

## Final report of APMP Key Comparison (APMP.M.P-K1c)

### Results of the APMP Pressure key comparison in gas media and gauge mode from 0.4 to 4.0 MPa

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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 0.4 to 4.0 MPa. The transfer standard was a pressure-balance with a piston-cylinder assembly with nominal effective area  $8.4 \text{ mm}^2$  (V-407) and was supplied by the National Metrology Institute of Japan, [NMIJ]. Ten 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 [1] as per the guidelines of APMP and International Bureau of Weights and Measures (BIPM) [2-4]. Detailed instructions for performing this key comparison were provided in the calibration protocol [1] and the required data were described in : (1) Annex 3 - characteristics of the laboratory standards, (2) Annex 4 - the effective area ( $A'_{p'}/\text{mm}^2$ )<sup>1</sup> at 23°C of the travelling standard as a function of nominal pressure ( $p'/\text{MPa}$ ) (five cycles both increasing and decreasing pressures at ten pre-determined pressure points) and (3) Annex 5 - the average effective area at 23°C ( $A'_{p'}/\text{mm}^2$ ) obtained for each pressure  $p' / \text{MPa}$  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 as per norm of the BIPM. It is observed that out of these eleven laboratories, six laboratories have primary standards [Category (I)], the remaining five laboratories are placed in Category (II). The obtained data were compiled and processed under the same program as per the Consultative Committee for Mass and Related Quantities (CCM)/BIPM guidelines. From the data of Category (I), we evaluated the APMP reference value as a function of  $p'/\text{MPa}$ . Then, we estimated the relative difference of the  $A'_{p'}$  values with reference to APMP reference value for all participating laboratories and we observed that they agree well within their expanded uncertainties. We further estimated the effective area at null pressure and at 23°C ( $A'_{0}/\text{mm}^2$ ) and the pressure distortion co-efficient ( $\lambda'/\text{MPa}^{-1}$ ) of the transfer standard for all the participating laboratories. We then estimated the relative deviation of the  $A'_{0}/\text{mm}^2$  from the reference value for all eleven laboratories and compared this with their estimated expanded uncertainties. The result is once again extremely encouraging and all these eleven laboratories are agreeing within their estimated maximum expanded uncertainties. We also estimated the degree of equivalence between any two participating laboratories following a matrix mechanism. This once again agrees extremely well within the estimated relative standard uncertainty, which is derived for the two participating laboratories. Finally, a new method has been introduced to evaluate these results and establish a link to CCM.P-K1c and EUROMET .M.P-K2 at two nominal pressures, near 1 MPa and 4 MPa. Again the results show an agreement of all participating laboratories in the present comparison to within the estimated expanded uncertainties using a coverage factor  $k=2$ .

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<sup>1</sup> The prime indicates values based on measured quantities

## 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) [7<sup>th</sup> CCM meeting at BIPM, Paris (France) from 12<sup>th</sup> to 14<sup>th</sup> 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 0.4 to 4.0 MPa 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 Planning

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<sup>2</sup>. Eleven laboratories namely IRL-MSL (New Zealand), CSIRO-NML (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. Because of the limitation of the ATA carnet protocol, it was decided that ten laboratories would be participating in first year of this comparison. These laboratories were NPL (India), IRL-MSL (New Zealand), CSIRO-NML (Australia), KRISS (Korea), SCL (Hong Kong), SPRING (Singapore), NML-SIRIM (Malaysia), NIMT (Thailand), CSIR-NML (South Africa) and NMI (Japan). Three remaining countries [NPSL (Pakistan), NIS (Egypt) and ITDI (Philippines)] would be accommodated in the next year program.

NPSL (Pakistan) and ITDI (Philippines) were contacted during the next year comparison, but they did not respond adequately. In consultation with the Chairman, TCM, APMP, it was decided to include these two countries in a future program. However, in view of the success of the first year comparison and also after the circulation of the first year progress report, some of the participating APMP members requested that the pilot laboratory establish a link between this comparison and the CCM key comparison CCM.P-K1c. This would help the present comparison establish adequate credence with the BIPM key comparison data base (KCDB). Based on their requests, the pilot laboratory explored the possibility to invite a

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

laboratory that had taken part in the above mentioned comparison. PTB (Germany) responded to this call and offered to participate in the present comparison. It is worthwhile to mention that PTB (Germany) had not only participated in the above mentioned CCM.P-K1c - key comparison but also in a EUROMET key comparison EUROMET.M.P-K2. Since NMIJ from the APMP region had also taken part in CCM.P-K1c, it would strengthen the link of this comparison data with CCM.P-K1c. 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. The detail of the program is shown in Table 1.

## 2. Transfer standard

### 2.1 Description of the standard and calibration procedure

The transfer standard was a Ruska (Model 2465) pressure-balance base with piston-cylinder assembly V-407. The details of the standard and the calibration procedure were circulated to all the laboratories earlier [1]. Without repeating the prepared procedure, a few important points are mentioned.

- (a) The piston-cylinder unit is named as V-407 with a nominal effective area of  $8.4 \text{ mm}^2$  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 (in MPa) of: 0.41, 0.81, 1.21, 1.61, 2.01, 2.41, 2.81, 3.21, 3.61, 4.01 (increasing order)- 4.01, 3.6, 3.21, 2.81, 2.41, 2.01, 1.61, 1.21, 0.81, 0.41 (decreasing order)<sup>3</sup>. The procedure was repeated for a total of

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<sup>3</sup> Two effective areas at each nominal pressure point

5 cycles, giving 20 experimental determinations of the effective area of the transfer standard for each of the 10 nominal pressure points and a total of 100 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.

## 2.2 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<sup>-6</sup> 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  $A'_{p'}(23^{\circ}\text{C}, p')$  /mm<sup>2</sup> versus  $p'/\text{MPa}$  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). Figure 2 shows  $A'_{p'}(23^{\circ}\text{C}, p')$  /mm<sup>2</sup> versus  $p'/\text{MPa}$  which were obtained by NPLI during that period. It is clear that the results, which are shown in Figs.1 and 2, are typical for this type of piston gauge [Ruska 2465]. The estimated expanded uncertainty of these two laboratories 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. For the quantitative estimation, Table 2 provides the data  $A'_{p'}(23^{\circ}\text{C}, p')$ /mm<sup>2</sup> versus  $p'/\text{MPa}$  of the transfer standard at NMIJ during these two transits. It is very interesting to note that from these two sets of data, the maximum estimated instability is  $4 \times 10^{-6}$ , which also supports the 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  $4 \times 10^{-6}$  or 4 ppm.

### 3. Participants Standards

#### 3.1 About the Standards ( Annex 3 of the calibration procedure)

In Table 3, 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 3, the laboratories mainly used pressure balances of different kinds and ranges. Table 3 also shows the piston and cylinder materials of the standards used by participants and the effective area at null pressure and at 20° C or 23° C ( $A'_{p0}$ ) and the pressure distortion coefficient ( $\lambda'$ ) 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). Table 3 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 3. It is therefore needless to mention that all the guidelines provided by CCM/BIPM for RMO key comparisons have been rigorously maintained and executed.

#### 3.2 Results obtained by participants ( Annexes 4 and 5 of the calibration procedure)

Based on this information, the pilot laboratory has carried out a detailed analysis as follows:

##### (a) Estimation of the average value of effective areas $A'_{p'}/\text{mm}^2$ at 23° C of the transfer standard for each laboratory as a function of $p'/\text{MPa}$ :-

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

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

where n is the number of observations at each pressure point which in this case is 10. The standard deviation ( $\sigma_A$ ) of  $A'_{p'}/\text{mm}^2$ , the standard uncertainty ( $u_A$ ) is also obtained from  $u_A = \sigma_A/\sqrt{10}$  uniformly for all participating laboratories. Table 4 shows the average values of the effective area of the transfer standard  $A'_{p'}/\text{mm}^2$  (23°C,  $p'$ ) versus  $p'/\text{MPa}$  for all the participating laboratories.

**(b) Estimation of expanded uncertainty of  $A'_{p'}/\text{mm}^2$ :**

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  $A'_{p'}/\text{mm}^2$  at each pressure for each laboratory has been estimated from the root sum square Eq.(2),

$$u_c \equiv \sqrt{(u_A^2 + u_{T'}^2 + u_{p'}^2)} \dots (2)$$

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

$$U_{Lab} = k u_c \dots (3)$$

Here  $k=2$  has been taken into account. Table 5 summarizes the expanded uncertainty at  $k=2$  of all the participating laboratories as per Eq. (3).

**(c) But when evaluating the uncertainties below, all the other standard uncertainties of  $A'_{p'}/\text{mm}^2$  are expressed as  $k=1$ , so that the analysis of data of the comparison will be made in the same way.**

#### **4. Analysis of the results**

##### **4.1 Reference value of RMO key comparison**

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. However, to the best of our knowledge and also under CCM in pressure metrology except EUROMET.M.P-K2, there is no standard format to establish one rigid, robust and stable reference value in one pressure region in the CCM and RMO key comparisons. The basic reasons for not getting rigid, robust and stable values, stem from the following facts:

- (a) The range of pressure for the CCM key comparison and RMO key comparison may overlap but need not always be exactly the same.
- (b) The artifact used for a CCM key comparison may not be the same as that of a RMO key comparison.
- (c) The statement of the expanded uncertainty of the standard used by the participating laboratories in the RMO key comparison, is relatively large and cannot be compared with the selected best primary standard used by the participating laboratories in the CCM key comparison.
- (d) The pressure points at which both the comparisons were carried out, may not be the same.

Of course, many more disparities may be mentioned. However, because of these aforementioned major limitations, it is almost impossible to formulate one to one correspondence or translation of the CCM reference value to the RMO key comparison in total. Nevertheless, in the present context, our endeavor is to effectively link the CCM reference value in a realistic manner to the RMO key comparison.

As mentioned in **EUROMET.M.P-K2 (5)**, the participating laboratories are BEV (Austria), CEM (Spain), MIKES (Finland), FFA (Sweden), BNM-LNE (France) and PTB (Germany). **The reference values of the comparison [EUROMET.M.P-K2] and their uncertainties are estimated as the weighted mean of the effective areas obtained by the two primary laboratories BNM-LNE and PTB, who have also participated in the CCM.P-K1c.** The relation between the EUROMET.M.P-K2 and CCM.P-K1c has been established as the relative deviations from the reference values observed by both primary laboratories (BNM-LNE and PTB) in both comparisons, which are not very different from each other and are considerably smaller than the expanded uncertainties of both the reference values. These allow the relative deviations of all secondary laboratories from the reference value of the EUROMET.M.P-K2 comparison to be transferred directly to the comparison CCM.P-K1c.

However, on applying the similar weighted mean procedure in the APMP.M.P-K1c, we have two laboratories NMIJ and PTB who have taken part in the CCM.P-K1c comparison. Figure 3 shows the obtained reference values at different pressures and the values of other three laboratories which are maintaining the primary standard are also included for ready reference. From Fig. 3, it is clear that even if the calculations of the reference value are correct, it is very near to the PTB and NMIJ values but reasonably far off from the other three laboratories namely, CSIRO-NML, KRISS, NPLI. Therefore, it will be difficult to explain that this present estimated reference value as derived above, is the reference value of all the five participating laboratories that are maintaining primary standards. This assumption of weighted mean has been debated among the participants and also with other colleagues (6). After a long deliberation, it has been unanimously accepted that the present RMO key comparison has to be elaborated on the same model as the CCM.P-K1c one. **The reference value has to be calculated from the values of the laboratories, which are maintaining primary standards in the region. Then the link with the CCM and the EUROMET will be done using the differences from the reference values calculated for each comparison.** It has been done for the link of CCM.P-K1c and EUROMET.M.P-K2 (see the database). During the last meeting of the High Pressure Working Group (HPWG) of the CCM (May, 2002), the Chairman of the HPWG proposed a similar model for the CCM.P-K8, the EUROMET.M.P-K5 and the EUROMET.M.P-K6 comparisons.

Based on the above arguments, we propose to calculate the reference value from the values of the laboratories that are maintaining primary standards. Initially, we summarized the results of  $A'_{p'}$  as a function of  $p'$  for the six primary laboratories and plotted the same for all the laboratories. On plotting, it was observed that the distribution of the set of data provided by one of the laboratories (IRL-MSL) was distinctly different from all other five laboratories. In order to have a meaningful and realistic reference value and with the consent of the IRL-MSL, **we have estimated the reference value from the results of five laboratories, namely, NPLI, KRISS, CSIRO-NML, NMIJ and PTB.** Therefore, the key comparison reference value ( $x_R$ ) for the transfer standard was obtained as the linear fit  $A'_{p'}$  versus pressure  $p'$  of the results from the five participating laboratories that are maintaining primary pressure standards. For a better approximation, the standard uncertainty of reference value ( $u_R$ ) was taken as the standard deviation of the residuals from the linear fit.

$$x_R / \text{mm}^2 = A'p'(p', 23 \text{ }^\circ\text{C}) / \text{mm}^2 = 8,3860379 + 1,947 \cdot 10^{-5} \cdot p' / \text{MPa}.$$

$$u_R / x_R = 5,6 \cdot 10^{-6} \quad \dots \quad (4)$$

#### 4.2 Estimation of the relative deviation from the reference value:

Following the method adopted in CCM.P-K1c, we have estimated the degree of equivalence of each laboratory with respect to each reference value. Therefore, we define the relative deviation of the laboratory value from the reference value as:

$$D_i = (x_i - x_R) / x_R, \quad \dots \quad (5)$$

where  $x_i$  represents the laboratory  $i$  and  $x_R$  represents the reference value. The expanded uncertainty at  $k=2$  for this reference value is given by:

$$U_i = 2 (u_i^2 + u_R^2)^{0.5} / x_R, \quad \dots \quad (6)$$

where  $u_i$  represents the standard uncertainty of the laboratory  $i$  value.

#### 4.3 Estimation of the zero or null pressure effective area $A'_o(23^\circ\text{C})$ of the transfer standard

We have further probed the experimental data by determining the zero or null pressure effective area  $A'_o(23^\circ\text{C})$  of the transfer standard from the linear fit of  $A'p'$  vs. pressure  $p'$  obtained from all participating laboratories:

$$A'p'(p', 23 \text{ }^\circ\text{C}) / \text{mm}^2 = x_o^i + k^i \cdot p' / \text{MPa} \quad \dots \quad (7)$$

where  $x_o^i = A'_o(23 \text{ }^\circ\text{C})$  and  $k^i = A'_o(23 \text{ }^\circ\text{C}) \lambda$ .

Following the above mentioned procedure, the relative deviation from the reference value at zero pressure is given as

$$D_i^o = (x_o^i - x_o^R) / x_o^R \quad \dots \quad (8)$$

where  $x_o^R = 8,3860379 \text{ mm}^2$  and  $i$  represents laboratory  $i$ .

$$U_i^{\max} = 2 (u_i^2 + u_R^2)^{0.5} / x_o^R \quad \dots \quad (9)$$

is the maximum expanded uncertainty at  $k = 2$ .

#### 4.4 Degree of equivalence among the participating laboratories:

Following the method adopted in CCM.P-K1c, we have estimated the degree of equivalence between two laboratories, which is given for each transfer standard by a pair of numbers:

$$D_{ij} = D_i - D_j = (x_i - x_j) / x_R, \quad \dots \quad (10)$$

the relative difference between their results, and

$$U_{ij} = 2 (u_i^2 + u_j^2 + u_{tr.std.}^2)^{0.5} / x_R, \quad \dots \quad (11)$$

its expanded uncertainty ( $k = 2$ ). Here,  $u_{tr.std.}$  is the transfer standard stability ( $4 \times 10^{-6}$ ).

#### 4.5 Linkage to CCM.P-K1c and EUROMET.M.P-K2 key comparisons

**The results of the present comparison can easily be linked to the results of the key comparison CCM.P-K1c performed in the gauge mode up to 7 MPa. The participating laboratories are NMIJ and PTB.** Since the relative deviations  $D_i$  from the reference values  $x_R$  observed by both these laboratories (NMIJ and PTB) are not very different from each other and are considerably smaller than the expanded uncertainties of both reference values. They allow the relative deviations of all the other laboratories from the reference value of the present comparison to be transferred directly to the comparison CCM.P-K1c.

In **CCM.P-K1c**, the relative deviation from the reference value of the participating laboratories (PTB and NMIJ) was defined as  $D_{PTB}$  and  $D_{NMIJ}$  with standard uncertainties given by  $u_{PTB}$  and  $u_{NMIJ}$ . The uncertainty of the key comparison reference value (KCRV) is not involved in the computation of the linkage. Therefore, the combined differences may be calculated as the weighted mean of the deviations where the weights are the inverse square of the corresponding standard uncertainties :

$$D_{NMIJ+PTB} = (u_{NMIJ}^2 \cdot D_{PTB} + u_{PTB}^2 \cdot D_{NMIJ}) / (u_{NMIJ}^2 + u_{PTB}^2) \quad \dots \quad (12)$$

Following the same procedure, we can estimate the relative deviation from the reference value of the participating laboratories (PTB and NMIJ) in APMP.M.P-K1c comparison.

$$D_{NMIJ+PTB} = - 1.8 \cdot 10^{-6} \text{ and } - 0.15 \cdot 10^{-6} \text{ respectively near 1 MPa and 4 MPa for the CCM.P-K1c comparison.} \quad \dots \quad (13)$$

$$D_{NMIJ+PTB} = 2.0 \cdot 10^{-6} \text{ and } 7.0 \cdot 10^{-6} \text{ respectively near 1.2 MPa and 4 MPa for the APMP.M.P-K1c comparison.} \quad \dots \quad (14)$$

$$\text{Therefore, } D_{NMIJ+PTB} (\text{CCM.P-K1c}) - D_{NMIJ+PTB} (\text{APMP.M.P-K1c}) = - 3.8 \cdot 10^{-6} \text{ near 1 MPa.} \quad \dots \quad (15)$$

$$\text{and } D_{NMIJ+PTB} (\text{CCM.P-K1c}) - D_{NMIJ+PTB} (\text{APMP.M.P-K1c}) = -7.1 \cdot 10^{-6} \text{ near 4 MPa.} \quad \dots \quad (16)$$

The degrees of equivalence of NPLI, KRISS, CSIRO-NML, MSL-IRL, SPRING, NML-SIRIM, SCL, CSIR-NML, NIS-Egypt obtained in the APMP comparison can be transferred to the CCM.P-K1.c comparison as follows :

$$\begin{aligned} D_i &= D_{i-APMP} - 3.8 \text{ (expressed in } 10^{-6}\text{) and} \\ U_i &= U_{i-APMP} \text{ at pressures close to 1.2 MPa} \end{aligned} \quad \dots \quad (17)$$

$$\begin{aligned} D_i &= D_{i-APMP} - 7.1 \text{ (expressed in } 10^{-6}\text{) and} \\ U_i &= U_{i-APMP} \text{ at pressures close to 4 MPa} \end{aligned} \quad \dots \quad (18)$$

It may be mentioned here that similar methods can be adopted for the EUROMET.M.P-K2 comparison. However, it is to be remembered that CCM.M.P-K1c and EUROMET.M.P-K2 measurands are effective areas referred to 20°C. Since the link is expressed in relative terms of deviations, there are no problems even if the effective area of the APMP.M.P-k1c comparison is referred to 23° C.

## 5. Discussions:

In the previous section, we have discussed briefly the mathematical methods for determining the degree of equivalence between two participating laboratories. We have also shown the subsequent linkage to the CCM and another RMO key comparison. But as the methods are still being developed, especially those for combining regional key comparison data with CCM key comparison data, it is required to have some discussion regarding the universality of the present method.

- (a) It is noteworthy to mention that, in this regional key comparison, all the participating laboratories are National Metrological Institutes (NMIs). Of course, 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]. Also, generally the artifact is a well-studied transfer standard. Moreover, a few NMIs have usually taken part in CCM key comparisons. Therefore, in this method the estimation of the reference values of the travelling standard has been carried out in such away that all the important NMIs in the region are equally responsible for the determination of the reference value as has been done in the CCM key comparison. This has further checked the long term stability of the transfer standard which is  $4 \cdot 10^{-6}$  as has been claimed by the donor country (NMIJ).
- (b) Ideally, the philosophy of any travelling transfer standard is that the comparison procedure should contribute as little as possible to the uncertainty. However, in reality, it is not ideally possible because of various reasons. It is for this reason, the reference value plays a very important and crucial role in any comparison, either CCM or regional key comparison.
- (c) It is to be remembered here that in the earlier reported regional key comparison EUROMET.M.P-K2, the reference values were calculated by weighting the values of two participants, BNM-LNE and PTB, who were the participants in the CCM.M.P-K1c comparison. Figure 3 shows such an effort in the present comparison when we consider the method of weighted mean of PTB and NMIJ who are the participants of the CCM.P-K1c. It is clear that even if the calculations of the reference value are correct, it is very near to the PTB and NMIJ values but reasonably far off from the other three laboratories namely, CSIRO-NML, KRISS, NPLI. Secondly, if we call it as the APMP.M.P-K1c

reference value, then the calculated values are not fully issued from all the measurements reported for this comparison. It is in this context, the statistical argument against the weighted means is also known - weighted means are not statistically robust because they are too easily influenced by individual results. Median values are generally the most robust but, if the number of primary laboratories is small, arithmetic mean is still considerably better than a weighted mean or median values. The arithmetic mean values of PTB and NMIJ can be taken but once again, it can be shown that they are far off from the other three laboratories namely, CSIRO-NML, KRISS, NPLI. Therefore, after a long deliberation, it was decided to take the fitted value of  $A'_p/\text{mm}^2$  versus  $p'/\text{MPa}$  for five laboratories that are maintaining primary standards (shown in Fig. 4). Figure 5 shows the  $A'_p/\text{mm}^2$  versus  $p'/\text{MPa}$  for all the laboratories which are maintaining secondary standards. The reference values are also shown in both the figures for ready reference. It is very interesting to note that for all eleven participating laboratories,  $A'_p/\text{mm}^2$  data at all the pressure points  $p'/\text{MPa}$  are evenly distributed around the reference value. This shows that this reference value is reasonable and stable which is further supported by the fact that the standard uncertainty statement obtained by this fitting method is comparable to the standard uncertainty statement of any of the primary laboratories.

(d) We have further enunciated the stability of the reference value in Fig. 6 where the relative difference between laboratory values and reference values (in  $\times 10^{-6}$  or ppm), have been plotted with reference to  $p'/\text{MPa}$  [ Eq. (5)]. Table 6 shows the summary of the relative difference between laboratory values and reference values in ppm for all the participating laboratories as a function of  $p'/\text{MPa}$ . The expanded uncertainty statement at  $k=2$  is also shown for ready reference. Two important inferences can be drawn from Fig.6 and Table 6:

- (1) For all the laboratories maintaining primary standards, namely NPLI, KRISS, CSIRO-NML, NIMJ and PTB, the relative difference between laboratory values and reference values at all pressures is agreeing to within  $\pm 20$  ppm. IRL-MSL is maintaining a primary standard but their agreement seems to be on the higher side although it is within the claimed uncertainty statement of the laboratory.
- (2) For all the laboratories maintaining secondary standards, namely SPRING, NML-SIRIM, SCL, CSIR-NML and NIS-Egypt, the relative difference between laboratory values and reference values at all pressures is agreeing to within  $\pm 60$  ppm. Special reference has to be made to SPRING and NML-SIRIM. Their relative difference between laboratory values and reference values at all pressures is agreeing to within  $\pm 20$  ppm.

(e) In order to get the overall agreement of all the participating laboratories, we have fitted the data of  $A'_p/\text{mm}^2$  versus  $p'/\text{MPa}$  from all the eleven participating laboratories linearly. We have also determined the reference value using Eq.(7) and the relative deviation from the reference value with maximum uncertainty at  $k=2$  using Eqs. (8) and (9). We have obtained  $A'_o/\text{mm}^2$  and  $k$  for all the laboratories which have been shown in Fig. 7 and tabulated in Table 7. The expanded uncertainty statement at  $k=2$  is also shown for ready reference. It is clear once again that these eleven participating laboratories said to have performed equivalent measurements, that is, the mean value of the results obtained by

these laboratories measuring the same quantity lies within the expanded uncertainty of each laboratory and this provides further confidence in our estimation.

- (j) The degree of equivalence between two laboratories is given for each transfer standard through Eqs. (10) and (11). Tables 8 and 9 show for two nominal pressures at 1.2 MPa and 4 MPa. . It should be noted that the transfer standard stability ( $u_{tr.std.}$ ) which is  $4 \cdot 10^{-6}$  (4 ppm) have been taken into account. The relative differences between their results ( $D_{ij}$ ) with their expanded uncertainty  $U_{ij}$  at  $k=2$  are shown in these two tables. Overall agreements between the participating laboratories within their expanded uncertainty statements are very encouraging.
- (k) Finally, a new method of linking CCM.P-K1c and EUROMET.M.P-K2 key comparisons has been evolved. Since it is not possible to carry out all the pressure points, we have carried out at two common points near 1 MPa and 4 MPa. Equations (12) to (18) are the step by step procedure for carrying out such exercises. We have elaborated the model at every step to avoid any ambiguity. The uncertainty of the key comparison reference value (KCRV) is not involved in the computation of the linkage. Tables 10-12 clearly demonstrate the 1 MPa pressure point but in the attached EXCEL file, we have carried out for both pressures near 1 MPa and 4 MPa. Here also, overall agreements between the participating laboratories within their expanded uncertainty statements are very encouraging.

## 6. 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 0.4 to 4.0 MPa. The transfer standard was a pressure-balance with a piston-cylinder assembly with nominal effective area of  $8.4 \text{ mm}^2$  and was supplied by NIMJ. Eleven laboratories have participated out of which two laboratories have taken part in the corresponding CCM 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  $4 \times 10^{-6}$  (4 ppm).
- (d) All participating laboratories were asked to provide their uncertainty budgets of their standard, which were used for this comparison.
- (e) Average value of effective areas  $A'_{p'}/\text{mm}^2$  at  $23^\circ\text{C}$  of the transfer standard for each laboratory as a function of  $p'/\text{MPa}$  with their uncertainty statement have been estimated uniformly.
- (f) The reference value for this APMP regional comparison has been obtained from the fitted value of  $A'_{p'}/\text{mm}^2$  versus  $p'/\text{MPa}$  for five laboratories that are maintaining primary standards.
- (g) The relative difference between laboratory values and the APMP reference value at all pressures is within the maximum deviation of  $\pm 20$  ppm for the participating laboratories

that are maintaining primary standards and  $\pm 60$  ppm for the laboratories that are maintaining secondary standards.

- (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  $k=2$ .
- (k) Linkage with CCM.P-K1c and with EUROMET M.P-K2 at two nominal pressures near 1 MPa and 4 MPa has been established.

## 7. Acknowledgements

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## 8. References:

- [1] APMP sponsored regional pneumatic pressure comparison: (i) 20 kPa to 105 kPa and (ii) 0.4 MPa to 4.0 MPa (Gauge Mode), Calibration Procedure,, A.K. Bandyopadhyay, Pressure and Vacuum Standards, National Physical Laboratory, New Delhi – 110012, India (Unpublished).
- [2] Results of the CCM pressure key comparison (Phase B) in gas media and gauge mode 80 kPa to 7 MPa, G. Molinar, J.C. Legras, J. Jaeger, A. Ooiwa and J. Schmidt (CCM.P-K1c) , IMGC-CNR Technical Report 42, October 2000.
- [3] Guide to the expression of uncertainty in measurement, International Bureau of Weights and Measures (BIPM), Switzerland, 1995.
- [4] CCM key comparison in the pressure range 50 kPa to 1000 kPa (gas medium, gauge mode). Phase A2: pressure measurements, J.C. Legras, W. Sabuga, G. Molinar and J. Schmidt, Metrologia 36, 663-668 (1999).
- [5] Regional key comparison EUROMET.M.P-K2 within the pressure range (0.5) 1 MPa to 4 (5) MPa, S. Ban, J. Jaeger, J.C. Legras, C. Matila, M. Rantanen and D. Steindl, KCDB, CCM, BIPM, Paris (France), February 28<sup>th</sup>, 2002.
- [6] Dr. J. C. Legras and Dr. G. F. Molinar - Private discussion.

Figures Caption:

- Figure 1 :  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  for NIMJ during September, 1999 and October, 2000 with standard uncertainty at  $k=1$ .
- Figure 2 :  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  for NPLI during October, 1998 and May 2001 with standard uncertainty at  $k=1$ .
- Figure 3:  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  for laboratories that are maintaining primary standard in their laboratories. The reference values are obtained from weighted mean of the values of PTB and NMIJ.
- Figure 4:  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  for the laboratories that are maintaining primary standard in their laboratories. The key comparison reference value ( $x_R$ ) for the transfer standard is obtained from the linear fit of  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  of the results from the five participating laboratories that are maintaining primary pressure standards.
- Figure 5 :  $A_p'/\text{mm}^2$  versus  $p'/\text{MPa}$  for laboratories that are maintaining secondary standards in their laboratories. The key comparison reference value ( $x_R$ ) for the transfer standard is also shown.
- Figure 6 : Relative difference of  $A'_p$  with reference to APMP reference value  $D_i = (x_i - x_R) / x_R$ , where  $x_i$  represents the laboratory  $i$  and  $x_R$  represents the reference value for all participating laboratories. The expanded uncertainty at  $k=2$  for this reference value is given by  $U_i = 2 (u_i^2 + u_R^2)^{0.5} / x_R$ ,
- Figure 7: Relative difference of  $A'_o$  value with reference to APMP reference value with uncertainty statement at  $k=2$  for all participating laboratories.  $D_i^o = (x_o^i - x_o^R) / x_o^R$  where  $x_o^R = 8,3860379 \text{ mm}^2$  where  $i$  represents laboratory  $i$  and  $U_i^{\max} = 2 (u_i^2 + u_R^2)^{0.5} / x_R$

Figure 1

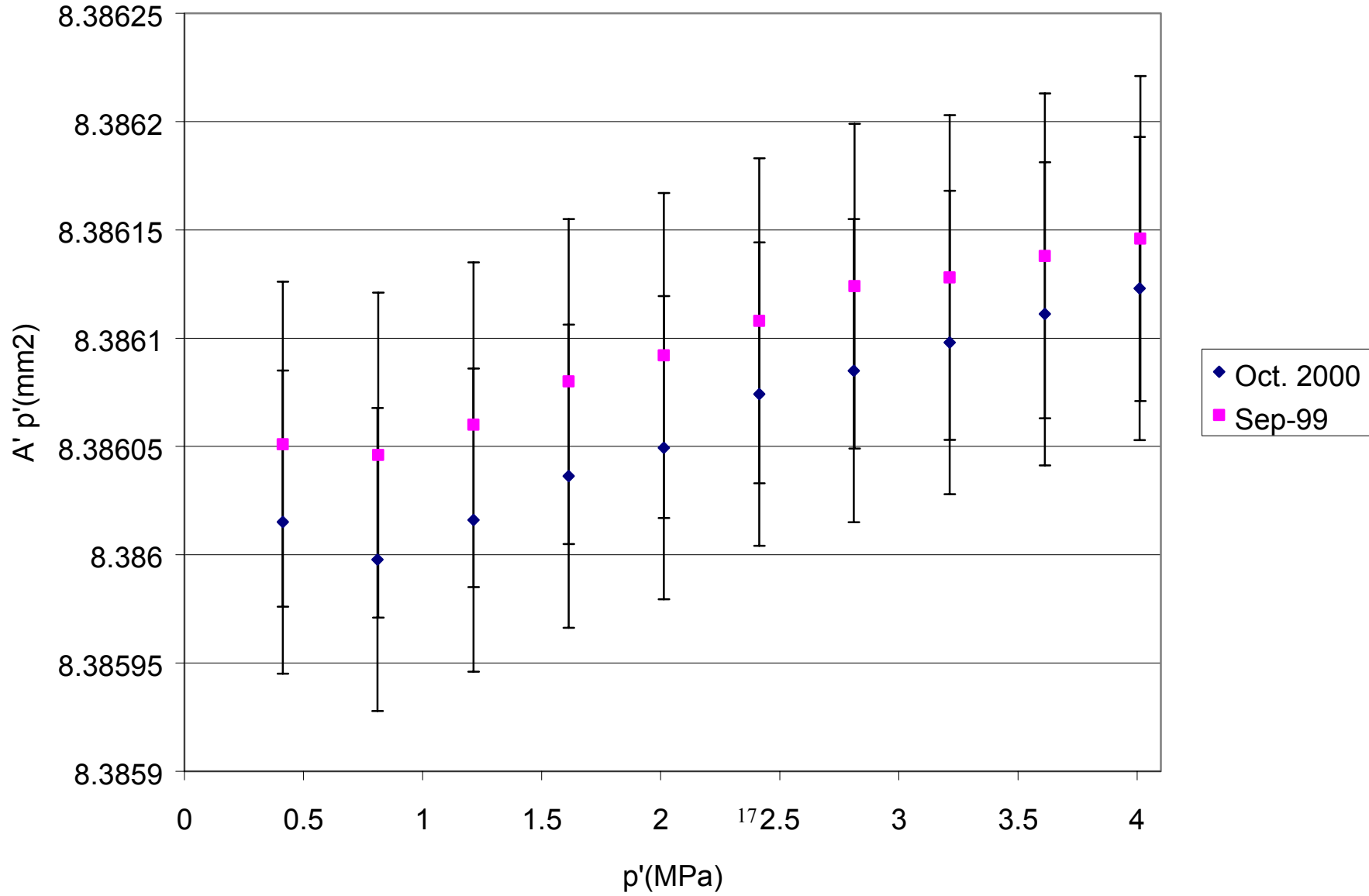


Figure 2

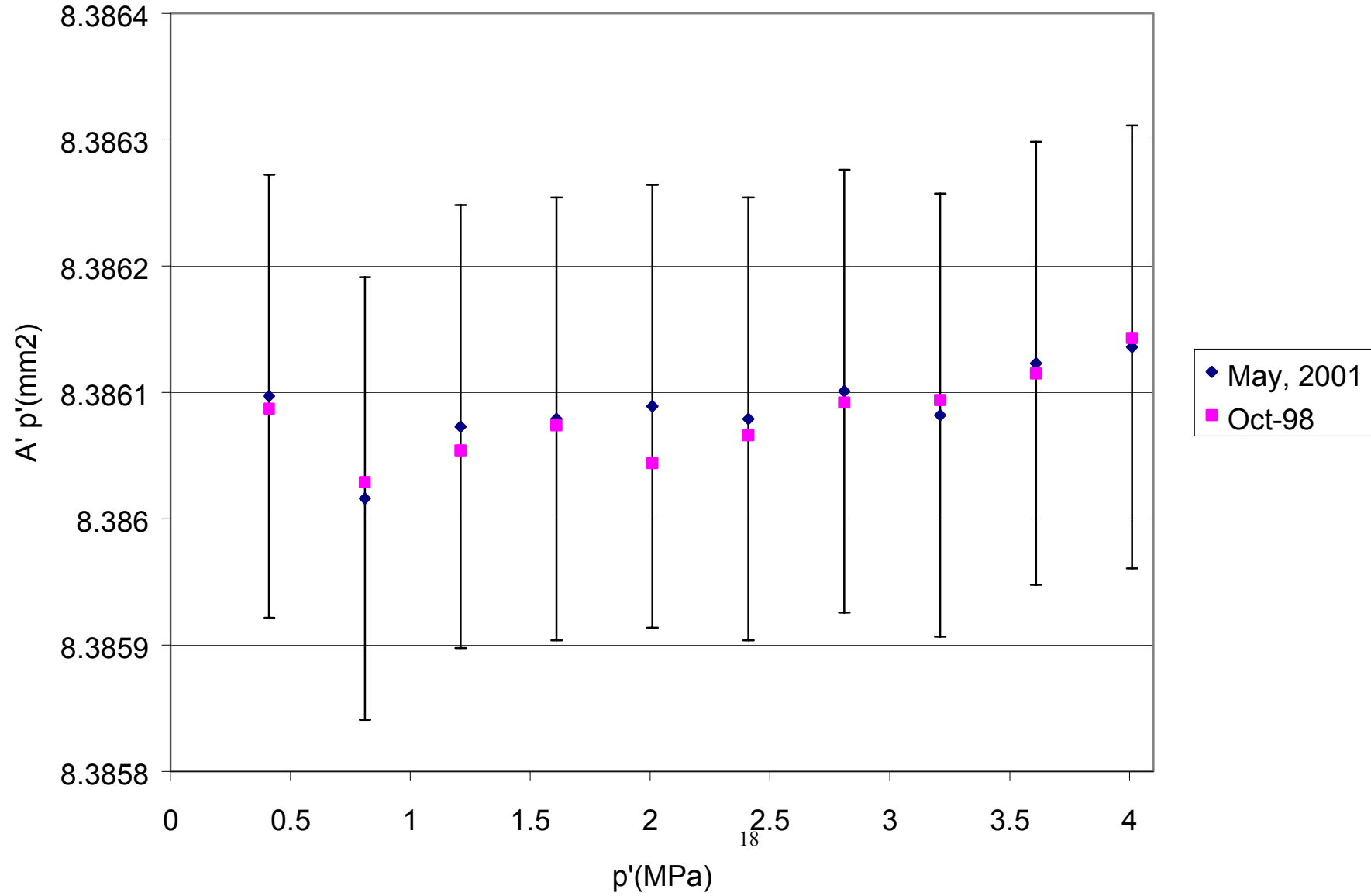


Figure 3

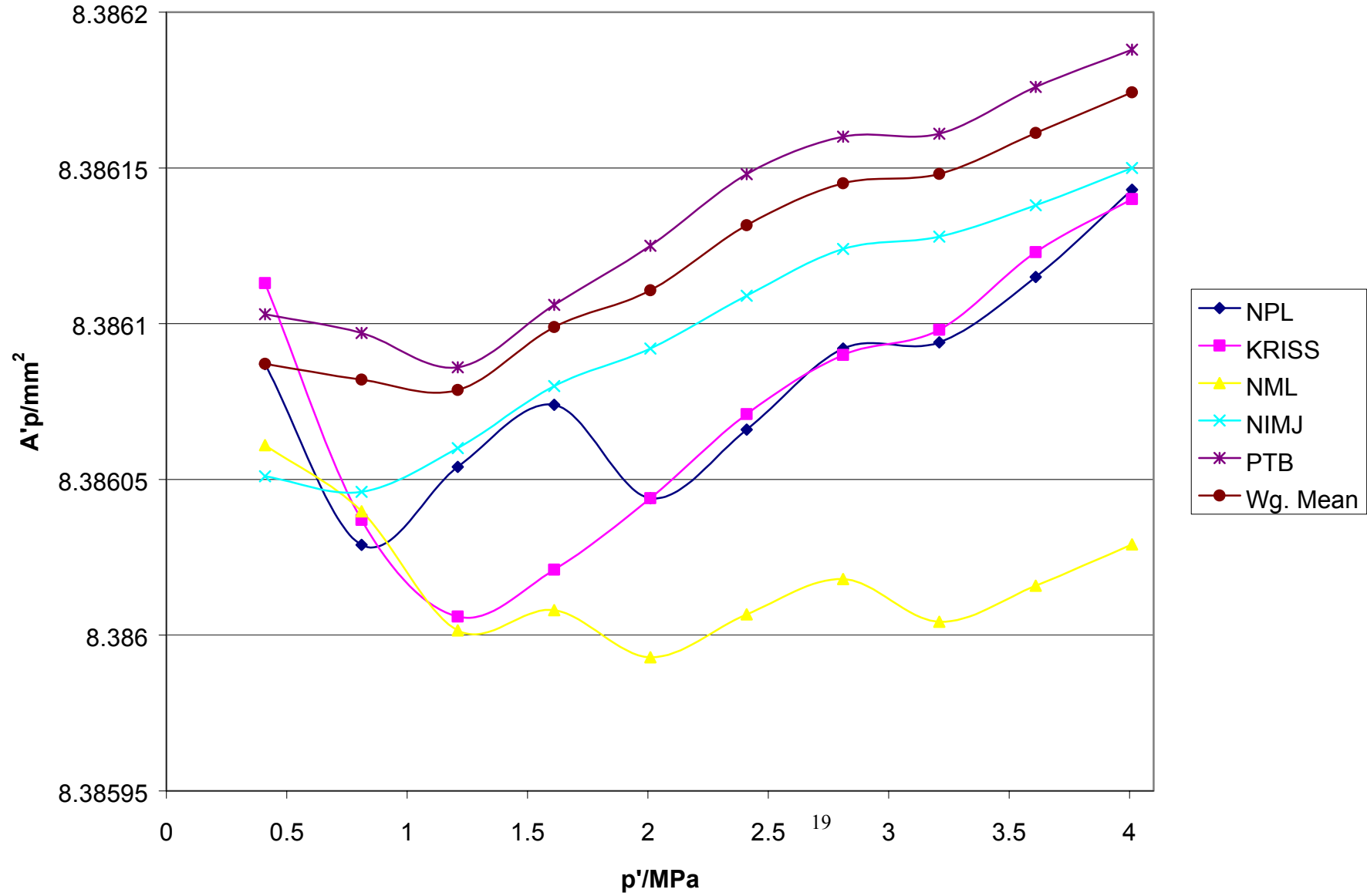


Figure 4

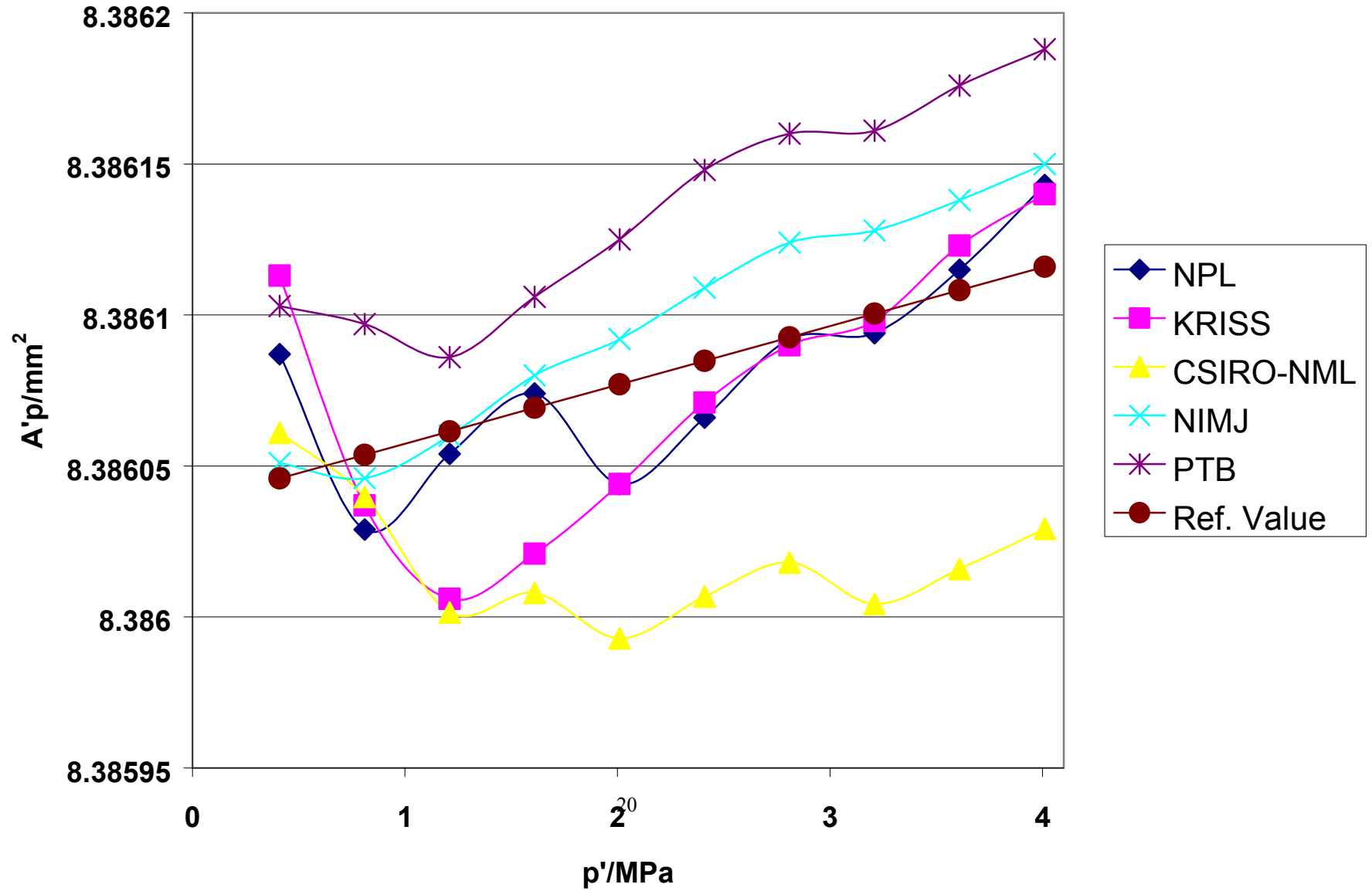


Figure 5

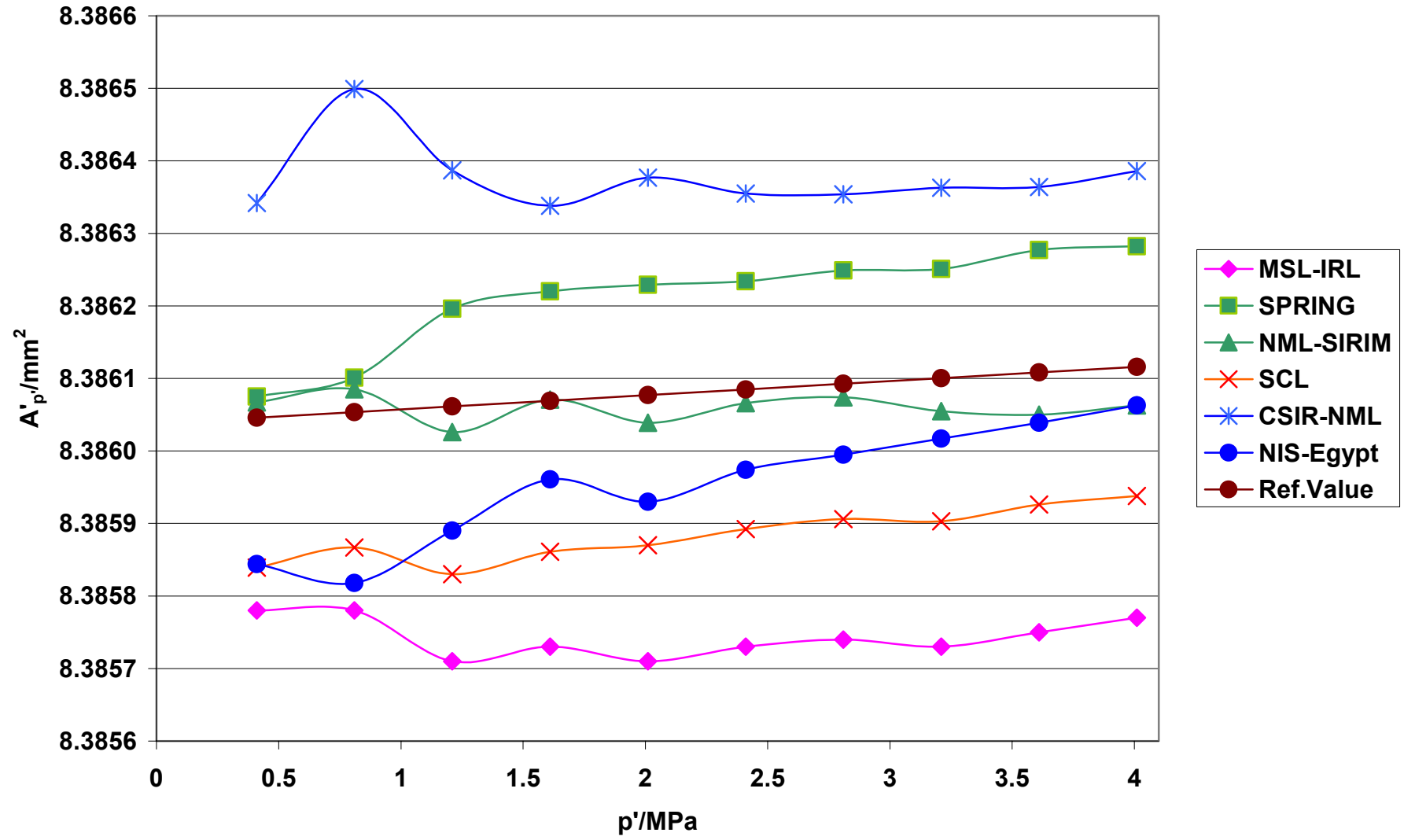


Figure 6

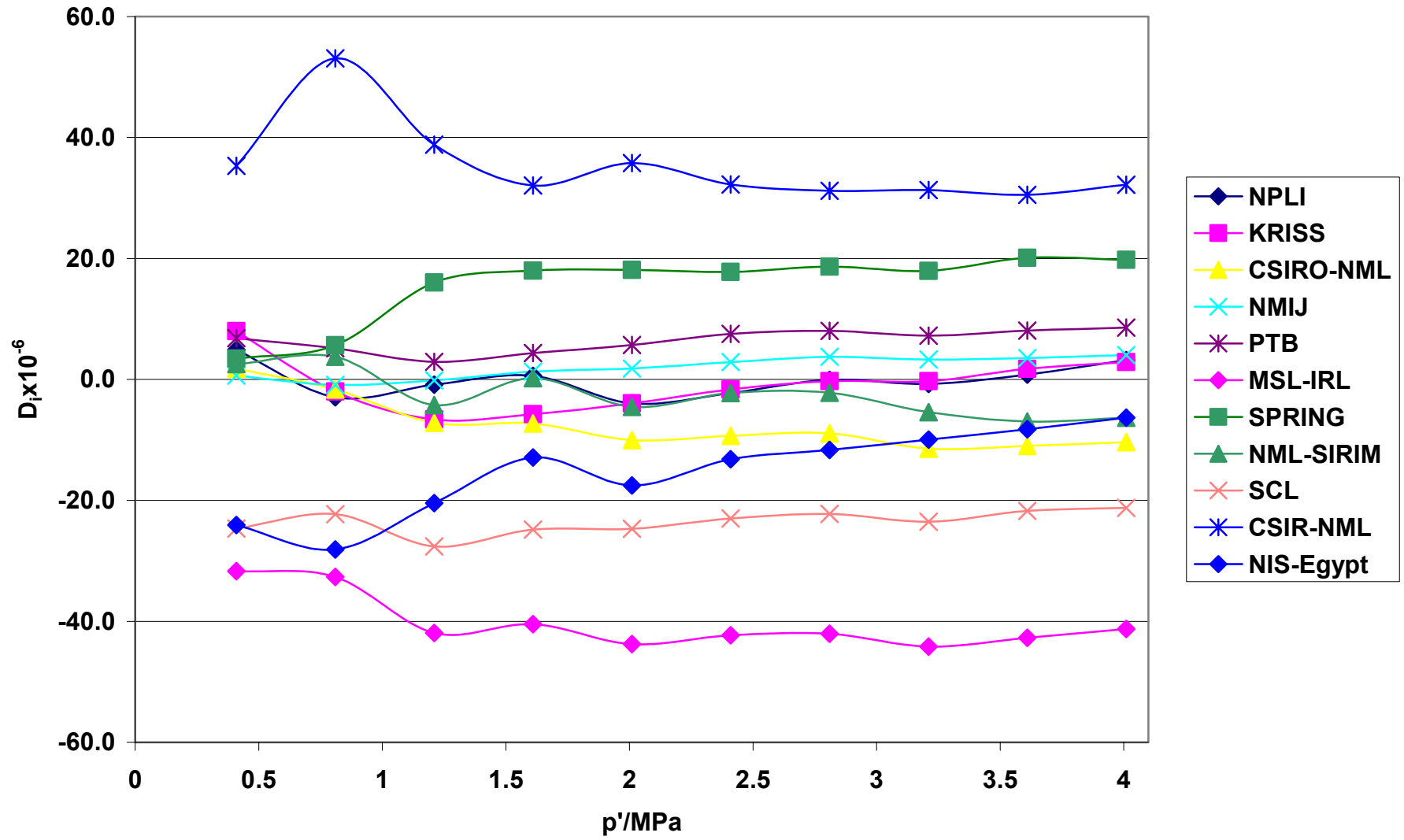
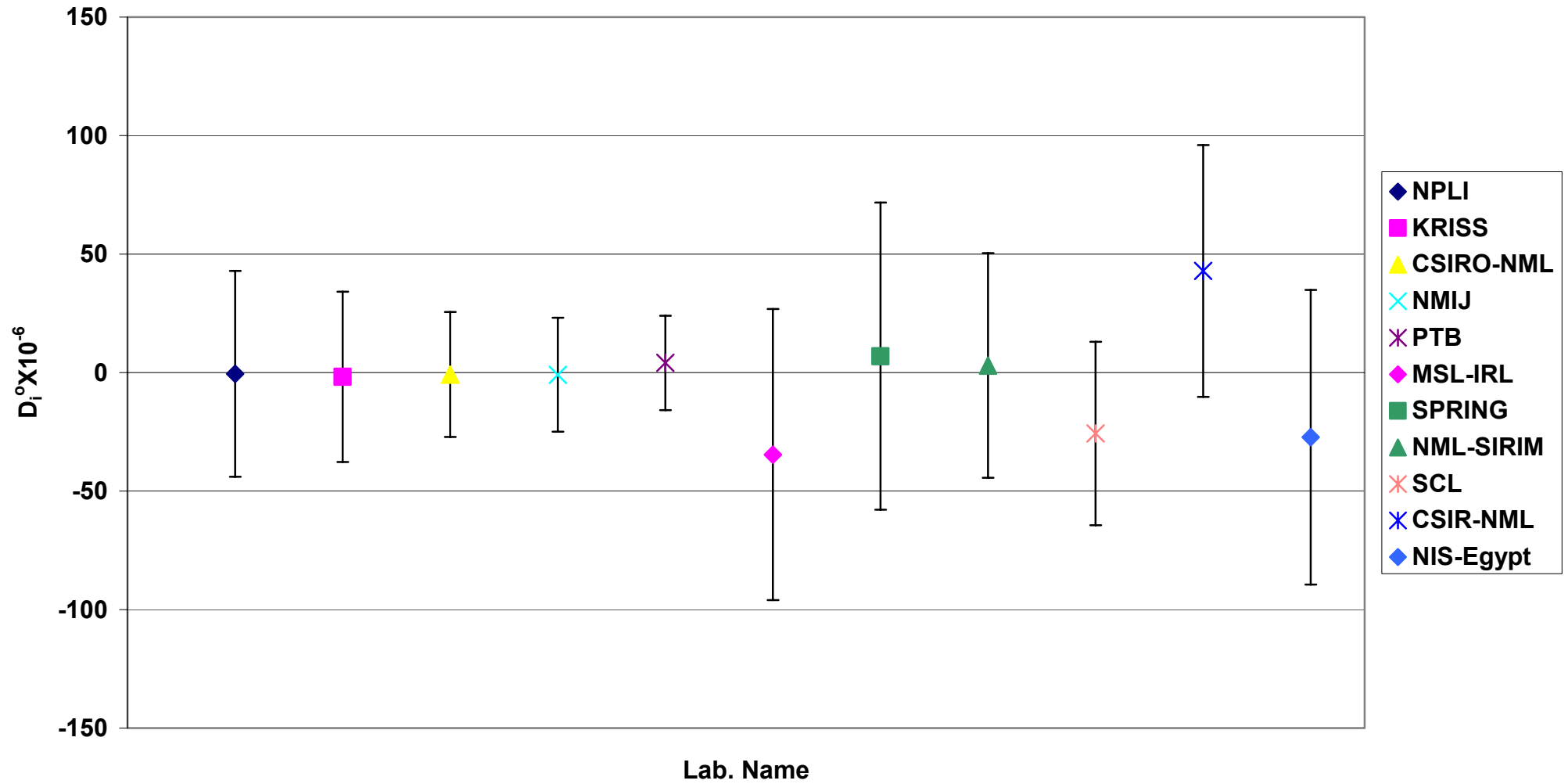


Figure 7



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Table 10 : Linkage of EUROMET M.P-K2 with CCM.P-K1c at a nominal pressure 1 MPa. Lab.j are the participating laboratories in the CCM key comparison.

Table 11 : Linkage of APMP.M.P-K-1c with CCM.P-K1c at a nominal pressure 1 MPa. Lab.j are the participating laboratories in the CCM key comparison.

Table 12 : Linkage of APMP.M.P-K-1c with EUROMET M.P-K2 at a nominal pressure 1 MPa. . Lab.j are the participating laboratories in the EUROMET key comparison.

Table 1

Serial No.	Date of arrival	Date of departure	Name of the Laboratories
1.	1 <sup>st</sup> October, 98	15 <sup>th</sup> November, 98	NPLI
2.	22 <sup>nd</sup> November, 98	7 <sup>th</sup> January, 1999	SPRING
3.	14 <sup>th</sup> January, 99	14 <sup>th</sup> February, 99	NML-SIRIM
4.	21 <sup>st</sup> February, 99	21 <sup>st</sup> March, 99	NIMT
5.	28 <sup>th</sup> March, 99	28 <sup>th</sup> April, 99	KRISS
6.	7 <sup>th</sup> May, 99	7 <sup>th</sup> June, 99	IRL-MSL
7.	14 <sup>th</sup> June, 99	14 <sup>th</sup> July, 99	SCL
8.	21 <sup>st</sup> July, 99	21 <sup>st</sup> August, 99	CSIRO-NML
9.	1 <sup>st</sup> September, 99	7 <sup>th</sup> October, 99	NMIJ
10.	15 <sup>th</sup> , October, 99	15 <sup>th</sup> December, 99	CSIR-NML
11.	15 <sup>th</sup> January, 00	14 <sup>th</sup> April, 00	NPLI
12.	15 <sup>th</sup> June, 00	15 <sup>th</sup> September, 00	NIS-Egypt
13.	1 <sup>st</sup> October, 00	30 <sup>th</sup> November, 00	NMIJ
14.	15 <sup>th</sup> December, 00	28 <sup>th</sup> February, 01	CSIRO-NML
15.	1 <sup>st</sup> March, 01	30 <sup>th</sup> May, 01	PTB
16.	15 <sup>th</sup> June, 01	15 <sup>th</sup> September, 01	NPLI

Table 2

Laboratory Name :		NMIJ				
Local g and std. uncertainty u(g) :		9.799485			0.000003	m/s <sup>2</sup>
Transfer std. Piston-cylinder # :		V-407				
Std. Unc. for air density, u( $\rho_a$ ) :		1.1854			0.0040	kg/m <sup>3</sup>
Nominal pressure	Date(period) Y1999 M09 D22-29		Date (period) Y2000 M10 D17-23		Average of A' <sub>p</sub>	Deviation of A' <sub>p</sub> ( $\Delta A'_{p'} / A'_{p'}$ )
	Average of A' <sub>p</sub>	Uncertainty of A' <sub>p</sub>	Average of A' <sub>p</sub>	Uncertainty of A' <sub>p</sub>		
(MPa)	(mm <sup>2</sup> )	(ppm)	(mm <sup>2</sup> )	(ppm)	(mm <sup>2</sup> )	(ppm)
0.4	8.386051	8.8	8.386015	8.8	8.386033	3.04
0.8	8.386046	8.9	8.385998	8.9	8.386022	4.05
1.2	8.38606	9.0	8.386016	9.0	8.386038	3.71
1.6	8.38608	9.1	8.386036	9.1	8.386058	3.71
2.0	8.386092	9.3	8.386049	9.3	8.386071	3.63
2.4	8.386109	9.5	8.386074	9.5	8.386091	2.95
2.8	8.386124	9.7	8.386085	9.7	8.386105	3.29
3.2	8.386128	10.0	8.386098	10.0	8.386113	2.53
3.6	8.386138	10.3	8.386111	10.3	8.386124	2.28
4.0	8.38615	10.6	8.386123	10.6	8.386136	2.28

Table 3

Laboratories / Parameters	Category I Laboratories which are having Primary standards						Category II Laboratories which are having Secondary standards				
	NPLI	KRISS	IRL-MSL	CSIRO-NML	NMIJ	PTB	SPRING	NML-SIRIM	SCL	CSIR-NML	NIS-Egypt
Measurement Range (MPa)	.1 to 4.2	7.0	0.1 to 11	0.25 to 7.0	0.1 to 7.0	7.0	0.2 to 7.0	0.2 to 6.0	0.1 to 7.0	30	0.1 - 8
Materials of The Piston And Cylinder	WC	WC	WC	WC	WC	WC	WC	WC	WC	WC	WC
	WC	WC	WC	WC	WC	WC	WC	WC	WC	WC	WC
A <sub>0</sub> at Atm. Pres. and Ref. Temp.(mm <sup>2</sup> )	8.392196	49.02002	49.0142	8.385262	49.03465	49.01916	49.02760	8.397916	8.39067	19.6107	98.05335
Relative Uncertainty of A <sub>0</sub> (k=1) (in 10 <sup>-6</sup> )	20	15	60	8		7.7	63	22	12.5	30.6	8.1xA <sub>0</sub>
Pressure Distortion Co-efficient (λ)(MPa <sup>-1</sup> )	7.52 x10 <sup>-6</sup>	0	-2.35 x10 <sup>-6</sup>	2.18 x10 <sup>-6</sup>	-1.4 x10 <sup>-6</sup>	-2.35 x10 <sup>-6</sup>	0	-1.45 x10 <sup>-6</sup>	3.3 x10 <sup>-6</sup>	0.6 x10 <sup>-6</sup>	0.77 x10 <sup>-6</sup>
Standard uncertainty of λ (MPa <sup>-1</sup> )	3.5 x10 <sup>-7</sup>	-	2.3 x10 <sup>-7</sup>	2 x10 <sup>-7</sup>	1.5 x10 <sup>-7</sup>	2.35 x10 <sup>-7</sup>	-	2.8 x10 <sup>-7</sup>	3 x10 <sup>-7</sup>	-	3 x10 <sup>-7</sup>
Reference density of the Weight	7920	7800	8000	7856		8000	7920	7800	8000	7920	7920
Relative uncertainty Of Mass (in	1	1.0	1.0	0.8		0.5	0.4	2.5	1.6	10.0	10

$10^6$											
$\alpha_p$ ( $\times 10^{-6}/^\circ\text{C}$ )	4.5	4.5	4.5	4.50	4.5	4.5	4.5	4.5	4.5	4.5	4.5
$\alpha_c$ ( $\times 10^{-6}/^\circ\text{C}$ )	4.5	4.5	4.5	4.50	4.5	4.5	4.5	4.5	4.5	4.5	4.5
$T_{op}$ (in $^\circ\text{C}$ )	20	23	20	20	20	20	20	20	20	20	23
Traceability							BNM-LNE	NIST	NPL	NPL	BNM-LNE

Table 4

<b>Nominal Pressure (MPa)</b>	<b>NPLI</b>	<b>KRISS</b>	<b>IRL-MSL</b>	<b>CSIRO-NML</b>	<b>NMIJ</b>	<b>PTB</b>	<b>SPRING</b>	<b>NML-SIRIM</b>	<b>SCL</b>	<b>CSIR-NML</b>	<b>NIS -Egypt</b>
0.41	8.386087	8.386113	8.38578	8.386061	8.386051	8.386103	8.386075	8.386067	8.385839	8.386342	8.385844
0.81	8.386029	8.386037	8.38578	8.38604	8.386046	8.386097	8.386101	8.386085	8.385867	8.386499	8.385818
1.21	8.386054	8.386006	8.38571	8.386002	8.38606	8.386086	8.386196	8.386026	8.38583	8.386387	8.38589
1.61	8.386074	8.386021	8.38573	8.386008	8.38608	8.386106	8.38622	8.386071	8.385861	8.386338	8.385961
2.01	8.386044	8.386044	8.38571	8.385993	8.386092	8.386125	8.386229	8.386039	8.38587	8.386377	8.38593
2.41	8.386066	8.386071	8.38573	8.386007	8.386109	8.386148	8.386234	8.386066	8.385892	8.386355	8.385974
2.81	8.386092	8.38609	8.38574	8.386018	8.386124	8.38616	8.386249	8.386074	8.385906	8.386354	8.385995
3.21	8.386094	8.386098	8.38573	8.386004	8.386128	8.386161	8.386251	8.386055	8.385903	8.386363	8.386017
3.61	8.386115	8.386123	8.38575	8.386016	8.386138	8.386176	8.386277	8.38605	8.385926	8.386364	8.386039
4.01	8.386143	8.38614	8.38577	8.386029	8.38615	8.386188	8.386282	8.386063	8.385938	8.386386	8.386063

Table 5

<b>Nominal Pressure (MPa)</b>	<b>NPLI</b>	<b>KRISS</b>	<b>IRL-MSL</b>	<b>CSIRO-NML</b>	<b>NMIJ</b>	<b>PTB</b>	<b>SPRING</b>	<b>NML-SIRIM</b>	<b>SCL</b>	<b>CSIR-NML</b>	<b>NIS-Egypt</b>
0.41	41.9	34.07	60.4	23.84	17.61	11.7	63.86	46.12	36.99	61.22	50.63
0.81	41.32	34.09	60.6	23.84	17.72	11.4	63.87	45.13	37.06	61.22	44.74
1.21	41.35	34.06	60.4	23.81	17.93	11.2	63.84	45.13	37.02	40.33	63.02
1.61	41.26	34.06	60.2	23.81	18.22	11.2	63.82	45.13	37.06	36.44	51.29
2.01	41.38	34.07	60.2	23.88	18.56	16.2	63.84	45.13	37.04	35.47	44.28
2.41	41.34	34.06	60.2	23.85	18.99	16.2	63.82	45.13	37.06	35.47	44.01
2.81	41.28	34.07	60.2	23.82	19.48	16.4	63.82	45.13	37.04	34.51	42.77
3.21	41.27	34.08	60.2	23.81	20.03	16.1	63.82	45.12	37.06	34.5	46.7
3.61	41.34	34.06	60.2	23.81	20.63	16.5	63.82	45.13	37.06	34.5	49.01
4.01	41.29	34.07	60.2	23.82	21.28	16	63.83	45.13	37.06	34.49	46.95

**Table –6**

Laboratories which are maintaining primary standards													
p' nom / MPa	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$			
0.41	4.9	43	8.0	36	1.8	26	0.6	21	6.8	16			
0.81	-2.9	43	-2.0	36	-1.7	26	-0.9	21	5.2	16			
1.21	-0.9	43	-6.6	36	-7.1	26	-0.2	21	2.9	16			
1.61	0.6	43	-5.8	36	-7.3	26	1.3	21	4.4	16			
2.01	-3.9	43	-3.9	36	-10.0	26	1.8	22	5.7	20			
2.41	-2.2	43	-1.6	36	-9.3	26	2.9	22	7.5	20			
2.81	-0.1	43	-0.3	36	-8.9	26	3.7	22	8.0	20			
3.21	-0.8	43	-0.3	36	-11.5	26	3.3	23	7.2	20			
3.61	0.8	43	1.8	36	-11.0	26	3.6	23	8.1	20			
4.01	3.2	43	2.9	36	-10.3	26	4.1	24	8.6	20			
	NPLI, Oct.1998		KRISS, Apr. 1999		CSIRO-NML, Aug.1999		NMIJ, Sep. 1999		PTB, Mar. 2001				

Laboratories which are maintaining secondary standards															
p' nom / MPa	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$	$D_i \cdot 10^{-6}$	$U_i \cdot 10^{-6}$			
0.41	-31.7	61	3.5	65	2.5	47	-24.7	39	35.3	62	-24.1	52			
0.81	-32.6	62	5.6	65	3.7	46	-22.3	39	53.1	62	-28.1	46			
1.21	-41.9	61	16.0	65	-4.2	46	-27.6	39	38.8	42	-20.4	64			
1.61	-40.5	61	18.0	65	0.2	46	-24.8	39	32.0	38	-12.9	52			
2.01	-43.8	61	18.1	65	-4.5	46	-24.7	39	35.8	37	-17.5	46			
2.41	-42.3	61	17.8	65	-2.2	46	-23.0	39	32.2	37	-13.2	45			
2.81	-42.0	61	18.6	65	-2.2	46	-22.3	39	31.2	36	-11.6	44			
3.21	-44.2	61	18.0	65	-5.4	46	-23.5	39	31.3	36	-9.9	48			
3.61	-42.7	61	20.1	65	-6.9	46	-21.7	39	30.5	36	-8.3	50			
4.01	-41.3	61	19.8	65	-6.3	46	-21.2	39	32.2	36	-6.3	48			
	MSL-IRL, May 1999		SPRING, Nov. 1998		NML-SIRIM, Jan.1999		SCL, June 1999		CSIR-NML, Oct.1999		NIS-Egypt, June 2000				

**Table –7**

Name of Lab.	$x_0^i$	$k^i$ in $10^5$	$D_i^0 \cdot 10^{-6}$	$U_i^{\max} \cdot 10^{-6}$
	/mm <sup>2</sup>	/(mm <sup>2</sup> /MPa)		
<b>NPLI</b>	8.386034	2.09	-0.5	43.4
<b>KRISS</b>	8.386023	2.33	-1.8	35.9
<b>CSIRO-NML</b>	8.386031	-0.60	-0.8	26.4
<b>NMIJ</b>	8.386030	3.07	-0.9	24.0
<b>PTB</b>	8.386072	2.85	4.1	19.9
<b>MSL-IRL</b>	8.385748	-0.23	-34.6	61.4
<b>SPRING</b>	8.386095	5.25	6.9	64.8
<b>NML-SIRIM</b>	8.386063	-0.15	3.0	47.4
<b>SCL</b>	8.385822	2.77	-25.7	38.7
<b>CSIR-NML</b>	8.386398	-0.97	42.9	53.1
<b>NIS-Egypt</b>	8.385809	6.51	-27.3	62.2

Table 8

		Lab j										Lab j									
V-407	$p' = 1,2 \text{ MPa}$	NPLI		KRISS		CSIRO-NML		NMI J		PTB		MSL-IRL		SPRING		NML-SIRIM		SCL		CSIR-NML	
		$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$
Lab i	KRISS	-5.7	54																		
	CSIRO-NML	-6.3	48	-0.5	42																
	NMIJ	0.7	45	6.4	38	7.0	30														
	PTB	3.8	43	9.5	36	10.1	26	3.1	21												
	MSL-IRL	-41.0	73	-35.3	69	-34.8	65	-41.7	63	-44.8	61										
	SPRING	16.9	76	22.7	72	23.2	68	16.2	66	13.1	65	58.0	88								
	NML-SIRIM	-3.3	61	2.4	57	2.9	51	-4.1	49	-7.2	46	37.7	75	-20.3	78						
	SCL	-26.7	55	-21.0	50	-20.5	44	-27.4	41	-30.5	39	14.3	71	-43.6	74	-23.4	58				
	CSIR-NML	39.7	58	45.4	53	46.0	47	39.0	44	35.9	42	80.7	73	22.8	76	43.0	61	66.4	55		
	NIS-Egypt	-19.6	75	-13.8	72	21.5	67	-20.3	66	-23.4	64	21.5	87	-36.5	90	-16.2	78	7.2	73	-59.3	90

Table 9

		Lab j										Lab j										
V-407	$p' = 4,0 \text{ MPa}$	NPLI		KRISS		CSIRO-NML		NMI J		PTB		MSL-IRL		SPRING		NML-SIRIM		SCL		CSIR-NML		
		$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	$\frac{D_{ij}}{10^{-6}}$	$\frac{U_{ij}}{10^{-6}}$	
		KRISS	-0.4	54																		
Lab i		CSIRO-NML	-13.6	48	-13.2	42																
		NMIJ	0.8	46	1.2	40	14.4	32														
		PTB	5.4	44	5.7	38	18.9	29	4.5	27												
		MSL-IRL	-44.5	73	-44.1	69	-30.9	65	-45.3	64	-49.8	62										
		SPRING	16.6	76	16.9	72	30.1	68	15.7	67	11.2	66	61.1	88								
		NML-SIRIM	-9.5	61	-9.2	57	4.0	51	-10.4	50	-14.9	48	34.9	75	-26.1	78						
		SCL	-24.4	55	-24.1	50	-10.9	44	-25.3	43	-29.8	40	20.0	71	-41.0	74	-14.9	58				
		CSIR-NML	29.0	54	29.3	48	42.5	42	28.1	41	23.6	38	73.5	69	12.4	73	38.5	57	53.4	51		
		NIS-Egypt	-9.5	63	-9.2	58	34.9	53	-10.4	52	-14.9	50	34.9	76	-26.1	79	0.0	65	14.9	60	-38.5	79

Table 10

Lab j



$p' = 1 \text{ MPa}$

Lab i



	IMGC-CNR		BNM-LNE		PTB		NMIJ		NIST	
	$D_H$ $10^{-6}$	$U_H$ $10^{-6}$	$D_H$ $10^{-6}$	$U_H$ $10^{-6}$	$D_H$ $10^{-6}$	$U_H$ $10^{-6}$	$D_H$ $10^{-6}$	$U_H$ $10^{-6}$	$D_H$ $10^{-6}$	$U_H$ $10^{-6}$
IMGC-CNR			-3	24	-6	25	2	27	-13	29
BNM-LNE	3	24			-3	13	5	17	-10	20
PTB	6	25	3	13			8	18	-7	21
NMIJ	-2	27	-5	17	-8	18			15	24
NIST	13	29	10	20	7	21	-15	24		
BEV	25	51	22	47	19	47	27	49	12	50
MIKES	-7	41	-10	35	-13	35	-6	37	-20	38
CEM	7	50	4	45	1	45	9	47	-6	48
SP/FFA	3	41	0	35	-3	35	5	37	-10	38

Table 11

Lab j



	IMGC-CNR		BNM-LNE		PTB		NMIJ		NIST	
	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$
<b>IMGC-CNR</b>			- 3	24	- 6	25	+ 2	27	- 13	29
<b>BNM-LNE</b>	+ 3	24			- 3	13	+ 5	17	- 10	20
<b>PTB</b>	+ 6	25	+ 3	13			+ 8	18	- 7	21
<b>NMIJ</b>	- 2	27	- 5	17	- 8	18			+ 15	24
<b>NIST</b>	+ 13	29	+ 10	20	+ 7	21	- 15	24		

Lab i ↓

<b>NPLI</b>	+ 1	50	- 2	46	- 5	46	+ 3	48	- 12	49
<b>KRISS</b>	- 4	44	- 7	39	- 10	40	- 2	41	- 17	42
<b>CSIRO-NML</b>	- 5	37	- 8	31	- 11	31	- 3	33	- 18	35
<b>MSL-IRL</b>	- 40	67	- 43	63	- 46	64	- 38	65	- 53	65
<b>SPRING</b>	+ 18	70	+ 15	67	+ 12	67	+ 20	68	+ 5	69
<b>NML-SIRIM</b>	- 2	53	- 5	49	- 8	49	+ 0	51	- 15	52
<b>SCL</b>	- 25	47	- 28	42	- 31	42	- 23	44	- 38	45
<b>CSIR-NML</b>	+ 41	49	+ 38	45	+ 35	45	+ 43	47	+ 28	48
<b>NIS-Egypt</b>	- 18	69	- 21	66	- 24	66	- 16	67	- 31	68

Table 12

Lab j



	BEV		MIKES		CEM		SP/FFA	
	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$	$D_{ij}$ $10^{-6}$	$U_{ij}$ $10^{-6}$
<b>BEV</b>			+ 32	47	+ 18	55	+ 22	47
<b>MIKES</b>	- 32	47			- 14	45	- 10	35
<b>CEM</b>	- 18	55	+ 14	45			+ 4	45
<b>SP/FFA</b>	- 22	47	+ 10	35	- 4	45		

Lab i ↓

<b>NPLI</b>	- 24	61	+ 8	53	- 6	60	- 2	53
<b>KRISS</b>	-29	57	+3	47	-11	55	-7	47
<b>CSIRO-NML</b>	- 30	51	+ 2	41	- 12	50	- 8	41
<b>MSL-IRL</b>	- 65	75	- 33	69	- 47	74	- 43	69
<b>SPRING</b>	- 7	78	+ 25	72	+ 11	77	+ 15	72
<b>NML-SIRIM</b>	- 27	64	+ 5	56	- 9	63	- 5	56
<b>SCL</b>	- 50	59	- 18	50	- 32	57	- 28	50
<b>CSIR-NML</b>	+ 16	61	+ 48	52	+ 34	59	+ 38	52
<b>NIS-Egypt</b>	- 43	78	- 11	71	- 25	77	- 21	71