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APMP.SIM.M.P-K1c.2023
Final Report

APMP.SIM.M.P-K1c.2023: BILATERAL COMPARISON OF PNEUMATIC PRESSURE STANDARDS IN THE REGION 0.4 MPA TO 4.0 MPA

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We report the results of a second bilateral comparison of pressure measurement between NIST (USA) and NPLI (India) over the applied pressure range 0.4 MPa to 4.0 MPa. This comparison is a repeat of one performed in 2003. The comparison was performed using a piston gauge transfer standard. This TS was cross-floated against the laboratory secondary standards "PG13" at NIST and "NPLI-8" at NPLI. Measurements at the nominal pressure points were first made on increasing pressure and subsequently on decreasing pressure. The comparison data were analyzed to determine the values of the effective area A_{eff} of the TS over the above-mentioned pressure range. We used these values to estimate the zero-pressure effective area A_{o} and the pressure distortion coefficient λ of the transfer standard. The degree of equivalence of the A_{eff} results over the range is within the expanded (k = 2) uncertainty.

1. Introduction

There has been considerable interest in international and bilateral key comparisons to ensure worldwide uniformity of measurements and their traceability to the International System of Units (SI). In 2003, a bilateral comparison of pressure standards over the range 0.4 MPa to 4.0 MPa was performed between the National Institute of Standards and Technology (NIST, USA) and the National Physical Laboratory (NPLI, India), denoted APMP-SIM.M.P-K1c [1], to determine the degree of equivalence of their piston gauge pressure standards over this range. In 2020 a CCM comparison of pressure standards over the range 0.7 MPa to 7.0 MPa, denoted CCM.P-K18 [2], was agreed on and subsequently performed, with NIST as one of the participants. In 2023, NPLI and NIST agreed to perform a new bilateral comparison that will allow linkage to CCM.P-K18. This comparison has been denoted APMP-SIM.M.P-K1c.2023, and its results are reported in this report. We have evaluated the degree of equivalence by determining at both NIST and NPLI the effective area A_{eff} of a piston/cylinder transfer standard as a function of pressure p using the conventional cross-float method [3]. The transfer standard was cross-floated against the secondary laboratory standards "PG13" of NIST and "NPLI-8" of NPLI. Both laboratories provided bases, calibrated masses and temperature probes, and pressure balancing hardware for the transfer standard as well as for their laboratory standards.

2. Participants

NIST	**Christopher Meyer** National Institute of Standards and Technology 100 Bureau Drive Gaithersburg, MD 20899 USA	Tel.: 301-975-4825 Fax: 301-548-0206 e-mail : cmeyer@nist.gov
NPLI	**Nita Dilawar Sharma** National Physical Laboratory of India Dr. K.S. Krishnan Marg New Delhi - 110 012 India	Tel.: +91-11-47091207 Fax: +91-11-45609310 e-mail: ndilawar@nplindia.res.in

3. Apparatus

a. Transfer standard

The transfer standard used in this comparison, NPLI-4, was provided by NPLI. It is a Ruska 2465[1] piston-cylinder with serial number V-607. It has a nominal effective area 8.40 mm^2 and a pressure range of 0.036 MPa to 4.0 MPa. It has been in service since 1982. Table 1 lists the various metrological characteristics of this piston-cylinder assembly, including the effective area A_o at atmosphere pressure and 23 °C, the pressure distortion coefficient λ, and the relative standard uncertainty in effective area. Details of NPLI-4 are found in [4-7].

During a span of forty years, it has been observed that the relative stability of A_o of the transfer standard is within 4×10^{-6}.

b. Laboratory standards

NIST. The NIST laboratory standard used in this comparison, PG13, is also a Ruska 2465 piston gauge. Its serial number is V-373 and it has been in service since 1972. The effective area A_{eff} of PG13 was most recently determined in 2008 by a cross-float comparison to NIST piston gauges PG34, PG37, and C415 in gauge mode. These three pistons, which are used up to a pressure of 1.4 MPa, had been calibrated against NIST primary piston gauge standards PG38 and PG39, which are dimensionally based primary standards. PG13 was calibrated from 289 kPa to 1390 kPa, and the 2006/2007 reference values for effective area of PG34, PG37, and C415 were used. The linear distortion coefficient λ for fitting the data of PG13 was determined by a cross-float of PG13 to NIST piston gauge DHI380, whose distortion coefficient was determined by elasticity theory.

[1] In order to describe materials and experimental procedure adequately, it is occasionally necessary to identify commercial products by manufacturer's name. In no instance does such identification imply endorsement by NIST, nor does it imply that the particular product or equipment is necessarily the best available for the purpose.

The details of the metrological characteristics of PG13 are listed in Table 1 and described in [8]. PG13 is rotated manually.

Table 1. Description of the piston cylinder assemblies used in NIST – NPLI bilateral pressure comparison. The information for NPLI-8, PG13, and NPLI-4 come from Refs. [3,4,7], Refs. [5-6], and Refs. [1,4,7], respectively.

	Laboratory Standards		**Transfer Standard**
	NPLI **NPLI-8** [4-7]	**NIST** **PG13** [8]	**NPLI-4**[1,4-7]
Manufacturer	Desgranges et Huot, France	Ruska Instrument Corporation, USA	Ruska Instrument Corporation, USA
Range in pressure (MPa)	0.4 to 8.0	0.35 to 7.0	0.036 to 4.0
Effective area A_o at atmosphere pressure and at 23°C (m^2) ($\times 10^{-6}$)	49.025504	8.389145	8.4 (nominal) Measured in comparison
Relative standard uncertainty of A_o ($\times 10^{-6}$)	10.9	5.9	Measured in comparison
Piston material	Tungsten carbide	Tungsten carbide	Tungsten carbide
Cylinder material	Tungsten carbide	Tungsten carbide	Tungsten carbide
Piston and cylinder serial number	DH-2943	V-373	V-607
Thermal expansion coefficient of piston ($\times 10^{-6}$)	4.55	4.55	4.55
Thermal expansion coefficient of cylinder ($\times 10^{-6}$)	4.55	4.55	4.55
Pressure distortion coefficient λ ($\times 10^{-6}$ MPa^{-1})	-3.30	2.66	Measured in comparison
Relative standard uncert. in A_{eff} produced by standard uncertainty in λ at 4 MPa ($\times 10^{-6}$)	0.95	3.5	Measured in comparison
Combined relative standard uncertainty of A_{eff} at 4 MPa ($\times 10^{-6}$)	**11.0**	**6.8**	Measured in comparison

NPLI. The NPLI laboratory standard, NPLI-8, is an oil-lubricated, gas-operated piston gauge and has been in service since the late eighties. It was manufactured by Desgranges et Huot, France, Model 5502 and has serial number 2943. The nominal effective area is 49 mm^2. The piston is rotated by a pulley driven by a DC motor mounted remotely from the piston-cylinder assembly. The non-conductive pulley is used to avoid heat transmission to the system and hence good thermal stability is achieved. The traceability of NPLI-8 to the SI is through the NPLI Ultrasonic Interferometric Manometer and intermediary NPLI piston gauges. The distortion coefficient of one of the intermediary pistons, NPLI-4, was determined using elasticity theory. NPLI-8 was earlier used in a bilateral comparison between NPLI and Physikalisch-Technischen Bundesanstalt (PTB), Germany [9]. Table 1 also lists the metrological characteristics of this piston-cylinder assembly, which are described in more detail in [5].

4. Calibration procedure

Both laboratories used their laboratory standards to calibrate the transfer standard. The gas used for the comparison was ultra-high purity nitrogen. The calibration procedure followed well-known methods for cross-float comparison between two piston gauges [3, 8]. For each nominal pressure, the piston gauges were loaded with masses chosen to levitate their respective pistons at that pressure. The actual pressure underneath the pistons was raised to the nominal pressure, floating the pistons between their bottom stop and top stop. The balance of the pressures underneath the two pistons was determined by either of two methods: the fall rate method at NPLI, or the differential pressure cell method at NIST. Both methods are commonly used for cross-float calibrations and are described in [10]. If the pressures underneath the pistons were not in balance, small masses were added to the piston needing more pressure underneath. Both the transfer and laboratory standards were housed in a room that provided a stable temperature to within $\pm$0.5 K. For each calibration point, the temperature of the piston gauges was measured with digital thermometers attached near the pistons, and their outputs were recorded on a computer. Also, the ambient temperature and relative humidity were measured and recorded for determining the buoyancy force on the pistons and masses. Both piston gauges were mounted on a stainless-steel base to minimize vibration and magnetic effects. A pressure head correction term was applied to compensate for the difference in the reference levels of the pistons. Before the measurement cycle, each piston was leveled to ensure the verticality of its axis and the system was checked for leaks to its full-scale pressure value of 4.0 MPa.

The comparison was performed at NIST, USA from October 21-25, 2023, and at NPLI, India in February 2024. Five sets of measurements were made. For each set, the nominal measurement pressures were (0.4, 0.7, 1.0, 2.0, 3.0, 4.0, 4.0, 3.0, 2.0, 1.0, 0.7, and 0.4) MPa, and the measurements were made in this order. After changing pressures, the pistons were rotated. They were then given a minimum of 15 minutes to allow for the piston temperatures to stabilize before finalizing the measurement.

5. Results and discussion

a. Mathematical Model

The effective area A_{eff} of the transfer standard for each observation, at a reference temperature of 23°C, is calculated using the equation

$$A_{\mathrm{eff}}(T,p)=\frac{\sum_i m_i g\left(1-\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{m}i}}\right)+\gamma C}{p\left[1+\left(\alpha_{\mathrm{p}}+\alpha_{\mathrm{c}}\right)\left(T-T_{\mathrm{r}}\right)\right]} \tag{1}$$

where m_i are the conventional masses of the piston, the weight carrier, and the mass pieces placed on the weight carrier of the TS; $\rho_{\mathrm{m}i}$ are the densities of the parts with masses m_i; ρ_{a} is the air density; g is the local acceleration of gravity; p is the pressure generated by the laboratory standard at the transfer standard reference level; α_{p} and α_{c} are the thermal expansion coefficients of the piston and cylinder materials, respectively; T is the temperature of the transfer standard; and T_{r} is the reference temperature (23 °C); γ is the surface tension of the pressurizing fluid ($\gamma = 0$ for gases), and C is the circumference of the piston. Because the laboratory standard is also a piston gauge, the pressure it generates is determined by an equation very similar to (1) with p and A_{eff} transposed. In the transposed equation for the laboratory standard, mass values and other parameters are those of the laboratory standard, and its A_{eff} is determined from A_{o} and λ given in Table 1. The value for g in the NIST piston gauge lab is 9.801011 ± 0.000002 m/s^2. The value for g in the NPLI piston gauge lab is 9.791241 ± 0.000025 m/s^2.

For each measurement pressure, we estimate the value of the effective area $A_{\mathrm{eff}}(p)$ for the transfer standard to be the average of this area for 10 observations, that is:

$$A_{\mathrm{eff}}(p)=\frac{1}{n}\sum_{k=1}^{n}A_{\mathrm{eff},k}(p) \tag{2}$$

The Type A standard uncertainty is taken as the standard deviation of the average, $u_{\mathrm{A}}(A_{\mathrm{eff}})$:

$$u_{\mathrm{A}}(A_{\mathrm{eff}})=\left[\frac{1}{n(n-1)}\sum_{k=1}^{n}\left(A_{\mathrm{eff},k}-A_{\mathrm{eff}}\right)^2\right]^{1/2} \tag{3}$$

Type B uncertainties come from the uncertainties in the parameters of the measurement equations (eq. (1) for the transfer standard and its companion for the laboratory standard), which are summed in quadrature according to the methods in [9]. The major source of Type B uncertainty is the uncertainty in effective area of the laboratory standard.

The uncertainty given by Eq. (3) is added in quadrature with the Type B uncertainty discussed above to give the standard relative uncertainty u_{r} of A_{eff}, or

$$u_{\mathrm{r}}(A_{\mathrm{eff}})=\frac{\left[u_{\mathrm{A}}(A_{\mathrm{eff}})^2+u_{\mathrm{B}}(A_{\mathrm{eff}})^2\right]^{1/2}}{A_{\mathrm{eff}}} \tag{4}$$

The expanded relative uncertainty U_r of A_{eff} is given by $U_r(A_{eff}) = ku_r(A_{eff})$, where $k = 2$. Relative uncertainties are evaluated at each pressure. The effective area and the expanded relative uncertainty for the transfer standard obtained from NIST and NPLI are listed in Table 2. We have also fitted the effective area data for the transfer standard from each laboratory standard by least squares regression to the linear distortion model:

$$A_{\text{eff, fit}} = A_o(1+\lambda p) \tag{5}$$

Results of the fit parameters are listed in Table 3. The standard relative uncertainty of the effective area calculated from the linear distortion model, $u_r(A_{eff,fit})$, is taken as the standard deviation of the values of $(A_{eff,fit} - A_{eff})/A_{eff}$ added in quadrature with the average value of $u_r(A_{eff})$. The expanded relative uncertainty $U_r(A_{eff,fit})$, with $k = 2$, is listed in Table 3.

Table 2. Effective area of the transfer standard A_{eff} and its expanded relative uncertainty, as measured at NIST and NPLI.

Nominal p (MPa)	NIST			NPLI		
	p (MPa)	A_{eff} (mm^2)	$U(A_{eff})/A_{eff}$ ($\times 10^{-6}$)	p (MPa)	A_{eff} (mm^2)	$U(A_{eff})/A_{eff}$ ($\times 10^{-6}$)
0.4	0.399835	8.392327	15.5	0.413282	8.392356	25.6
0.7	0.696166	8.392340	14.1	0.712761	8.392495	25.6
1.0	0.999421	8.392354	13.5	1.012165	8.392445	25.6
2.0	1.998825	8.392407	14.0	2.010345	8.392473	25.6
3.0	2.998174	8.392457	14.1	3.008548	8.392523	25.7
4.0	3.997481	8.392508	15.0	4.006782	8.392514	25.9

Table 3. Linear regression fit coefficients for the effective area A_{eff} of the transfer standard, using data from NIST and NPLI. Expanded relative uncertainty in the transfer standard using the fit coefficients is also listed. See text for explanation of $U_r(A_{eff,fit})$.

Laboratory	A_o (mm2)	λ (MPa^{-1})	$U_r(A_{eff,fit})$ ($\times 10^{-6}$)
NIST	8.392305	6.05×10^{-6}	14.4
NPLI	8.392410	3.11×10^{-6}	27.5

b. Degree of equivalence

The relative degree of equivalence is evaluated by calculating the difference in effective area of the transfer standard, as found by NIST and NPLI, as a function of pressure, and dividing it by the average of the effective areas determined by NIST and NPLI at each pressure:

$$D_{\mathrm{r}} = \frac{\left(A_{\mathrm{eff}}^{\mathrm{NIST}} - A_{\mathrm{eff}}^{\mathrm{NPLI}}\right)}{\left(A_{\mathrm{eff}}^{\mathrm{NIST}} + A_{\mathrm{eff}}^{\mathrm{NPLI}}\right)/2} \tag{6}$$

The associated standard uncertainty in the relative degree of equivalence is determined from:

$$u\left(D_{\mathrm{r}}\right) = \frac{\left[u\left(A_{\mathrm{eff}}^{\mathrm{NIST}}\right)^2 + u\left(A_{\mathrm{eff}}^{\mathrm{NPLI}}\right)^2 + u\left(A_{\mathrm{eff,drift}}\right)^2\right]^{1/2}}{\left(A_{\mathrm{eff}}^{\mathrm{NIST}} + A_{\mathrm{eff}}^{\mathrm{NPLI}}\right)/2} \tag{7}$$

where $u\left(A_{\mathrm{eff,drift}}\right)$ is the uncertainty of the effective area of the transfer standard due to drift. If D_{r} is less than or equal to the expanded uncertainty $U(D_{\mathrm{r}}) = ku(D_{\mathrm{r}})$, where $k = 2$, at a pressure point, then there is equivalence between the laboratory standards of NIST and NPLI at that pressure.

c. Results of the comparison

Measurements of A_{eff} at NPLI taken shortly before the transfer standard was sent to NIST resulted in a value of A_{o} that was 3.5×10^{-6} higher than its value after it was returned to NPLI. This is within one standard deviation of the NPLI values of A_{o} determined in this comparison (4.1×10^{-6}); we therefore consider $u\left(A_{\mathrm{eff,drift}}\right)$ to be negligible here.

Results for effective area A_{eff} of the transfer standard as measured by NIST and NPLI are listed in Table 2 and plotted in Figure 1 from 0.4 MPa to 4.0 MP. The expanded uncertainty, $U(A_{\mathrm{eff}})$ is shown as error bars. The transfer standard exhibited a linear increase of effective area with pressure at both NIST and NPLI. For all pressures of the comparison, the values of A_{eff} agree to within their combined expanded (k=2) uncertainties. The difference between the NIST and NPLI values for the zero-pressure effective area (A_{o}) of the transfer standard, as determined by linear least squares fitting and shown in Table 3, is 12.5×10^{-6}. This difference is also less than the combined expanded relative uncertainty (31.0×10^{-6}) of the two A_{eff} values from the fits given in Table 3. The distortion coefficient (λ) differs by 2.34×10^{-6} MPa^{-1} between NIST and NPLI.

Results for D_{r} are listed in Table 4 and plotted in Figure 2. The figure shows the expanded uncertainties (k = 2) of D_{r} values plotted as error bars, range from 28.9×10^{-6} to 29.9×10^{-6}. For all pressures of the comparison, D_r is less than $u(D_r)$, demonstrating the equivalence between NIST and NPLI for realizing pressure over the range of 0.4 to 4.0 MPa.

Once the results of CCM.P-K18 are published, we will submit an appendix to this report linking the results shown here to those of the CCM.P-K18.

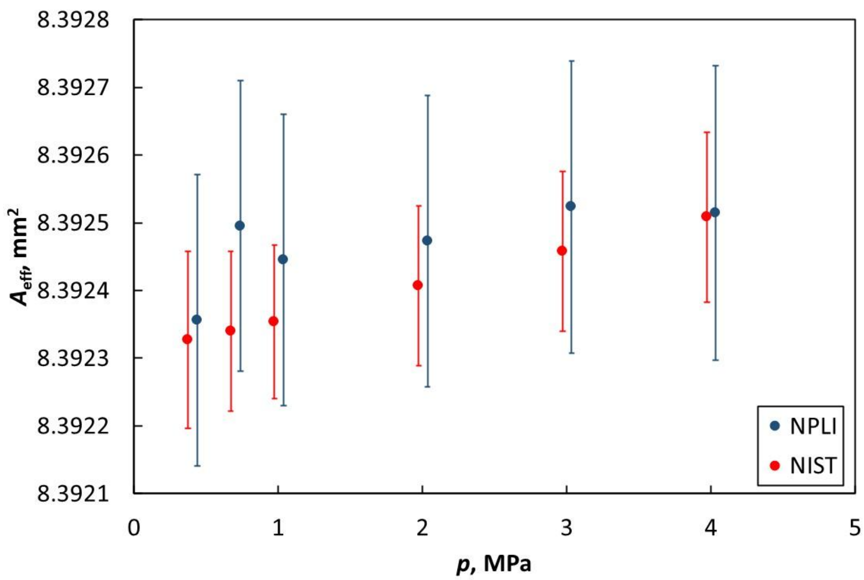

Figure 1. Effective area A_{eff} of the transfer standard as a function of pressure as measured by the laboratory standards at NIST and NPLI. Standard uncertainty shown as error bars.

6. Conclusion

We have determined the effective area of a transfer standard (NPLI-4) against the pneumatic laboratory standards of NIST (PG13) and NPLI (NPLI-8) over the pressure range 0.4 to 4.0 MPa. The piston cylinder assembly only was exchanged between the two institutes, while the bases, masses, and temperature instrumentation were provided at NIST and NPLI. We observed that the relative degree of equivalence in the effective area of the transfer standard over the pressure range is within 19×10^{-6}, which is always less than the expanded relative uncertainty (k = 2) of the difference (average value 29×10^{-6}). The results demonstrate equivalence between NPLI and NIST for pressure measurement in the pneumatic region up to 4.0 MPa, which is a pressure range of importance for both countries. Once the results of CCM.P-K18 are published, we will submit an appendix to this report linking the results shown here to those of the CCM.P-K18.

7. Acknowledgement

We gratefully thank Dr. Ashok Kumar for safely transporting the transfer standard from NPLI to NIST and back.

Table 4: Relative Degree of equivalence, D_r, between NIST and NPLI for effective area of transfer standard at measured pressures. Expanded uncertainty (k = 2) in D_r, $U(D_r)$, given for same pressure.

Present Comparison		
Nominal p (MPa)	D_r ($\times 10^{-6}$)	$U(D_r)$ ($\times 10^{-6}$)
0.4	-3.5	29.9
0.7	-18.5	29.2
1.0	-10.9	28.9
2.0	-7.9	29.2
3.0	-7.9	29.3
4.0	-0.7	29.9

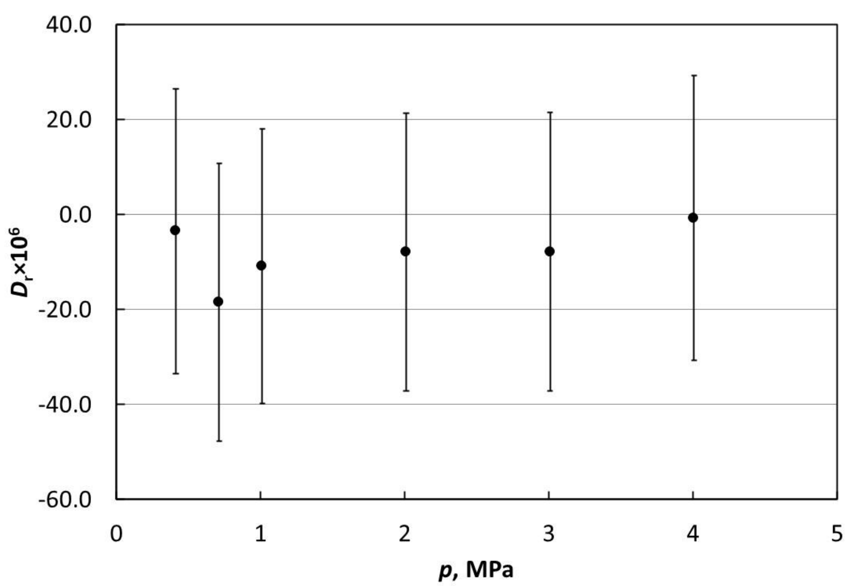

Figure 2. Relative degree of equivalence, D_r, between NIST and NPLI from present comparison. The expanded uncertainty ($k = 2$) in D_r is shown as error bars.

8. References

(1) R.G. Driver, D.A. Olson, N. Dilawar and A.K. Bandyopadhyay, "Bilateral comparison between NIST (USA) and NPLI (India) in the pneumatic pressure region 0.4 MPa to 4.0 MPa", *Metrologia* 44, Tech. Suppl. 07002, 2007.

(2) Final Report of CCM.P-K18, to be submitted to *Metrologia*.

(3) P.L.M. Heydemann and B.E. Welch, "Piston Gauges" in *Experimental Thermodynamics,* Volume II, (Edited B LeNeindre and B Vodar), Butterworth & co. Ltd., London, 147-202, 1975.

(4) Jasveer Singh, L. A. Kumaraswami-dhas, Neha Bura, Shanay Rab and Nita Dilawar Sharma, Characterization of a standard pneumatic piston gauge using finite element simulation technique vs cross-float, theoretical and Monte Carlo approaches Advances in Engineering Software 2020, DOI: 10.1016/j.advengsoft.2020.102920

(5) J. Singh, O. Prakash, H. Kumar, A. Kumar and Nita D. Sharma, Improved Measurement Capabilities in Pneumatic Pressure Measurements at NPLI Through Re-establishment of the Traceability Chain 2020 MAPAN-Journal of Metrology Society of India, https://doi.org/10.1007/s12647-020-00395-0

(6) J.K.N. Sharma, K.K. Jain and A.K. Bandyopadhyay, "Characterization of the piston gauge to assess the suitability of its use with several working fluids up to 5 MPa", *Review of Scientific Instruments*, **5**9, 2063- 2069, 1988.

(7) A.K. Bandyopadhyay and Nita Dilawar, "Uniformity and compatibility of National Standards during the participation of any Key Comparison", *Proc. NCSL International Workshop and Symposium*, Serving the World of Measurement, Washington DC, USA, August 7 - 11, 2005.

(8) D.A. Olson, "NIST Calibration Services for Pressure Using Piston Gauge Standards", *NIST Special Publication 250-39*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, U.S.A., 2009. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=902889.

(9) J.K.N. Sharma, K.K. Jain, A.K. Bandyopadhyay and J. Jager, "International intercomparison of pressure standards in the pneumatic pressure region 0.4-4.0 MPa between NPL(India) and PTB (FRG)", *Journal of Physics E: Scientific Instruments* 21, 635-641, 1988.

(10) B.N. Taylor and C.E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, *NIST Technical Note 1297*, 1994.

Appendix 1. Summary of Measuring Cycles

Laboratory Name: National Institute of Standards and Technology, USA (NIST)
Tr. Std. Piston-cylinder S/N V-607
Date (period): October 21-25, 2023 Local g and $u_{(g)}$: 9.801010 ± 0.000002 m/s2
Std. unc. for air density, $u_{(a)}$: 0.03 kg/m^3

Nominal Pressure (MPa)	(a) Typical mass m (mg)	Average A_{eff} value (mm^2)	(b) Standard deviation of A_{eff} (ppm)	(c) Uncertainty of p (ppm)	Uncertainty contribution of T (ppm)	Total Uncertainty of A_{eff} (ppm)
0.4	2	8.392327	3.0	6.3	0.5	7.8
0.7	2	8.392340	2.0	6.3	0.5	7.0
1.0	2	8.392354	1.2	6.3	0.5	6.7
2.0	2	8.392407	2.1	6.4	0.5	7.0
3.0	2	8.392457	0.8	6.8	0.5	7.0
4.0	2	8.392508	1.0	7.2	0.5	7.5

Laboratory Name: CSIR-National Physical Laboratory, India (NPLI)
Tr. Std. Piston-cylinder S/N V-607
Date (period): February 2024 Local g and $u_{(g)}$: 9.791241216 m/s^2 and 2.45E-05 m/s^2
Std. unc. for air density, $u_{(a)}$: 0.006 kg/m^3

Nominal Pressure (MPa)	(a) Typical mass m (mg)	Average A_{eff} value (mm^2)	(b) Standard deviation of A_{eff} (ppm)	(c) Uncertainty of p (ppm)	Uncertainty contribution of T (ppm)	Total Uncertainty of A_{eff} (ppm)
0.4	10.0	8.392356	3.2	12	0.3	12.8
0.7	10.0	8.392495	2.6	12	0.3	12.8
1.0	10.0	8.392445	2.1	12	0.3	12.8
2.0	10.0	8.392473	1.5	12	0.3	12.8
3.0	10.0	8.392523	1.6	12	0.3	12.8
4.0	10.0	8.392514	1.8	12	0.3	12.9

(a) m is the smallest weight adjusted on laboratory standard during equilibrium determination
(b) standard deviation of the mean value of A_{eff} at the reported nominal pressure value
(c) uncertainty of pressure p' measured by the laboratory standard, at the transfer standard reference level, including uncertainty of h and ρ_a (ρ_a,T)

Appendix 2. Comparison Protocol

ASIA-PACIFIC METROLOGY PROGRAMME

BILATERAL PNEUMATIC PRESSURE INTERLABORATORY COMPARISON BETWEEN NPLI (INDIA) and NIST (USA) IN THE RANGE FROM 0.4 MPa to 4.0 MPa (GAUGE MODE)
Comparison Identifier: APMP.SIM.M.P-K1c.2023

FINAL PROTOCOL

August, 2023

Pilot Institute:
NIST

1. General information

The National Physical Laboratory, NPLI (India), and the National Institute of Standards and Technology (NIST), USA have proposed to organize a bilateral interlaboratory comparison in pressure measurement up to 4 MPa in the pneumatic pressure region.

The objective of the project is to compare the performance of pneumatic pressure standards in participating institutes in gauge mode from 0.4 MPa to 4.0 MPa using nitrogen gas as the pressure-transmitting media. The results of this comparison will be essential supporting evidence for pneumatic pressure CMCs. The transfer standard is a piston-cylinder assembly that has to compare to the pressure standards of each of the participating laboratories. NPLI prepared the measurement protocol in cooperation with NIST.

Pilot institute:

NIST, USA

CSIR-National Physical Laboratory, India (NPLI)

Program Coordinators:

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Document:

This document has been prepared by Dr. Christopher Meyer, NIST USA and Dr. Nita Dilawar Sharma, NPL India. Although this has been checked several times, there may be minor inadequacies which may be corrected in the future communication.

The participating institutes are requested to follow the instruction in total, so that uniformity may be obtained. It is further requested that the participating institutes should pay particular attention to the transportation and customs problem, so that a strict time schedule is maintained.

2. Participating institutes

The number of participating institutes is 2 including the pilot institute. The participating institutes along with coordinators for contacts are as follows:

Participating Institutes	Contact Persons
Country: USA **Acronym:** NIST **Institute:** National Institute of Standards and Technology **Address:** 100 Bureau Dr., Gaithersburg, MD 20899 USA	**Name: Dr Christopher Meyer** **Tel:** +1 (301) 975-4825 **Fax:** **E-mail: christopher.meyer@nist.gov**
Country: India **Acronym:** NPLI **Institute:** National Physical Laboratory of India **Address:** Dr. K.S. Krishnan Marg New Delhi - 110 012 India	**Name: Dr. Nita Dilawar Sharma** **Tel:** +91-11-47091207 **Fax:** +91-11-45609310 **E-mail: ndilawar@nplindia.org**

3. Time schedule

Time schedule for this comparison has been developed as follows:

Period of measurement	Country	Institute	ATA carnet
2023, September – October	USA	NIST	Yes
2023, October- 2024, April	India	NPLI	Yes

This comparison program is scheduled to commence in September 2023 and to finish in May 2024. The artifact will be under an ATA CARNET valid for one year.

The time period for measurement at NIST USA is about **2 months.** The transfer standard has already arrived there in satisfactory condition.

To prevent the transfer package from any damage, all efforts should be made by each participant. The equipment must be handled with care, i.e. only by qualified metrology personnel.

4. Reporting of Results:

It is decided that the participating laboratories will report the measured effective area of the piston cylinder assemblies of transfer standard at the reference temperature of 23° C, as well as the uncertainties in measurement (at each generated pressure).

5. Details of Transfer standard

In this comparison, the transfer standard would be provided by NPLI (India) which is a piston cylinder assembly designated as NPLI-4. The piston cylinder assembly has range of 0.4 MPa to 4.0 MPa.

Type	Piston-cylinder
Manufacturer	RUSKA
Model	2465
Serial number	V-607
Range	0.036 – 4.0 MPa
Material of Piston-cylinder	Tungsten carbide with 6 % cobalt
Density of the piston material	(10300±140)kg/m^3
Measured mass of the piston at NPLI	(11.97953±0.00010)g
Thermal expansion coefficient (α_p+ α_c) and its uncertainty	9.1x10^{-6}C^{-1}, U=2.59x10^{-7}C^{-1}
Piston working position above its rest position	5.0 mm
Typical cross-float sensitivity and reproducibility at pressures /kPa, in mg	10 mg or 0.01158 kPa

At the beginning of the comparison, the transfer standard will be calibrated at NIST, USA, followed by calibration at NPLI, India. Both the institutes would use their own base and mass set for the measurements.

Some general information concerning the piston cylinder assembly is given in the operation and maintenance manuals, which will be enclosed in a transfer package.

A single box is used for carrying the transfer standard. The transfer standard is placed in the box. The contents of the transfer package are as follows:

Contents:

Carrying box	(1)
Transfer standard (Piston-cylinder assembly)	(1)
Manual	(1)
Protocol	(1) This document

As soon as the laboratory receives the package containing the transfer standard, they will have to certify that all the materials as mentioned above have been received and send the acknowledgment through e-mail to the coordinator.

A platinum resistance thermometer probe may be used to measure the temperature of the piston-cylinder assembly. The labs will use their own mass set and mass values. The value of piston mass would be given by NPLI.

A spirit level is used to adjust the level of the base plate. The working position of the piston is 5 mm higher than the rest position. There is an evident line marked in the Ruska base. All other needed measurements related to the comparison, for example, atmospheric pressure, ambient temperature and humidity, etc. useful to calculate air density at the time of measurement will be assumed to be available at each laboratory. The handling, mounting, cleaning, etc., and instructions of the piston-cylinder assemblies are described in the operating manual. The operated pressurized fluid will be dry pure nitrogen gas (best is to use 99.99 % nitrogen).

6. Details of the reference standards

NIST PG13 (Ruska S/N V373)

CHARACTERISTICS	LABORATORY STANDARD
Measurement Range (MPa)	350 kPa to 7 MPa
Material of piston	Tungsten Carbide
Material of cylinder	Tungsten Carbide
A_0, effective area at atm. Pressure and reference temperature (mm^2)	8.3891453
Relative uncertainty of A_0 in 10^{-6}	5.9
Pressure distortion coefficient, λ	+2.661E-6
Relative uncertainty of Ap, due to λ determination, in 10^{-6}	1.12E-6 $MPa^{-1} \times p$
ρ_M, reference density of the weights	10.24 g/cm^3
Relative uncertainty of weight mass, in 10^{-6}	2
α_p, linear thermal expansion coefficient of piston (°C^{-1})	4.55E-6
α_c, linear thermal expansion coefficient of cylinder (°C^{-1})	4.55E-6
T_o, reference temperature (°C)	23

Comments on NIST PG13

Traceable to the SI through calibration against NIST primary PG standards PG38 and PG39. Used in APMP.SIM.M.P-K1c.

NPLI-8A (Desgranges et Huot, Piston-cylinder S/N 2943)

CHARACTERISTICS	LABORATORY STANDARD
Measurement Range (MPa)	0.4-8 MPa
Material of piston	Tungsten Carbide
Material of cylinder	Tungsten Carbide
A_0, effective area at atm. Pressure and reference temperature (mm^2)	49.025504
Relative uncertainty of A_0 in 10^{-6}	10.9
Pressure distortion coefficient, λ	- 3.30E-06
Relative uncertainty of Ap, due to λ determination, in 10^{-6}	2.37E-07
ρ_M, reference density of the weights	10.30 g/cm^3
Relative uncertainty of weight mass, in 10^{-6}	2.3
α_p, linear thermal expansion coefficient of piston (°C^{-1})	4.55E-6
α_c, linear thermal expansion coefficient of cylinder (°C^{-1})	4.55E-6
T_o, reference temperature (°C)	23

Comments on NPLI Reference Standard

Traceable to the SI through calibration against NPL primary standard NPLI-P1 and secondary standard PG-B01 (Ruska 2465). Used in APMP.SIM.M.P-K1c.

7. Transportation

To prevent the transfer package from any damage, all efforts would be made by both participants. The equipment must be handled with care, i.e., only by qualified metrology personnel.

ATA carnet:

For the transportation of this comparison, ATA CARNET will be used. ATA CARNET is valid for a year. Upon each movement of the package the person organizing the transit must ensure that the carnet is presented to customs on leaving the country, and upon its arrival in the country of destination. When the package is sent unaccompanied the carnet must be included with the other forwarding documents so that the handling agent can obtain customs clearance.

Arrival:

When the package arrives at the participating institute, the package must be unpacked, and an inspection of the appearance and the function should be made immediately. The transfer standard should be removed from the carrying box by two people for safety. Also, the function of the devices should be checked. The results should be noted on the corresponding paper sheets attached in annexure A1 and A2. The NPLI from where it has been received should be informed about the arrival time and about the result of the inspection as soon as possible. The forms needed for the report are as follows:

(i) Report for transportation (Arrival) [Annexure A1]

(ii) Record of the appearance of the transfer standard [Annexure A2]

Departure:

When the package departs from the participating institute to the next institute, special attention must be given to put all parts in the original package appropriately. The institute should choose the best way to send the package to the next institute as early as possible. An inspection of the appearance should be made, and the function of the devices should be checked. The results should be noted on the corresponding paper sheets attached in annexures A1 and A2. The forms needed for the report are as follows:

(i) Report for transportation (Departure) [Annexure A1]

(ii) Record of the appearance of the transfer standard [Annexure A2]

When the artifact is received by participating institute safely, it will be their responsibility. Every incident where the standard may have been damaged should be documented and communicated to the pilot institute as soon as possible.

8. Cost

Each participant bears the costs for its own measurements, any customs charges and the costs occurring from a loss or damage of TS within its country.

9. Comparison Measurement

9.1 Inspection

Check that all equipment is as expected and that it operates well (e.g., all equipment has safely arrived).

9.2 Cleaning of piston-cylinders

Prior to mounting the piston into the cylinder and starting calibrations, cleaning of the piston-cylinder unit is of high importance. The first operation is related to disassembling each piston-cylinder from its container. Please refer to Figure 1 for the piston-cylinder V-407. Both pistons and cylinders are supposed to be assembled clean (this is a must in reassembling the units before their shipment to other laboratories, in any case, do not separate parts and fit each piston inside its cylinder), but it is better to repeat anyway the cleaning operation when receiving the units.

Be careful that the cylinder must be mounted as in Figure 2. It is important that the snap ring of the piston is very carefully removed and reassembled. Always remember that this small snap ring is part of the Piston mass. It is relatively easy to lose this piece during removing or mounting it. This must absolutely not happen. So when removing or mounting the snap ring, use appropriate tools and operate in a space where the ring cannot fly away and be lost. For cleaning, operate according to the practice in your laboratory, but avoid the use of cleaning solvents that may leave a residue on the surface.

Frequently the piston-cylinders are simply cleaned by washing them with soap and water (following the manufacturer's instruction), in other cases using extremely pure ethyl alcohol.

Avoid a long immersion of piston and cylinder in solvents, it is better to use a clean paper wet with the appropriate solvent. Dry the parts using clean soft paper (e.g., lens tissue) or a rag. Blow with air nitrogen very well and repeat the cleaning with soft paper or a rag. Use your practice to evaluate the state of the surface before mounting. Use only clean tools and use clean areas for doing all these important operations. Now you are ready to reassemble the piston and cylinder following Figures 1 and 2 (attention to the snap ring for V-407 piston), and to mount them in the measuring base before proceeding in other tests. Following cleaning, the piston and cylinder should be left for 4 hours before use in order to reach thermal equilibrium.

9.3 Masses

Lab's own mass set would be used by the participating labs. All mass pieces (including pistons) have been measured with standard uncertainty values. All this is feasible and useful only if all masses are used with extreme care in order to avoid contamination and damage. Consequently, masses have to be used always with appropriate gloves, and they must be softly cleaned only in case of suspected contamination.

9.4 Assembling of piston-cylinder

The piston and cylinder units should be mounted as indicated in Figure 1. If you have never used such piston-cylinders, be acquainted with all parts represented in Figures 1 and 2, understand well the sequence of mounting, and carefully Control the state of O-rings (no O-ring lubrication is needed). The paper filter will not be used, because it is assumed that all laboratories use filtered nitrogen of high purity. Some parts (lower thrust washer, lower thrust bearing and filter retainer) must always be kept in the base. Before mounting, be sure that these parts are also clean and blow nitrogen in the experimental set-up connected to the transfer standard in order to verify as well that all internal surfaces of connecting tubing are perfectly clean and dry.

9.5 Mounting of piston-cylinder in the Ruska pressure balance base

After the assembling of the piston-cylinder, with all its parts, you just have to fit them into the pressure balance base. Ensure that the base is firmly mounted on a leveled surface. Now assemble the piston-cylinder units by fitting them carefully into the mounting post. Be careful to verify that during this operation all O-rings and other items are kept at their places (see Figures 1). Do not forget the cylinder retainer as indicated in Figures 1. Close the upper nut above the cylinder by tightening by hand, having used a small 2 mm diameter clean rod inserted into a hole of the base to prevent cylinder rotation. The same rod must be used in disassembling the system, by first removing the cylinder upper nut. Adjust the height of the transfer standard in respect of the height of your standard. To appropriately level the piston, do not use only the spirit level mounted on the base, this gives just an initial indication of correct leveling of the piston. To appropriately level the piston, use a spirit level for example having 0,05 mm/m sensitivity) on the top of the piston. Pressurize until the piston is floating and adjust the base-nuts until the piston is leveled when it is slowly rotated through any angle. The connection of the pressure port of the pressure balance is located in the base of the pressure balance, with the possibly of using a Swagelok connector adaptable to metal tubes of 1/4" or 6 mm diameter or a brass fitting. For transportation, be careful in fixing with appropriate tape the plastic bell jar to the pressure balance base.

9.6 Height difference and head correction

To minimize uncertainties in pressure measurement, the height difference between the reference levels of the two intercompared standards (laboratory standard(s) and transfer standards) will be kept as low as possible.

Due to the fact that the transfer standard system has small dimensions, it is possible to adjust the level using flat spacer and to measure by the use of cathetometer having at least a resolution of 0,01 mm the height difference until they are within 1 mm.

If the height difference between the participant standard and the reference level on the transfer standard is within 0,5 mm this gives a contribution variable from 0,13 ppm (at 80 kPa) to 0,06 ppm (at 4 MPa). For height difference of larger values, each laboratory has to make appropriate corrections to the pressure value measured by its standard(s), refer always to the reference level of the transfer standard, and report to the pilot laboratory indications of the values of this correction, as well, as uncertainty evaluation of their contributions to the uncertainty of the measured pressure p'.

9.7 Initial checks

Before performing the comparison work, verify the following optional points:

(1) If any anomaly in TS behaviour is observed, the magnetization of the piston and cylinder is recommended to be checked. The magnetic flow density at their surfaces should not exceed $2x10^{-4}$ Tesla. If it is higher, the parts should be demagnetized, and the magnetization should be checked again. Do not underestimate this point; sometimes tungsten-carbide parts show very high magnetized spots, even of more than 60 Gauss. Be careful to measure the surface magnetization again after the demagnetization process.

(2) Electrostatic effects can be measured with an electrostatic charge locator. At the pilot laboratory, even in the bell jar electrostatic charges were very small. The two checks, described above, are to be done before the cleaning of piston-cylinder assemblies.

(3) Piston fall rates' typical values, at some specific pressures, are to be noted carefully. If the piston fall rate is largely not in agreement, check O-rings and all connections in the tubing in order to be sure that there are no leaks.

(4) Rate of piston revolution versus time is to be noted for both piston-cylinders. If the participating laboratories find any difficulty, it means that the piston-cylinders are not clean and well leveled. So it is recommended to do this verification before starting cross-floating measurements. Appropriate leveling of piston, appropriate rotations are important points for obtaining regular and linear decrease of the rate of piston rotation.

9.8 Measurement procedures

The purpose of this activity is to compare effective areas (at 23 °C and at the measured pressures) of the transfer standard piston-cylinder unit, obtained by participating laboratories.

Each laboratory can adjust the added masses needed for the determination of the equilibrium condition at each cross-floating pressure on the laboratory standard.

9.9 Measurement points

The comparisons will be performed at the nominal pressures (in MPa) of:

(0.4, 0.7, 1.0, 2.0, 3.0, 4.0, 4.0, 3.0, 2.0, 1.0, 0.7, 0.4)

This will be considered as one cycle and will give 12 effective area determinations (2 points for each nominal pressure). Calibrations can be done in ascending and descending sequence of pressures. A waiting time of at least 10 min. is to be observed between the two measurements at 4 MPa.

For each cycle we will have 12 comparison points. The procedure should be repeated 4 more times, for a total of 5 cycles, giving 10 experimental determinations of the effective area of the transfer standard for each nominal pressure and a total of 60 experimental effective area determinations distribution over the selected nominal pressure values.

10. Results

The pilot laboratory will be provided with the information related to the laboratory standard as listed in the table reported in Annex 4. Detailed comments on the type of the piston-cylinder assembly used as laboratory standard, the way of determination of its effective area and the estimation of the uncertainty of pressure measured by the laboratory standard, as well as any other useful information, will be added to this table. If more than one standard is used, the participants will need to prepare a table as Annex 4 for each standard used. It must be clearly indicated that which standard has been used in respect of the established nominal pressure points, for each of the two piston-cylinder assemblies of the transfer standards. To help the pilot laboratory to get the data of each laboratory in a consistent form, it is recommended that each laboratory should use Annexes 6 and 7 to send their data. Annex 6 is essentially a data sheet reporting the data obtained at each comparison point, for each cycle of the planned comparison. In this case each participant would have 5 data sheets for the piston-cylinder assemblies. Annex 7 gives the average data obtained for each transfer standard piston-cylinder assembly and lists the uncertainty components useful to estimate the uncertainty of A'_p. The participating laboratories are asked to conform strictly with indications given in the two annexes, and to supply the pilot laboratory with all information's requested as well in the footnotes; participating laboratories may add other information they think useful. The effective area is derived from the well-known formula used to calculate the pressure p measured by a gas-operated pressure balance of the laboratory standard at its reference level (see Annex 3. Notations):

$$p = \frac{\sum M_i\, g(1-\rho_a/\rho_{Mi})}{A_0\,[1+\lambda P]\{1+(\alpha_p+\alpha_c)(T-T_0)\}}$$

The pressure measured by the laboratory standard at the transfer standard reference

$$p' = p \pm (\rho_f - \rho_a)\cdot gh$$

Where ρ_f is the nitrogen density at the pressure p and temperature T and ρ_a is the air density at time of measurement. The sign will be + or - depending on experimental installation in each laboratory. It is once more strongly recommended to set the experimental installation in order to have as much as possible the condition h = 0. In this favorable case also, the estimated uncertainty associated to the measurements of the level between the two standards have to be considered in the error budget. In equilibrium condition between the two standards and by reversing the above formula and using the pressure p' measured by the laboratory standard at the reference level of the transfer standard, we obtain the effective area of the transfer standard

$$A'_{p'} = \frac{\sum M'\, g(1-\rho_a/\rho'_{M'})}{p'\{1+(\alpha'_p+\alpha'_c)(T'-T'_0)\}} = \frac{F'}{p'\{1+(\alpha'_p+\alpha'_c)(T'-T'_0)\}}$$

11. Data Collection and Result Analysis

Participants in the comparison measurements are kindly requested to send their data to the pilot laboratory after finishing measurements. All data may be communicated via soft mode.

Measurement and calculation results:

The participating institutes will report their results, which are measured and calculated values at the 6 nominal pressures specified, each with an uncertainty in the measurement (coverage factor *k*=1) and the date(s) on which practical work was undertaken in the sheet for the measurement results. The uncertainties shall be estimated and combined following the *Guide to the Expression of Uncertainty in Measurement* (GUM).

Participating institute's standard:

Each institute will provide the pilot institute with the information related to the institute standard against which the transfer standard was calibrated, including the origin of its traceability to the SI, as listed in the table reported in annexure A4. The participating institute should provide information concerning all institute standards used for this comparison. If more than one standard is used, the standards used in respect of the established nominal pressure points must be clearly indicated. Detailed comments on the type of the piston-cylinder assembly used as institute standard, the characteristics of its effective area and, the estimation of the uncertainty, as well as any other useful information, will be added to the table.

Parameters used for the comparison:

The parameters used for the measurements will be reported using Annexure A5. These include local gravity, the differential height of the reference levels between the participating institute's standard and the transfer standard, density of working fluid, power supply used for the pressure monitors. The instruments for measuring environmental condition, as well as any other useful information, will be added to the table.

Uncertainty budget:

A list of the principal components of the uncertainty budget to be evaluated by each participant, and any necessary advice on how uncertainties are estimated may be listed (this is based on the principles laid out in the *Guide to the Expression of Uncertainty in Measurement* (GUM)[4]. Uncertainties are evaluated at a level of one standard uncertainty (coverage factor k=1).

Submission:

In principle, we would like to use E-mail for communication with participants during this comparison. In the case of E-mail, please attach the data file to the mail.

12. Preparation of the report

The pilot institute is responsible for the preparation of a report on the comparison. The analysis of data, based on results of participants, will be done by the pilot institute. In principle, the pilot institute will treat all data and reports according to the guidelines described in the reference [1].

References:

1. Mutual recognition of national measurements standards and of calibration and measurement certificates issued by national metrology institutes (MRA), Technical Report, International Committee for Weights and Measures, 1999 (http://www.bipm.org/pdf/mra.pdf)

2. Measurement comparisons in the CIPM MRA CIPM MRA-G-11

3. Overview and implementation of the CIPM MRA CIPM MRA-P-11

Guidelines for approval and publication of the final reports of key and supplementary comparisons, Version 5.2

4. Formalities required for the CCM key comparisons (2nd revised draft), 2001.

5. Guide to the Expression of Uncertainty in Measurement (GUM), JCGM 100: 2008.

6. Entering the details and results of RMO key and supplementary comparisons into the BIPM key comparison database, 2000.

7. RUSKA 2465, Operation and Maintenance Manual (https://as.flukecal.com/products/pressure-calibration/piston-gauges/2465a-gas-piston-gauge?quicktabs_product_details=1)

8. Bandyopadhyay, A K et al. "Results of the APMP Pressure key comparison APMP.M.P-K1c in gas media and gauge mode from 0.4 MPa to 4.0 MPa." Metrologia 40 (2003): 07002 - 07002.

9. Driver, R. Gregory et al. "Final report on Key Comparison APMP.SIM.M.P-K1c: Bilateral comparison between NIST (USA) and NPLI (India) in the pneumatic pressure region 0.4 MPa to 4.0 MPa." Metrologia 44 (2007): 07002-07002.

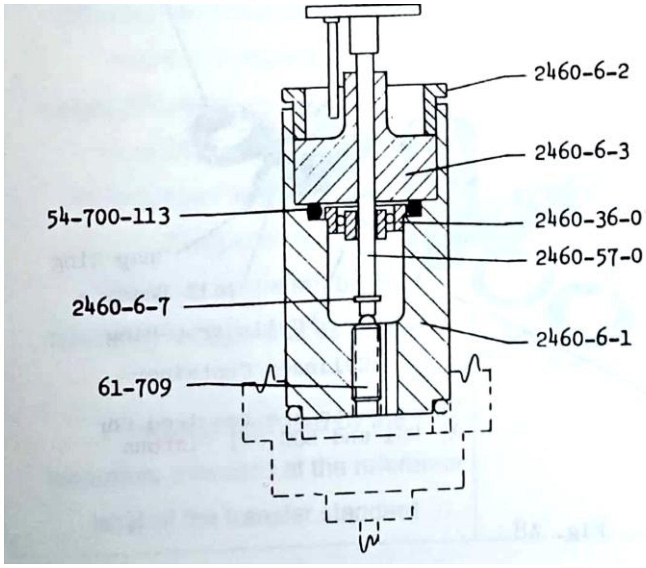


Figure 1.Piston-cylinder assembly

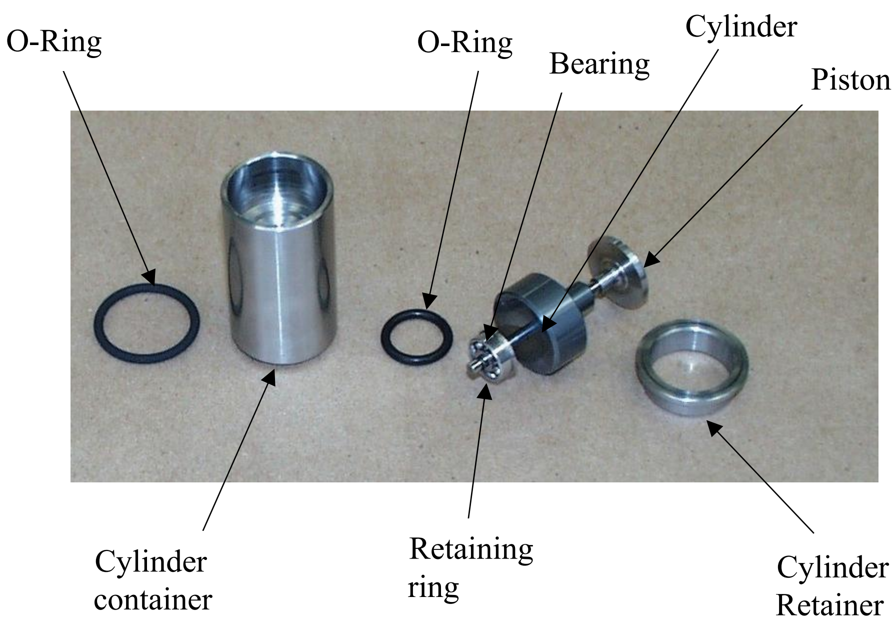


Figure 2. Various parts of piston-cylinder assembly

Annexure 1

A1. Report for transportation (Arrival)

Institute:	
Report date:	

Arrival of transfer standard:

Date:	
Time:	
From:	

Contents: (See protocol)

Carrying box	
Transfer Standard	
Protocol	
Manual	

Conditions of the transfer standards on arrival:

Carrying Box:	
Transfer Standard	
Other remarks:	

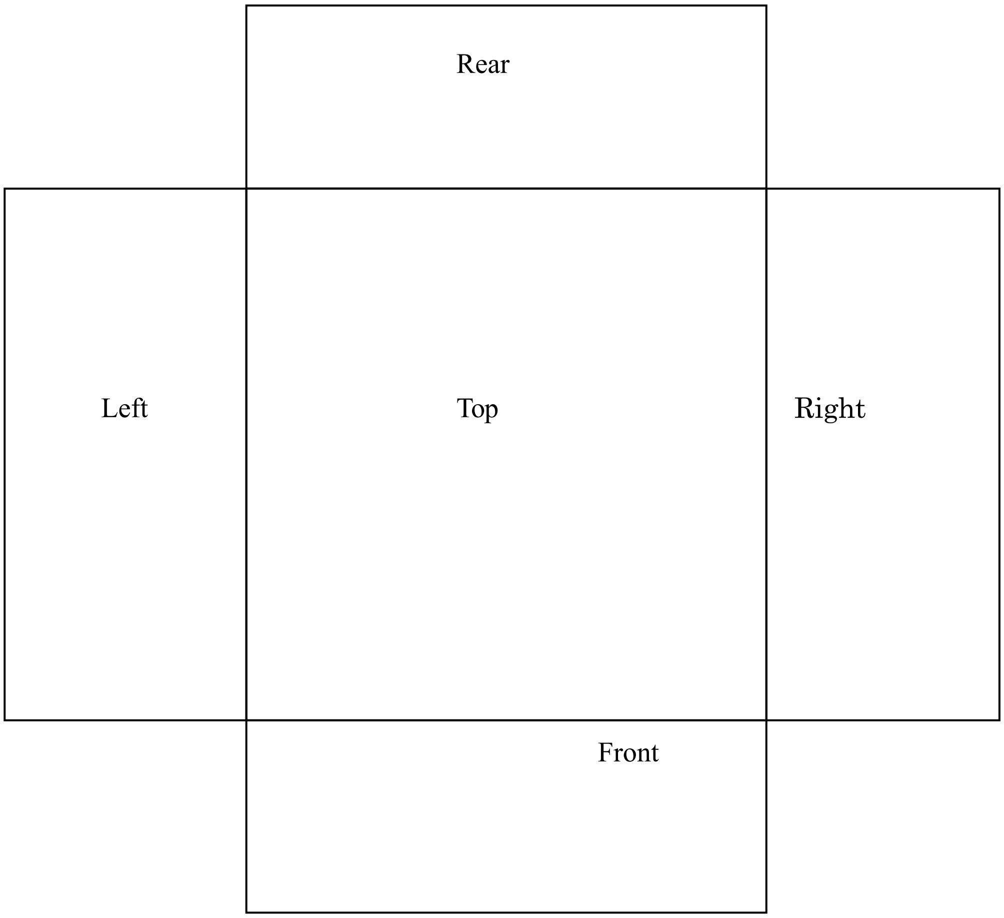
Contact person:

Name:	
Mailing Address:	
Telephone:	
Fax:	
E-mail:	

Annexure 2

A2. Record of the appearance of the transfer standard

Institute:	
Report date:	



Please use this figure to indicate any damage.

Comments:

Piston	
Cylinder	
Others:	

Annexure 3

A3. Notations

CHARACTERISTICS	LABORATORY STANDARD	TRANSFER STANDARD
Applied mass	M	M’
Applied conventional mass		M_i’
Local gravity	g	G
Air density	ρ_a	ρ_a
Conventional air density		$\rho_{0a=1.2\ kg/m^3}$
Mass density	ρ_M	ρ'_M
Conventional mass density		$\rho_{0=8000\ kg/m^3}$
Mass density of masses M_i’		ρ'_{Mi}
Total force applied on piston	F	F’
Effective area at atm. Pressure and reference temperature	A_0	A'_0
Reference temperature	T_0	T'_0
Measurement temperature	T	T’
Temperature coefficient of piston cylinder assembly	$\alpha_p + \alpha_c$	$\alpha'_p + \alpha'_c$
Piston distortion coefficient	λ	λ'
Effective area at pressure p or p’ and ref. temperature T	A_p	$A'_{p'}$
Height difference between reference level of the two standards	H	
Fluid density at pressure p and temperature T	ρ_f	
Pressure measured by the laboratory standard at its reference level	ρ	

Pressure measured by the laboratory standard at the reference level of the transfer standard		P’

Annexure 4

A4. Details of the participating institute's standard

Institute:	
Report date:	

Details of the pressure balances used for the comparison:

CHARACTERISTICS	LABORATORY STANDARD
Measurement Range (MPa) Material of piston Material of cylinder A_0, effective area at atm. Pressure and reference temperature (mm^2) Relative uncertainty of A_0 in 10^{-6} Pressure distortion coefficient, λ Relative uncertainty of Ap, due to λ determination, in 10^{-6} ρ_M, reference density of the weights Relative uncertainty of weight mass, in 10^{-6} α_p, linear thermal expansion coefficient of piston (°C^{-1}) α_c, linear thermal expansion coefficient of cylinder (°C^{-1}) T_o, reference temperature (°C)	

Comments:

Annexure 5

A5. Details of the parameters used for the comparison

Institute:	
Report date:	

Local gravity:

g [m/s^2]		$u(g)$ [m/s^2] (k=1)	

Differential height of the reference levels between the participating institute's standard and the transfer standard:

(Positive: if the level of the institute's standard is higher).

H [mm]		$u(H)$ [mm] (k=1)	

Density of working fluid: (Constant or Function of pressure, P, and/or temperature, t.)

ρ_f [kg/ m^3]		$u(\rho_f)$ [kg/ m^3] (k=1)	

Instruments for measuring environmental condition:

	Manufacturer	Model	Uncertainty[k=1]	Comments
Atmo. Temp				
Atmo. RH				
Atmo. Pressure				

Comments:

Annexure 6

A6. (one table each of the five calibration cycles)

Laboratory Name : Tr. Std. Piston-cylinder no. :

Date (period) : Cycle number

Average air density ρ_a and $u_{(a)}$:

Meas. Number	Nominal Pressure (MPa)	A_p (p, 23) (mm^2)	T (°C)	p' (a) (MPa)	F (b) (N)	T' (°C)	$A'_{p'}$ (p', 23°C) (mm^2)
1 2 3 4 5 6							
7 8 9 10 11 12							

(a) p' is the pressure measured with the laboratory standard at the local g and the local air density pa, and calculated at the reference level of the transfer standard.
The complete formula used for the definition of p' must be reported.
(b) F' is the total force applied on the piston of the transfer standard (piston included) when in equilibrium
(c) standard uncertainties at 1σ level. Indicate how ρ_a been calculated.

Annexure 7

A7. Summary of Measuring Cycles

Laboratory Name :

Tr. Std. Piston-cylinder # V-607

Date (period) :

Local g and $u_{(g)}$

Std. unc. for air density, $u_{(a)}$:

Nominal Pressure (MPa)	Typicla mass m (a) (mg)	Average $A'_{p'}$ value (mm^2)	Standard deviation of $A'_{p'}$ (b) (ppm)	Unc. of p' (c) ppm	Unc. contr. of T' (ppm)	Unc. Of $A'_{p'}$ (d) (ppm)

a) m is the smallest weight adjusted on laboratory standard during equilibrium determination
(b) standard deviation of the mean value of A'p' at the reported nominal pressure value
(c) uncertainty of pressure p' measured by the laboratory standard, at the transfer standard reference level, including uncertainty of h and ρ_a (ρ_a,T)