stem and the binary tray must be lubricated with krytox grease. The grease has a tendency to lose mass over time. Tests have shown this to be within 10 mg, and is always negative, but since all uncertainties in this technical note are being considered symmetrical, an uncertainty of ± 10 mg using a coverage factor of 2 is included. Note that this uncertainty is based on the assumption that the proper procedure is followed for removing and applying the grease during calibration and that the residual grease is never removed between calibrations.

Because the mass uncertainties result in a different pressure value for each piston-cylinder size they are listed separately for each size available in the tables below.

PG9607 and PG9602 Piston-Cylinder size	**Sensitivity**	**Piston** (1 Std Unc)	**Bell** (1 Std Unc)	**AMH Bell** (1 Std Unc)
5 kPa/kg	0.005 Pa/mg	n/a	0.04 Pa	0.025 Pa
10 kPa/kg (500 g)	0.01 Pa/mg	0.05 Pa	0.08 Pa	0.05 Pa
10 kPa/kg (400 g)	0.01 Pa/mg	0.04 Pa	0.08 Pa	0.05 Pa
20 kPa/kg	0.02 Pa/mg	0.08 Pa	0.16 Pa	0.1 Pa
50 kPa/kg	0.05 Pa/mg	0.15 Pa	0.4 Pa	0.25 Pa
100 kPa/kg	0.1 Pa/mg	0.3 Pa	0.8 Pa	0.5 Pa

Type of uncertainty: Absolute type B
Sensitivity: See table
Distribution: Considered normal
Standard uncertainty: See table

B3a: Bell assembly density

As is stated in B3 the density of the average density of the piston and the bell assembly is considered to be ± 100 kg/m^3 using a coverage factor of 2, and a standard uncertainty of 50 kg/m^3. The uncertainty is a function of the pressure created with the bell mass plus the piston or cylinder mass.

PG9607 and PG9602 Piston-Cylinder size	**Piston (or Cylinder) + Bell Assembly Mass**	**Piston (or Cylinder) + Bell Assembly Density**	**1 Std Unc**
5 kPa/kg	2.1 kg	7374 kg/m^3	0.012 Pa
10 kPa/kg (500 g)	1.3 kg	5754 kg/m^3	0.023 Pa
10 kPa/kg (400 g)	1.2 kg	5478 kg/m^3	0.024 Pa
20 kPa/kg	1.2 kg	5605 kg/m^3	0.045 Pa
50 kPa/kg	1 kg	4872 kg/m^3	0.125 Pa
100 kPa/kg	1 kg	4969 kg/m^3	0.241 Pa

Type of uncertainty: Absolute type B
Sensitivity: 1Pa/Pa
Distribution: Considered normal
Standard uncertainty: See table

B18: Differential offset

The differential offset is the uncertainty due to the short term repeatability of the determination of zero differential or gauge in differential mode using an RPM barometer. Reference DHI technical note 9940TN02 “*PG7000 Differential Mode for Defining Low and Negative Differential Pressure at Various Static Pressures*”.

Type of uncertainty: Absolute type B
Sensitivity: 1 Pa/Pa
Distribution: Considered normal
Standard uncertainty: 0.15 Pa

A1: Type A contribution

Because this uncertainty analysis covers a population of instruments, a specific Type A uncertainty cannot be assigned from a set of data. Generally a Type A uncertainty will be determined when a customer uses the piston gauge to calibrate another instrument to be used in the uncertainty analysis of that instrument. The specific Type A uncertainties depend upon the system configuration, the environment, the pressure connections and hardware between the piston gauge and the test, and also any contributions from the piston gauge. Since it is impossible to know what Type A influences a given PG7000 user will have in a specific situation, we have only included the contribution of Type A from the piston gauge. This is done for each piston-cylinder size.

To determine the contribution of Type A by an instrument, there must be another instrument with performance characteristics that exceed the instrument being evaluated. For piston gauges no such instrument is available except for other piston gauges with documented performance. The best known source of this information comes from the Type A uncertainties determined in the Fluke Calibration Piston-Cylinder Calibration Chain. This is the only source where all systematic influences are corrected well enough to allow a normal distribution to be observed for a population of piston-cylinders. The values listed in the table below show nominal Type A uncertainties that are slightly larger than the Type A uncertainties determined in the Fluke Calibration Piston-Cylinder Calibration Chain. It should also be noted that the effects from piston (or cylinder) rotation, or piston position inside of the free zone stroke are required to be within the Type A uncertainties shown below.

PG7601 and PG7102 Piston-Cylinder size	**Type A** (k=2)	**Uncertainty in pressure** (1 Std Dev)
5 kPa/kg	± 1 ppm	0.5 ppm
10 kPa/kg (500 g)	± 1 ppm	0.5 ppm
10 kPa/kg (400 g)	± 1 ppm	0.5 ppm
20 kPa/kg	± 2 ppm	1.0 ppm
50 kPa/g	± 2 ppm	1.0 ppm
100 kPa/g	± 2 ppm	1.0 ppm

Type of uncertainty: Relative type A
Sensitivity: 1 ppm/ppm
Distribution: Normal
Standard uncertainty: See table

Combining uncertainties

The tables that follow list the uncertainties defined in the previous sections of this document for all piston-cylinder sizes, for minimum and maximum mass loads and for the four different pressure measurement modes offered by PG9000 systems. All individual uncertainties are categorized into relative or absolute uncertainties and listed as one standard uncertainty. The uncertainties are then combined by root sum squaring the individual uncertainties. Values shown in ppm or pressure are combined separately. Finally, the relative and absolute combined uncertainty are each multiplied by a coverage factor of 2 and listed.

Note: If it is required to calculate a specific confidence level for this uncertainty analysis (such as 95 %), greater knowledge of the effective degrees of freedom for each standard uncertainty must be obtained. However, it should be noted that as all the dominant standard uncertainties are considered to have normal distributions with a high degree of confidence, and observing the Central Limit Theorem, a coverage factor of 2 (k=2) should sufficiently approximate a confidence level of 95 %.

PG9607, 5 kPa/kg piston-cylinder

Typical pressure measurement uncertainty:
± [10 ppm + (100 MPa absolute or 50 MPa guage)]

		When used with an AMH set				When used with an manual mass set			
Variable or parameter	**Uncertainity ID**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**
Full mass load: relative uncertainties		**MS-AMH-100**				**MS-7002-100**			
Mass (M)	B1	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm
Local G	B2	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Air density	B3	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a
Mass density	B4	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm
Resolution	B9	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm
PC Temperature	B10	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B11	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm
Effective area	B12	3.5 ppm	3.5 ppm	3.5 ppm	3.5 ppm	3.5 ppm	3.5 ppm	3.5 ppm	3.5 ppm
Linearity	B14	0.50 ppm	0.50 ppm	0.50 ppm	0.50 ppm	0.50 ppm	0.50 ppm	0.50 ppm	0.50 ppm
Elastic deformation	B15	0.11 ppm	0.11 ppm	0.11 ppm	0.11 ppm	0.11 ppm	0.11 ppm	0.11 ppm	0.11 ppm
Thermal expansion	B16	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm
Stability Ae	B17	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Sensitity	B13	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm
Type A	A1	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Combined		**4.6 ppm + 0.037 Pa**	**4.6 ppm + 0.025 Pa**	**4.6 ppm + 5.0 Pa**	**4.6 ppm + 0.15 Pa**	**4.6 ppm + 0.049 Pa**	**4.6 ppm + 0.040 Pa**	**4.6 ppm + 5.0 Pa**	**4.6 ppm + 0.15 Pa**
Expanded to k=2		**9.2 ppm + 0.07 Pa**	**9.2 ppm + 0.05 Pa**	**9.2 ppm + 10.0 Pa**	**9.2 ppm + 0.30 Pa**	**9.2 ppm + 0.10 Pa**	**9.2 ppm + 0.08 Pa**	**9.2 ppm + 10.0 Pa**	**9.2 ppm + 0.30 Pa**
Absolute uncertainties									
Barometric pressure	B8	n/a	n/a	5 Pa	n/a	n/a	n/a	5 Pa	n/a
Vacuum	B7	0.025 Pa	n/a	n/a	n/a	0.025 Pa	n/a	n/a	n/a
Sensitivity	B13	0.003 Pa	0.003 Pa	0.003 Pa	0.003 Pa	0.003 Pa	0.003 Pa	0.003 Pa	0.003 Pa
Mass bell grease	B1c	0.025 Pa	0.025 Pa	0.025 Pa	n/a	n/a	n/a	n/a	n/a
Bell assembly density	B1d	0.012 Pa	n/a	n/a	n/a	0.012 Pa	n/a	n/a	n/a
Bell mass (manual)	B1a	n/a	n/a	n/a	n/a	0.04 Pa	0.04 Pa	0.04 Pa	n/a
Piston mass	B1b	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Differential mode reference	B18	n/a	n/a	n/a	0.15 Pa	n/a	n/a	n/a	0.15 Pa

PG9602, 10 kPa/kg piston-cylinder (400 g or 500 g)

Typical pressure measurement uncertainty: ± (12 ppm + 0.2 Pa)

		When used with an AMH set				**When used with an manual mass set**			
Variable or parameter	**Uncertainity ID**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**
Full mass load: relative uncertainties		MS-AMH-100				MS-7002-100			
Mass (M)	B1	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm
Local G	B2	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Air density	B3	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a
Mass density	B4	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm
Resolution	B9	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm
PC Temperature	B10	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B11	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm
Effective area	B12	5 ppm	5 ppm	5 ppm	5 ppm	5 ppm	5 ppm	5 ppm	5 ppm
Linearity	B14	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm
Elastic deformation	B15	0.21 ppm	0.21 ppm	0.21 ppm	0.21 ppm	0.21 ppm	0.21 ppm	0.21 ppm	0.21 ppm
Thermal expansion	B16	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm
Stability Ae	B17	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Sensitivity	B13	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm
Type A	A1	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Combined		**5.9 ppm + 0.079 Pa**	**5.9 ppm + 0.071 Pa**	**5.9 ppm + 5.0 Pa**	**5.9 ppm + 0.15 Pa**	**5.9 ppm + 0.101 Pa**	**5.9 ppm + 0.095 Pa**	**5.9 ppm + 5.0 Pa**	**5.9 ppm + 0.15 Pa**
Expanded to k=2		**11.8 ppm + 0.16 Pa**	**11.8 ppm + 0.14 Pa**	**11.8 ppm + 10.0 Pa**	**11.8 ppm + 0.30 Pa**	**11.8 ppm + 0.20 Pa**	**11.8 ppm + 0.19 Pa**	**11.8 ppm + 10.0 Pa**	**11.8 ppm + 0.30 Pa**
Absolute uncertainties									
Barometric pressure	B8	n/a	n/a	5 Pa	n/a	n/a	n/a	5 Pa	n/a
Vacuum	B7	0.025 Pa	n/a	n/a	n/a	0.025 Pa	n/a	n/a	n/a
Sensitivity	B13	0.006 Pa	0.006 Pa	0.006 Pa	0.006 Pa	0.006 Pa	0.006 Pa	0.006 Pa	0.006 Pa
Mass bell grease	B1c	0.050 Pa	0.050 Pa	0.025 Pa	n/a	n/a	n/a	n/a	n/a
Bell assembly density	B1d	0.023 Pa	n/a	n/a	n/a	0.023 Pa	n/a	n/a	n/a
Bell mass (manual)	B1a	n/a	n/a	n/a	n/a	0.08 Pa	0.08 Pa	0.08 Pa	n/a
Piston mass	B1b	0.050 Pa	0.050 Pa	n/a	n/a	0.050 Pa	0.050 Pa	0.050 Pa	n/a
Differential mode reference	B18	n/a	n/a	n/a	0.15 Pa	n/a	n/a	n/a	0.15 Pa

PG9602, 20 kPa/kg piston-cylinder

Typical pressure measurement uncertainty: ± (13 ppm + 0.3 Pa)

		When used with an AMH set				When used with an manual mass set			
Variable or parameter	**Uncertainity ID**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**
Full mass load: relative uncertainties		**MS-AMH-100**				**MS-7002-100**			
Mass (M)	B1	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm
Local G	B2	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Air density	B3	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a
Mass density	B4	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm
Resolution	B9	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm
PC Temperature	B10	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B11	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm
Effective area	B12	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm
Linearity	B14	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm	1.00 ppm
Elastic deformation	B15	0.26 ppm	0.26 ppm	0.26 ppm	0.26 ppm	0.26 ppm	0.26 ppm	0.26 ppm	0.26 ppm
Thermal expansion	B16	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm
Stability Ae	B17	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Sensitivity	B13	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm
Type A	A1	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm
Combined		**6.4 ppm + 0.139 Pa**	**6.4 ppm + 0.129 Pa**	**6.4 ppm + 5.0 Pa**	**6.4 ppm + 0.15 Pa**	**6.4 ppm + 0.187 Pa**	**6.4 ppm + 0.179 Pa**	**6.4 ppm + 5.0 Pa**	**6.4 ppm + 0.15 Pa**
Expanded to k=2		**12.8 ppm + 0.28 Pa**	**12.8 ppm + 0.26 Pa**	**12.8 ppm + 10.0 Pa**	**12.8 ppm + 0.30 Pa**	**12.8 ppm + 0.37 Pa**	**12.8 ppm + 0.36 Pa**	**12.8 ppm + 10.0 Pa**	**12.8 ppm + 0.30 Pa**
Absolute uncertainties									
Barometric pressure	B8	n/a	n/a	5 Pa	n/a	n/a	n/a	5 Pa	n/a
Vacuum	B7	0.025 Pa	n/a	n/a	n/a	0.025 Pa	n/a	n/a	n/a
Sensitivity	B13	0.012 Pa	0.012 Pa	0.012 Pa	0.012 Pa	0.012 Pa	0.012 Pa	0.012 Pa	0.012 Pa
Mass bell grease	B1c	0.100 Pa	0.100 Pa	0.100 Pa	n/a	n/a	n/a	n/a	n/a
Bell assembly density	B1d	0.045 Pa	n/a	n/a	n/a	0.045 Pa	n/a	n/a	n/a
Bell mass (manual)	B1a	n/a	n/a	n/a	n/a	0.16 Pa	0.16 Pa	0.16 Pa	n/a
Piston mass	B1b	0.080 Pa	0.080 Pa	0.080 Pa	n/a	0.080 Pa	0.080 Pa	0.080 Pa	n/a
Differential mode reference	B18	n/a	n/a	n/a	0.15 Pa	n/a	n/a	n/a	0.15 Pa

PG9602, 50 kPa/kg piston-cylinder

Typical pressure measurement uncertainty: ± (14 ppm + 0.7 Pa)

		When used with an AMH set				**When used with an manual mass set**			
Variable or parameter	**Uncertainity ID**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**
Full mass load: relative uncertainties		MS-AMH-100				MS-7002-100			
Mass (M)	B1	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm
Local G	B2	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Air density	B3	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a
Mass density	B4	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm
Resolution	B9	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm
PC Temperature	B10	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B11	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm
Effective area	B12	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm	5.5 ppm
Linearity	B14	2.50 ppm	2.50 ppm	2.50 ppm	2.50 ppm	2.50 ppm	2.50 ppm	2.50 ppm	2.50 ppm
Elastic deformation	B15	0.42 ppm	0.42 ppm	0.42 ppm	0.42 ppm	0.42 ppm	0.42 ppm	0.42 ppm	0.42 ppm
Thermal expansion	B16	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm
Stability Ae	B17	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Sensitivity	B13	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm
Type A	A1	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm
Combined		**6.8 ppm + 0.320 Pa**	**6.8 ppm + 0.293 Pa**	**6.8 ppm + 5.0 Pa**	**6.8 ppm + 0.15 Pa**	**6.8 ppm + 0.447 Pa**	**6.8 ppm + 0.428 Pa**	**6.8 ppm + 5.0 Pa**	**6.8 ppm + 0.15 Pa**
Expanded to k=2		**13.6 ppm + 0.64 Pa**	**13.6 ppm + 0.59 Pa**	**13.6 ppm + 10.0 Pa**	**13.6 ppm + 0.31 Pa**	**13.6 ppm + 0.89 Pa**	**13.6 ppm + 0.86 Pa**	**13.6 ppm + 10.0 Pa**	**13.6 ppm + 0.31 Pa**
Absolute uncertainties									
Barometric pressure	B8	n/a	n/a	5 Pa	n/a	n/a	n/a	5 Pa	n/a
Vacuum	B7	0.025 Pa	n/a	n/a	n/a	0.025 Pa	n/a	n/a	n/a
Sensitivity	B13	0.029 Pa	0.029 Pa	0.029 Pa	0.029 Pa	0.029 Pa	0.029 Pa	0.029 Pa	0.029 Pa
Mass bell grease	B1c	0.250 Pa	0.250 Pa	0.250 Pa	n/a	n/a	n/a	n/a	n/a
Bell assembly density	B1d	0.125 Pa	n/a	n/a	n/a	0.125 Pa	n/a	n/a	n/a
Bell mass (manual)	B1a	n/a	n/a	n/a	n/a	0.4 Pa	0.4 Pa	0.4 Pa	n/a
Piston mass	B1b	0.150 Pa	0.150 Pa	0.150 Pa	n/a	0.150 Pa	0.150 Pa	0.150 Pa	n/a
Differential mode reference	B18	n/a	n/a	n/a	0.15 Pa	n/a	n/a	n/a	0.15 Pa

PG9602, 100 kPa/kg piston-cylinder

Typical pressure measurement uncertainty: ± (20 ppm + 1.3 Pa)

		When used with an AMH set				When used with an manual mass set			
Variable or parameter	**Uncertainity ID**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**	**Absolute by Vac**	**Gauge**	**Absolute by ATM**	**Differential**
Full mass load: relative uncertainties		MS-AMH-100				MS-7002-100			
Mass (M)	B1	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm	2.5 ppm
Local G	B2	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Air density	B3	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a
Mass density	B4	0.38 ppm	n/a	n/a	0.38 ppm	0.38 ppm	n/a	n/a	0.38 ppm
Head (height)	B5	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm	0.35 ppm
Head (density)	B6	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm	0.23 ppm
Resolution	B9	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm	0.29 ppm
PC Temperature	B10	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm	0.45 ppm
Verticality	B11	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm
Effective area	B12	8 ppm	8 ppm	8 ppm	8 ppm	8 ppm	8 ppm	8 ppm	8 ppm
Linearity	B14	3.00 ppm	3.00 ppm	3.00 ppm	3.00 ppm	3.00 ppm	3.00 ppm	3.00 ppm	3.00 ppm
Elastic deformation	B15	1.23 ppm	1.23 ppm	1.23 ppm	1.23 ppm	1.23 ppm	1.23 ppm	1.23 ppm	1.23 ppm
Thermal expansion	B16	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm	1.11 ppm
Stability Ae	B17	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm	0.5 ppm
Sensitivity	B13	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm	0.14 ppm
Type A	A1	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm	1 ppm
Combined		**9.2 ppm + 0.634 Pa**	**9.2 ppm + 0.586 Pa**	**9.2 ppm + 5.0 Pa**	**9.2 ppm + 0.16 Pa**	**9.2 ppm + 0.890 Pa**	**9.2 ppm + 0.856 Pa**	**9.2 ppm + 5.1 Pa**	**9.2 ppm + 0.16 Pa**
Expanded to k=2		**18.3 ppm + 1.27 Pa**	**18.3 ppm + 1.17 Pa**	**18.3 ppm + 10.1 Pa**	**18.3 ppm + 0.32 Pa**	**18.3 ppm + 1.78 Pa**	**18.3 ppm + 1.71 Pa**	**18.3 ppm + 10.1 Pa**	**18.3 ppm + 0.32 Pa**
Absolute uncertainties									
Barometric pressure	B8	n/a	n/a	5 Pa	n/a	n/a	n/a	5 Pa	n/a
Vacuum	B7	0.025 Pa	n/a	n/a	n/a	0.025 Pa	n/a	n/a	n/a
Sensitivity	B13	0.058 Pa	0.058 Pa	0.058 Pa	0.058 Pa	0.058 Pa	0.058 Pa	0.058 Pa	0.058 Pa
Mass bell grease	B1c	0.500 Pa	0.500 Pa	0.500 Pa	n/a	n/a	n/a	n/a	n/a
Bell assembly density	B1d	0.241 Pa	n/a	n/a	n/a	0.241 Pa	n/a	n/a	n/a
Bell mass (manual)	B1a	n/a	n/a	n/a	n/a	0.8 Pa	0.8 Pa	0.8 Pa	n/a
Piston mass	B1b	0.300 Pa	0.300 Pa	0.300 Pa	n/a	0.300 Pa	0.300 Pa	0.300 Pa	n/a
Differential mode reference	B18	n/a	n/a	n/a	0.15 Pa	n/a	n/a	n/a	0.15 Pa

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