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Bilateral comparison between NIST (USA) and NPLI (India) in the hydraulic pressure region 40 MPa to 200 MPa

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Abstract

We report here the results of a bilateral comparison of pressure measurement between the National Institute of Standards and Technology (NIST), Gaithersburg, USA and the National Physical Laboratory (NPLI), New Delhi, India, over the range of nominal applied pressure 40 MPa to 200 MPa at a reference temperature of 23°C. The comparison used two transfer standards (TS), designated as NPLI-100MPN (pressure range 10 MPa to 100 MPa with nominal effective area 9.80 mm^2) and NPLI-500MPN (pressure range 50 MPa to 500 MPa with nominal effective area 1.96 mm^2). These two TSs were cross-floated against the laboratory standards of NPLI and NIST at nominal pressure points of (40, 60, 80, 80, 60, 40) MPa for NPLI-100MPN and (80, 100, 120, 140, 160, 180, 200, 200, 180, 160, 140, 120, 100, 80) MPa for NPLI-500MPN, respectively. The NPLI laboratory standard was NPLI-200MPN with nominal effective area 4.90 mm^2, and the NIST laboratory standard was PG21 with nominal effective area 8.40 mm^2. Testing occurred at NIST during July to August, 2003, and testing occurred at NPLI during January to February, 2004. The comparison was performed in both the institutes in three complete and identical pressure cycles in increasing and decreasing pressures using both TSs. The comparison data were analyzed in terms of the effective area [A_p (mm^2)] as a function of pressure [p (MPa)] of the two transfer standards in the respective pressure ranges of (40 to 80) MPa and (80 to 200) MPa. The degree of equivalence between NPLI and NIST is given as the relative difference in the institutes' results for effective area of the transfer standards, and is within 7.7×10^{-6} in the whole pressure range (40 to 200) MPa. This is substantial smaller than the standard uncertainty in the difference in effective area, which is estimated as 44×10^{-6}.

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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). The various activities of the Bureau International des Poids et Mesures (BIPM) is guided by the respective Consultative Committees (CC). Mass and related quantities are the responsibility of the Comite Consultatif pour la Masse (CCM). The High Pressure Working Group under CCM has been coordinating a large number of key comparisons. Presently, a major key comparison designated as CCM.P-K7 in the hydraulic pressure region (10 to 100) MPa is underway. However, there is no major key comparison in the pressure range (40 to 200) MPa except CCM.P-K8 (50 to 500) MPa and APMP.M.P-K7.TRI (40 to 200) MPa neither of which have been published in the key comparison database (KCDB) of BIPM. The pressure region (40 to 200) MPa is very important because of the many industrial applications occurring within this pressure region. The present attempt to undertake a bilateral intercomparion in this pressure range serves two purposes: firstly, it will explore directly the linkage between NIST (USA) and NPLI (India), and secondly, if the results are accepted in the KCDB, it will provide a model for other bilateral/supplementary comparisons. Like other CCM/RMO (Regional Metrology Organization) sponsored key comparisons in pressure metrology, we have also determined the effective areas of two piston and cylinder assemblies as a function of pressure at the reference temperature (23^{o}C) by using the conventional cross-float method, cross-floating both the transfer standards against the secondary laboratory standards of NPLI (NPLI-200MPN) and NIST (NIST PG21). The transfer standards were the two piston cylinder assemblies only, without base and masses. Both the laboratories provided adequate bases and well-calibrated masses, temperature probes, and pressure balancing hardware.

2. Apparatus

(a) Transfer standards

The transfer standards used in this comparison are designated as NPLI-500MPN and NPLI-100MPN, provided by NPLI. The piston cylinder assemblies are capable of measuring the pressure over the range (50 to 500) MPa and (10 to100) MPa, respectively, and have been in service since 1999. Table-1 shows relevent details of the two transfer standards. These pistons are rotated with a synchronous motor. Prior to the present comparison, the effective area with pressure (A_p) and the subsequent A_o and λ of the piston cylinder assemblies were determined by cross-floating against the NPLI primary standard, which is a controlled clearance piston gauge (Harwood Inc. USA). The details of this NPLI primary standard, designated as NPLI-1, are found in Yadav at. al. [1]. NPLI-100MPN was also used as the NPLI laboratory standard during two recently concluded key comparisons, CCM.P-K7 (10 to 100) MPa in March 2004, and also APMP.M.P-K7 (10 to 100) MPa in December 2002. NPLI has already established the practical pressure scale up to 500 MPa [2]. During this span of five years, it has been observed that the relative stability of A_o of both the transfer standards [NPLI-500MPN and NPLI-100MPN] is within $4x10^{-6}$. As mentioned above, only these two piston-cylinder assemblies were transported and used during the inter-comparison. The respective laboratories provided the corresponding bases and mass sets.

(b) Laboratory standards

NIST PG21

PG21 is the highest range oil piston gauge transfer standard of NIST and has been in service since 1978. The characterization and uncertainty of this standard comes from cross-float data against two NIST controlled clearance primary pressure standards, designated as PG20 and PG67. The details of the metrological characteristics of PG21 are shown in Table 1 and described by Olson [3] and Bean [4].

NPLI-200 (NPLI-200MPN)

NPLI-200MPN is the piston cylinder assembly capable of measuring the full scale pressure up to 200 MPa and has been in service since 1999. Table 1 shows the various metrological characteristics of this piston-cylinder assembly. The piston is rotated with a synchronous motor. The effective area with pressure A_p and the subsequent A_o and λ of the piston cylinder assembly was determined by cross-floating it against the NPLI-1 which is the NPLI primary pressure standard over the pressure range (20 to 200) MPa.

3. Calibration procedure

The basic principle followed in the bilateral comparison measurement between the laboratory standards and the transfer standards up to 200 MPa is that, when these standards are pressurized to a constant arbitrarily chosen pressure, the ratio of their effective areas is equal to the ratio of the total downward forces acting on each piston gauge at equilibrium. At equilibrium there is no net fluid flow through the common pressure line, which is usually obtained by adjusting the fractional masses on the laboratory standard piston gauges (NIST PG21 or NPLI-200MPN) to reproduce their fall rates when isolated from the transfer standards. Although we have used the same combination of S2 class masses on NPLI-100MPN and NPLI-500MPN in both the laboratories, the deviations in the pressures measured by the transfer standards at the two laboratories is mainly attributed to the difference of "*g*" value. The bilateral comparison is performed by comparing the effective area as a function of various applied pressures [Eq. (1)] because effective area is independent of "*g*".

The comparison was performed on the transfer standards by cross-floating them against NIST PG21 from July to August, 2003 at NIST, USA and against NPLI-200MPN from January to February, 2004 at NPLI, India. Both the transfer and laboratory standards were housed in a room that provides a stable temperature to within ±0.5 K. The temperature of the piston gauges was measured with platinum resistance thermometers (PRT) attached near the pistons, and their outputs were read with autoranging digital multimeters. Normal hydraulic oil (Spinesstic 22 for NIST and J13 for NPLI) was used as the pressure-transmitting fluid in the comparison. A pressure-regulating control pack together with needle valves and a manually operated screw pump was used to generate and control the appropriate applied pressures. Both piston gauges were mounted on a heavy non-magnetic wood base at NIST and stainless steel base at

NPLI in order to minimize vibration and magnetic effects. At NIST, it was not possible to bring both the pistons of NIST PG21 and the transfer standards to the same horizontal level; therefore, a pressure head correction term was applied to compensate the difference in their operating levels. At NPLI, the NPLI-200MPN and the transfer standards were housed in a similar Desgranges et Huot[1] base and a minor head correction was introduced. Before the measurement cycle, each piston was leveled to ensure the verticality of the axis and the system was checked for leaks to its full-scale pressure value of 100 MPa for NPLI-100MPN and 200 MPa for NPLI-500MPN. During the measurements, the transfer standard piston gauge was isolated from the rest of the pressure system by means of the isolation valve, and its fall rate was measured. Then the isolation valve was opened to the laboratory standard (that is, NIST PG21 or NPLI-200MPN), and the fractional weight on the laboratory standard was adjusted until the fall rate of the transfer standard matched that obtained during isolation [Heydemann and Welch (5)]. The pressure was changed in steps to values of (40, 60, 80, 80, 60 and 40) MPa for NPLI-100MPN, and (80, 100, 120, 140, 160, 180, 200, 200, 180, 160, 140, 120, 100 and 80) MPa for NPLI-500MPN. Three identical cycles were carried out, hence each pressure had 6 data points. About 15 minutes time was adequate for changes in pressure to allow the system to return to equilibrium, and about 10 minutes was required to repeat observations at the same pressure.

4. Results and discussion

(a) Mathematical Model

The effective area (A_p) of the TS for each observation, referred to 23°C, is calculated using the equation

$$A_p = \frac{\sum_i m_i g\left(1 - \frac{\rho_{0\mathrm{a}}}{\rho_0} + \frac{\rho_{0\mathrm{a}} - \rho_\mathrm{a}}{\rho_i}\right) + 2\sigma\sqrt{\pi A_{0,nom}}}{p\left[1 + \left(\alpha_p + \alpha_c\right)\left(t - t_0\right)\right]} \quad , \qquad [1]$$

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; ρ_i are the densities of the parts with masses m_i; ρ_a is the air density; $\rho_{0\mathrm{a}}$ is the conventional value of the air density ($\rho_{0\mathrm{a}}$ = 1.2 kg/m^3); ρ_0 is the conventional value of the mass density (ρ_0 = 8000 kg/m^3); g is the local acceleration of gravity; σ is the surface tension of the pressure transmitting oil (Spinesstic 22 or J13); $A_{0,nom}$ is the nominal effective area of the TS; p is the pressure generated by the laboratory secondary standard at the TS 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 TS; and t_0 is reference temperature (t_0 = 23 °C).

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[1] In order to describe materials and experimental procedure adequately, it is occasionally necessary to identify commercial products by manufacturers' 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 experimental data points for A_p as a function p from both laboratories are listed in Table 2 for TS NPLI-500MPN, and Table 4 for TS NPLI-100MPN. We estimate the average value of $A_{p,av}$ for each pressure point from n = 6 observations, that is:

$$A_{p,av} = \left(\sum_{k=1}^{n} A_{p,k} \right) / n \quad . \qquad [2]$$

The uncertainties in the measurement of effective area arise from two main sources. One is the inherent uncertainty associated with the gauge (Type B) and the other is associated with random effects in experimentation (Type A). The Type B uncertainty is mainly attributed to the uncertainty in pressure generated from the laboratory standard, but also includes the effects of the uncertainties in other parameters in Eq. (1), such as the mass, gravitational constant, and thermal expansion. Type A uncertainties arise effects including (i) random uncertainties in temperature, (ii) resolution of the balancing method for determining equilibrium between the two systems, (iii) other random effects in the pressure generated by the transfer standard or the laboratory standard. The Type A standard uncertainty of the average effective area, $u_A(A_{p,av})$, is taken as the standard deviation of the average, or:

$$u_A(A_{p,av}) = \left[\frac{1}{n(n-1)} \sum_{k=1}^{n} \left(A_{p,k} - A_{p,av} \right)^2 \right]^{1/2} . \qquad [3]$$

The uncertainty given by Eq. (3) is added in quadrature with the Type B uncertainty discussed above to give the combined standard uncertainty in the average effective area, or

$$u_C(A_{p,av}) = \left[u_A(A_{p,av})^2 + u_B(A_{p,av})^2_{NISTorNPLI} \right]^{1/2} . \qquad [4]$$

The average effective area and the various uncertainty components are listed in Table 3 for NPLI-500MPN and in Table 5 for NPLI-100MPN.

We have also fit the average effective area data for each TS from each laboratory standard by least squares regression to the linear distortion model of:

$$A_{p,\mathrm{mod}} = A_0 \left(1 + \lambda p \right) \quad . \qquad [5]$$

Results of the four fits are shown in Table 6. The model standard uncertainty of the effective area calculated from the linear distortion model, $u(A_{p,mod})$, is taken as the standard deviation of the linear fit added in quadrature with u_c from Eq. (4). The model uncertainty is listed in Table 6 and is the maximum over the pressure range for each of the four fits. The uncertainty is nearly constant over the pressure because the standard deviation of the fit is small compared to $u_c(A_{p,av})$.

b. Degree of equivalence

The degree of equivalence is evaluated by calculating the difference in average effective area of each transfer standard found by NIST and NPLI at similar pressure points. The difference is made dimensionless by dividing it by the “reference effective area” of the transfer standard, defined as the average of the effective areas determined by NIST and NPLI at each pressure. Or,

$$D = \frac{\left(A_{p,av}^{NIST} - A_{p,av}^{NPLI}\right)}{A_{p,ref}} \quad \text{, with } A_{p,ref} = \left(A_{p,av}^{NIST} + A_{p,av}^{NPLI}\right)/2 \quad . \qquad [6]$$

The associated standard uncertainty (k =1) in the difference is determined from:

$$u(D) = \left[u_C(A_{p,av})_{NIST}^2 + u_C(A_{p,av})_{NPLI}^2 + u_{tr.std}^2\right]^{1/2} / A_{p,ref} \qquad [7]$$

where $u_{tr.std.}$ is the relative stability of the transfer standard (4x10^{-6}, in the present case). If D is less than or equal to the relative standard uncertainty in the difference at a pressure point, than there is equivalence between the laboratory standards of NIST and NPLI at that pressure. Results for D are listed in Table 7, along with the degree of equivalence from CCM.P-K7 between NIST and NPLI at the common pressures of (40, 60, 80, and 100) MPa [6].

c. Results of the comparison

Figure 1 shows the effective area A_p of the traveling standard NPLI-500MPN from 80 MPa to 200 MPa as measured by both NIST PG21 and NPLI-200MPN for all three runs. The data obtained from NIST PG21 have been evaluated with the NIST standard computer software which is described in detail by Bean [5]. NPLI uses its own software that has been revalidated in the ISO 17025 technical peer review of the laboratory in December 2003. Figure 2 shows the average effective area, $A_{p.av}$ for NPLI-500MPN as a function of pressure.

Similarly, the effective area of traveling standard NPLI-100MPN, as measured by NIST PG21 and NPLI-200MPN from 40 MPa to 80 MPa, is plotted in Figure 3 for all three runs. The average effective area is plotted in Figure 4. Both transfer standards exhibit linear change of effective area with pressure when compared to both NIST and NPLI, which is common for the Desgrange et Huot design, further confirming the characterization of the laboratory standards at the two institutions.

The zero pressure effective area (A_0), as determined by linear least squares fitting, differs by 3x10^{-6} (relative) for NPLI-500MPN between NIST and NPLI. A_0 for NPLI-100MPN differs by 0.7x10^{-6} between NIST and NPLI. In both cases, A_0 as determined by NIST is larger. The distortion coefficient (λ) of NPLI-500MPN differs by 1.5 % between NIST and NPLI, and the distortion coefficient of NPLI-100MPN differs by 1.0 % between NIST and NPLI.

The degree of equivalence is shown in Figure 5. The relative difference ranges from 0.4x10^{-6} to 7.7x10^{-6}. The relative standard uncertainty of the difference is about

44×10^{-6} for both transfer standards used, hence in all cases D is less than the relative standard uncertainty. In the overlapping region of the CCM.P-K7 comparison from 40 MPa to 100 MPa, $D_{NIST\text{-}NPLI}$ is larger but well within its relative standard uncertainty of 31×10^{-6}.

5. Conclusion

Two transfer standards NPLI-500MPN (80 to 200) MPa and NPLI-100MPN (40 to 80) MPa have been compared against the laboratory standards of NPLI and NIST (NPLI-200MPN and NIST PG21). The piston cylinder assemblies only were exchanged between the two institutes, while the bases, masses, and temperature instrumentation were provided at NIST and NPLI during the comparison. It is observed that when these two transfer standards are compared at any constant applied pressure in the pressure range (40 to 200) MPa, the agreement between NPLI and NIST for effective area is within 10^{-5}, which is substantially less than the uncertainty of the difference. The results demonstrate the degree of equivalence between NPLI and NIST for pressure measurement in the hydraulic region up to 200 MPa, which is a region of industrial importance for both countries.

References

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Table 1. Description of the piston cylinder assemblies used in NIST – NPLI bilateral pressure comparison.

	Laboratory Standards		**Transfer Standards**[1]	
	NPLI-200 MPN [1-2]	**NIST PG21** [3-4]	**NPLI-100MPN**	**NPLI-500MPN**
Manufacturer	Desgranges et Huot, France	Ruska Instrument Corporation, USA	Desgranges et Huot, France	Desgranges et Huot, France
Range in pressure (MPa)	20 to 200	14 to 276	10 to 100	50 to 500
Effective area at atmosphere pressure and at 23°C [A_o(m^2)]	4.9026748×10^{-6}	8.402894×10^{-6}	-	-
Relative standard uncertainty of A_o ($\times 10^{-6}$)	15.8	16.0	-	-
Piston material	Tungsten carbide	Tungsten carbide	Tungsten carbide	Steel
Cylinder material	Tungsten carbide	Tungsten carbide	Tungsten carbide	Tungsten carbide
Piston and cylinder serial number	7619		7618	7620
Thermal expansion coefficient of piston	4.55×10^{-6}	4.55×10^{-6}	4.55×10^{-6}	10.5×10^{-6}
Thermal expansion coefficient of cylinder	4.55×10^{-6}	4.55×10^{-6}	4.55×10^{-6}	4.55×10^{-6}
Pressure distortion coefficient (λ) (MPa^{-1})	8.76×10^{-7}	-2.744×10^{-6}	-	-
Relative standard uncert. in A_p ($\times 10^{-6}$) produced by standard uncertainty in λ	27.4	Note 1	-	-
Total estimated relative standard uncertainty of A_p ($\times 10^{-6}$)	**40.0**	**16.0**	**-**	**-**

[*] Reference numbers indicate the source of information of this Table 1.

Note 1. NIST includes the uncertainty in λ with the uncertainty in A_0.

Table 2. A_p (mm^2) of the transfer standard NPLI-500MPN with *p (MPa)* against NIST PG21 and NPLI-200MPN

Laboratory Standard	NPLI-500MPN (TS)					
	1st Run		2nd Run		3rd Run	
	p (MPa)	A_p *(mm^2)*	*p (MPa)*	A_p *(mm^2)*	*p (MPa)*	A_p *(mm^2)*
NIST PG21	79.95515	1.9609969	79.95507	1.9609950	79.95492	1.9610026
	99.94241	1.9610246	99.94210	1.9610268	99.94170	1.9610366
	119.92830	1.9610678	119.92790	1.9610684	119.92830	1.9610658
	139.91420	1.9610978	139.91360	1.9611003	139.91420	1.9610958
	159.89890	1.9611331	159.89820	1.9611358	159.89880	1.9611324
	179.88350	1.9611656	179.88320	1.9611650	179.88340	1.9611667
	199.86770	1.9611925	199.86690	1.9611965	199.86780	1.9611915
	199.86730	1.9611984	199.86740	1.9611916	199.86790	1.9611925
	179.88380	1.9611643	179.88290	1.9611682	179.88390	1.9611652
	159.89900	1.9611339	159.89830	1.9611385	159.89960	1.9611285
	139.91420	1.9610997	139.91340	1.9611070	139.91420	1.9611017
	119.92790	1.9610743	119.92770	1.9610756	119.92820	1.9610733
	99.94198	1.9610350	99.94176	1.9610354	99.94187	1.9610411
	79.95504	1.9610035	79.95490	1.9610050	79.95497	1.9610092
NPLI-200MPN	79.86785	1.9609960	79.86839	1.9609960	79.86798	1.9610060
	99.83305	1.9610380	99.83372	1.9610330	99.83317	1.9610370
	119.79750	1.9610600	119.79830	1.9610660	119.79770	1.9610570
	139.76110	1.9610930	139.76210	1.9610960	139.76150	1.9610860
	159.7240	1.9611280	159.72530	1.9611280	159.72450	1.9611180
	179.68630	1.9611550	179.68760	1.9611560	179.68680	1.9611500
	199.64790	1.9611850	199.64950	1.9611900	199.64850	1.9611830
	199.64790	1.9611860	199.64940	1.9611880	199.64850	1.9611820
	179.68620	1.9611540	179.68760	1.9611550	179.68660	1.9611550
	159.72390	1.9611240	159.72510	1.9611240	159.72420	1.9611180
	139.76080	1.9610840	139.76180	1.9610960	139.76110	1.9610830
	119.79710	1.9610450	119.79800	1.9610560	119.79740	1.9610510
	99.83267	1.9610170	99.83335	1.9610230	99.83281	1.9610250
	79.86749	1.9609880	79.86805	1.9609930	79.86760	1.9609950

Table 3. **$A_{p,av}$ (mm^2) of the transfer standard, NPLI-500MPN with p (MPa) against NIST PG21 and NPLI-200MPN**

Laboratory Standard	**NPLI-500MPN (TS)**			
	p_{av} (MPa)	**$A_{p,av}$ (mm^2)**	**Type A Rel. Std. Uncer. u_A ($A_{p,av}$) [x10^{-6}]**	**$u_c(A_{p,av})$ [x10^{-6}]**
NIST PG21	79.955000	1.9610020	2.7	16.2
	99.942000	1.9610330	3.2	16.3
	119.928100	1.9610710	2.1	16.1
	139.914000	1.9611000	2.0	16.1
	159.898800	1.9611340	1.7	16.1
	179.883500	1.9611660	0.7	16.0
	199.867500	1.9611940	1.5	16.1
NPLI-200MPN	79.867890	1.9609960	3.0	40.1
	99.833130	1.9610290	4.3	40.2
	119.797700	1.9610560	3.7	40.2
	139.761400	1.9610900	3.1	40.1
	159.724500	1.9611230	2.3	40.1
	179.686800	1.9611540	1.1	40.0
	199.648600	1.9611860	1.5	40.0

Table 4. **A_p (mm^2) of the transfer standard, NPLI-100MPN, with p (MPa) against NIST PG21 and NPLI-200MPN**

	NPLI-100MPN (TS)					
Laboratory Standard	**1st Run**		**2nd Run**		**3rd Run**	
	p (MPa)	***A_p (mm^2)***	***p (MPa)***	***A_p (mm^2)***	***p (MPa)***	***A_p (mm^2)***
NIST PG21	39.972440	9.8062330	39.972540	9.8062080	39.972450	9.8062300
	59.957730	9.8063870	59.957720	9.8063880	59.957830	9.8063700
	79.942220	9.8065570	79.942210	9.8065580	79.942170	9.8065630
	79.942110	9.8065700	79.942250	9.8065530	79.942170	9.8065630
	59.957730	9.8063870	59.957820	9.8063720	59.957810	9.8063730
	39.972380	9.8062470	39.972450	9.8062300	39.972580	9.8061980
NPLI-200MPN	39.935730	9.8062340	39.935470	9.8062180	39.935290	9.8062150
	59.902500	9.8063950	59.902160	9.8063800	59.901860	9.8063830
	79.868570	9.8065890	79.868140	9.8065170	79.867760	9.8065300
	79.868500	9.8065720	79.868140	9.8065140	79.867730	9.8065180
	59.902350	9.8063880	59.902030	9.8063540	59.901800	9.8063510
	39.935500	9.8061860	39.935380	9.8062100	39.935200	9.8061900

Table 5. **$A_{p,av}$ (mm^2) of the transfer standard, NPLI-100MPN, with p (MPa) against NIST PG21 and NPLI-200MPN**

Laboratory Standard	NPLI-100MPN (TS)			
	p (MPa)	$A_{p,av}$ (mm^2)	Type A Rel. Std. Uncer. u_A ($A_{p,av}$) [x10^{-6}]	u_c($A_{p,av}$) [x10^{-6}]
NIST PG21	39.972470	9.8062250	1.8	16.1
	59.957770	9.8063790	0.9	16.0
	79.942190	9.8065600	0.7	16.0
NPLI-200MPN	39.935430	9.8062090	1.9	40.0
	59.902120	9.8063750	1.9	40.0
	79.868140	9.8065400	3.3	40.1

Table 6. **Effective area at zero pressure and at 23°C [A_o (mm^2)], and pressure distortion coefficient [λ (MPa^{-1})] of the transfer standards, NPLI-500MPN and NPLI-100MPN, as obtained from NPLI-200MPN and NIST PG21.**

Laboratory standard	Traveling standards	A_o (mm^2)	λ (MPa^{-1}) [x10^{-7}]	Rel. Std. Uncer. of $A_{p,mod}$ $u(A_{p,mod})$ [x10^{-6}]
NIST PG21	NPLI-500 MPN	1.9608740	8.23	16.4
	NPLI-100 MPN	9.8058850	8.55	16.4
NPLI-200MPN	NPLI-500MPN	1.9608680	8.10	40.2
	NPLI-100 MPN	9.8058780	8.46	40.3

Table 7: **Degree of equivalence, D, between NIST and NPLI from difference in effective area of transfer standards at measured pressures. Relative standard uncertainty in difference given for same pressures. $D_{NIST-NPLI}$ are also provided from CCM.P-K7 (6) for comparison.**

	Present Comparison			CCM.P-K7	
Nominal	D(x10^{-6})		$u(D)$ (x10^{-6})		
Pressure (MPa)	100MPN	500MPN		$D_{NIST-NPLI}$ (x10^{-6})	$u(D_{NIST-NPLI})$ (x10^{-6})
40	1.6		43.3	17.2	30.5
60	0.4		43.3	8.5	30.5
80	2.0		43.4	5.4	30.5
80		3.1	43.5	5.4	30.5
100		2.0	43.6	5.5	30.5
120		7.6	43.5		
140		5.1	43.4		
160		5.6	43.4		
180		6.1	43.3		
200		4.1	43.3		

Figure 1 : A_p (mm^2) of the transfer standard - NPLI-500MPN with p *(MPa)* against NIST PG21 and NPLI-200MPN

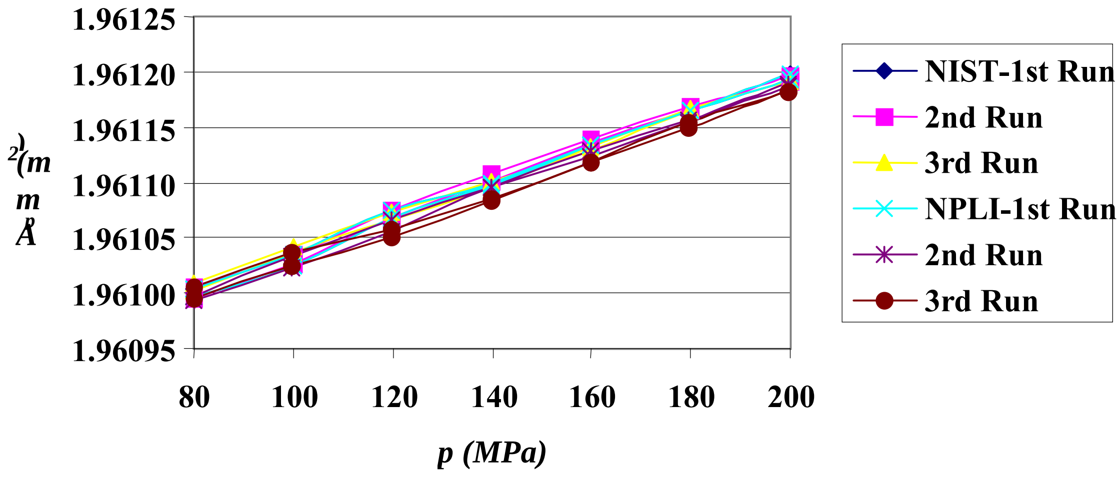
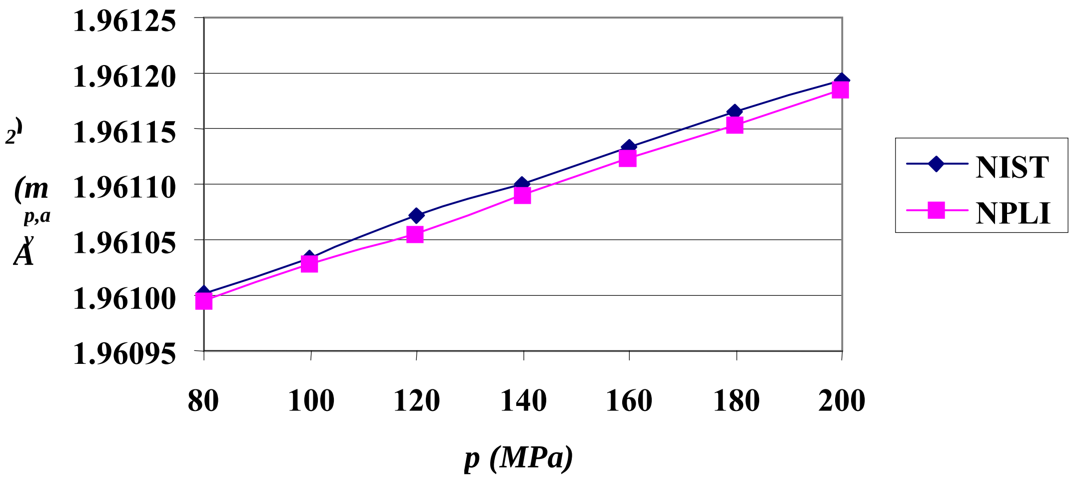


Figure 2 : $A_{p,av}$ (mm^2) of the transfer standard - NPLI- with p *(MPa)* against NIST PG21and NPLI-200MPN



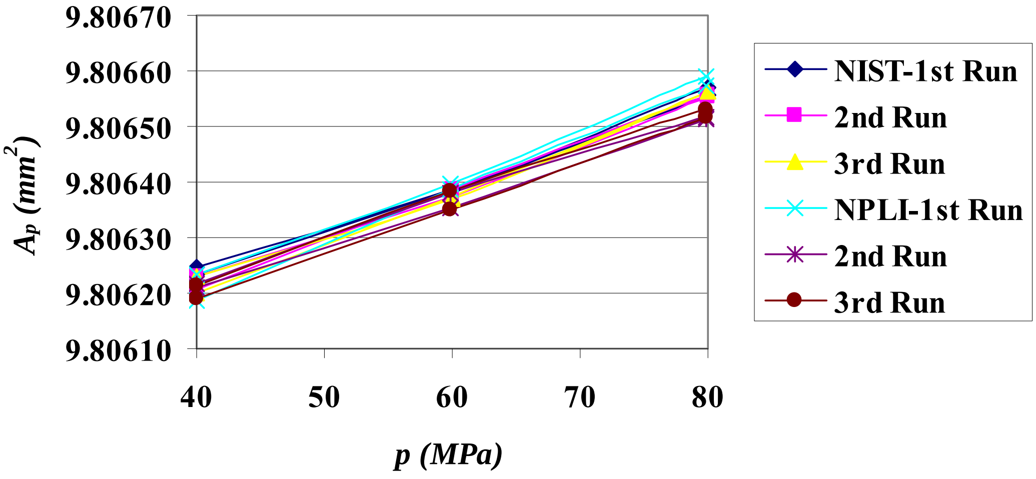


Figure 3 : A_p (mm^2) of the transfer standard - NPLI-100MPN with p (MPa) against NIST PG21 and NPLI-200MPN

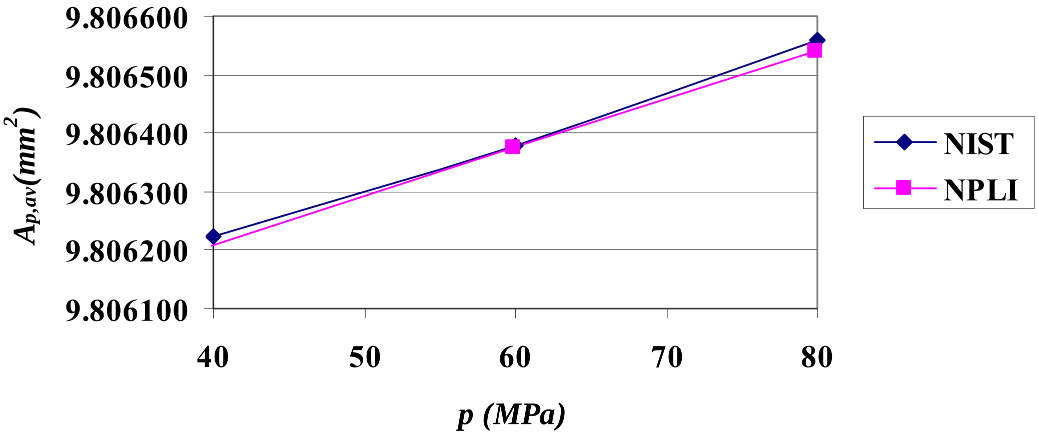


Figure 4: $A_{p,av}$ (mm^2) of the transfer standard - NPLI-100MPN with p (MPa) against NIST PG21 and NPLI-200MPN

Figure 5: Degree of equivalence (D) as a function of p *(MPa)* and $D_{NIST\text{-}NPLI}$ from CCM.P-K7 *[40 MPa to 100 MPa]* shown for comparison