A Force Balanced Piston Gauge for Very Low Gauge and Absolute Pressure

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Abstract
A new piston gauge covers the range of gauge and absolute pressure from less than 1 Pa to 15 kPa. The instrument uses a mass comparator to measure the force resulting from differential pressure across a non-rotating piston in a close fitting cylinder. Resolution is up to 1 mPa and measurement uncertainty as low as $\pm (5\ \text{mPa} + 3 \cdot 10^{-5} p)$ is estimated. The instrument is calibrated through the determination of mass and piston-cylinder effective area. An automated pressure controller is included. Integrated software allows multi-point comparisons with another device to be run unattended. The system has been used to test capacitance diaphragm gauges in a variety of ranges.

1. Introduction

The range of pressure from less than 1 Pa to 5 kPa relative and absolute is important to many industrial processes. There are a wide variety of process instruments and transfer standards in this range that require calibration. However, there is a lack of fundamental standards to support them. Conventional piston gauges are effective to a minimum of about 5 kPa. Manometers cover lower pressures but uncertainties increase quickly as column height decreases and their application, particularly for very low pressure, is not practical in most calibration laboratories.

This paper describes a new fundamental pressure standard intended to cover the range of relative and absolute pressure from less than 1 Pa to 15 kPa. Operation is fully automated and the complete system can be installed on a typical calibration laboratory bench.

2. General Principle and Design

The standard includes two major components (see Figure 1): the pressure measuring portion (left) and the pressure controlling portion (right). The overall system is interfaced with and controlled by a dedicated personal computer running specialized software.

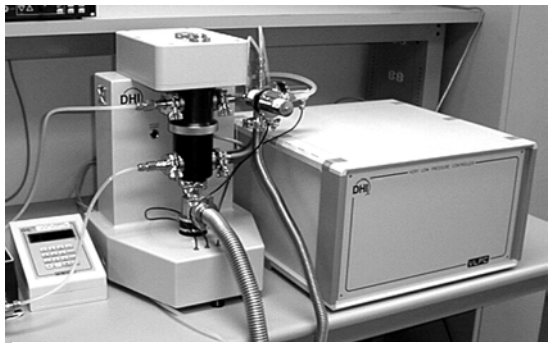

Figure 1. Force balanced piston gauge system.

The pressure measuring portion operates on the piston gauge principle. However, the force resulting from pressure on the piston is measured by a force balanced load cell rather than balanced against masses subjected to the acceleration due to gravity (see Figure 2). For this reason, the measuring portion is designated a force balanced piston gauge (FPG).

The piston-cylinder is suspended below the load cell. Rather than rotating the piston in the cylinder, the piston-cylinder gap is conical and gas flow through the gap is used to center the piston and avoid dry static friction [1,2]. The force across the piston is transmitted to the load cell through a coupling system that holds the piston at its center of gravity. There are two independent, symmetrical chambers at either end of the piston-cylinder. The lower chamber is held at

atmosphere or vacuum while the pressure to be measured is applied to the upper chamber. The net force resulting from the difference in pressure between the two chambers is transmitted to the load cell through the coupling. The value of the pressure is calculated from the effective area of the piston-cylinder and the net force value.

The FPG system is operated in three measurement modes. In gauge mode, the lower chamber is connected to the low side of the device under test and left open to atmosphere. In absolute mode, the lower chamber is connected directly to a vacuum pump and the residual vacuum is measured by a capacitance diaphragm gauge. The residual pressure obtained with a turbo-molecular pump is typically 0.04 Pa (0.3 mTorr). In absolute differential mode, the lower chamber is connected to the low side of the device under test and the two are evacuated together with a single common vacuum source. This mode has the advantage of allowing a comparison at vacuum reference pressure with no influence of uncertainty on vacuum measurement in the uncertainty on the differential pressure.

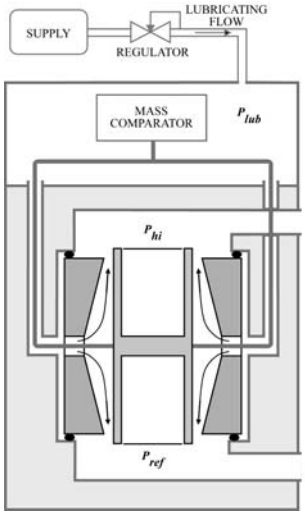

Figure 2. Non-rotating piston principle.

3. Instrument Description

3.1 Piston-cylinder with conical gap

The FPG piston-cylinder is made of tungsten carbide and has an effective diameter of 35 mm. The piston is straight while the cylinder is tapered symetrically from the middle in both directions. The gap between the piston and the cylinder goes from about 6 micrometers at the center to less than 1 micrometer at the ends. An independent lubricating pressure causes gas to flow through the piston-cylinder gap from the middle of the cylinder (see Figure 2). The lubricating pressure is supplied to a hermetic chamber around the load cell. The gas flows from this chamber through two connecting passages to the center of the cylinder through opposing holes in the cylinder wall. These holes and the lubricating gas connecting passage are shared by the mechanical coupling system that connects the piston to the load cell. The lubricating pressure is regulated to 40 kPa above the reference pressure (40 kPa absolute for absolute mode operation and 40 kPa gauge for gauge mode operation). The gas flow through the conical piston-cylinder gap centers the piston in the cylinder eliminating the need to rotate the piston [1, 2]. As the piston-cylinder gap is very small, the maximum gas flow towards the pressure measurement chambers does not exceed 1 ml/min. The lubricating gas flow into the measured pressure is easily handled by the pressure control system and/or reference vacuum pump.

The mechanical connection of the piston to the balance is by a double universal joint coupling system. This coupling provides two rotational and two translational degrees of freedom for the piston which is mounted about its center of gravity. This allows the piston to center itself in the cylinder while preventing rotation about its axis.

3.2 Load cell

The load cell is purchased from a mass comparator manufacturer [3]. It has a full span of 2 kg. The piston and connecting system mass use 500 g of the span and the remaining 1 500 g is used to measure the force resulting from differential pressure across the piston. The load cell is equipped with a reference mass and mechanism to load and unload it automatically. This allows the load cell span to be calibrated at any time under actual operating conditions. Many precautions have been taken to obtain the best possible performance from the load cell. It is mounted on a thick aluminum base plate fitted with a finned natural convection plate to maximize temperature stability and homogeneity. The base plate attaches to the bottom of a hermetic chamber enclosing the load cell which is supplied with the piston-cylinder lubricating gas. Following the load cell manufacturer's recommendation, the gas (typically air or nitrogen) is conditioned to 50 % relative humidity to avoid interference from static effects associated with a dry operating environment. By design, even when the FPG is measuring absolute pressure, the load cell is never subjected to vacuum. This was found to be indispensable as, even after an extensive temperature stabilization period, the thermal conditions in the load cell resulting from the application of vacuum were found to make its behavior unpredictable.

The bulk of the development work was performed with load cell resolution of 1 mg. Once the load cell conditioning issues just described had been identified and addressed, it became clear that the overall system was capable of performance well inside of 1 mg. In consequence, resolution was later increased to 0.1 mg with excellent results. The higher resolution of 0.1 mg is now offered as an option on the system.

3.3 Pressure controller

The pressure controlling portion of the standard is in a separate enclosure. The pressure control principle is the adjustment of flow across a flow restriction (see Figure 3). The upstream side of the restriction is connected to the upper FPG pressure chamber and the downstream side is connected to the lower FPG pressure chamber and to atmosphere for gauge mode operation or to an independent vacuum source for absolute mode operation. There are several flow restrictions of different conductance and the one appropriate for the pressure range being explored is selected automatically. Two mass flow controllers, one for rough pressure control and the other, lower range, for fine pressure control, are used in parallel to adjust the flow in a feedback loop with control based on the difference between the pressure set point and the FPG pressure measurement. A two stage pressure regulator whose second stage is referenced to the downstream side of the flow restrictions supplies a stable input pressure to the mass flow controllers.

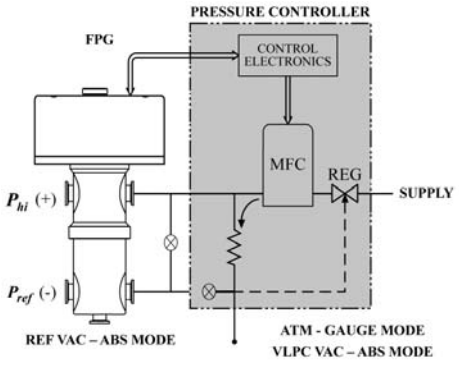

Figure 3. Pressure controller principle.

3.4 System controller

A personal computer serves as a dedicated system controller. It is interfaced with the FPG system components by RS232. Specialized software reads and displays all FPG outputs including: lubricating gas pressure, lubricating gas temperature, lubricating gas humidity, piston-cylinder temperature, load cell output, reference vacuum capacitance diaphragm gauge output. These outputs and piston-cylinder characteristics in memory are used to calculate the current FPG measured pressure real time. Individual variables are monitored to alert the operator to excessive change or when normal operating limits are exceeded. The software also operates FPG valves and the load cell reference mass loading mechanism. These are used to automate common system maintenance and diagnostic functions such as zeroing the load cell, calibrating the span of the load cell with the reference mass and switching the lubricating pressure regulator when changing measurement modes. Finally, the software supports automatic data acquisition from analog and digital devices under test with custom dwell and data averaging time settings at each point. Averaging readings over time integrates random pressure control noise in the system and increases the reproduceability of FPG measurements with a test instrument. Complete multi-increment test scripts in any sequence can be set up and executed allowing complex and/or lengthy comparisons to run unattended.

4. Calculation of the Measured Pressure

The basic calculation of the pressure measured by the FPG follows the standard equation of a conventional piston gauge:

$$\Delta P = F/A_e$$

Where:

ΔP:	Differential pressure between the upper and lower FPG chambers	[Pa]
F:	Force applied to the load cell as a result of the differential pressure	[N]
Ae:	Effective area of the piston-cylinder at 20 ºC	[m^2]

The force, F, measured by the load cell when it displays a number of counts, N, is calculated using a calibration coefficient, Kcal, following:

$$K_{cal} = g_l \bullet (1 - \rho_{lub} / \rho_m) \bullet (m_{cal}/N_{cal})$$

Where:

g_l:	Acceleration due to gravity at the location of calibration of the load cell	[m/s^2]
ρ_{lub}:	Density of the lubricating gas in the calibration conditions	[kg/m^3]
ρ_m:	Density of the stainless steel load cell calibration mass	[kg/m^3]
m_{cal}:	True mass of the load cell calibration mass	[kg]
N_{cal}:	Change in the number of counts output by the load cell when the calibration mass is loaded	[count]

The force is calculated following:

$$F = K_{cal} \bullet N$$

Where:

N:	Number of counts displayed by the load cell representing the force measured (one count representing the force corresponding to a mass of 1 or 0.1 mg loaded on the load cell under the calibration conditions)	[counts]
K_{cal}:	Calibration coefficient of the load cell under the calibration conditions (density of the gas around the reference mass or masses when the calibration is performed, local acceleration due to gravity) at the calibration location	[N/count]

The expanded equation for the calculation of the differential pressure measured by the FPG with the piston-cylinder at temperature ϕ, is:

$$\Delta P = K_{cal} \bullet (N + \delta N_1 + \delta N_2 + \delta N_3) / A_{e(20°C)} \bullet [1+ (\alpha_p + \alpha_c) \bullet (\phi - 20)]$$

Where:

αp, αc:	Linear thermal expansivity of the piston and the cylinder	[K-1]
δN_1:	Change in buoyancy on the load cell and the piston coupling parts due to the variation in lubricating gas pressure since the system was zeroed	[count]
δN_2:	Change in the drag force resulting from the flow of lubricating gas acting on the upper and lower piston-cylinder gap shape since the system was zeroed	[count]
δN_3:	Change in gas buoyancy on the piston due to the change in gas density in the lower chamber since the system was zeroed (this value is zero in absolute measurement mode)	[count]

The expressions for the force correction terms are:

$$\delta N_1 = -K_b \bullet (P_{lub} - P_{lub0})$$

$$\delta N_2 = K_d \bullet [(P_{lub} - P_{ref}) - (P_{lub0} - P_{ref0})]$$

$$\delta N_3 = V \bullet g_l [(P_{ref}/T_{ref}) - (P_{ref0} /T_{ref0})] \bullet M_{gas}/K_{cal} \bullet Z_{gas\ (Pref0,Tref0)} \bullet R$$

All three terms remain zero if the current operating conditions do not change after the load cell is zeroed at zero differential pressure. In typical operation, the uncertainty on these second order corrections does not contribute significantly to the uncertainty on the FPG measured pressure.

5. Calibration

Calibration of the FPG consists of determining the effective area of the piston-cylinder assembly and finding the value of the calibration coefficient of the load cell.

The sensors used to make the measurements used for the calculation of systematic corrections, including piston-cylinder temperature and lubricating gas conditions, are also calibrated. These are routine pressure, temperature and humidity calculations.

5.1 Piston-cylinder effective area determination

As the FPG operates up to 15 kPa, the effective area of its piston-cylinder can be determined by comparison with a conventional piston gauge. A gas operated piston gauge with a 20 cm^2 piston-cylinder whose effective area is known within $\pm 9 \cdot 10^{-6}$ (k = 2) has been used for this purpose. The comparison process is the same in principle as the crossfloat process commonly used to compare piston gauge effective areas.

The crossfloat is conducted in gauge mode to avoid the uncertainties associated with the measurement of residual vacuum on both devices. The pressure underneath the reference piston gauge piston is applied to the upper chamber of the FPG (see Figure 4). The bell jar normally used to operate the reference piston gauge in absolute mode is installed over its masses and piston and connected to the FPG lower chamber. Though open to atmosphere, creating this common circuit helps assure that the instantaneous static pressure on the FPG and the piston gauge is the same.

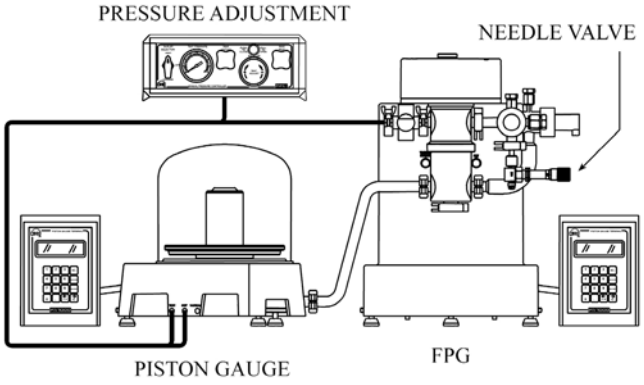

Figure 4. Set up of piston gauge and FPG comparison.

Before floating the piston gauge piston at each pressure, a procedure is used to eliminate the effect of the lubrication gas flow into the FPG upper chamber on the natural drop rate of the piston gauge. The pressure value of the comparison point is applied to the FPG upper chamber and a bypass valve on the tube connecting to the piston gauge is closed. With the FPG upper chamber so isolated, a needle valve is used to adjust a leak from the FPG upper chamber to atmosphere such that the FPG pressure reading is stable. The leak then compensates the flow of lubricating gas into the upper chamber so that when the bypass valve on the connecting tube is opened, there is no flow in the tube and the pressure between the two instruments is in equilibrium. The piston gauge is used in this manner to apply pressures from its 5 kPa low point up to the FPG's 15 kPa maximum pressure. The ratio the FPG piston-cylinder effective area to the reference piston gauge effective area can then be determined for each point and the FPG piston-cylinder effective area calculated from the reference piston-cylinder effective area and the ratios. The difference in effective area ratios observed when performing the crossfloat in absolute mode or gauge mode is less than the uncertainty associated with the measurement of the residual vacuum on the FPG and the piston gauge.

5.2 Load cell calibration

To find the calibration coefficient, Kcal, of the load cell, first the true mass of the load cell's built-in reference mass is determined independently by double substitution comparison with a known mass. The calibration coefficient of the load cell is then determined by loading the reference mass on the load cell, reading the counts output by the load cell and calculating the calibration coefficient, K_{cal}, taking into account lubricating gas pressure, temperature and humidity as described in the Calculation section above. Since the reference mass can be loaded and unloaded automatically onto the load cell at any time and lubricating gas conditions are monitored real time, the load cell calibration coefficient can be determined at any time, in both gauge and absolute mode operation, under actual operating conditions.

The coefficients, K_b and K_d, used in calculating the force correcting terms are determined experimentally by observing the load cell output while varying the lubricating pressure or the reference pressure by a magnitude about 100 times greater than that experienced in normal operation.

6. Measurement Uncertainty

The uncertainty analysis for pressure measured by the FPG is summarized in Table 1. The full commentary of the analysis is beyond the scope of this paper and will be the subject of a future publication.

The uncertainty in the pressure measured by the 0.1 mg resolution FPG, with a coverage factor of two, is estimated to be:

Gauge and absolute differential modes:

$$\pm (5 \text{ mPa} + 3 \bullet 10^{-5} p)$$

Absolute mode:

$$\pm (8 \text{ mPa} + 3 \bullet 10^{-5} p)$$

The constant term is increased significantly in the 1 mg resolution version.

The dominant uncertainties in the pressure measured by the FPG are the resolution and linearity of the load cell and the uncertainty on the effective area of the piston-cylinder. The load cell resolution and a linearity component are fixed values across the range while a second linearity component and the uncertainty in the piston-cylinder effective area are relative to the measured pressure.

The absolute and relative uncertainties are roughly equal at 250 Pa with the absolute uncertainty becoming dominant below this value.

The reason for a higher uncertainty estimate in absolute mode is the contribution of the uncertainty on the measurement of the residual vacuum in the FPG lower chamber. This uncertainty is not present in the other operating modes in which the readings are purely differential.

Table 1. FPG uncertainty analysis.

Variable or Parameter	Unc Type	Gauge Mode	Abs Diff Mode	Abs Mode
Full Mass Load -	---------	1.5 kg	1.5 kg	1.5 kg
(relative unc's)		ppm	ppm	ppm
Cal Mass (M)	B1	2.5	2.5	2.5
Local G	B2	2.5	2.5	2.5
Air Density(lube)	B3	0.15	0.11	0.11
Mass Density	B4	2.09	0.58	0.58
Head (height)	B5	0.35	0.35	0.35
Head (density)	B6	0.23	0.23	0.23
PC Temp	B7	0.5	0.5	0.5
Verticality	B8	0.1	0.1	0.1
Effective Area	B9	13	13	13
Linearity	B10	2.5	2.5	2.5
Elastic Deformation	B11	0	0	0
Thermal Expansion	B12	0.25	0.25	0.25
Stability Mass	B13	0.1	0.1	0.1
Stability Ae	B14	2	2	2
Sensitivity	B15	0.11	0.11	0.11
Type A	A1	0	0	0
COMBINED		14.02 ppm + 2.52 mPa	13.88 ppm + 2.52 mPa	13.88 ppm + 3.85 mPa
COMBINED & EXPANDED FOR (K=2)		28.05 ppm + 5.03 mPa	27.76 ppm + 5.03 mPa	27.76 ppm + 7.70 mPa
(absolute unc's)	---------	mPa	mPa	mPa
Resolution (N)	B16	0.29	0.29	0.29
Vacuum (zero drift)	B17	0	0	1.5
Linearity (N)	B18	2.5	2.5	2.5
Vacuum (slope)		0	0	2.5

7. Comparisons and Calibrations

7.1 Comparison with conventional piston gauge

The FPG has been compared in gauge mode with a conventional piston gauge over the two instruments' common pressure range of 5 to 15 kPa. Figure 5 shows the difference between the two in two runs. The differences are inside of the estimated uncertainty in the piston gauge (see Figure 5). Of course, the zero point shown in the data was not defined by the piston gauge. It was defined by connecting the FPG upper and lower chambers together to establish zero differential pressure. This point is included in the comparison to emphasize that a reference point well below the 5 kPa minimum pressure of the piston gauge was available and is consistent with other points measured.

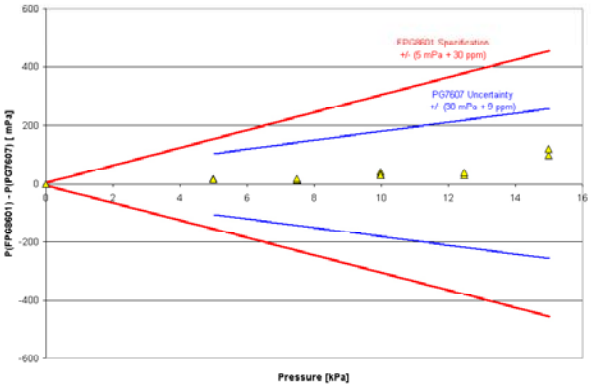

Figure 5. Piston Gauge – FPG Comparison Results.

7.2 Calibration of capacitance diaphragm gauges in different modes and ranges

The FPG's ability to run automated tests has been used to run extensive tests with capacitance diaphragm gauges (CDG) in various ranges and operating modes. For example, Figure 6 shows measurements made over a three day period using an FPG with 10 mPa resolution in all three operating modes (gauge, absolute differential, absolute) with a 1.3 kPa (10 Torr) capacitance diaphragm gauge used as a transfer standard in international comparisons [4].

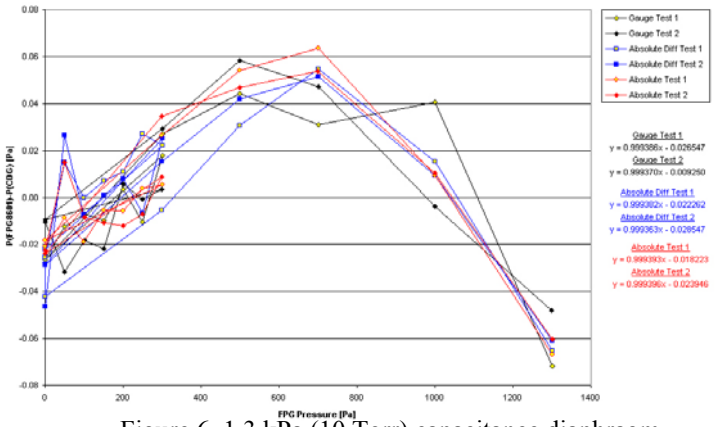

Figure 6. 1.3 kPa (10 Torr) capacitance diaphragm gauge calibration with 10 mPa resolution FPG.

The measurements were performed twice for each of the three operating modes. Figure 6 plots the residuals relative to a best fit linear regression for each test. The equations of the linear fits are in the margin. The plots show that the form of the CDG response to differential pressure is not affected by line pressure and the first order coefficients of the different linear regressions reflect that the CDG span is also very stable with line pressure. The repeated tests in each operating mode also reflect the reproduceability of the FPG system measurements. The disagreement between the absolute and gauge plots at pressures under 100 Pa are due to the fact that no thermal transpiration correction was applied to the data to take into account the difference between the CDG temperature regulated at 45 ºC and the FPG operating at 20 ºC.

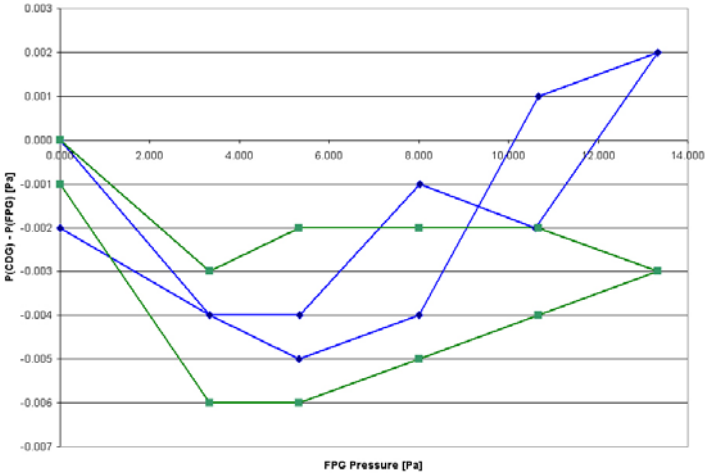

Figure 7. 13 Pa (100 mTorr) capacitance diaphragm gauge calibration with 1 mPa resolution FPG.

Figure 7 shows two consecutive runs on a 13 Pa (100 mTorr) CDG using the 0.1 mPa FPG in absolute differential mode and applying a thermal transpiration correction for the difference in temperature between the FPG and the CDG. The CDG readings are "as received" after zeroing prior to the first run.

8. Conclusions

The FPG provides new capability in the pressure domain below conventional piston gauges while overlapping with them over a sufficient range to be compared with them precisely. It can be characterized from a reference mass and its piston-cylinder's effective area, providing an alternate fundamental standard in the low pressure range. At the same time it is reasonably portable and simple to operate, allowing it to be readily intercompared with difficult to transport standards operating on different principles at other laboratories. Intercomparisons of FPG with primary standards in several national laboratories, particularly under the conventional piston gauge range, are both planned and underway.

In the traditional calibration laboratory, FPG offers a new tool for the support of transfer standards, particularly high performance capacitance diaphragm gauges. In this environment, the ability to automate tests is especially important.

The original FPG development was performed with a 1 mg resolution load cell. After evaluation revealed performance that appeared to be inside of 1 count of resolution, the resolution was expanded to 0.1 mg. With the higher resolution, it has become very clear that the system's limitation is not the piston-cylinder or its coupling system and that improvements in load cell zero stability would further improve the performance of the FPG at the low end.

Likely further developments include expanding the range of the FPG to higher pressures.

9. References

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3. Mettler Toledo GmbH, CH-8686, Greifensee, Switzerland.
4. Model 698A S/N 95198220 manufactured by MKS Instruments, 6 Shattuck Rd., Andover, MA 01080, USA; property of Mittatekniikan Kesku, Center for Metrology and Accreditation, Lonnrotinkatu 37, FIN-00181 Helsinki, Finland.