Final report of APMP Key Comparison (APMP.M.P-K6)

Results of the APMP Pressure key comparison in gas media and gauge mode from 20 kPa to 105 kPa

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Abstract

This report summarizes the results of a regional key comparison (APMP-IC-2-97) under the aegis of Asia Pacific Metrology Program (APMP) for pressure measurements in gas media and in gauge mode from 20kPa to 105 kPa. The transfer standard was a pressure-balance with a piston-cylinder assembly with nominal effective area 335.7 mm^2 (TL-391) and was supplied by the National Metrology Institute of Japan, [NMIJ]. Nine standard laboratories from the APMP region with one specially invited laboratory from the EUROMET region namely, Physikalisch-Technische Bundesanstalt (PTB), Germany, participated in this comparison. The comparison had started from October, 1998 and was completed in May, 2001. The pilot laboratory prepared the calibration procedure as per the guidelines of APMP and International Bureau of Weights and Measures (BIPM) [1-4]. Detailed instructions for performing this key comparison were provided in the calibration protocol and the required data were described in : (1) Annex 3 - characteristics of the laboratory standards, (2) Annex 4 - the effective area ($A'_{p'}$ /mm^2)[1] at 23°C of the travelling standard as a function of nominal pressure (p'/kPa) (five cycles both increasing and decreasing pressures at five pre-determined pressure points) and (3) Annex 5 - the average effective area at 23°C ($A'_{p'}$/mm^2) obtained for each pressure p' / kPa with all uncertainty statements. The pilot laboratory processed the information and the data provided by the participants for these three annexes, starting with the information about the standards as provided in Annex 3. Based on this information, the participating laboratories are classified into two categories: (I) laboratories that are maintaining primary standards, and (II) laboratories that are maintaining standards loosely classified as secondary standards with a clear traceability from other established National Metrology Institute (NMI) as per norm of the BIPM. It is observed that out of these ten laboratories, six laboratories have primary standards [Category (I)], the remaining four laboratories are placed in Category (II).

During process of comparison, there was a loss of mass of the piston TL-391 by an amount roughly 23.4 mg in two instances, originally noticed at NMIJ and then at NMISA within the first year of circulation. Unfortunately, we do not have any information where it had happened and when. But after that, there was no change of mass of the piston for nearly two years till the end of this comparison. NMIJ reported that it happened due to the damage of the pin attached to the piston. Interestingly, loss of mass of the piston by an amount of 7.6 mg was reported in the transit between NMIJ to NMISA and within one month. Since the damage and subsequent loss of mass occurs instantaneously, we belief that the first damage had happened close to NMIJ and second at NMISA where the necessary corrections have been already made. Therefore, we have not introduced any correction to any datum provided by the participating laboratories in both the phase A and phase B loops.

The obtained data were compiled and processed under the same program as per the Consultative Committee for Mass and Related Quantities (CCM)/BIPM guidelines [5]. Following the approach of Elster et. al [6], we have evaluated these results and establish a link with CCM.P-K6 through the link laboratory PTB(Germany). From the CCM.P-K6 key comparison reference value (KCRV), we have estimated the relative deviation of the A'_o/mm^2 from the reference value for all ten laboratories and compared this with their estimated expanded uncertainties at k=2. The bilateral degree of equivalence of the participating laboratories in the APMP.M.P-K6 comparison has been estimated from the degree of equivalence between two laboratories. These results show an excellent agreement of all participating laboratories within the estimated expanded uncertainties using a coverage factor k=2.

[1] The prime indicates values based on measured quantities

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1. Introduction

The regional comparison program was organized by the APMP Secretariat under the guidance of the Technical committee for Mass and Related Quantities (TCM) of APMP and also the High and Medium-Pressure Working group of the Consultative Committee for Mass and Related Quantities (CCM), International Bureau of Weights and Measures (BIPM) [7th CCM meeting at BIPM, Paris (France) from 12th to 14th May, 1999]. It was expressed that this will be a good opportunity for the APMP laboratories to add to the confidence in their measurement capabilities and also to gain international acceptance.

1.1 Objective

The purpose of this activity was to compare the performance of pneumatic pressure standards in the APMP region that operate in gauge mode from 20 kPa to 105 kPa using nitrogen gas as the pressure transmitting media and to link with the corresponding CCM key comparison. The transfer standard was a piston cylinder assembly that was compared to pressure standards of each of the participating laboratories.

1.2 Back ground of the Key Comparison and chronology

Based on the recommendation of APMP in the second quarter of 1997, NPL (India) initiated a process to acquire an artifact that could be used as the transfer standard for this regional pneumatic pressure comparison. The potential laboratories that could offer to lend an artifact were contacted. NRLM, Japan [presently NMIJ] gratefully responded to the request and supported this comparison by providing an artifact i.e. Ruska 2465 with a piston cylinder assembly under ATA carnet[2]. Eleven laboratories namely IRL-MSL (New Zealand), NMIA (Australia), KRISS (Korea), SCL (Hong Kong), SPRING (Singapore), NML-SIRIM (Malaysia), NIMT (Thailand), NMI (Japan), NPSL (Pakistan), NIS (Egypt) and ITDI (Philippines) responded to the call for taking part in the comparison. CSIR-NML (South Africa) was also permitted to take part. As a precondition of the validity of ATA Carnet protocol, it was decided that nine laboratories would be participating in first year of this comparison. These laboratories were NPL (India), IRL-MSL (New Zealand), NMIA (Australia), KRISS (Korea), SCL (Hong Kong), SPRING (Singapore), NML-SIRIM (Malaysia), NMI (South Africa) and NMIJ (Japan). Three remaining countries [NPSL (Pakistan), NIS (Egypt) and ITDI (Philippines)] would be accommodated in the next year program if the ATA carnet is extended in the next year.

After the successful completion of the first year, in consultation with the participating laboratories, it was decided to circulate the progress report [first draft A] in the beginning of 2000. The report was inconclusive as there was not much understanding of the method of analysis the results. However as the MRA was signed in BIPM (Paris), some of the participating APMP members requested that the pilot laboratory establish a link between this comparison and the CCM key comparison [CCM.P-K6] which was ongoing. It was felt that this would help the present comparison to establish adequate credence with the BIPM key comparison data base (KCDB). It may be mentioned here that although NPLI, NMIA, PTB and NMIJ had participated in CCM.P-K10 [10-140 kPa (absolute mode)] which is approved for provisional equivalence, the data of CCM.P-K10 can not be taken in to account as the data are more than ten years old and also they are in

[2] an international customs document/the Merchandise Passport - carnets facilitate temporary imports into foreign countries and are valid for up to one year.

absolute mode. Therefore, linking with CC key comparison may not be possible with these laboratories. The pilot laboratory explored the possibility to invite a laboratory that had taken part in the CCM.P-K6 comparison. PTB (Germany) responded to this call and offered to participate in the present comparison. Therefore, for linking of RMO key comparison to CC-key comparison [CCM.P-K6], PTB (Germany) is the only laboratory for our convenience. NPSL (Pakistan) and ITDI (Philippines) were contacted during the next year comparison, but they did not respond adequately. NIS (Egypt) had participated in APMP.M.P-K1c (0.4 to 4.0 MPa) but did not take part in this comparison. In consultation with the then Chairman, TCM, APMP, it was decided to include these three countries in a future program. The present comparison was declared complete in May, 2001 after the participation of PTB (Germany) and the final measurement by the pilot laboratory NPL (India). The whole comparison process was successfully completed within two and half years as promised to APMP.

2. Participating Laboratories and their Standards

The list of participating laboratories is shown in Table 1.

Table -1 : List of participating laboratories

	Laboratory	***Country***
1.	National Metrology Institute of Japan, [NMIJ]	Japan
2.	National Physical Laboratories [NPLI]	India
3.	SPRING	Singapore
4.	National Metrology Laboratory [NML-SIRIM]	Malaysia
5.	Korea Research Institute of Standards & Science (KRISS)	Korea
6.	Industrial Research Limited [IRL-MSL]	New Zealand
7.	Standards and Calibration Laboratory [SCL],	Hongkong
8.	National Measurement Institute of Australia (NMIA)	Australia
9.	National Metrology Institute [NMISA]	South Africa
10.	Physikalisch-Technische Bundesanstalt [PTB]	Germany

In Table 2, we have provided the essential information of the main characteristics of the standards used by the participating laboratories in this comparison. As can be seen from Table 2, the laboratories mainly used pressure balances of different kinds and ranges. Table 2 also shows the piston and cylinder materials of the standards used by participants and the effective area at null pressure and at 20^{o} C or 23^{o} C (A'_{o}) and the pressure distortion co-efficient (λ') along with temperature coefficients of the piston and cylinder etc. It is interesting to note that all the piston cylinder materials of the participant standards were tungsten carbide (WC) and a few of them SS and Ceramic. Table 2 finally shows the nature of maintenance of the standard. A distinction has been made between the laboratories that are maintaining primary standards and those laboratories that are maintaining standards which we loosely call “secondary standards”. The former group of participating laboratories are not only maintaining primary standards but are also characterizing their standards under their own responsibility. The latter group of participating laboratories are maintaining standards, which may be a primary standard in their own laboratory, but they do not characterize this standard on their own but rather calibrate it against primary standards from other NMIs. For this reason, we designate them as secondary standards. These laboratories were asked to provide their traceability, which is also shown in Table 2. It is therefore needless to mention that all the guidelines provided by CCM/BIPM for RMO key comparisons have been rigorously maintained and executed.

Table 2 : Details of the Participants Standards and traceability

	Category I Laboratories which are having Primary standards					
Lab. (Country) / Parameters	**NPL (India)**	**KRISS (Korea)**	**NMIA (Australia)**	**NMI (Japan)**	**PTB* (Germany)**	**MSL (New Zealand)**
Measurement Range (kPa)	1.4 to 105		16 to 190	2.5 to 175	2000	10 to 350
Materials of the Piston and Cylinder	SS	WC	SS	Ceramic	WC	SS
	WC	WC	WC	WC	WC	SS
A_o at Atm. Pres. and Ref. Temp.(mm^2)	335.721	980.5610	335.65112	1961.091	490.26345	80.63665
Relative Uncertainty of A_0 (k=1) (in 10^{6})	15	10	11	10	4.1	10
Pressure Dist. Co-efficient (λ)(Pa^{-1})	0	0	0	$4.54x10^{-12}$	$1.47x10^{-12}$	0
Relative unce of A_0 due to λ	0	0	0	$1.5x10^{-12}$	$1.47x10^{-13}$	0
Reference density of the Weight	7920	7800	7856	-	7920	7880
Relative uncertainty of Mass (in 10^6)	1	1.0	1.0	-	0.5	1.0
α_p (10^{6} / o C)	10	4.5	10.5	5.5	4.5	10.8
α_c (10^{6} / o C)	4.5	4.5	4.5	4.5	4.5	10.8
$T_{o\,p}$ (in ^{o}C)	23	23	20	20	20	20
Traceability						

- \- PTB(Germany) uses also Mercury –manometer in range 20kPa to 105 kPa [5]

Table 2 (continued)

Category II Laboratories which are having Secondary standards			
NMC (Singapore)	**NML-SIRIM (Malaysia)**	**SCL (Hong Kong)**	**NMI (South Africa)**
1.4 to 104	172	3.5 to 175	175
SS	SS	SS	SS
WC	WC	WC	WC
335.7274	335.6647	335.812	335.684
18	7	12	10.9
0	6.98 $\times 10^{-11}$	0	0.62 $\times 10^{-10}$
0	0.24	0	
7800	7800	8000	7920
1	2.5	1.1	10.0
10	10	10	10
4.5	4.5	4.5	4.5
20	20	20	20
LNE(France)	NIST(USA)	NPL(UK)	NPL(UK)

3. Transfer standard

3.1 Description of the standard and calibration procedure

The transfer standard was a Ruska (Model 2465) pressure-balance base with piston-cylinder assembly TL-391. The details of the standard and the calibration procedure were circulated to all the laboratories [along with the APMP.M.P-K1c (0.4 MPa to 4.0 MPa)]. The details of the calibration procedure has already published in Metrologia Tech. Supp. 40, 07002 (2003). A few important points are mentioned as follows:

(a) The piston-cylinder unit is named as TL-391 with a nominal effective area of 335.7 mm^2 and it is mounted in a Ruska base Type 2465 fully equipped with weight set, temperature probe, etc.

(b) All mass pieces (including piston) were measured to within a well-defined standard uncertainty. It was requested that all masses were to be used with extreme care, in order to avoid contamination and damage.

(c) Height difference between the reference levels of the two compared standards (participant's laboratory standard(s) and transfer standard) was advised to be kept small. For height difference of larger values, each laboratory was advised to make appropriate corrections to the pressure value measured by its standard(s).

(d) Cleaning of the piston-cylinder was advised to be an important point.

(e) Piston rotation rate versus time was advised to be checked from time to time to ensure the leveling and cleaning of the piston cylinder assembly. The effect of direction of rotation was also advised to be checked.

(f) In order to simplify the handling of data the same masses on the transfer standard were to be used; each laboratory was advised to adjust the added masses needed for the determination of the equilibrium condition at each cross-floating pressure on their own laboratory standard.

(g) The comparisons were performed at the nominal pressures (kPa) of - 21.4 - 41.3 – 61.3 – 81.3 – 101.2 (increasing order)- 101.2 – 8134 – 61.3 – 41.3 - 21.4 (decreasing order)[3]. The procedure was repeated for a total of 5 cycles, giving 10 experimental determinations of the effective area of the transfer standard for each of the 5 nominal pressure points and a total of 50 experimental effective area determinations distributed over the selected nominal pressure values.

(h) Each laboratory was asked to provide the pilot laboratory with the information related to the laboratory standard as listed in the table reported in Annex 3 of the participant's calibration report [1]. Detailed comments were asked on the type of piston-cylinder assembly used as the laboratory standard, the method 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 like the traceability certificate etc.

(i) To help the pilot laboratory get the data from each laboratory in a consistent form, it was recommended that each laboratory should use Annexes 4 and 5 of the calibration procedure [1] to send their data. Annex 4 was essentially a data sheet reporting the data obtained at each comparison point, for each cycle of the planned comparison. Annex 5 is the summary of measuring cycles.

3.2 Organization of the Key Comparison and chronology

Table 3: Planned time schedule for the comparison

Laboratory	***Country***	***Date of Arrival***	***Date of Departure***
National Metrology Institute of Japan, [NMIJ]	Japan		15th September, 1999
National Physical Laboratories [NPLI]	India	1st October, 1998	15th November, 1998
SPRING	Singapore	22nd November,1998	7th January, 1999
National Metrology Laboratory [NML-SIRIM]	Malaysia	14th January, 1999	14th February,1999
National Metrology Institute of Thailand [NIMT] [4]	Thailand	21st February,1999	21st March, 1999
Korea Research Institute of Standards & Science (KRISS)	Korea	28th March, 1999	28th April, 1999
Industrial Research Limited [IRL-MSL]	New Zealand	7th May, 1999	7th June, 1999
Standards and Calibration Laboratory [SCL],	Hong Kong	14th June, 1999	14th July, 1999
National Measurement Institute of Australia (NMIA)	Australia	21st July,1999	21st August, 1999

[3] Two effective areas at each nominal pressure point
[4] Participated but did not submit the result.

National Metrology Institute of Japan [NMIJ]	Japan	1st September, 1999	7th October, 1999
National Metrology Institute [NMISA]	South Africa	15th October, 1999	15th December, 1999
National Physical Laboratories [NPLI]	India	15th January, 2000	14th April, 2000
National Institute for Standards [NIS] [5]	Egypt	15th June, 2000	15th September, 2000
National Metrology Institute of Japan [NMIJ] [6]	Japan	1st October, 2000	30th November, 2000
National Measurement Institute of Australia (NMIA)	Australia	15th December, 2000	28th February, 2001
Physikalisch-Technische Bundesanstalt [PTB]	Germany	1st March, 2001	30th May, 2001
National Physical Laboratories [NPLI]	India	15th June, 2001	14th September, 2001

3.3 Stability of the Transfer Standard

Long-term stability of the transfer standard is an important criteria for the selection of an artifact in any international key comparison. This is because when we compare the result of one laboratory with another over a span of three years, if the transfer standard is not stable or it does not behave satisfactorily, the factors that may affect the performance of the transfer standard will be difficult to evaluate. It is for this reason the long-term stability of the transfer standard is very important and the artifact should also withstand inter-continental transportation. Compared to other artifacts, the piston gauge is very stable and has been recommended to be used as the travelling standard in almost all international key comparisons in high pressure measurement. Therefore, the systematic uncertainty (**type B evaluation)** does not change but the **type A** standard uncertainty, which characterizes the repeatability of the measurements performed with the transfer standard, is required to be estimated.

Regarding the present piston gauge, the history shows that in the span of more than 25 years [from 1973], the type A uncertainty is within **(2 – 4)x10^{-6} or [2 - 4 ppm]** at NMIJ. This low estimated type A uncertainty has definitely added significance to the choice of this particular piston gauge to be used as the travelling standard of this comparison. We have carried out the stability test of the transfer standard both at NPLI and at NMIJ. In Fig.1 the values of the effective area $A'_{p'}$ (23 ^{o}C, p‘) /mm^{2} versus p'/ kPa which were obtained by NMIJ during September, 1999 and also October, 2000, are shown. Similarly, the pilot laboratory, NPLI also carried out the same stability test during the comparison in October, 1998 (beginning) and May, 2001 (end of the comparison). For the quantitative estimation, the data $A'_{p'}$(23^{o}C, p‘)/mm^{2} versus p'/ kPa of the transfer standard at NMIJ and NPLI during these two transit is shown in Figure 1. It is clear that the results are typical for this type of piston gauge [Ruska 2465]. The donor NMIJ is also reported relative standard uncertainty which is typically 8.8 x 10^{-6} (8.8 ppm) at k=1 is also indicated by the error bars to establish the long-term stability of the gauge in this two and half year time period. It is very interesting to note that from these two sets of data, the maximum estimated instability is 4x10^{-6}, which also supports the

[5] Participated in APMP.M.P-K1c only
[6] Monitor the characteristic of the Transfer standard

earlier data of this transfer standard during the period of 1973 to 1998. **Therefore, we propose to take the standard uncertainty contribution due to the instability of the transfer standard at all pressures as 4x10 $^{-6}$ or 4 ppm.**

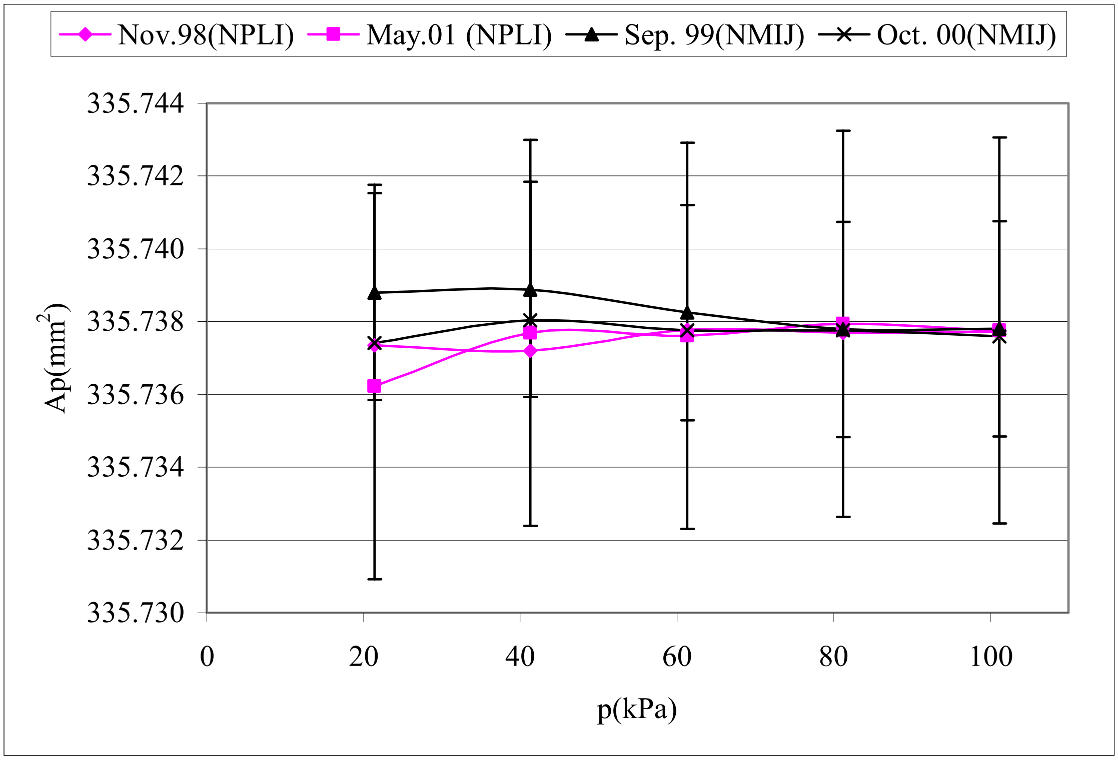

Figure 1 :**Stability of the Piston-cylinder assembly** : $A_{p'}/mm^2$ versus p'/kPa in NPLI during November, 1998 and May 2001 and in NIMJ during September, 1999 and October, 2000 with standard uncertainty at k=1.

4. Results

4.1 Loss of mass of the Piston

There was a decrease in the mass of TL-391 piston which was first observed by NMIJ in October, 1999 and subsequently by one of the participant laboratories (NMISA) in November, 1999. We have provided the data as obtained from NMIJ, NPLI, NMISA and NMIA (without pin) during the course of comparison in the span of three years in Table -4. From Table 4, it is clear that an amount of 15.8 mg has been decreased in one year from September, 1998 to October, 1999 and then there was a sudden decrease of 7.6 mg in November, 1999 at NMISA. MSL-IRL re-analysed their cross-float data after the Draft A report and calculated the piston mass to be 47.9179 g in May 1999. Interestingly, there was no further loss from December, 1999 to September, 2001 which has been verified by NMISA, NPLI and NMIJ. The loss of mass of the Piston TL-391 was discussed with NMIJ and also with the participants of this key comparison. NMIJ made a special effort to investigate the physical appearance of the piston and they observed that although there was no visible damage of the piston during that year but the pin attaching to the piston was coming loose. This observation suggested that due to rough handling during transit or otherwise, the pin might have cracked and broken. So it is inferred that the "loss" in mass of roughly 15.8 mg of the TL-391 piston may be due to the partial loss of materials of the said pin. In the same argument, the loss of mass of 7.6 mg observed by NMISA within one-month, may be due to the loss of the remaining broken part of the pin. Interestingly, NMIA had measured the true mass of the piston TL-391 and had reported the value 47.5333 g without pin in the Phase B. As suggested in a memorandum dated on 28 November 2000 by NMIJ, NMIA had used the piston TL-391 without the pin during the comparison measurements. But we have not received without pin data from other laboratories. However, the constancy of the mass after that incident for nearly two year up to September 2001, may be due to fact that once the broken pieces came out completely, then there was no further damage. As we are aware, the transportation of the artifact is a big risk and the damage may cause from the sudden impulse either from the dropping or mishandling. Unfortunately, we do not have any information where exactly happened and when. But we anticipate that the change of mass due to cracking might have started instantaneously from one place and ended at NMISA during the circulation loop in phase A. The phase A loop starts from NMIJ-NPLI-SPRING-NML-SIRIM-NIMT-KRISS-IRL-MSL-SCL-NMIA-NMIJ and Phase B starts from NMIJ-NMISA-NPLI-NIS-NMIJ-NMIA-PTB-NPLI. The sudden loss of 7.6 mg from NMIJ to NMISA within one month also indicative that 15.8 mg loss of weight might have happened very close to reaching NMIJ in Phase A loop. Therefore, the results provided by the participating laboratories as per the Annexes 4 and 5 of the calibration procedure have been for analysis without any modification.

Table -4 : Mass Value of the Piston during the comparison

	NMIJ	**NPLI**	**NMIJ**	**NMISA***	**NPLI**	**NMIJ**	**NMIJ**	**NMIJ**	**NMIA**	**NPLI**
Date	**xx/xx/98**	**10/xx/98**	**10/xx/99**	**11/xx/99**	**02/xx/00**	**09/28/00**	**10/02/00**	**10/24/00**	**2/xx/01**	**09/xx/01**
TL-391(g)	47.9279	47.92828	47.9121	47.9045	47.9046	47.9045	47.9047	47.9045	47.5333*	47.9046

* without pin

4.2 Estimation of the average value of effective areas A'_p /mm^2 at 23^o C of the transfer standard for each laboratory as a function of p'/kPa

The reported data of $A'_{p'}$ /mm^2 as a function of pressure (p'/kPa) for each laboratory has been analyzed using the simple averaging method as,

$$(A'_{p'})_{av} = \frac{\sum_i (A'_{p'})_i}{n} \qquad \ldots \qquad (1)$$

where n is the number of observations at each pressure point which in this case is 10. The standard deviation (σ_A) of $A'_{p'}$/mm^2, the standard uncertainty (u_A) is also obtained from $u_A = \sigma_A/\sqrt{10}$ uniformly for all participating laboratories. Table 5 shows the average values of the effective area of the transfer standard $A'_{p'}$/mm^2 (23^{o}C, p') versus p'/kPa for all the participating laboratories. Figures 2 and 3 represent the average values of the effective area of the transfer standard $A'_{p'}$/mm^2 (23^{o}C, p') versus p'/kPa (as mentioned in Table – 5) for laboratories that are maintaining primary standard in their laboratories and also that are maintaining secondary standards in their laboratories as mentioned in section 2 . The apparent increase in the effective area at low pressures in Figure 2 for MSL-IRL is largely an artefact due to using the supplied value for the piston mass (47.9279 g) rather than the measured value

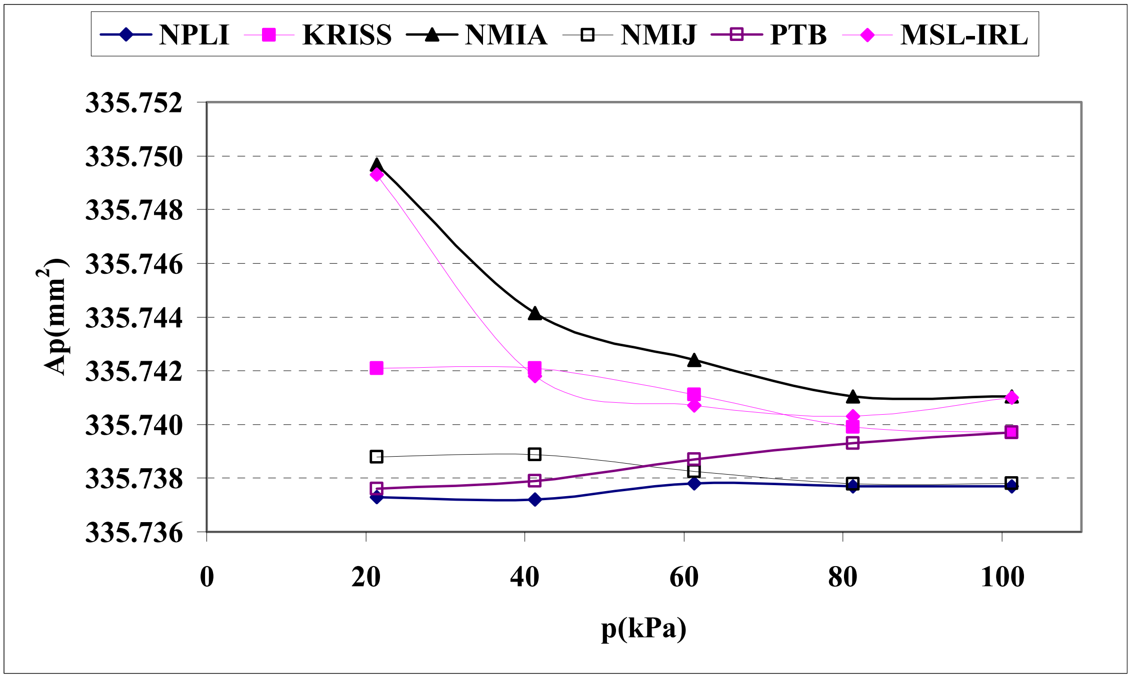

Figure 2: A_p/mm^2 versus p/kPa for laboratories that are maintaining primary standard in their laboratories.

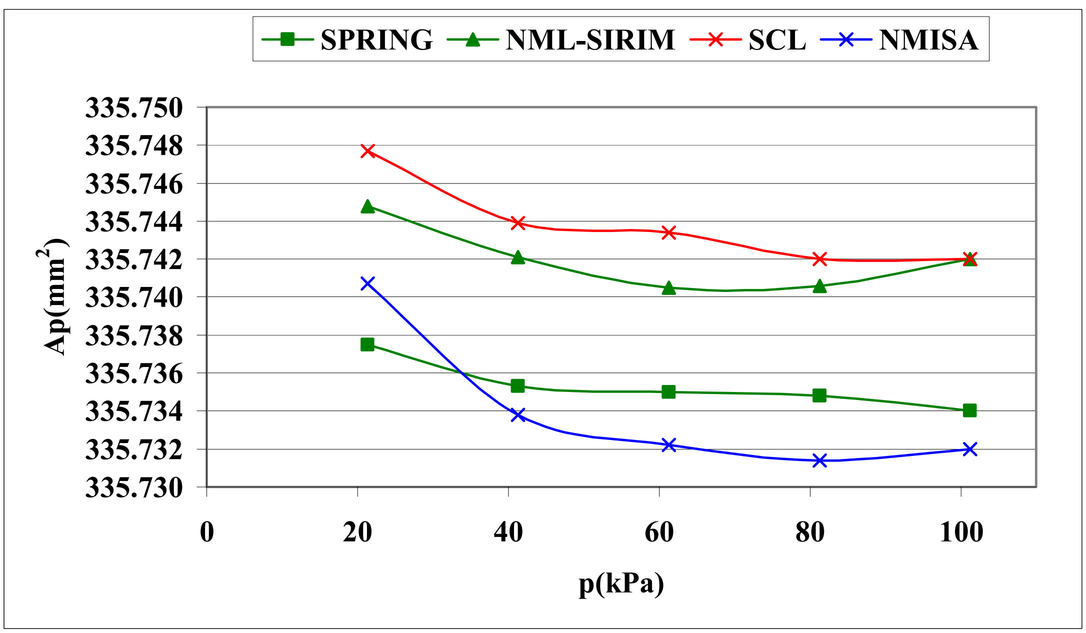

Figure 3 : $A_{p'}/mm^2$ versus p/kPa for laboratories that are maintaining secondary standards in their laboratories.

Table 5: ***Average values of the effective area of the transfer standard $A'_{p'}$ (23 °C, p') / mm² as a function of pressure p'/kPa for all laboratories which are taking part in this comparison. Standard uncertainty (u) of all participating laboratories are also indicated for ready reference.***

Laboratories which are maintaining primary standards												
p' nom / kPa	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$
21.4	335.7373	15.80	335.7421	11.10	335.74967	12.60	335.7388	8.80	335.7376	6.40	335.7493	11.80
41.3	335.7372	15.80	335.7421	11.10	335.74414	12.60	335.73888	8.80	335.7379	6.00	335.7416	11.60
61.3	335.7378	15.80	335.7411	11.10	335.7424	12.60	335.73825	8.80	335.7387	6.20	335.7406	11.70
81.3	335.7377	15.80	335.7399	11.10	335.74105	12.60	335.73779	8.80	335.7393	5.90	335.7403	11.70
101.2	335.7377	15.80	335.7397	11.10	335.74104	12.60	335.7378	8.80	335.7397	5.90	335.741	11.70
	NPLI, Oct.1998		KRISS, Apr. 1999		NMIA, Feb.2001		NMIJ, Sep. 1999		PTB, Mar. 2001		MSL-IRL, May 1999	

Laboratories which are maintaining secondary standards								
p' nom / kPa	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$	x_i / mm²	$u_i/x_i \cdot 10^{-6}$
21.4	335.7375	19.20	335.7448	11.40	335.7477	18.00	335.7407	14.60
41.3	335.7353	19.20	335.7421	11.50	335.7439	17.90	335.7338	14.60
61.3	335.735	19.20	335.7405	11.40	335.7434	17.70	335.7322	14.60
81.3	335.7348	19.20	335.74	11.40	335.742	17.60	335.7314	14.60
101.2	335.7340	19.10	335.742	11.40	335.742	17.60	335.732	14.60
	SPRING, Nov. 1998		NML-SIRIM, Jan.1999		SCL, June 1999		NMISA, Oct.1999	

4.3 Estimation of expanded uncertainty of $A'_{p'}$/mm²:

Standard uncertainty of pressure ($u_{p'}$) and the standard uncertainty of temperature ($u_{T'}$) at each pressure have been provided by the laboratories (Annex 5). Therefore, the combined uncertainty of $A'_{p'}$/mm² at each pressure for each laboratory has been estimated from the root sum square of Eq.(2),

$$u_c \equiv \sqrt{(u_A^2 + u_{T'}^2 + u_{p'}^2)} \quad . \qquad \ldots \qquad (2)$$

The expanded uncertainty at each pressure for each laboratory is estimated as U_{Lab} :

$$U_{Lab} = ku_c \quad . \qquad \ldots \qquad (3)$$

Here k =2 has been taken into account. But when evaluating the uncertainties, all the other standard uncertainties of $A'_{p'}$/mm² are expressed as k=1, so that the analysis of data of the comparison will be made in the same way. Table 5 also summarizes also this standard uncertainty for all the participating laboratories.

5. Analysis of the results

Under the Mutual Recognition Arrangement (MRA), National Metrology Institutes (NMIs) who are participating both in a CCM key comparison and also a RMO key comparison, are the linking laboratories for transferring the CCM reference value to the RMO key comparison. It may be mentioned here that in CCM.P-K6**,** the participating laboratories are NPL(UK) (Pilot Laboratory), METAS (Switzerland), NIM (China), NIST (USA), NMi-VSL (The Netherlands), NRC (Canada) and PTB (Germany). The final report of CCM.P-K6 has recently published (1). As one can notice that in the present APMP key comparison, we have PTB (Germany) is only linking laboratory to the corresponding CCM.P-K6.

It should be mentioned here that

- The APMP.M.P-K6 and CCM.P-K6 comparisons are undertaken at different temperatures.
- The APMP.M.P-K6 and CCM.P-K6 comparisons are undertaken at different (nominal) pressures.
- The measured values within each (separate) comparison are assumed to have no associated correlation.

***5.1 Elster et al (6) approach* - Linkage of APMP.M.P-K6 with CCM.P-K6 key comparison**

A proposal for linking the results of a key comparison (KC) and a Regional Metrological Organization (RMO) comparison is made in Elster *et al* (6) (2003). It is suggested that the use of an "additive correction" as the basis of the linking may not be appropriate in cases where the results of the KC and the RMO comparison are of a different magnitude or whenever the results are of different physical dimension. The idea is to determine a "factor" that is used to transform the quantities measured in the RMO comparison in such a way that comparisons of the transformed quantities with the KCRV (and measured quantities in the KC) become meaningful. The approach uses the weighted mean to establish reference values and allows for more than one linking laboratory. Based on the approach, a proposal for linking the results in the case that there is a single laboratory is as follows. Define

$$Z_k = RX_k, \qquad k = 1, \ldots, N, \qquad \textbf{(4)}$$

where X_k denotes the "property" measured by the kth laboratory in the RMO comparison and Z_k is the corresponding transformed quantity. The factor R that defines the transformation is chosen such that the transformed quantity for the linking laboratory equals the "property" measured by the linking laboratory in the KC, i.e.,

$$Z_L = RX_L = X_L^{kc}, \qquad \textbf{(5)}$$

so that,

$$R = \frac{X_L^{kc}}{X_L}. \qquad \textbf{(6)}$$

An estimate r of R is given by

$$r = \frac{x_L^{kc}}{x_L}, \qquad \textbf{(7)}$$

with an associated uncertainty (the "linking uncertainty") that depends on the uncertainties associated with x_L and x_L^{kc} and the correlation associated with these values (which arises because the measured values are provided by the same laboratory).

It follows that the degree of equivalence for the linking laboratory is

$$D_L = Z_L - X_0^{kc} = X_L^{kc} - X_0^{kc}, \quad \textbf{(8)}$$

where X_0^{kc} is the KCRV, and so is the same whether obtained from the KC or the RMO comparison.

5.2 Method of linking

We shall now use the above mentioned equations for linking the CC key comparison CCM.P-K6 with the RMO key comparison APMP.M.P-K6. As mentioned, the only link laboratory, which has taken part both in the CCM.P-K6 and APMP.M.P-K6, is PTB (Germany). Table 5 shows the data of the effective areas /mm^2 of the CCM.P-K6 transfer standard (x_{PTB}^{kc}) as a function of measured pressure p/kPa and their standard uncertainty $u(x_{PTB}^{kc})$. Also shown the data of the effective areas /mm^2 of the APMP.M.P-K6 transfer standard (x_{PTB})as a function of measured pressure p/kPa with their standard uncertainty $u(x_{PTB})$. The reference values (x_0^{kc}) of key comparison (KCRV) in the CCM.P-K6 and with their standard uncertainty $u(x_0^{kc})$ are also mentioned. Considering the correlation coefficient (ρ_L) of PTB (Germany) is 0.8, we can estimate the linking factor (r) from the above mentioned Eq. (7) and *u(r),* which is the standard uncertainty associated with *r*, at a given measured pressure say p = 20 kPa,

$$r = \frac{x_{PTB}^{kc}}{x_{PTB}} = \frac{335.7444\ \text{mm}^2}{335.7376\ \text{mm}^2} = 1.000020, \quad \textbf{(9)}$$

and $$\left(\frac{u(x_{PTB}^{kc})}{x_{PTB}}\right) = \frac{1.8801x10^{-3}\,mm^2}{335.7376mm^2} = 5.6x10^{-6},$$

$$\left(\frac{x_{PTB}^{kc} \times u(x_{PTB})}{x_{PTB}{}^2}\right) = 5.6x10^{-6},$$

$$\left(\frac{1}{x_{PTB}}\right)\left(\frac{x_{PTB}^{kc}}{x_{PTB}{}^2}\right)\left(\rho_L \times u(x_{PTB}^{Kc}) \times u(x_{PTB})\right) = 2.5\times10^{-11},$$

and thus,

$$u(r) = \sqrt{\left[\left(\frac{u(x_{PTB}^{kc})}{x_{PTB}}\right)^2 + \left(\frac{x_{PTB}^{kc} \times u(x_{PTB})}{x_{PTB}{}^2}\right)^2 - 2\left(\frac{1}{x_{PTB}}\right)\left(\frac{x_{PTB}^{kc}}{x_{PTB}{}^2}\right)\left(\rho_L \times u(x_{PTB}^{Kc}) \times u(x_{PTB})\right)\right]} = 3.6\times10^{-6}.$$

(10)

Table 6: A comparison of data of the single linking laboratory PTB(Germany) both in the CCM.P-K6 and APMP.M.P-K6 is shown along with CCM.P-K6 key comparison

reference value (KCRV). A coefficient of 0.8 has been assumed for the correlation between the two sets of PTB results.

PTB (Germany)						CCM.P-K6 (KCRV)		
CCM.P-K6			APMP.M.P-K6					
p/kPa	x_i^{kc} / mm²	$u_i / x_i^{kc} \cdot 10^{-6}$	p/kPa	x_i / mm²	$u_i / x_i \cdot 10^{-6}$	p/kPa	$x0_i$ / mm²	u_i / mm²
20	335.7444	5.6	21.4	335.7376	6.4	20	335.7444	0.0007
40	335.7446	4.1	41.3	335.7379	6.0	40	335.7441	0.0009
60	335.7449	4.5	61.3	335.7387	6.2	60	335.7443	0.0005
80	335.7453	5.3	81.3	335.7393	5.9	80	335.7445	0.0006
100	335.7453	3.8	101.2	335.7397	5.9	100	335.7445	0.0009

5.3 ***Degree of Equivalence***

The degree of equivalence of a laboratory [say NPLI] in APMP.M.P-K6 is obtained from Eq. (8). $x_0^{kc} = 335.7444$ mm² and $u(x_0^{kc}) = 0.0007$ mm² are the *KCRV* and its standard uncertainty. $x_{NPLI} = 335.7373$ mm² *and* $u(x_{NPLI}) = 0.0053$ mm²

$$D_{NPLI} = z_{NPLI} - x_0^{kc} = r \times x_{NPLI} - x_0^{kc} = -0.0003 mm^2 \quad \textbf{(11)}$$

$$U(D_{NPLI}) = 2\sqrt{\left[(x_{NPLI} \times u(r))^2 + (u(x_{NPLI}) \times r)^2 + u(x_0^{kc})^2\right]} = 0.0110 mm^2 . \quad \textbf{(12)}$$

Similar estimations can be obtained for the other participating laboratories.

The relative degree of equivalence of a laboratory [say NPLI] in APMP.M.P-K6 is obtained

$$\frac{D_{NPLI}}{x_0^{kc}} \times 10^6 = -0.77 \quad \textbf{(13)}$$

$$\frac{U(D_{NPLI})}{x_0^{kc}} \times 10^6 = 32.80 \quad \textbf{(14)}$$

Similar estimations can be obtained for the other participating laboratories.

5.4 Bilateral degree of equivalence

Bilateral degree of equivalence of the participating laboratories in the APMP.M.P-K6 comparison has been estimated from the degree of equivalence between two laboratories. Similarly, the bilateral expanded uncertainty (k=2) is also estimated among the participating laboratories in the APMP region at various measured pressures.

$$D_{ij} = D_i - D_j \tag{15}$$

$$U(D_{ij}) = 2\sqrt{\left[\left((x_i - x_j)\times u(r)\right)^2 + \left(u(x_i)^2 + u(x_j)^2\right) \times r^2\right]} \tag{16}$$

Let us take the case [say NPLI - KRISS], we have already estimated D_{NPLI} in Eq. (11) and $U(D_{NPLI})$ in Eq. (12). Let us take the case of KRISS,

$$D_{KRISS} = z_{KRISS} - x_0^{kc} = r \times x_{KRISS} - x_0^{kc} = -0.00045mm^2 \tag{17}$$

$$U(D_{KRISS}) = 2\sqrt{\left[(x_{KRISS} \times u(r))^2 + (u(x_{KRISS})\times r)^2 + u(x_0^{kc})^2\right]} = 0.0080mm^2 \tag{18}$$

Therefore, from Eqs.(15) and (16), we get

$$D_{NPLI-KRISS} = D_{NPLI} - D_{KRISS} = -0.0048mm^2$$

$$U(D_{NPLI-KRISS}) = 2\sqrt{\left[\left((x_{NPLI} - x_{KRISS})\times u(r)\right)^2 + \left(u(x_{NPLI})^2 + u(x_{KRISS})^2\right) \times r^2\right]} = 0.0130mm^2$$

The relative bilateral degree of equivalence of a laboratory in APMP.M.P-K6 is obtained

$$\frac{D_{NPLI-KRISS}}{x_0^{kc}} \times 10^6 = -14.30 \tag{25}$$

$$\frac{U(D_{NPLI-KRISS})}{x_0^{kc}} \times 10^6 = 38.62 \tag{22}$$

Similar estimations can be obtained for the other participating laboratories. The calculated relative bilateral degrees of equivalence are given in Table 7(a) – (e).

6. Discussions

In the previous sections, we have discussed briefly the description of the transfer standards and its stability. The artifact, which is provided by NMI (Japan), is 15 years old. NMIJ has provided also the history of long-term stability of the artifact. We have also mentioned about the performance of the artifact during the nearly two year long experimentation. Secondly, we have elaborated the standards used by the participating National Metrological Institutes (NMIs). Some of them have primary standards and some of them have secondary standards traceable to some advanced laboratory [as mentioned before "secondary standards" is loosely written]. The long term stability of the transfer standard which is $4 \cdot 10^{-6}$ as has been claimed by the donor country (NMIJ). However, the donor laboratory NMIJ has made a categorical statement that the stability of the transfer standards from their two measurements is about 2-4 x10^{-6}. Ideally, the philosophy of any key comparison is that the hardware of the traveling transfer standard should be unchanged during period of the comparison. However, in reality, it is sometime difficult because during the process of key comparison, the artifact has to undergo intercontinental transportation and subsequently sometimes a risk of unexpected mishap - the loss of mass of the piston is an example. As mentioned, 15.8 mg + 7.6 mg = 23.4 mg mass has been lost in one year [September, 1998 to November, 1999] but there was absolutely no loss in the next nearly two year in Phase B loop [November 1999 to September, 2001]. To compensate the mass loss, one of the participating laboratories suggested that we should follow a linear decrease of mass with time in the Phase A loop. But some laboratories have some reservation as it is technically difficult because we do not know when the loss had actually happened. Therefore, it was decided to process the data without any correction assuming that the damage has taken place close to NMIJ. It may be mentioned here just before NMIJ, it was NMIA took part and they had taken part also in Phase B in February 2001 and their data were taken into consideration during that period. The data as obtained from the participating laboratory were estimated to get the average value of effective areas A'_p /mm^2 at 23^o C of the transfer standard for each laboratory as a function of p'/kPa. Standard uncertainty of pressure ($u_{p'}$) and the standard uncertainty of temperature ($u_{T'}$) at each pressure have been provided by the laboratories (Annex 5). Therefore, the combined uncertainty of $A'_{p'}$/mm^2 at each pressure for each laboratory has been estimated. Finally, the results of the comparison have been linked to the CCM.P-K6 comparison using the method described by Elster et al (6). Equations (12) to (16) are the step by step procedure for carrying out such exercises. This method is particularly suited where the results of the comparisons are of different magnitude or whenever the results are of different physical dimension, as in this case where the measurement of effective area in the two comparisons are at a different temperature and different pressures. There is only one linking laboratory between the two comparisons, which is PTB, Germany. A coefficient of 0.8 has been assumed for the correlation between the two sets of PTB results. The calculated relative bilateral degrees of equivalence are given in Table 5 (a) to (e).

7. **Conclusion**

(a) We have carried out a regional key comparison (APMP-IC-2-97) for pressure measurements in gas media and in gauge mode from 20kPa to 105 kPa.. The transfer standard was a pressure-balance with a piston-cylinder assembly with nominal effective area of 335.7 mm^2 and was supplied by NIMJ. Eleven laboratories have participated out of which only one laboratory have taken part in the corresponding CCM.P-K6 key comparison.

(b) The details of the standard and the calibration procedure were prepared by the pilot laboratory and circulated to all the laboratories.

(c) The relative standard uncertainty contribution of the instability of the transfer standard at all pressures is 4 x 10^{-6} (4 ppm).

(d) All participating laboratories were asked to provide their uncertainty budgets of their standard, which were used for this comparison.
(e) There was a loss of mass of the piston TL-391 by an amount roughly 23.4 mg which was noticed by NMIJ. We do not have any information where it is happened and when. Assuming that it happened close to NMIJ where the necessary correction has been made, we have not introduced any correction of any datum provided by the participating laboratory in both the phase A and phase B loops.
(f) Average value of effective areas $A'_{p'}/mm^2$ at 23°C of the transfer standard for each laboratory as a function of p'/kPa with their uncertainty statement have been estimated uniformly.

(g) Linkage with CCM.P-K6 has been established. PTB took part in phase B loop and also they are the linking laboratory of CCM.P-K6 and APMP.M.P-K6 key comparisons

(h) The relative deviation from the reference value for all the eleven participating laboratories was estimated and as well as their expanded uncertainty statement at k=2.

(i) Comparing the differences between each pair of laboratories, it can be shown that all differences, for all laboratories and for all pressures, are within the combined standard uncertainty of the effective area $A'_{p'}$ of the transfer standard declared by each laboratory.

(j) A full agreement exists in terms of expanded uncertainty with the coverage factor k=2.

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8. References:

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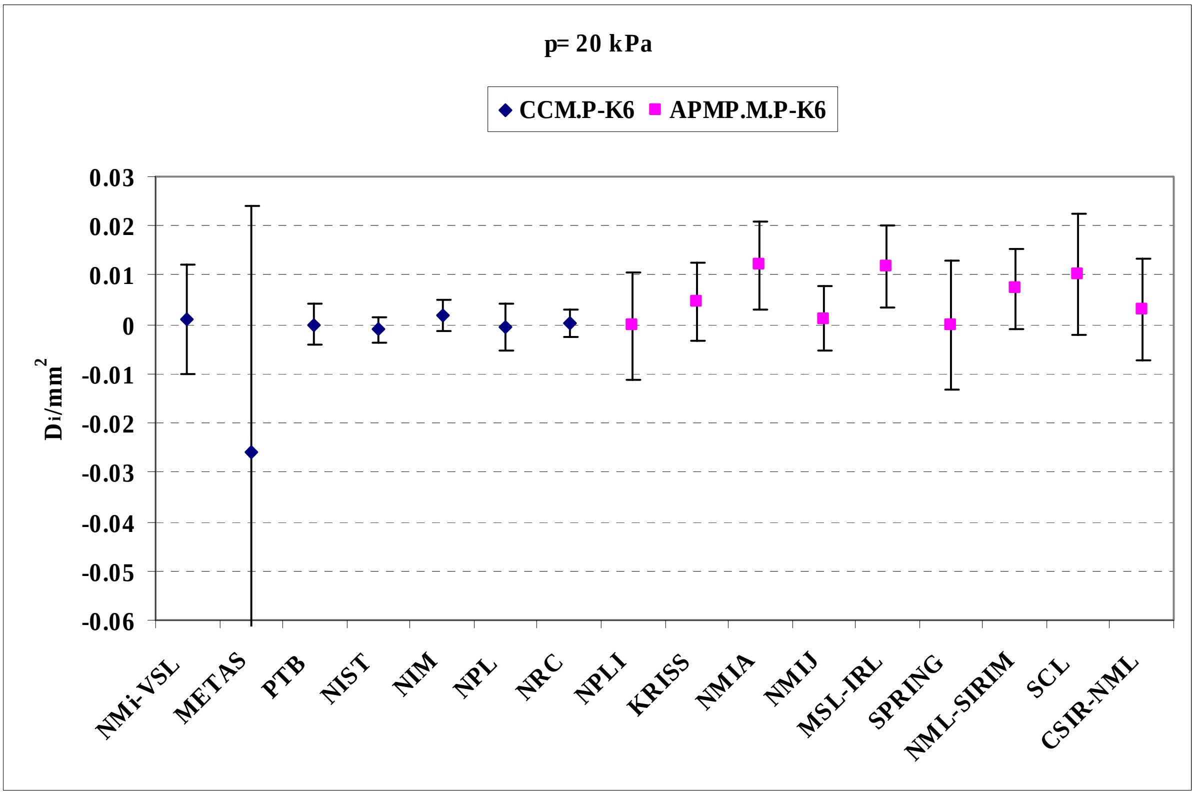
Figure –4 (a)



p= 20 kPa
CCM.P-K6
APMP.M.P-K6
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
Di/mm2
NMi-VSL
METAS
PTB
NIST
NIM
NPL
NRC
NPLI
KRISS
NMIA
NMIJ
MSL-IRL
SPRING
NML-SIRIM
SCL
CSIR-NML

Figure –4 (b)

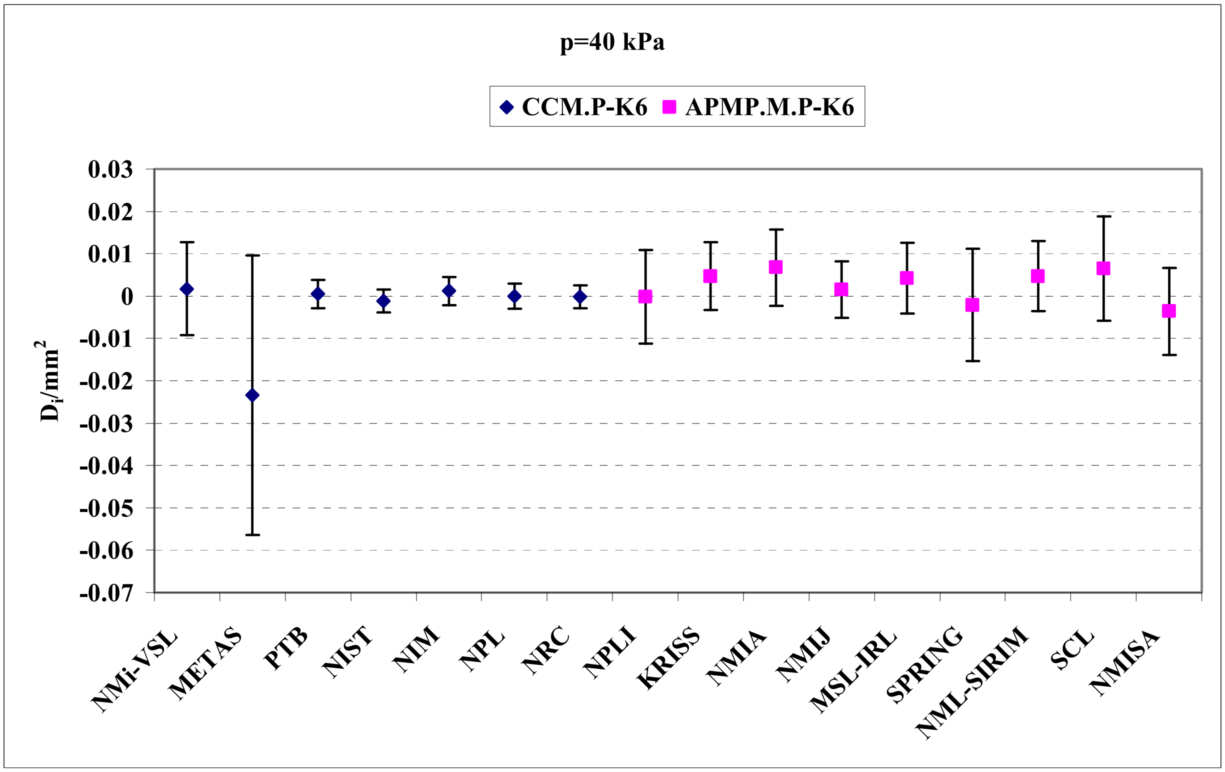

p=40 kPa
CCM.P-K6
APMP.M.P-K6
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
Di/mm2
NMi-VSL
METAS
PTB
NIST
NIM
NPL
NRC
NPLI
KRISS
NMIA
NMIJ
MSL-IRL
SPRING
NML-SIRIM
SCL
NMISA

Figure –4 (c)

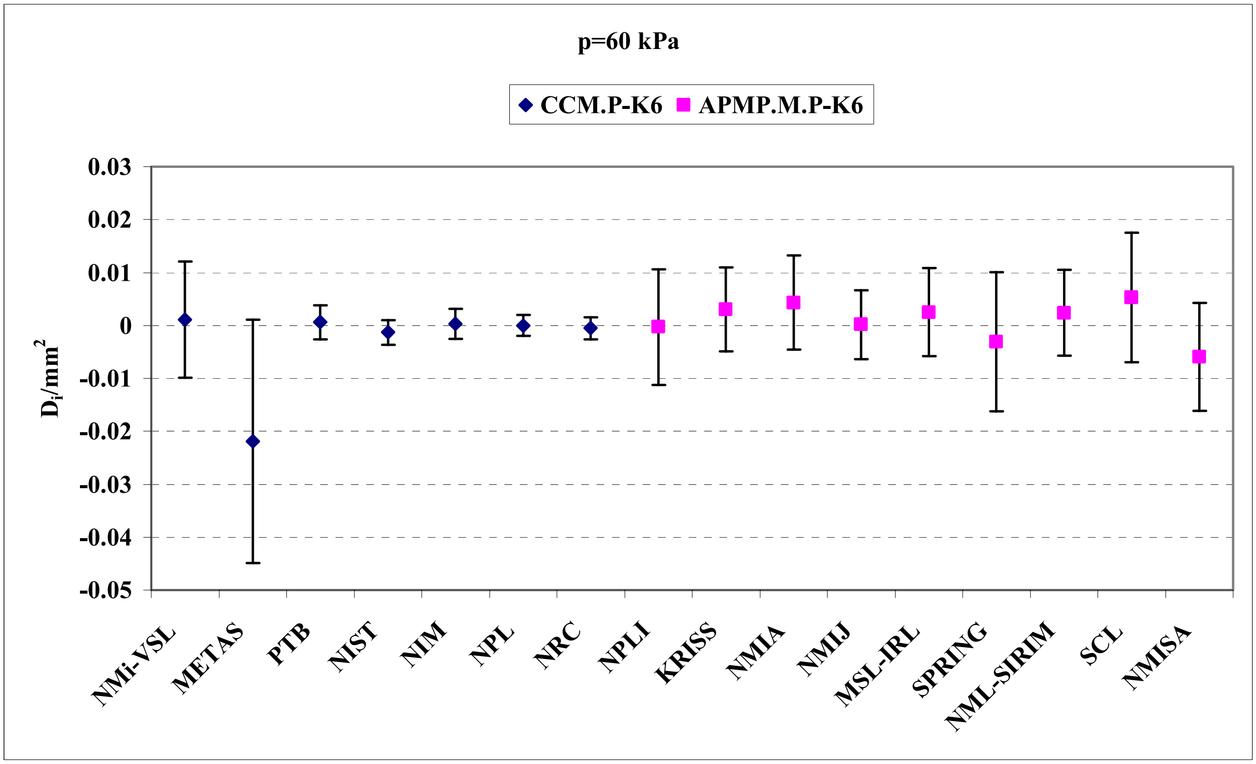

p=60 kPa
CCM.P-K6
APMP.M.P-K6
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Di/mm2
NMi-VSL
METAS
PTB
NIST
NIM
NPL
NRC
NPLI
KRISS
NMIA
NMIJ
MSL-IRL
SPRING
NML-SIRIM
SCL
NMISA

Figure –4 (d)

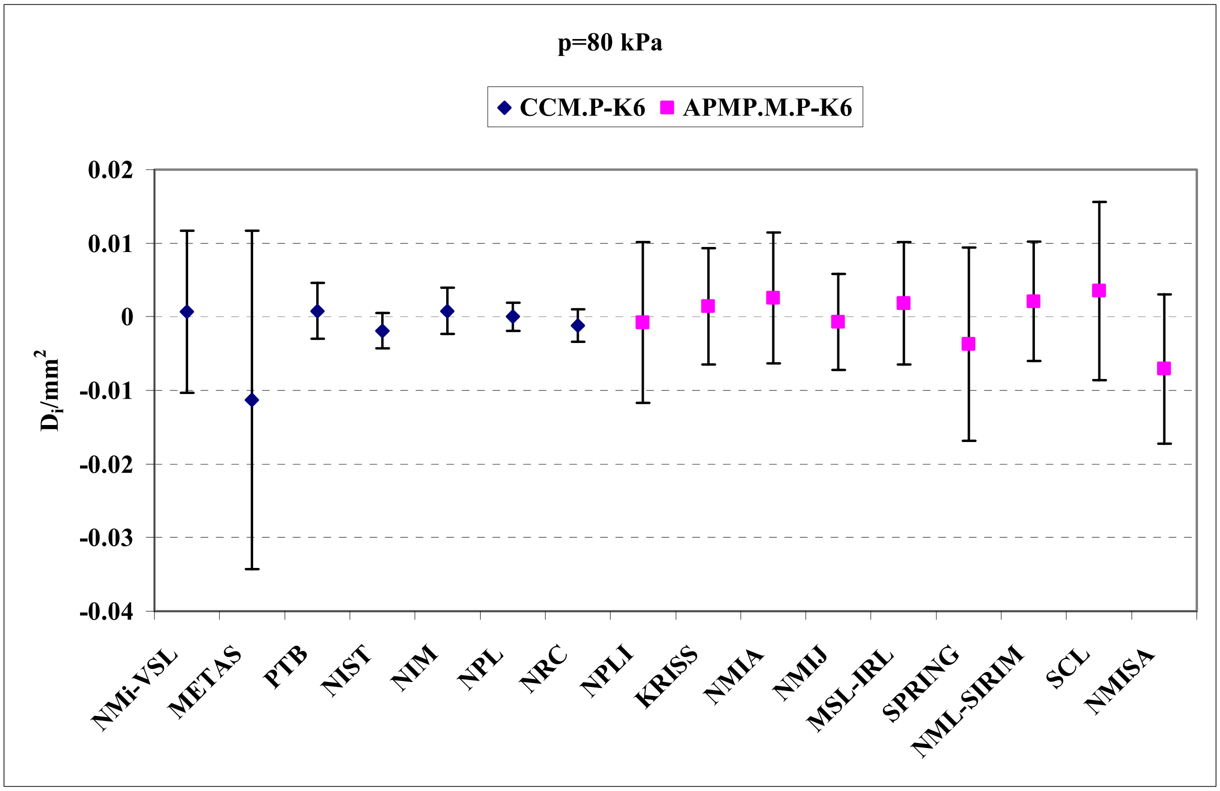


Figure –4 (e)

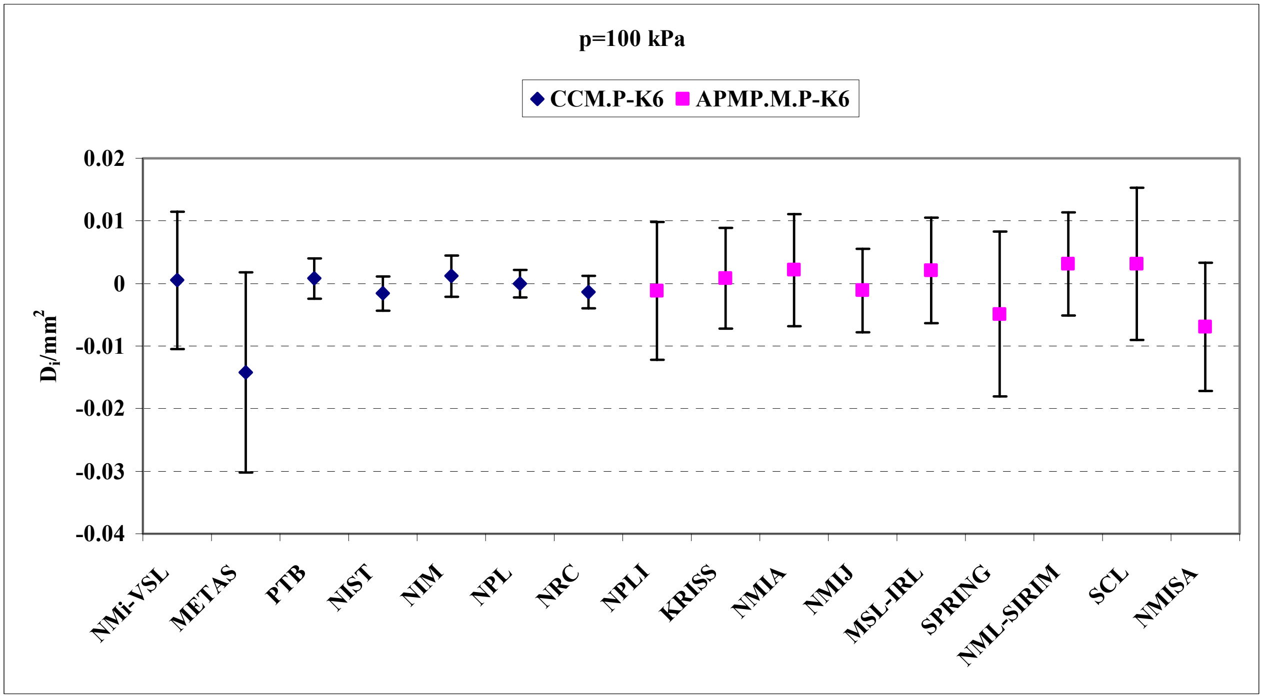

p=100 kPa
CCM.P-K6
APMP.M.P-K6
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
D$_i$/mm^2
NMi-VSL
METAS
PTB
NIST
NIM
NPL
NRC
NPLI
KRISS
NMIA
NMIJ
MSL-IRL
SPRING
NML-SIRIM
SCL
NMISA

Table 7 (a)

A) Measured pressure : 20 kPa

	NPLI		KRISS		NMIA		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$
NPLI	0.00	0.00	-14.30	38.62	-36.84	40.42	-4.47	36.18	-0.89	34.09
KRISS	14.30	38.62	0.00	0.00	-22.55	33.58	9.83	28.34	13.40	25.63
CSIRO-NML	36.84	40.42	22.55	33.58	0.00	0.00	32.38	30.74	35.95	28.27
NMIJ	4.47	36.18	-9.83	28.34	-32.38	30.74	0.00	0.00	3.57	21.77
PTB	0.89	34.09	-13.40	25.63	-35.95	28.27	-3.57	21.77	0.00	0.00
MSL-IRL	35.74	39.44	21.45	32.40	-1.10	34.53	31.27	29.45	34.85	26.85
SPRING	0.60	49.65	-13.70	44.27	-36.25	45.85	-3.87	42.15	-0.30	40.38
NML-SIRIM	22.34	38.97	8.04	31.82	-14.51	33.98	17.87	28.81	21.45	26.15
SCL	30.98	47.90	16.68	42.30	-5.87	43.95	26.51	40.08	30.08	38.21
CSIR-NML	10.13	43.03	-4.17	36.68	-26.72	38.57	5.66	34.10	9.23	31.88

MSL-IRL		SPRING		NML-SIRIM		SCL		NMISA	
D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$
-35.74	39.44	-0.60	49.65	-22.34	38.97	-30.98	47.90	-10.13	43.03
-21.45	32.40	13.70	44.27	-8.04	31.82	-16.68	42.30	4.17	36.68
1.10	34.53	36.25	45.85	14.51	33.98	5.87	43.95	26.72	38.57
-31.27	29.45	3.87	42.15	-17.87	28.81	-26.51	40.08	-5.66	34.10
-34.85	26.85	0.30	40.38	-21.45	26.15	-30.08	38.21	-9.23	31.88
0.00	0.00	35.15	44.99	13.40	32.82	4.77	43.05	25.62	37.55
-35.15	44.99	0.00	0.00	-21.74	44.57	-30.38	52.56	-9.53	48.16
-13.40	32.82	21.74	44.57	0.00	0.00	-8.64	42.61	12.21	37.05
-4.77	43.05	30.38	52.56	8.64	42.61	0.00	0.00	20.85	46.35
-25.62	37.55	9.53	48.16	-12.21	37.05	-20.85	46.35	0.00	0.00

Table 7 (b)

B) Measured pressure : 40 kPa

	NPLI		KRISS		NMIA		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$	$x10^{6}$
NPLI	0.00	0.00	-14.59	38.62	-20.67	40.42	-5.00	36.18	-2.08	33.80
KRISS	14.59	38.62	0.00	0.00	-6.08	33.58	9.59	28.34	12.51	25.24
CSIRO-NML	20.67	40.42	6.08	33.58	0.00	0.00	15.67	30.74	18.59	27.91
NMIJ	5.00	36.18	-9.59	28.34	-15.67	30.74	0.00	0.00	2.92	21.31
PTB	2.08	33.80	-12.51	25.24	-18.59	27.91	-2.92	21.31	0.00	0.00
MSL-IRL	13.11	39.20	-1.49	32.11	-7.57	34.25	8.10	29.13	11.02	26.12
SPRING	-5.66	49.65	-20.25	44.27	-26.33	45.85	-10.66	42.15	-7.74	40.14
NML-SIRIM	14.59	39.03	0.00	31.89	-6.08	34.05	9.59	28.89	12.51	25.85
SCL	19.96	47.68	5.36	42.04	-0.71	43.70	14.95	39.81	17.87	37.66
CSIR-NML	-10.13	43.03	-24.72	36.68	-30.80	38.57	-15.13	34.10	-12.21	31.57

MSL-IRL		SPRING		NML-SIRIM		SCL		NMISA	
D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$
-13.11	39.20	5.66	49.65	-14.59	39.03	-19.96	47.68	10.13	43.03
1.49	32.11	20.25	44.27	0.00	31.89	-5.36	42.04	24.72	36.68
7.57	34.25	26.33	45.85	6.08	34.05	0.71	43.70	30.80	38.57
-8.10	29.13	10.66	42.15	-9.59	28.89	-14.95	39.81	15.13	34.10
-11.02	26.12	7.74	40.14	-12.51	25.85	-17.87	37.66	12.21	31.57
0.00	0.00	18.76	44.78	-1.49	32.60	-6.85	42.58	23.23	37.29
-18.76	44.78	0.00	0.00	-20.25	44.62	-25.62	52.36	4.47	48.16
1.49	32.60	20.25	44.62	0.00	0.00	-5.36	42.41	24.72	37.11
6.85	42.58	25.62	52.36	5.36	42.41	0.00	0.00	30.08	46.12
-23.23	37.29	-4.47	48.16	-24.72	37.11	-30.08	46.12	0.00	0.00

C) Measured pressure : 60 kPa

Table 7(c)

	NPLI		KRISS		NMIA		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$
NPLI	0.00	0.00	-9.83	38.62	-13.70	40.42	-1.34	36.18	-2.68	33.95
KRISS	9.83	38.62	0.00	0.00	-3.87	33.58	8.49	28.34	7.15	25.43
CSIRO-NML	13.70	40.42	3.87	33.58	0.00	0.00	12.36	30.74	11.02	28.09
NMIJ	1.34	36.18	-8.49	28.34	-12.36	30.74	0.00	0.00	-1.34	21.54
PTB	2.68	33.95	-7.15	25.43	-11.02	28.09	1.34	21.54	0.00	0.00
MSL-IRL	8.34	39.32	-1.49	32.26	-5.36	34.39	7.00	29.29	5.66	26.48
SPRING	-8.34	49.65	-18.17	44.27	-22.04	45.85	-9.68	42.15	-11.02	40.26
NML-SIRIM	8.04	38.97	-1.79	31.82	-5.66	33.98	6.70	28.81	5.36	25.95
SCL	16.68	47.45	6.85	41.79	2.98	43.45	15.34	39.54	14.00	37.51
CSIR-NML	-16.68	43.03	-26.51	36.68	-30.38	38.57	-18.02	34.10	-19.36	31.72

MSL-IRL		SPRING		NML-SIRIM		SCL		NMISA	
D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$
-8.34	39.32	8.34	49.65	-8.04	38.97	-16.68	47.45	16.68	43.03
1.49	32.26	18.17	44.27	1.79	31.82	-6.85	41.79	26.51	36.68
5.36	34.39	22.04	45.85	5.66	33.98	-2.98	43.45	30.38	38.57
-7.00	29.29	9.68	42.15	-6.70	28.81	-15.34	39.54	18.02	34.10
-5.66	26.48	11.02	40.26	-5.36	25.95	-14.00	37.51	19.36	31.72
0.00	0.00	16.68	44.88	0.30	32.67	-8.34	42.44	25.02	37.42
-16.68	44.88	0.00	0.00	-16.38	44.57	-25.02	52.15	8.34	48.16
-0.30	32.67	16.38	44.57	0.00	0.00	-8.64	42.11	24.72	37.05
8.34	42.44	25.02	52.15	8.64	42.11	0.00	0.00	33.36	45.89
-25.02	37.42	-8.34	48.16	-24.72	37.05	-33.36	45.89	0.00	0.00

C) Measured pressure : 80 kPa

Table 7(d)

	NPLI		KRISS		NMIA		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$	$x10^6$
NPLI	0.00	0.00	-6.55	38.62	-9.98	40.42	-0.27	36.18	-4.77	33.73
KRISS	6.55	38.62	0.00	0.00	-3.43	33.58	6.28	28.34	1.79	25.14
CSIRO-NML	9.98	40.42	3.43	33.58	0.00	0.00	9.71	30.74	5.21	27.83
NMIJ	0.27	36.18	-6.28	28.34	-9.71	30.74	0.00	0.00	-4.50	21.20
PTB	4.77	33.73	-1.79	25.14	-5.21	27.83	4.50	21.20	0.00	0.00
MSL-IRL	7.74	39.32	1.19	32.26	-2.23	34.39	7.48	29.29	2.98	26.21
SPRING	-8.64	49.65	-15.19	44.27	-18.62	45.85	-8.91	42.15	-13.40	40.08
NML-SIRIM	8.64	38.97	2.08	31.82	-1.34	33.98	8.37	28.81	3.87	25.67
SCL	12.81	47.23	6.25	41.53	2.83	43.21	12.54	39.27	8.04	37.03
CSIR-NML	-18.76	43.03	-25.32	36.68	-28.74	38.57	-19.03	34.10	-23.53	31.49

MSL-IRL		SPRING		NML-SIRIM		SCL		NMISA	
D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6
-7.74	39.32	8.64	49.65	-8.64	38.97	-12.81	47.23	18.76	43.03
-1.19	32.26	15.19	44.27	-2.08	31.82	-6.25	41.53	25.32	36.68
2.23	34.39	18.62	45.85	1.34	33.98	-2.83	43.21	28.74	38.57
-7.48	29.29	8.91	42.15	-8.37	28.81	-12.54	39.27	19.03	34.10
-2.98	26.21	13.40	40.08	-3.87	25.67	-8.04	37.03	23.53	31.49
0.00	0.00	16.38	44.88	-0.89	32.67	-5.06	42.19	26.51	37.42
-16.38	44.88	0.00	0.00	-17.28	44.57	-21.45	51.95	10.13	48.16
0.89	32.67	17.28	44.57	0.00	0.00	-4.17	41.86	27.40	37.05
5.06	42.19	21.45	51.95	4.17	41.86	0.00	0.00	31.57	45.66
-26.51	37.42	-10.13	48.16	-27.40	37.05	-31.57	45.66	0.00	0.00

D) Measured pressure : 100 kPa

Table 7(e)

	NPLI		KRISS		NMIA		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6
NPLI	0.00	0.00	-5.96	38.62	-9.95	40.42	-0.30	36.18	-5.96	33.73
KRISS	5.96	38.62	0.00	0.00	-3.99	33.58	5.66	28.34	0.00	25.14
CSIRO-NML	9.95	40.42	3.99	33.58	0.00	0.00	9.65	30.74	3.99	27.83
NMIJ	0.30	36.18	-5.66	28.34	-9.65	30.74	0.00	0.00	-5.66	21.20
PTB	5.96	33.73	0.00	25.14	-3.99	27.83	5.66	21.20	0.00	0.00
MSL-IRL	9.83	39.32	3.87	32.26	-0.12	34.39	9.53	29.29	3.87	26.21
SPRING	-11.02	49.58	-16.98	44.18	-20.97	45.76	-11.32	42.06	-16.98	39.98
NML-SIRIM	12.81	38.97	6.85	31.82	2.86	33.98	12.51	28.81	6.85	25.67
SCL	12.81	47.23	6.85	41.53	2.86	43.21	12.51	39.27	6.85	37.03
CSIR-NML	-16.98	43.03	-22.93	36.68	-26.93	38.57	-17.28	34.10	-22.93	31.49

MSL-IRL		SPRING		NML-SIRIM		SCL		NMISA	
D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6	x10^6
-9.83	39.32	11.02	49.58	-12.81	38.97	-12.81	47.23	16.98	43.03
-3.87	32.26	16.98	44.18	-6.85	31.82	-6.85	41.53	22.93	36.68
0.12	34.39	20.97	45.76	-2.86	33.98	-2.86	43.21	26.93	38.57
-9.53	29.29	11.32	42.06	-12.51	28.81	-12.51	39.27	17.28	34.10
-3.87	26.21	16.98	39.98	-6.85	25.67	-6.85	37.03	22.93	31.49
0.00	0.00	20.85	44.80	-2.98	32.67	-2.98	42.19	26.81	37.42
-20.85	44.80	0.00	0.00	-23.83	44.49	-23.83	51.88	5.96	48.08
2.98	32.67	23.83	44.49	0.00	0.00	0.00	41.86	29.79	37.05
2.98	42.19	23.83	51.88	0.00	41.86	0.00	0.00	29.79	45.66
-26.81	37.42	-5.96	48.08	-29.79	37.05	-29.79	45.66	0.00	0.00