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RESEARCH REPORT

Evaluation of Laboratory Performance Through Interlaboratory Comparison

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Abstract

This paper reports the performance of the calibration results obtained by 21 laboratories using digital pressure calibrator as an artifact in the pressure range 7-70 MPa. National Physical Laboratory (NPLI), New Delhi has coordinated this programme and also acted as a reference laboratory. The program started in May, 2006 and completed during May, 2008. The comparison was carried out at 10 equally spaced pressure points i.e. 7, 14, 21, 28, 35, 42, 49, 56, 63 and 70 MPa throughout the entire pressure range of 7 – 70 MPa. The calibration results thus obtained were analyzed as per ISO/IEC GUM document. The 92.7 % measurement results are found in agreement with the results of NPLI. The relative deviations between laboratories values and reference values are well within the 0.05 % for 123 measurement points, 0.1% for 162 measurement points and 0.25% for 177 measurement points. The difference of the laboratories values with reference values are found almost well within the uncertainty band of the reference values at 68.0 % measurement results, within their reported expanded uncertainty band at 81.5% measurement results and within the combined expanded measurement uncertainty band at 92.7 % measurement results. Overall, the results are considered to be reasonably good being the first proficiency testing for most of the participating laboratories.

1. Introduction

The last few decades have witnessed the growing need of the industrial utilization of pressure metrology day by day. The control, monitor and measurement of pressure are not only important to increase the productivity but also play a vital role from the safety point of view. As we move in to the new millennium, the globalization and international competitiveness, the international trade and commerce will continue to significantly impact our economy. As trade barriers are lifted, our economy, in particular manufacturers must be prepared to comply with international standards, including the assessment of competency in measurements.

In order to establish the international / national compatibility, uniformity and affirmation of measurement results, considerable efforts are being made globally so that the measurements made in one location in the world are equivalent / compatible in other locations on the same or related products. Such tasks are achieved by organizing international comparisons and proficiency testing by inter-laboratory comparisons of the measurement results carried out on the same artifact. The National Measurement Institutes (NMIs) provide traceability to industries and other users in terms of calibration.

The Mutual Recognition Arrangement (MRA) also stipulates the requirement for measurement laboratory to participate in the proficiency testing and establish the technical competence. To meet the requirements of MRA [4], ISO 17025 [5] and APLAC MR001 [6], the National Accreditation Board for Testing & Calibration Laboratories (NABL) has conducted several Proficiency Testing (PT) experiments in pressure metrology in the pressure range 5–70 MPa amongst the NABL accredited Indian pressure calibration laboratories in conformity with ISO/IEC Guide 43 [7] through the National Metrology Institute (NMI) of India i.e. National Physical Laboratory (NPLI), New Delhi which acts as a Reference laboratory.

In a series of 7 PTs organized, the 1st and 4th PTs, designated as NABL-Pressure-PT001 and NABL-Pressure-PT004 were organised / being organised for 7 and 10 laboratories, respectively having measurement capabilities better than 0.05% of full scale pressure using dead weight tester as an artifact [8-9]. The 2nd PT i.e. NABL-Pressure-PT002 was conducted for another 7 laboratories, having measurement capabilities coarse than 0.05% and better than 0.25 % of full scale pressure using digital pressure calibrator [10-11]. The 3rd and 6th PTs i.e. NABL-Pressure-PT003 and NABL-Pressure-PT006, included 11 and 17 laboratories, respectively having measurement capabilities 0.25% or coarse than 0.25% of full scale pressure using pressure dial gauge as an artifact [12-13]. Similarly, another PT experiment i.e. NABL-Pressure-PT007 was carried out for 14 laboratories having measurement capabilities 0.25% or coarse than 0.25% of full scale pressure using pressure dial gauge as an artifact in the pressure range 6 – 60 MPa [14].

The present PT experiment, designated as NABL-Pressure-PT005, is recently completed during May 2008. This PT programme is designed and organized in the hydraulic pressure region covering pressure range 7–70 MPa (70 to 700 bar) using the digital pressure calibrator as an artifact. The 21 NABL accredited pressure calibration laboratories, having measurement capabilities coarser than 0.05% and better than 0.25 % of full scale pressure have been covered in this PT. The report summarizes the results of measurement of pressure at equally spaced pressure points. The circulation of the artifact started in July 2006 and completed in April 2008 in a record time.

2. Methodology

The PT programme is designed as per guidelines stipulated in ISO/IEC 17025 [5], ISO/IEC Guide 43 [7] and NABL-162 [15]. The artifact used for the measurements is a high precision Digital Pressure Calibrator, Serial No. H540/101, make-DH-Budenberg, UK. Selection of the measurement points is an important aspect of the proficiency testing programme. The entire pressure range of 7 to 70 MPa was divided into 10 equally spaced measurement points of 7, 14, 21, 28, 35, 42, 49, 56, 63 and 70 MPa. The programme was running smoothly and almost all the participants performed their measurements well in time. Generally, all the participants were advised to complete the measurements in two weeks time and dispatch the artifact to next participant within next one week. However, one week time for measurements and one week time for dispatch was given for the participants when artifact was moved within the same city. The whole circulation programme was completed in two loops. The movement of the artifact was smoothly monitored. After smooth completion of the programme of the first loop, the artifact reached NPLI, New Delhi during April, 2007. It was recalibrated at NPLI. New Delhi and then dispatched for the circulation of the second loop. There was no technical problem, fault, snag or difficulty reported by any of the participants. Schematic diagram of the movement of the artifact is depicted in Fig. 1.

3. Characterization of the Artifact and Assigning Reference Values

The characterization of the artifact was performed by direct comparison method [1-4] against the national hydraulic secondary pressure standard, designated as NPL200MPA, first at the start of the programme during June, 2006, second in the middle during March-April, 2007 and finally at the end of programme during April, 2008. The traceability of the NPL200MPA is established by cross-floating it against national secondary pressure standards [16-19] and its measurement uncertainty is estimated as $68 \times 10^{-6} \times p$ at a coverage factor $k = 1$. NPL200MPA has also been used as NPL standard to calibrate the transfer standards for the international key comparison i.e. APMP-SIM. M.P. K-7 [20]. In this comparison, our results agreed well within 7.7×10^{-6} with NIST, USA and were also found well within

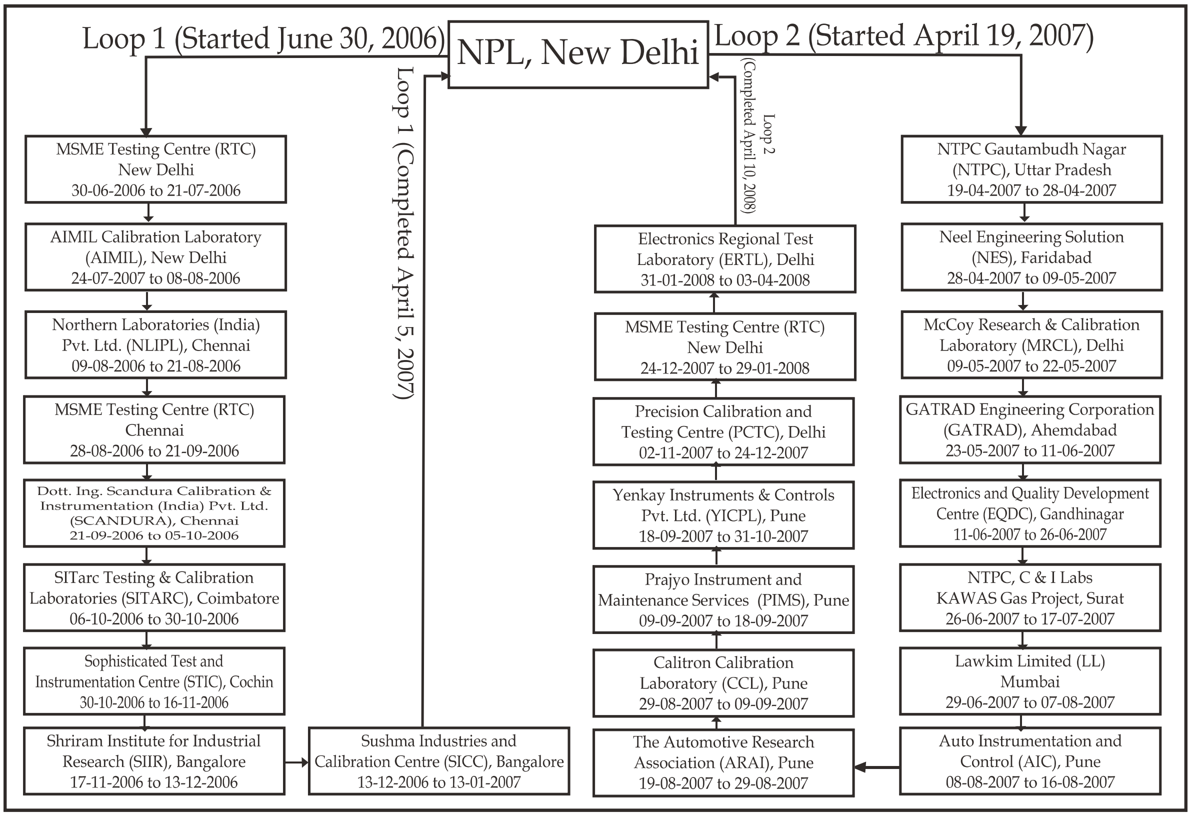

Fig. 1. Circulation and movement of the artifact during comparison

our claimed measurement standard uncertainty of 40 x 10^{-6}. Measurement were performed at 10 pressure points i.e. 7, 14, 21, 28, 35, 42, 49, 56, 63 and 70 MPa and observations were repeated six times, thrice in increasing order and thrice in decreasing order, for each pressure point and the values of measured pressure, their repeatability and expanded uncertainty were computed using method described and computer software developed for this purpose [21-23].

The values of measured pressures p_1, p_2 and p_3, for three successive calibrations, during June, 2006, March-April, 2007 and April, 2008 are shown in Table 1 along with the details of the uncertainty computation. The arithmetic mean of these pressure values (p_1, p_2 and p_3) are the reference values of the pressure measured (p) for individual measurement point throughout the entire pressure scale. In order to study the behaviour and stability of the artifact, the calibration factor (C_f) is determined as follows;

$$C_f = \frac{p_g}{p_S} \quad (1)$$

where, p_g is the reading of the artifact and p_S is corresponding pressure measured by the standard during calibration. The behavior of the artifact was found identical in all the three calibrations. It is clearly evident from Fig. 2(a) that during all the three calibrations, the artifact behaved almost in a similar fashion. Although, the behaviour of the artifact was slightly different during March 2007 but the values of calibration factor were found much closer to the unity which indicates a close agreement between gauge reading and the standard pressure. The relative deviations of the measured pressures p_1, p_2 and p_3 from the reference values, p are found well within ± 0.033 % of the reading [Fig. 2(b)] and ± 0.01 % of full scale [Fig. 2(c)]. The deviations are well within the manufacturer specifications of 0.05% of span (full scale), the maximum deviation of 0.033 % of reading is taken into consideration to estimate

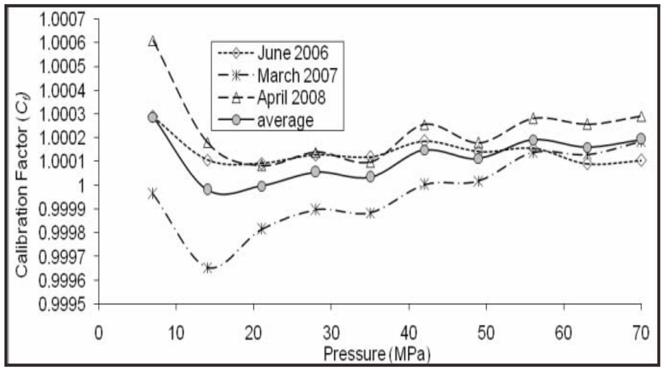

Fig. 2(a). The Calibration factor (C_f) and its average values plotted as a function of applied pressure p for all the three successive calibrations of the artifact

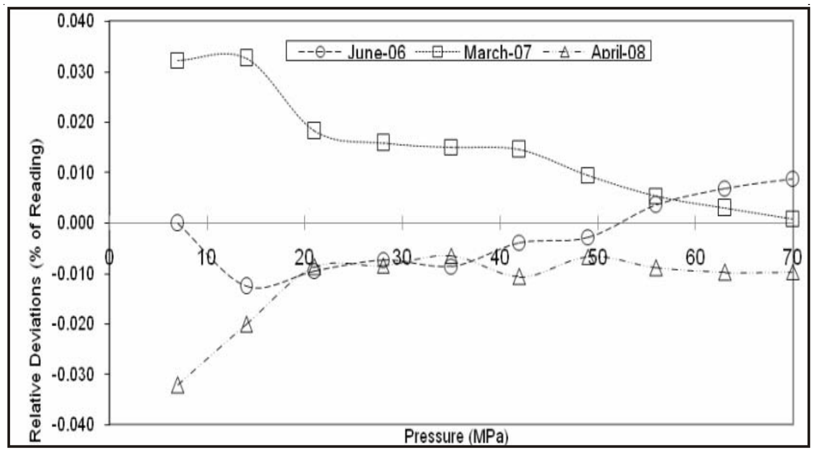

Fig. 2(b). Relative deviations (% of reading) of the measured pressures p_1, p_2 and p_3 from the reference values p for all the three successive calibrations

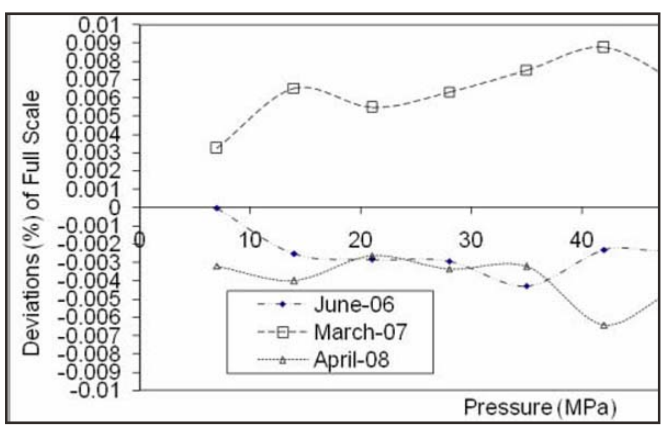

Fig. 2(c). Relative deviations (% of full scale pressure) of the measured pressures p_1, p_2 and p_3 from the reference values p for all the three successive calibrations

Table 1
Details of metrological characteristics of the artifact and assignment of reference values.

Nominal Pressure MPa	Pressure (MPa) p_1 June 2006	Pressure (MPa) p_2 March-April 2007	Pressure (MPa) p_3 April 2008	Average Pressure (MPa) p Reference Values	Dev. p_1-p (MPa)	Dev. p_2-p (MPa)	Dev. p_3-p (MPa)	Uncertainty Through Type A Method (MPa)	Uncertainty Through Type B Method (MPa)	Uncertainty Through Stability of the Artifact (MPa)	Combined Uncertainty $u_c(p)$ (MPa)	Expanded Uncertainty $U(p)$ (MPa)
7	6.9980	7.0003	6.9957	6.9980	0.0000	0.0023	-0.0023	0.0014	0.0033	0.0023	0.0042	0.0085
14	13.9985	14.0048	13.9975	14.0003	-0.0018	0.0046	-0.0028	0.0017	0.0047	0.0046	0.0068	0.0136
21	20.9981	21.0039	20.9982	21.0001	-0.0020	0.0038	-0.0018	0.0024	0.0060	0.0038	0.0075	0.0150
28	27.9964	28.0029	27.9961	27.9985	-0.0021	0.0044	-0.0024	0.0021	0.0059	0.0044	0.0077	0.0154
35	34.9958	35.0041	34.9965	34.9988	-0.0030	0.0053	-0.0023	0.0021	0.0063	0.0053	0.0085	0.0169
42	41.9921	41.9999	41.9893	41.9938	-0.0016	0.0061	-0.0045	0.0031	0.0088	0.0061	0.0112	0.0223
49	48.9931	48.9991	48.9912	48.9944	-0.0014	0.0047	-0.0033	0.0016	0.0051	0.0047	0.0071	0.0142
56	55.9912	55.9922	55.9842	55.9892	0.0020	0.0030	-0.0050	0.0030	0.0093	0.0050	0.0110	0.0219
63	62.9943	62.9918	62.9838	62.9899	0.0044	0.0018	-0.0062	0.0019	0.0065	0.0062	0.0092	0.0183
70	69.9926	69.9871	69.9797	69.9865	0.0062	0.0006	-0.0068	0.0017	0.0067	0.0068	0.0097	0.0193

	Uncertainty Contributions Evaluated through Type A Method				Uncertainty Contributions Evaluated through Type B Method				
Nominal Pressure MPa	$u_{a_1}=\frac{\sigma\ of\ the\ year\ 2006}{\sqrt{n}}$ MPa	$u_{a_2}=\frac{\sigma\ of\ the\ year\ 2007}{\sqrt{n}}$ MPa	$u_{a_3}=\frac{\sigma\ of\ the\ year\ 2008}{\sqrt{n}}$ MPa	$u_a=max(u_{a_1},u_{a_2},u_{a_3})$ MPa	u_{b1} MPa (resolution)	u_{b2} MPa (standard)	u_{b3} MPa (hysteresis)	$u_b=\sqrt{\left[(u_{b1})^2+(u_{b2})^2+(u_{b3})^2\right]}$ (MPa)	Stability of the Artifact
7	0.0011	0.0004	0.0014	0.0014	0.0003	0.0005	0.0033	0.0033	0.0023
14	0.0013	0.0014	0.0017	0.0017	0.0003	0.0010	0.0046	0.0047	0.0046
21	0.0023	0.0011	0.0024	0.0024	0.0003	0.0014	0.0058	0.0060	0.0038
28	0.0021	0.0009	0.0019	0.0021	0.0003	0.0019	0.0056	0.0059	0.0044
35	0.0021	0.0013	0.0021	0.0021	0.0003	0.0024	0.0058	0.0063	0.0052
42	0.0027	0.0010	0.0031	0.0031	0.0003	0.0029	0.0083	0.0088	0.0061
49	0.0016	0.0012	0.0014	0.0016	0.0003	0.0034	0.0039	0.0051	0.0047
56	0.0018	0.0010	0.0029	0.0029	0.0003	0.0039	0.0085	0.0093	0.0050
63	0.0008	0.0019	0.0013	0.0019	0.0003	0.0043	0.0048	0.0065	0.0062
70	0.0016	0.0016	0.0017	0.0017	0.0003	0.0048	0.0046	0.0067	0.0068

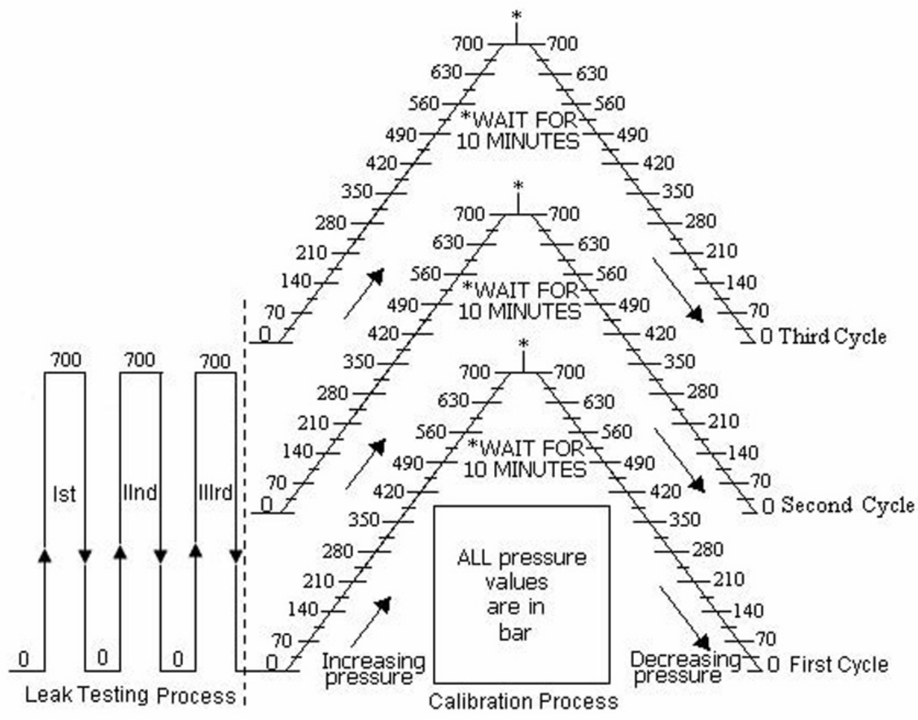

Fig. 3. Sequence of measurements taken

the expanded uncertainty $U(p) = (0.011 + 0.00015\ p)$ MPa. This concludes that the artifact remained stable during the whole PT programme within its estimated measurement uncertainty.

4. Calibration Procedure

A total of 21 laboratories participated in the program. Each participating laboratory was assigned a random code number while the reference laboratory, NPLI, was assigned '1.' The calibration procedure was identical to method used in NABL-Pressure – PT004 [10-11]. A layout diagram showing the sequence of measurements performed by each participant is shown in Fig. 3. After performing leak testing, zero setting, selection of datum level and generating pressure up to full scale, the participants were advised to wait for at least 10 minutes, before repeating the observations in the decreasing order of pressure till the pressure reaches to zero and then record the total 22 observations, 11 each in increasing and decreasing order of pressures for one cycle. The measurements were then repeated for at least 3 pressure cycles to make the total number of 66 observations.

They were requested to correct the values of the measured pressure for 23 ^{0}C using thermal expansion coefficient of the piston – cylinder assembly (if dead weight tester is used as standard) or elastic element (if pressure dial gauge or digital calibrator is used as standard) using standard equations. They were also requested to evaluate the uncertainty associated with pressure measurements as per ISO Guide to the Expression of Uncertainty in Measurement/ NABL Document 141 on uncertainty following Type A and Type B methods of evaluation [24-26]. Each participating laboratory was requested to prepare an uncertainty budget at maximum pressure, considering all Type A and Type B uncertainty components.

5. Reporting of Results and Data Analysis

The values of measured pressure, acceleration of local gravity and reference temperature and the measurement uncertainty estimated at maximum pressure, reported by the participants are shown in Table 2. Measurement performance of the participants has been assessed on the basis of Error Normalized (E_n) calculated for each measurement

Table 2

Details of the reference values of measured pressure (p), pressure measured by the participants (p'), reference temperature and other metrological characteristics of the laboratories standards.

	Laboratory Code										
p (MPa)	1	2	3	4	5	6	7	8	9	10	11
7	6.9980	6.9860	6.9914	7.0020	6.9870	6.9766	6.9920	6.9840	7.0020	6.9888	6.9990
14	14.0003	14.001	13.9938	14.0100	13.9970	13.9815	14.0040	13.9920	14.0050	13.9922	14.0085
21	21.0001	20.9870	21.0058	21.0020	21.0170	20.9821	20.9959	20.9940	21.0010	20.9945	21.0122
28	27.9985	27.9920	27.9929	28.0170	28.0137	27.9845	27.9980	27.9930	28.0010	27.9969	28.0140
35	34.9988	35	35.02513	35.003	35.01366	34.98679	35.01	35.001	35	34.99969	35.018
42	41.9938	41.9960	42.0236	42.0050	41.9570	41.9892	42.0119	42.0030	42.0030	42.0021	-
49	48.9945	49.0010	49.0063	49.0120	49.0537	48.9965	49.0137	49.0130	49.0000	49.0039	-
56	55.9892	55.9970	56.0267	56.0150	56.0537	55.9990	56.0157	56.0170	56.0060	56.0107	-
63	62.9899	63.0020	-	63.0130	63.0503	63.0014	63.0082	-	63.0080	63.0097	-
70	69.9865	70.0100	-	70.0200	70.0403	70.0137	-	-	70.0110	70.0163	-
g (m/s^2)	9.78281	9.7914503	9.791	9.7828872	9.78267503	9.7809443	9.78147	9.780191	9.780352	9.53	9.791
$T_{Ref.}$ (^{0}C)	20.9-23.7	23	23	23	20	20.9-23.7	20	22.7-23.4	23	23	23
Traceability	Measure Technique, Chennai	NPL, Delhi	NPL, Delhi	Nagman, Chennai	Measure Technique, Chennai	Measure Technique, Chennai	FCRI, Palghat	NPL, Delhi	UKAS	ERTL, Delhi	NCCBM, Faridabad

12	13	14	15	16	17	18	19	20	21	22
6.9812	7.0154	6.9940	7.0000	7.003	7.008	7.005	7.003	7.001	7.001035	6.9942
13.9917	14.0185	14.0010	14.0050	14.008	14.013	14.002	14.005	14.00083	14.0044	13.9897
20.9964	21.0297	20.999	21.0020	21.008	21.017	20.999	21.003	20.99267	21.00465	20.9874
28.0003	28.0327	28.003	28.0030	28.003	28.022	27.993	28	27.98983	28.00104	27.9824
35.01223	35.0374	35.001	35.0060	35.005	35.022	34.994	34.998	34.97333	35.00427	34.9773
42.0126	42.0404	41.995	42.0050	-	42.021	41.992	-	-	41.99984	41.9733
49.0176	49.0435	48.991	49.0050	-	49.022	48.996	-	-	48.99897	48.9702
55.9849	56.0465	55.983	56.0040	-	56.02	55.997	-	-	55.99623	55.9649
-	-	62.981	-	-	63.016	62.99	-	-	62.98813	62.958
-	-	-	-	-	70.01	69.978	-	-	69.98797	69.9532
9.7912393	9.78807	9.787023	-	9.893472	-	9.78	-	9.79111017	9.81618	9.78281
23	23	23	-	23	23-24	22.1	25	23	22.6-23.5	20.9-23.7
NCCBM, Faridabad	Measure Technique, Chennai	Nagman, Chennai	IDEMI, Mumbai	WIKA, Pune	IDEMI, Mumbai	WIKA, Pune	WIKA, Pune	NPL, Delhi	Measure Technique, Chennai	Measure Technique Chennai

Table 3
Relative deviations (in %) of the measured pressure (p') from reference values (p)

	Laboratory Code																					
p (MPa)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
7	-	-0.17	-0.09	0.06	-0.16	-0.31	-0.09	-0.20	0.06	-0.13	0.01	-0.24	0.25	-0.06	0.03	0.07	0.14	0.10	0.07	0.04	0.04	-0.05
14	-	0.01	-0.05	0.07	-0.02	-0.13	0.03	-0.06	0.03	-0.06	0.06	-0.06	0.13	0.01	0.03	0.06	0.09	0.01	0.03	0.00	0.03	-0.08
21	-	-0.06	0.03	0.01	0.08	-0.09	-0.02	-0.03	0.00	-0.03	0.06	-0.02	0.14	0.00	0.01	0.04	0.08	0.00	0.01	-0.04	0.02	-0.06
28	-	-0.02	-0.02	0.07	0.05	-0.05	0.00	-0.02	0.01	-0.01	0.06	0.01	0.12	0.02	0.02	0.02	0.08	-0.02	0.01	-0.03	0.01	-0.06
35	-	0.00	0.08	0.01	0.04	-0.03	0.03	0.01	0.00	0.00	0.05	0.04	0.11	0.01	0.02	0.02	0.07	-0.01	0.00	-0.07	0.02	-0.06
42	-	0.01	0.07	0.03	-0.09	-0.01	0.04	0.02	0.02	0.02	-	0.04	0.11	0.00	0.03	-	0.06	0.00	-	-	0.01	-0.05
49	-	0.01	0.02	0.04	0.12	0.00	0.04	0.04	0.01	0.02	-	0.05	0.10	-0.01	0.02	-	0.06	0.00	-	-	0.01	-0.05
56	-	0.01	0.07	0.05	0.12	0.02	0.05	0.05	0.03	0.04	-	-0.01	0.10	-0.01	0.03	-	0.05	0.01	-	-	0.01	-0.04
63	-	0.02	-	0.04	0.10	0.02	0.03	-	0.03	0.03	-	-	-	-0.01	-	-	0.04	0.00	-	-	0.00	-0.05
70	-	0.03	-	0.05	0.08	0.04	-	-	0.04	0.04	-	-	-	-	-	-	0.03	-0.01	-	-	0.00	-0.05

Table 4
Summary of the normalized error (E_n) of each participant

	Laboratory Code																				
p (MPa)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
7	-0.79	-0.45	0.22	-0.11	**-1.45**	-0.53	-0.81	0.14	-0.58	0.09	-0.37	0.63	-0.05	0.12	0.14	0.17	0.37	0.12	0.07	0.35	-0.07
14	0.04	-0.37	0.46	-0.03	**-1.04**	0.23	-0.41	0.15	-0.43	0.52	-0.19	0.61	0.01	0.23	0.23	0.21	0.08	0.11	0.01	0.30	-0.21
21	-0.53	0.30	0.08	0.16	-0.92	-0.23	-0.28	0.03	-0.27	0.73	-0.08	0.97	-0.01	0.09	0.23	0.27	-0.04	0.07	-0.16	0.30	-0.23
28	-0.23	-0.28	0.83	0.15	-0.69	-0.02	-0.25	0.08	-0.08	0.90	0.04	**1.11**	0.06	0.20	0.13	0.38	-0.15	0.03	-0.19	0.16	-0.28
35	0.04	**1.18**	0.17	0.14	-0.54	0.51	0.10	0.03	0.04	**1.04**	0.28	**1.20**	0.03	0.29	0.16	0.37	-0.11	-0.02	-0.53	0.31	-0.39
42	0.06	**1.11**	0.39	-0.35	-0.16	0.66	0.33	0.25	0.31	-	0.38	**1.29**	0.01	0.39	-	0.43	-0.03	-	-	0.26	-0.39
49	0.16	0.55	0.77	0.56	0.10	0.83	0.84	0.18	0.46	-	0.50	**1.55**	-0.04	0.43	-	0.45	0.03	-	-	0.29	-0.44
56	0.16	**1.34**	0.95	0.61	0.33	0.88	0.98	0.45	0.79	-	-0.08	**1.58**	-0.07	0.48	-	0.48	0.11	-	-	0.30	-0.45
63	0.23	-	0.90	0.57	0.39	0.63	-	0.51	0.81	-	-	-	-0.11	-	-	0.42	0.00	-	-	-0.09	-0.58
70	0.42	-	**1.34**	0.50	0.87	-	-	0.69	**1.17**	-	-	-	-	-	-	0.37	-0.10	-	-	0.07	-0.58

Table 5
Summary of the expanded uncertainty estimated and reported by the participants

	Laboratory Code																					
p (MPa)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
7	0.0085	0.0127	0.0121	0.0160	0.103	0.0120	0.0073	0.0150	0.0280	0.0132	0.0075	0.0440	0.0265	0.0806	0.0140	0.0338	0.06	0.0172	0.04239	0.04258	0.002076	0.0512
14	0.0136	0.0156	0.0111	0.0160	0.103	0.0119	0.0084	0.0147	0.0280	0.0132	0.0084	0.0440	0.0266	0.0806	0.0160	0.0312	0.06	0.0166	0.04232	0.0425	0.002146	0.0484
21	0.0150	0.0195	0.0115	0.0180	0.103	0.0125	0.0100	0.0156	0.0300	0.0138	0.0075	0.0440	0.0265	0.0807	0.0160	0.0318	0.06	0.0246	0.04226	0.04262	0.003874	0.0522
28	0.0154	0.0239	0.0126	0.0160	0.103	0.0130	0.0123	0.0156	0.0300	0.0140	0.0078	0.0440	0.0268	0.0807	0.0160	0.0328	0.06	0.0328	0.04224	0.04258	0.006228	0.055
35	0.0169	0.0285	0.0145	0.0180	0.103	0.0143	0.0140	0.0158	0.0300	0.0144	0.0074	0.0440	0.0274	0.0808	0.0180	0.0344	0.06	0.041	0.04222	0.0448	0.005614	0.053
42	0.0223	0.0334	0.0151	0.0180	0.103	0.0166	0.0160	0.0164	0.0300	0.0148	-	0.0440	0.0285	0.0808	0.0180	-	0.06	0.0488	-	-	0.006124	0.0482
49	0.0142	0.0384	0.0160	0.0180	0.104	0.0151	0.0183	0.0169	0.0280	0.0150	-	0.0440	0.0284	0.0811	0.0200	-	0.06	0.0572	-	-	0.007	0.0528
56	0.0219	0.0434	0.0175	0.0160	0.104	0.0193	0.0204	0.0178	0.0300	0.0160	-	0.0491	0.0287	0.0810	0.0220	-	0.06	0.0654	-	-	0.008048	0.0494
63	0.0183	0.0485	-	0.0180	0.105	0.0227	0.0225	-	0.0300	0.0162	-	-	-	0.0810	-	-	0.06	0.0734	-	-	0.009382	0.052
70	0.0193	0.0525	-	0.0160	0.1051	0.0245	-	-	0.0300	0.0166	-	-	-	-	-	-	0.06	0.0816	-	-	0.009856	0.0538

Table 6
Summary of the combined expanded uncertainty estimated during comparison

	Laboratory Code																					
p (MPa)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
7	0.0085	0.0153	0.0148	0.0181	0.1033	0.0147	0.0112	0.0172	0.0293	0.0157	0.0113	0.0448	0.0278	0.0811	0.0164	0.0349	0.0606	0.0192	0.0432	0.0434	0.0087	0.0519
14	0.0136	0.0207	0.0175	0.0210	0.1035	0.0181	0.0160	0.0200	0.0311	0.0190	0.0160	0.0460	0.0299	0.0818	0.0210	0.0340	0.0615	0.0215	0.0445	0.0446	0.0138	0.0503
21	0.0150	0.0246	0.0189	0.0234	0.1038	0.0195	0.0180	0.0216	0.0335	0.0203	0.0167	0.0465	0.0304	0.0821	0.0219	0.0351	0.0618	0.0288	0.0448	0.0452	0.0154	0.0543
28	0.0154	0.0285	0.0199	0.0222	0.1042	0.0202	0.0197	0.0219	0.0337	0.0208	0.0173	0.0466	0.0309	0.0821	0.0222	0.0362	0.0619	0.0362	0.0450	0.0453	0.0166	0.0571
35	0.0169	0.0332	0.0222	0.0247	0.1048	0.0221	0.0219	0.0231	0.0344	0.0222	0.0184	0.0471	0.0322	0.0825	0.0247	0.0383	0.0623	0.0443	0.0455	0.0479	0.0178	0.0556
42	0.0223	0.0402	0.0269	0.0287	0.1058	0.0278	0.0274	0.0277	0.0374	0.0268	-	0.0493	0.0362	0.0838	0.0287	-	0.0640	0.0537	-	-	0.0231	0.0531
49	0.0142	0.0409	0.0214	0.0229	0.1049	0.0207	0.0232	0.0221	0.0314	0.0207	-	0.0462	0.0317	0.0823	0.0245	-	0.0617	0.0589	-	-	0.0158	0.0547
56	0.0219	0.0486	0.0280	0.0271	0.1065	0.0292	0.0299	0.0282	0.0371	0.0271	-	0.0537	0.0361	0.0839	0.0310	-	0.0639	0.0690	-	-	0.0233	0.0540
63	0.0183	0.0518	-	0.0257	0.1063	0.0292	0.0290	-	0.0351	0.0244	-	-	-	0.0830	-	-	0.0627	0.0756	-	-	0.0206	0.0551
70	0.0193	0.0560	-	0.0251	0.1069	0.0312	-	-	0.0357	0.0255	-	-	-	-	-	-	0.0630	0.0839	-	-	0.0217	0.0572

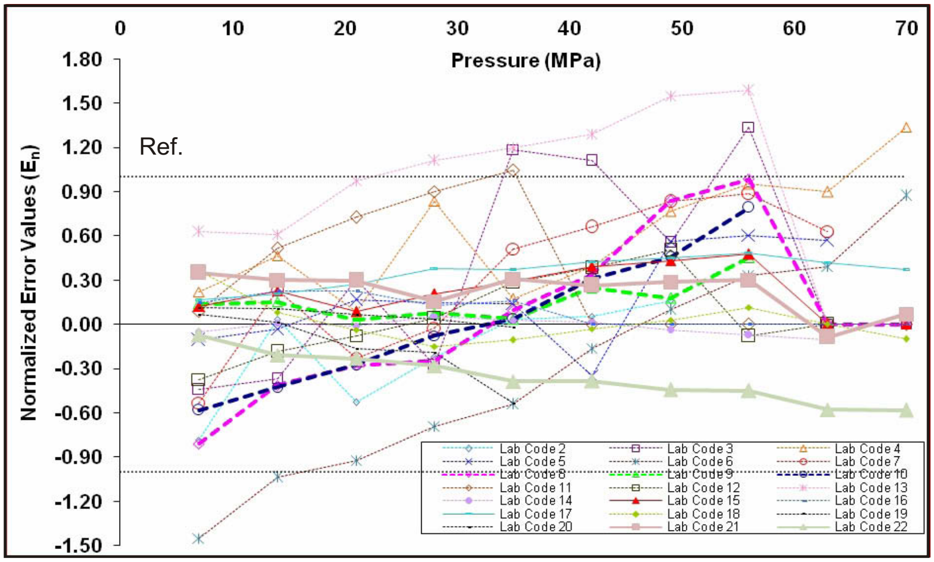

Fig. 4. The normalized error value (E_n) as a function of measured pressure (p') for each laboratory. The gap between two horizontal dotted lines shows the acceptable limit of the normalized error value

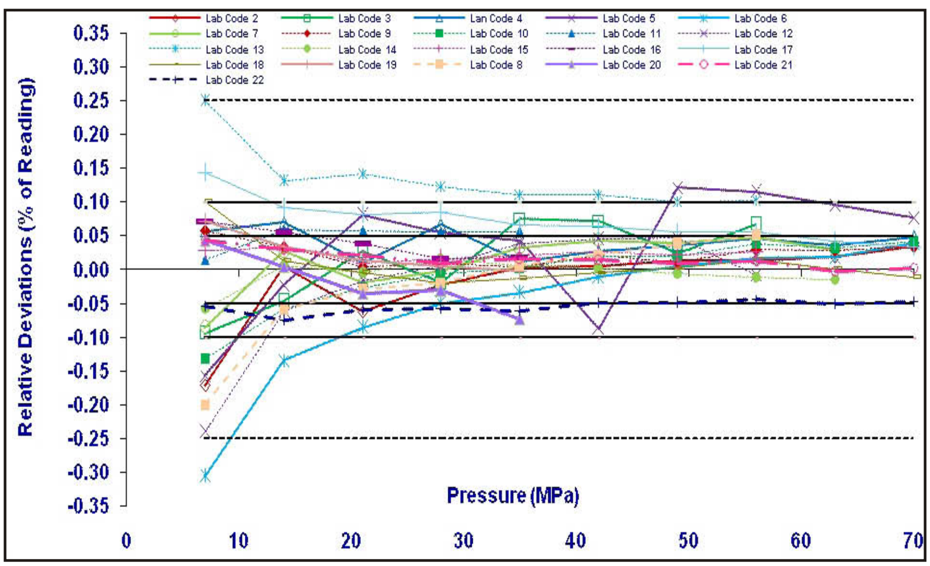

Fig. 5. Relative deviations of the measured pressure (p') by each laboratory from the reference value (p). The gap between two horizontal dark black solid lines represents deviations falling within ± 0.05 %, dim black lines represents deviations falling within ± 0.1 % and dotted lines represents deviations falling within ± 0.25%

point. The E_n values are estimated at each pressure as per guidelines in the literature [7, 15, 24];

$$E_n = \frac{p' - p}{\sqrt{\{U(p')\}^2 + \{U(p)\}^2}} \tag{2}$$

where p' is the participant's measured pressure value, p is the calculated reference value, $U(p')$ is the participant's claimed expanded uncertainty at a coverage factor k = 2 and $U(p)$ is the expanded measurement uncertainty of the reference value at a coverage factor k = 2. An E_n value of less than 1 indicates agreement within the combined uncertainties for the results to be internationally acceptable. An E_n number between–1 and +1 indicates an acceptable degree of compatibility between the laboratory's result and the reference value when the quoted uncertainties are taken into account. E_n number > ±1 is unacceptable and requires immediate investigation and corrective action by the laboratory concerned.

6. Results and Discussions

The relative deviations of measured pressure, p', of each participant from reference value, p, are shown in Table 3. The summaries of the normalized error values, E_n, estimated expanded measurement uncertainties, and the combined expanded measurement uncertainties are shown in Tables 4 to 6, respectively, for entire pressure scale of 7 to 70 MPa. The graphs plotted for the results for individual laboratories, are depicted as Figs. 5-6. In general, the performance of the laboratory is considered satisfactory if normalized error E_n is < ±1. The plots shown in Figs. 4-5 reveal that there are total 178 measurement results. Measurement results of 15 laboratories (Code No. 2, 5, 7-9, 12 and 14-22) out of total 21 laboratories are well within acceptable limits of normalized error over the entire pressure range of 7 – 70 MPa. However, the measurement results of another 3 laboratories with Code No. 4, 10 and 11 are also quite good having E_n values > ±1 only at one pressure point each. E_n values of 165 measurement results out of total 178 are < ±1, which is 92.7 %. These results are acceptable. En values of remaining 3 laboratories referred by Code No. 3, 6 and 13 are >±1 for 2 or more than 2 pressure points. The larger the absolute value of the E_n number, the bigger the problem. An E_n value greater than unity means that there is a significant bias in the laboratory's results and that the quoted value of its associated uncertainty does not adequately accommodate that bias, therefore further investigations are needed at the part of the laboratory.

The summary of the normalized error values (E_n) as a function of applied pressure (p') is depicted in Fig. 4. The relative deviations of measured pressure (p') from reference values (p) are shown in Fig. 5. The deviations lying within the uncertainty band of the reference laboratory is an indication of satisfactory results without any bias in the measurements. It is clearly evident from Fig. 5 that the relative deviations between laboratories values and reference values are well within the 0.05 % for 123 measurement points, 0.1% for 162 measurement points and 0.25% for 177 measurement points. As reported earlier, this PT was organized for the laboratories having measurement uncertainty within < 0.05 % to >0.25 % of full scale pressure, the relative deviations between laboratories values and reference values are well within 0.25 % for all the pressure point except one pressure point of 7 MPa for laboratory with Code No. 6. Further, the difference between the pressure values reported by the participating laboratories and the reference laboratory fall within the uncertainty band of reference laboratory at 121 measurement results i.e. 68.0 %, within their reported estimated expanded uncertainty band at 145 measurements results i.e. 81.5 % and within the combined estimated expanded uncertainty band of this PT experiment at 165 measurement results (92.7 %) (Fig. 4). Some of the laboratories, specially with Code No. 7, 11 and 21 have under estimated their measurement uncertainty at almost all the pressure points as shown in Table 5. Although, these laboratories have reported better measurement uncertainty than the reference laboratory, their E_n values are found within acceptable limits except one pressure point of 35 MPa for laboratory with Code No. 11. The main reasons for bias in the measurements may be due to errors in measuring instruments or in estimation / measurement of local acceleration of gravity, the error in applying the temperature and head corrections and the under estimation of measurement uncertainty. Laboratories would be able to rectify the problems by a review of their uncertainty calculations and other systematic affects as mentioned above.

All the participating laboratories were asked to submit the copy of the formal calibration certificate issued to the customer and traceability certificate of their standard. Almost all the laboratories submitted the copies of the formal calibration certificates of the digital pressure calibrator (artifact, in the present case) except 2 laboratories with Code Nos. 11 and 12. The traceability certificates were also received from 18 laboratories. Laboratories with code numbers 2, 11 and 14 did not submit such formal certificates. Certificates thus received were examined and found adequate except that there is little uniformity in the calibration certificates issued by the participants, specially in reporting the measurement results. There are few typo errors in some of the certificates, for example, capital 'K' for coverage factor '*k*' (laboratories with Code numbers 5, 15 and 16; also traceability certificate of Code No. 17), in pressure unit as 'kg/cm' in place of 'kg/cm^2 (laboratory with Code No. 3), used 'fro' in place of 'from' (laboratory with Code No. 4), in pressure unit as 'KPa' in place of 'kPa'(laboratory with Code No. 6) and wrong reporting of unit of '*g*' as '9.7865244 cm/s^2' in place of '9.7865244 m/s^2' (traceability certificate of the laboratory with Code No. 16). Although, these are minor errors but should have been avoided.

As mentioned earlier, E_n numbers greater than unity require investigations and corrective action by the participating laboratory. The laboratory's management needs to ensure that the problem is rectified and procedures are put in place to prevent a recurrence. Laboratories with Code No. 3, 6 and 13 were asked to review the results and take appropriate corrective actions. All these laboratories were asked to improve their calibration facilities and to modify the measurement method and to estimate the measurement uncertainties properly. Laboratories with Code No. 4, 10 and 11 may also be requested to review their results at their respective unacceptable measurement points (one each). During the follow-up process, these three laboratories have addressed the reasons for their results being outside the range, and they were advised to take part in at least one interlaboratory comparison with another laboratory having better measurement capabilities.

7. Conclusion

This interlaboratory comparison programme (proficiency testing) is carried out in the pressure range 7 - 70 MPa using pressure digital pressure calibrator as an artifact. Total number of 21laboratories participated in this programme. The comparison was performed at 10 equally spaced pressure points selected throughout the entire pressure range. The proficiency testing concludes that out of the total 178 measurement results reported here in this report, 165 (92.7 %) are in agreement with the reference laboratory. The E_n values of 15 laboratories are within acceptable limits through out the entire pressure scale. However, the E_n values of 3 other laboratories are also quite acceptable except only at one pressure point each. The E_n values of the remaining 3 laboratories are found beyond the acceptable limit for 2 or more than 2 pressure points. The difference between laboratories values and reference values of 121 measurement points (68.0 %) are well within the uncertainty bands of the reference values. Total 145 measurements results i.e. 81.5 % fall within their reported expanded uncertainty band. However, 92.7 % measurement results are found well within combined estimated expanded measurement uncertainty band. Since some of the laboratories have under estimated their measurement uncertainties, 7.3 % measurement results are found out of the combined uncertainty band during this comparison. The measurement process used for the present PT is quite good and may be used by other PT organizers for the assessment of measurement capabilities of their participating laboratories. The whole PT experiment was completed without any problem and technical issue. Since this is the first proficiency test experience for most of the participating laboratories, the results are considered to be very good.

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