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A METHOD OF TRACEABILITY FOR A FPG8601 FORCE BALANCED PISTON GAUGE TO DEFINE PRESSURES IN THE RANGE FROM 1 PA TO 15 KPA IN GAUGE AND ABSOLUTE MEASUREMENT MODES

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Abstract – The FPG8601 has become an important reference for many primary measurement laboratories in a pressure range from approximately 1 Pa to 15 kPa in both gauge and absolute measurement modes. The FPG8601 measurement range spans the gap between the traditional measurement regimes of ‘pressure’ and ‘vacuum’, a range where other primary pressure standards either do not exist or do not have uncertainties sufficient to support the FPG8601 traceability. The limitations of available primary standards create a challenge for FPG8601 users needing to define traceability in this range. This paper suggests a method of maintaining traceability using force, dimensional and primary pressure measurements in a manner different from that normally used for traditional ‘floating’ piston gauges.

Keywords**: Pressure, Vacuum, Traceability**

1. INTRODUCTION

Traceability in pressure is achieved primarily through piston gauges and manometers. For low absolute pressures, however, either the uncertainties of traditional standards are too high or, as with a piston gauge, the low end of the measurement range is too high due to the minimum mass load (mass of the piston and mass carrier). The absolute pressure range supported by FPG8601 is from a few Pascal to 15 kPa. This range helps fill a gap between the traditional style piston gauges and lower pressure references such as spinning rotor gauges and expansion systems. There are manometers that are comparable in both precision and range to an FPG8601, such as the low pressure oil UIM (ultrasonic interferometer manometer) at NIST, however such systems are rare and are not commercially available.

Since the FPG8601 fills a traceability gap for many high end laboratories, including several NMIs, maintaining traceability is a pertinent issue. This paper describes the reasoning and practices behind the method of traceability for an FPG8601. Included are discussions of FPG8601 design with emphasis on traceability, the method for maintaining this traceability, and measurement test results supporting this method.

This paper focuses on the primary traceability of effective area and force in greater detail than has been previously published. Several additional publications including [8] provide further detail with respect to ancillary traceability required to support the FPG8601.

2. FORCE BALANCED PISTON GAUGE DESIGN

The FPG system, shown in Fig. 1, includes the pressure measuring portion (center) and the pressure controlling portion (right). The overall system is interfaced with and controlled by a dedicated personal computer running specialized software.

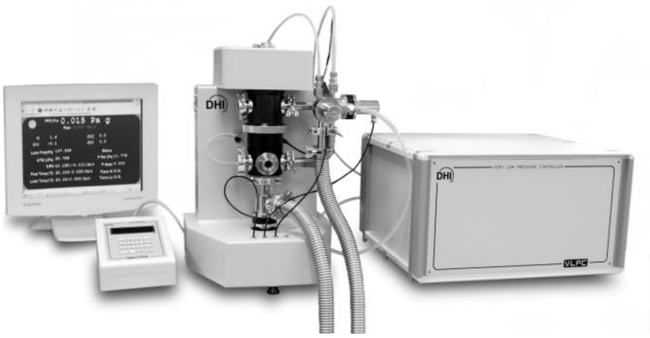

Fig. 1. Force balanced piston gauge system.

The FPG pressure measuring portion operates on the piston gauge principle, measuring a differential pressure on a piston by suspending it from a force balance [1]. Differential pressure is measured by connecting high test pressure to the top chamber and reference test pressure to the lower chamber. The difference in pressures acting on the effective area of the piston generates a change in force measured by the force balance. The non-rotating piston is attached at its center of gravity to the force balance by a linkage and is centered in the cylinder by a small lubrication gas flow through a double conical cylinder shown in Fig. 2 [2]. Absolute measurements are made by applying a vacuum to the reference pressure chamber and adding the value of the residual vacuum, as measured by a capacitance diaphragm gauge (CDG), to the differential pressure value to determine the resulting absolute pressure in the top chamber.

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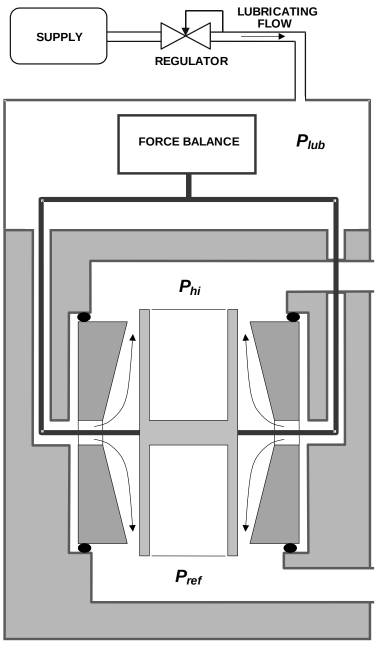

Fig. 2. FPG pressure measuring portion.

While detailed descriptions of FPG8601 operating principles and applications are available in references [1] and [6], a discussion of design topics particularly relevant to traceability follows.

2.1 Fundamental operation

The FPG8601 is designed to operate in the most fundamental way possible. To this end, the indicated differential pressure shown in equation (1) is a direct result of the force exerted on the piston, as measured by the force balance, and the effective area of the piston-cylinder [2]. The small correction terms (δN_1, δN_2, δN_3) result only from changes in conditions from the time of tare (zero) and the magnitudes are typically on the order of the resolution of the system (<1 part in 10^6).

$$\Delta P = \frac{K_{cal}\left(N + \delta N_1 + \delta N_2 + \delta N_3\right)}{A_{(20°C)}\left[1 + \left(\alpha_p + \alpha_c\right)\cdot\left(\theta - 20\right)\right]} \qquad (1)$$

Where:

- N: Number of counts indicated by the force balance representing the force measured.
- K_{cal}: Calibration coefficient of the force balance under the calibration conditions at the calibration location.
- α_p, α_c: Linear thermal expansion coefficients of the piston and the cylinder.
- Θ: Temperature of piston-cylinder [°C]
- $\delta N_{1,2,3}$: Changes on the force balance due to changes in buoyancy and drag force.

Determination of $A_{(20°C)}$ is discussed in section 3.1.

2.2 Lubrication pressure and flow

While a traditional piston gauge operates with lubrication pressure varying from test pressure to reference pressure (ambient or vacuum), the FPG operates with a supplied lubrication pressure regulated to 40 kPa above the reference pressure. This allows the force balance to operate in conditions well above vacuum in absolute measurement mode, improving consistency and stability. As a result of the constant lubrication pressure, lubrication flow behavior and typical flow regimes are relatively insensitive to test pressure.

Although calculation of an absolute effective area by means of typical analytical solutions [3] is not presented in this paper, equations such as these are helpful in estimating the sensitivity of system parameters and operating conditions. Using general equations for calculation of effective area for a nominal cylindrical piston and double conical cylinder with a gap that tapers from 5 µm to 0.8 µm, it may be shown that the sensitivity of test pressure on effective area across the full measurement range is less than 1 part in 10^6 in gauge mode and approximately 3 parts in 10^6 in absolute mode.

2.3 Geometry

The tapered gap resulting from the conical cylinder of the FPG produces the centering force that maintains piston position. The resulting pressure distribution is nonlinear, with half the pressure drop occurring in the last millimeter or so of the gap. This is particularly useful for low absolute pressure points since the majority of the gap is in the viscous realm (Knudsen number, Kn≤1) whereas a traditional piston gauge would experience molecular flow conditions through much if not all of the gap at low absolute pressures. The behavior of the FPG throughout its operational range is designed to be consistent and uniform regardless of reference pressure.

2.4 Mode of operation

In a similar manner to studying sensitivity to test pressure variations, as in section 2.2, analytical solutions may be used to estimate the sensitivity to measurement mode. As such, investigating a model of nominal geometry with uniform cylindrical tapers from 5 µm to 0.8 µm, the predicted difference in effective area between gauge and absolute modes is estimated to be less than 8 parts in 10^6 with the absolute mode effective area being the smaller.

2.5 Force balance calibration

The design of the linkage between the force balance and the piston permits automated loading of an internal calibration mass used to determine the calibration coefficient, K_{cal}. The mass is loaded coaxially with the piston to ensure direct comparison of force between operation and calibration.

3. CALIBRATION AND TRACEABILITY FOR A FORCE BALANCED PISTON GAUGE

3.1 Effective area determination

When calibrating traditional piston gauges it is necessary to measure and predict changes in effective area over a pressure range. This is due to the fact that the pressure distribution in the piston-cylinder gap changes directly with respect to changes in measured pressure. As such, effective area tests typically include crossfloat test points that are dispersed throughout the working range of the piston-cylinder being calibrated. As pressure increases the geometry of the piston-cylinder gap changes and the pressure distribution may change significantly.

As it is described in section 2.2 of this paper, the tapered gap of the FPG8601 piston-cylinder is lubricated with a constant regulated pressure above the measured pressure. Pressure induced deformation of the piston-cylinder is negligible so changes in effective area are almost solely due to changes in the distribution of pressure in the gap. Since the pressure distribution does not change significantly with pressure it is possible to consider that the effective area is uniform throughout the measured range and between gauge and absolute modes. Whether the effective area is determined by crossfloat or by dimensional characterization these assumptions play an important role in the method of effective area determination.

3.1.1 Effective area by crossfloat comparison

Effective area determination by crossfloat for a traditional 'floating' piston-cylinder can be performed such that the effective area variable is isolated from other influences. This is not the case with an FPG8601 where all parameters may influence the effective area determination. As a result all sensors including mounting post temperature measurement, force balance linearity, and lubrication chamber sensors must be adjusted as well as possible before an effective area determination is made.

To determine the effective area a DHI PG7607, 5kPa/kg, 50 mm diameter, piston-cylinder is used. The lowest pressure for the PG7607 is 5 kPa (1 kg mass load). Fig. 3 illustrates the crossfloat setup between an FPG8601 and a PG7607. The nominal effective area at 20 °C of 980.516 mm^2 is used as an initial value. The FPG8601 is zeroed and spanned using the internal calibration mass and comparison points are taken at 5, 7.5, 10, 12.5 and 15 kPa in gauge mode.

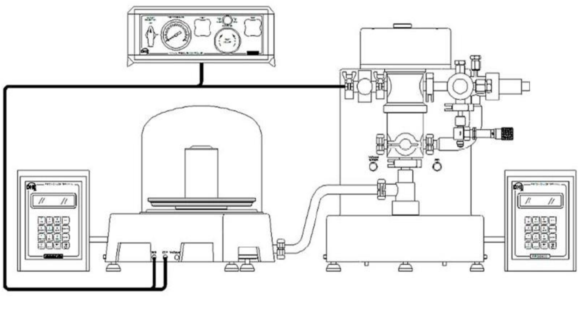

Fig. 3. PG7607 – FPG8601 comparison set-up.

The comparison is similar to crossfloat comparisons using traditional piston gauges. A significant exception to this is the lubrication gas exiting the FPG8601 piston-cylinder that could cause a pressure gradient due to flow in the connections between the FPG and the reference piston gauge. To create a static pressure condition a metering valve is used to bleed the lubrication flow on the high side by venting it to atmosphere. Since the gas flow exiting the piston-cylinder annulus is typically on the order of 0.5 sccm, the needle valve must have very fine control.

The procedure for taking each point is to set the pressure with the PG7607, then stabilize the output of the FPG8601 using the metering valve. Once stable the data can be taken. Each point is taken three times to ensure the test is repeatable. The nominal effective area is then adjusted by slope of the average pressure differences. Since typical FPG8601 piston-cylinders are manufactured within 50 parts in 10^6 of nominal, the adjustment is usually small.

Table 1 shows the average of deviations taken on DHI FPG8601 SN 101 over five calibrations in a five year time frame. The data supports the presumption that there is no significant pressure dependency on effective area from section 2.2. An apparent pressure dependency during crossfloat indicates a problem such as a leak or an error in balance output not detected in the linearity test.

Table 1. Average of deviations from five comparisons between FPG8601 SN 101 and PG7607 over a five year period.

Pressure	Average	1 std dev
[Pa]	[parts in 10^6]	[parts in 10^6]
5000	-0.1	2.8
7500	-0.9	2.4
10000	0.2	1.9
12500	-0.9	3.5
15000	-1.1	2.4

3.1.2 Effective area by dimensional characterization

Considering the 35 mm diameter of the FPG8601 piston-cylinder it is possible to perform dimensional measurements with low enough uncertainty to serve as a primary technique for determining effective area. There are a number of documented cases where 35 mm piston-cylinders for traditional piston gauges have been successfully dimensionally characterized as early as the mid 1980's. Included in these is DHI's 10 kPa/kg 35 mm diameter piston-cylinder performed by NIST (US) and LNE (France)[6].

There are two significant differences between dimensional characterization of FPG8601 piston-cylinders and traditional 35 mm piston-cylinders. The first is that the FPG8601 cylinder is conical. The second is that the pressure distribution starts at the middle of the piston-cylinder engagement length with pressure dropping towards test on the high side and reference on the lower. These differences can significantly affect the location and amount of dimensional measurements made and how they are applied to determine the effective area.

One advantage of determining effective area by crossfloat is that systematic errors in slope introduced by force or temperature measurement are absorbed by the effective area determination. Although a dimensional characterization would be necessary to define a FPG8601 as a fundamental reference in pressure, these systematic errors would no longer be absorbed in the process.

3.2 Internal reference mass

As is discussed in section 2.5 run time traceability in mass is maintained by the use of an internal calibration mass that is approximately 770 grams. The reference mass is re-calibrated at intervals based on the stability of the mass and is usually performed whenever the FPG8601 is re-calibrated as a whole.

During normal operation the balance is zeroed with pressure equalized between the upper and lower chambers. Zeroing the balance and determining the force balance span with the reference mass allow real time traceability in mass. This can occur before and during a pressure calibration.

3.3 Force balance linearity and repeatability

In addition to performing zero and span operations, it is important to ensure the force balance is linear and repeatable. The linearization is performed with a dedicated bracket installed in place of the piston-cylinder and a linearization mass set. The linearization mass set includes one 100 gram, two 200 gram, and four 500 gram masses to test and possibly adjust the linearity from 0.5kg to 2kg in 100 gram increments. The balance is linearized in this range because the mass of the piston, which is tared during operation, is approximately 500 grams.

In the linearization test the force balance is zeroed and spanned before the test is begun. The linearity is adjusted using the balance manufacturer's software, however this normally occurs only when the FPG8601 is initially characterized.

4. UNCERTAINTY ANALYSIS

Reference [8] presents a complete uncertainty analysis of an FPG8601. This section presents a more detailed look at the uncertainty in effective area considering the method of traceability described in the previous section. The uncertainty in force is also examined, considering the assumption that the balance output represents the force created by the difference in pressure between the measure and reference side of the piston-cylinder.

4.1 Uncertainty in effective area

Reference [8] states that the uncertainty in effective area is ±26 parts in 10^6 at k=2, approximating 95% confidence. Normally for a traditional piston gauge with 35 mm diameter, uncertainties in effective area are on the order of ±10 parts in 10^6 or less. There are a number of reasons the uncertainty in effective area is larger for an FPG8601.

One reason for the greater uncertainty is that an FPG8601 crossfloat result is based on the difference in pressure between the FPG8601 and the reference. Therefore the full uncertainty in pressure of the reference transfers to the effective area of the FPG8601. The uncertainty in pressure output of a PG7607 piston gauge, used to calibrate FPGs at DHI is approximately ±(0.05 Pa + 9 parts in 10^6 of reference pressure). In addition to the uncertainty of the reference, type A uncertainties of the test are also included.

Since the effective area is determined using FPG8601 pressure deviations, systematic errors of the influences introduced from the FPG8601 sensors are neutralized by zeroing the system before a test. As is mentioned in [8] only the uncertainties from the change in conditions from the zero conditions are applicable. For example if a hypothetical systematic error in piston-cylinder temperature from the platinum resistance thermometers exists, this error is neutralized when the system is zeroed. Errors due to the slope of the mounting post platinum resistance thermometers must be considered for uncertainties in effective area if conditions change during a test from zero conditions.

Another reason for the expansion of the uncertainty in effective area is the assumption that the effective area determined in gauge mode applies to the effective area when the FPG8601 is used in absolute mode. The uncertainty originally assigned to this was ± 20 parts in 10^6 at k=2. As discussed in section 2.4 a difference in the absolute effective area of approximately -8 parts in 10^6 from the effective area determined in gauge mode may be estimated from a model with a conical gap. Considering this is a systematic difference the uncertainty should probably be asymmetrical, but for ease of calculation in an uncertainty analysis, a conservative figure is used and treated as a symmetrical uncertainty. The value is expanded to a conservative 20 parts in 10^6 primarily since this difference is not tested systematically for each FPG8601.

Table 2 lists and combines the uncertainties in effective area described above for DHI FPG SN 101. The values for the type A uncertainties are an average of the last five calibrations performed on SN 101.

Table 2. Uncertainty analysis for DHI FPG8601 SN 101 effective area in absolute mode after calibration in gauge mode.

Crossfloat Pressure	Ref (U) k=1	Ref (U) k=1	Type A (1 std dev)	Absolute Mode	Combined	Expanded
[Pa]	[Pa]	[parts in 10^6]	[parts in 10^6]	[parts in 10^6]	[parts in 10^6]	[parts in 10^6]
5000	0.045	9.0	1.0	10	13.5	27.0
7500	0.055	7.3	0.7	10	12.4	24.8
10000	0.065	6.5	0.3	10	11.9	23.9
12500	0.075	6.0	0.3	10	11.7	23.3
15000	0.085	5.7	0.6	10	11.5	23.0

Table 3. Uncertainty analysis of DHI FPG8601 SN 101 effective area in gauge mode.

Crossfloat Pressure	Ref (U) k=1	Ref (U) k=1	Type A (1 std dev)	Combined	Expanded
[Pa]	[Pa]	[parts in 10^6]	[parts in 10^6]	[parts in 10^6]	[parts in 10^6]
5000	0.045	9.0	1.0	9.1	18.1
7500	0.055	7.3	0.7	7.4	14.7
10000	0.065	6.5	0.3	6.5	13.0
12500	0.075	6.0	0.3	6.0	12.0
15000	0.085	5.7	0.6	5.7	11.4

4.2 Uncertainty in force

The contribution of uncertainty in force is primarily based on the ability of the force balance to realize the difference in force across the effective area of the piston-cylinder. There are three sources of uncertainties in this respect: uncertainty of the calibration mass for the balance, uncertainty in the repeatability and linearity of the balance and uncertainty of run time drift of the balance (drift between zero and slope corrections). The uncertainty in force includes uncertainty in gravity but this contribution is relatively insignificant and is therefore excluded.

The size of the calibration mass is approximately 770 grams with an uncertainty of 5 parts in 10^6 at k=2. When applied, the mass is loaded on top of the piston and linkage and is near mid-scale of the 1.5 kg range. Since errors of repeatability and linearity are found through the linearization of the balance only the uncertainty of mass contributes, with a value of 2.5 parts in 10^6 at k=1.

Fig. 4 shows unadjusted linearity measurements between 0.5 and 2kg (zeroed is 0 to 1.5 kg) from measurements taken over a 5 year period for DHI FPG8601 SN 101. The tolerance is based on the balance manufacturer's specifications for repeatability and linearity. For the 2kg balance used with an FPG8601 this specification is ±(0.5 mg + 0.000002 * balance mass).

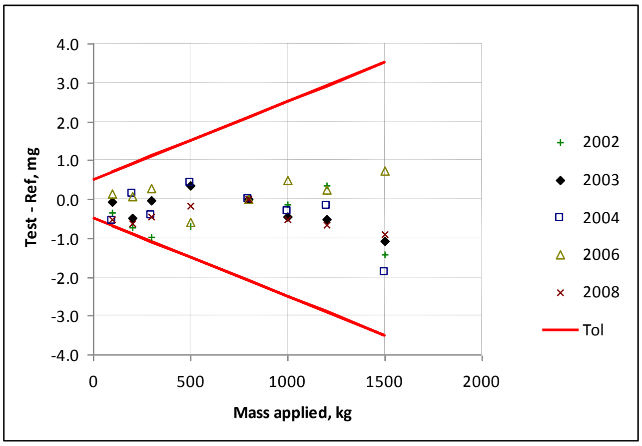

Fig. 4. Linearity verification of balance in FPG8601 SN 101.

The uncertainty analysis performed in [8] assumes regular and frequent use of zero and slope corrections on the balance. This is not always realistic in operation. Generally these functions are performed before a test is started and apply for a few hours. For SN 101 an additional uncertainty of ±(5 counts (0.5 mg) plus 2 parts in 10^6) is included. This is based on the reference calibration log for SN 101 and observations of zeroing stability.

Table 4 combines the uncertainties in force as read by the force balance in a FPG8601. The uncertainty resolved from this list of uncertainties with respect to pressure is ±(5 mPa + 4.4 parts in 10^6) at k=2.

Table 4. Uncertainty analysis in force (excluding gravity).

Mass	Linearity & Repeatability	Reference masses	Run Time Stability	Combined	Expanded
[g]	[mg]	[mg]	[mg]	[mg]	[mg]
100	0.35	0.25	0.35	0.55	1.11
200	0.45	0.3	0.45	0.70	1.41
300	0.55	0.45	0.55	0.90	1.80
500	0.75	0.75	0.75	1.30	2.60
800	1.05	1.2	1.05	1.91	3.82
1000	1.25	1.5	1.25	2.32	4.64
1200	1.75	1.8	1.45	2.90	5.80
1500	2.25	2.25	1.75	3.63	7.26

4.3 Combined uncertainties for FPG8601 SN 101

Table 5 lists a full uncertainty budget for FPG8601 SN 101. It has been modified to include the points of interest with respect to the uncertainty analysis of the effective area and force, and is based on the full uncertainty analysis described in [8].

Table 5. Uncertainty analysis in pressure for FPG8601 SN 101.

Variable or Parameter	**Gauge Mode**	**Absolute Mode**
(relative unc's)	[parts in 10^6]	[parts in 10^6]
Local G	1.00	1.00
Reference Mass	2.50	2.50
Air Density(lube)	0.36	0.36
Mass Density	2.37	0.67
Head (height)	0.35	0.35
Head (density)	0.22	0.22
PC Temp	0.45	0.45
Verticality	0.08	0.08
Effective Area	10.00	13.50
Force	2.20	2.20
Thermal Expansion	0.26	0.26
System Stability	2.80	2.80
COMBINED	11.2 parts in 10^6 + 2.2 mPa	14.3 parts in 10^6 + 4.0 mPa
COMBINED & EXPANDED FOR (K=2)	22 parts in 10^6 + 4 mPa	29 parts in 10^6 + 8 mPa
(absolute Unc's)	mPa	mPa
dN1,dN2,dN3	0.00	0.00
Resolution (N)	0.29	0.29
Vacuum (zero drift)	0.00	1.70
Vacuum (slope)	0.00	2.90
Force (N)	2.20	2.20

Although the uncertainty analysis is specific to SN 101 this artifact is not special or unique and is representative of any FPG8601.

5. EXISTING TEST DATA FROM NIST AND OTHER SOURCES

The following data is from four comparisons performed by the pressure and vacuum group at NIST and DHI on four FPG8601 systems on dates from 2002 through 2007. The tests were conducted to ensure the validity of the method of traceability in absolute pressure throughout the range of the FPG8601 and have significant value considering the devices have similar uncertainties yet represent completely different methods for defining pressure.

The averaged differences between the FPG8601 and applicable UIM at that pressure are shown in Figs. 5 and 6. The standard deviations of the comparisons are within the typical pressure measurement uncertainty shown as upper and lower limits. This uncertainty is ±(0.008 Pa + 30 parts in 10^6 of the measured pressure) and is very close to the uncertainty calculated for SN 101 in section 4. All points are within the typical pressure measurement uncertainty.

There have been other tests in absolute mode not facilitated by DHI that present similar results in [4], [5], [9] and [10], however the NIST UIMs have the lowest available uncertainty.

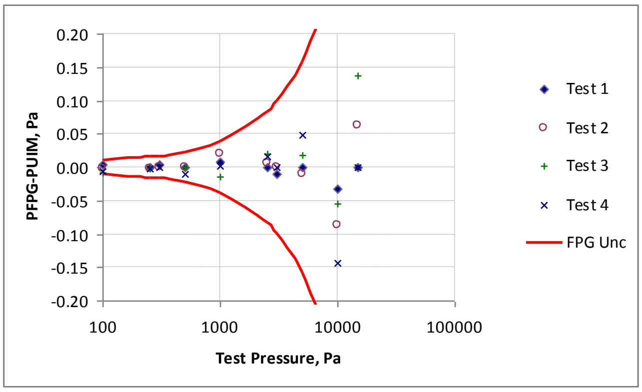

Fig. 5. Differences in pressure with the mercury UIM

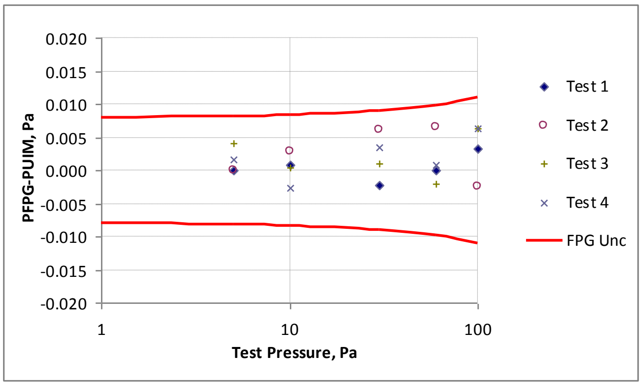

Fig. 6. Differences in pressure with the oil UIM

6. CONCLUSION

The FPG8601 is a standard that operates in physical principle very much like a traditional piston gauge. Characterization includes determination of fundamental quantities of effective area and force measurement that are combined with very small second order correction terms without further system calibration. All metrological quantities are determined independently with full traceability, the two most critical being the effective area and the force balance linearity and calibration. It has been shown, both from theoretical boundaries and from extensive empirical verification, that the performance of the FPG8601 meets the stated uncertainty specifications based on this traceability.

It is important to note that the effective area is expected to be uniform throughout the full operating range in both gauge and absolute measurement modes due to consistent lubrication conditions and negligible pressure induced deformation. This expectation has been verified by numerous successful comparisons with the lowest uncertainty reference standards available and is particularly relevant considering the vastly different technologies of the standards. The successful comparisons are further evidence that the independent determination of effective area and force measurement are valid for this standard.

Although not presented due to space constraints, more extensive work has been performed to explore the numerical predictions and sensitivity of the FPG8601 effective area to operating conditions and geometry. Given the successes thus far as well as the boundaries and sensitivities presented in this paper, it is the hope of the authors that future work will include characterization of the FPG8601 piston-cylinder effective area by directly traceable dimensional measurements.

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