ASIA-PACIFIC METROLOGY PROGRAMME

100 MPa HYDRAULIC PRESSURE INTERLABORATORY COMPARISON

Comparison Identifier: APMP.M.P-K7.3

# Final Report on Key Comparison APMP.M.P-K7.3 in Hydraulic Gauge Pressure from 10 MPa to 100 MPa

# Final Report

Padipat Wongthep[1], Hiroaki Kajikawa[2], Tawat Changpan[1], Likit Sainoo[1], Chaveng Khamnounsak[1], Tokihiko Kobata[2], Adindra Vickar Ega[3], R. Rudi Anggoro Samodro[3], Nguyen Nam Thang[4], Hoang Le Tuan[4], Radley F. Manalo[5], Maryness I Salazar[5]

[1] NIMT (Pilot institute): National Institute of Metrology (Thailand), 3/4 - 5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand

[2]NMIJ/AIST (Co-pilot and linkage institute): National Metrology Institute of Japan, AIST, AIST Tsukuba Central 3, 1-1, Umezono 1-Chome, Tsukuba, Ibaraki, 305-8563 Japan

[3]RCM-LIPI, Indonesia, Komplek Puspiptek, Serpong, Tangerang, 15314 Indonesia

[4]VMI: Vietnam Metrology Institute, 8 Hoang Quoc Viet Road – Cau Giay District - Ha Noi - Viet Nam

[5]NMLPHIL: National Metrology Laboratory- Industrial Technology Development Institute (Philippines), Metrology Bldg., Gen. Santos Ave., Bicutan, Taguig City, Metro Manila, Philippines

Revised version of 25 April 2022, containing corrected information in Table 10 and Table 18.

# Abstract

This report describes the results of a key comparison among hydraulic high pressure standards that have been maintained by seven National Metrology Institutes (NMIs: NIMT, NMIJ/AIST, NPLI, RCM-LIPI, NMIM, VMI and NMLPHIL). This comparison was carried out during the period March 2016 to October 2017 within the framework of Asia-Pacific Metrology Programme (APMP) in order to determine their degrees of equivalence in the pressure range from 10 MPa to 100 MPa, gauge mode. The pilot institute was the National Institute of Metrology (Thailand) (NIMT). All participating institute used hydraulic pressure balance as their pressure standards. In order to ensure the reliability, two high precision pressure transducers were used as the transfer standard. The sensing element of transducers was a precision quartz crystal resonator attached to a small Bourdon tube. During the comparison, the transfer standard was calibrated at the pilot institute two times, before and after circulating the transfer standard to participants. From the two NIMT calibration results, the transfer standard was sufficiently stable to meet the requirements of the comparison. The long-term instability obtained from the two calibration results was taken into account as the uncertainty of the transfer standard for all participant. As the matter of fact NPL India and NMIM participated in this comparison as one of the linkage institutes and participating institutes, respectively. However, it was found later that the systems of hydraulic pressure balance reference standards used in this comparison were not functioning. Therefore, the comparison results were withdrawn. The degrees of equivalence of each national measurement standard were expressed quantitatively by deviations from the key comparison reference value of the corresponding CCM key comparison, CCM.P-K7 through the linkage institute, NMIJ/AIST. In conclusion, the hydraulic pressure standards in the range 10 MPa to 100 MPa, gauge mode of the five participating NMIs were found to be equivalent within their claimed uncertainties.

**Contents:**

## 1. Introduction

An accurate measurement is required by scientific and legal metrology due to a basic function for fair trade society and improvement of a quality of life of the people in all countries. National Metrology Institute of each country has a roll to maintain the equivalent of the measurement capabilities. Pressure is one of those parameters which need to have an agreement between the measurement results of among NMI. Therefore, APMP, under the support from PTB, intend to organize the training workshop and inter-laboratory comparison in hydraulic pressure (10 to 100) MPa under MEDEA Project during 2016-2017 to support NMIs of APMP-DEC economies.

After the technical training was done during the kick off workshop in January 2016, an invitation was distributed to the member of APMP TCM by the pilot institute, NIMT and the linkage institute, NMIJ/AIST. The following NMIs: RCM-LIPI (Indonesia), NMIM (Malaysia), VMI (Viet-Nam) and NPLPHIL (Philippines) were invited to participate in the said comparison.

The National Institute of Metrology (Thailand) (NIMT) has been approved by the Technical Committee for Mass and Related Quantities (TCM) in the Asia-Pacific Metrology Programme (APMP) to coordinate an inter-laboratory comparison program for hydraulic high pressures as a pilot institute. The comparison has been defined as **APMP.M.P-K7.3** by the Consultative Committee for Mass and Related Quantities (CCM) of the International Committee for Weights and Measures (CIPM), the International Bureau of Weights and Measures (BIPM) and APMP.

The objective of this comparison was to compare the performance of hydraulic pressure standards of the NMIs, in the pressure range of 10 MPa to 100 MPa for a gauge mode by using Di(2)-ethyl-Hexyl-Sebacate (DHS) as a transmitting fluid according to the protocol [1,2,3,4,5]. To gain an international acceptance for the pressure standards, APMP.M.P-K7.3 will be linked to the CCM key comparison, CCM.P.K-7 [6] which has the same pressure range as APMP.M.P-K7.3 through linkage institute, NMIJ/AIST. All participating institute had the opportunity to get results in the comparison to improve their hydraulic pressure standard and uncertainty. The results of this comparison will be included in the Key Comparison Database (KCDB) of BIPM. The results will be used as an evidence to support for high pressure calibration and measurement capabilities (CMCs) of NMIs for the Mutual Recognition Arrangement (MRA) [7].

According to the performance of the transfer standards shown in APMP.M.P-K7 [3], the same unit of the transfer standard was provided from NMIJ/AIST. The protocol was prepared by the pilot institute that almost the same procedure as APMP.M.P-K7. The first edition was distributed to the participating institutes on March 2016. After that, the second edition of the protocol was approved by the participants, the transfer standards were circulated for measurement during April 2016 and October 2017. All NMIs generally used hydraulic pressure balances as their pressure standards to calibrate the transfer standard. The calibration results obtained from each participating institute have been submitted to the pilot institute. The preparation of a report on the comparison and the analysis of data on the basis of the results from the participants has been done by the pilot institute and NMIJ/AIST. A uniform treatment was made for all participants according to the protocol. This report gives the calibration results of the transfer standard from five NMIs. The following sections provide descriptions of the participating institutes and their pressure standards, the details of the transfer standard, the circulation of the transfer standard, the general calibration procedure for the transfer standard, the method for analysis of the calibration data and the comparison results.

## 2. Participating institutes and description of pressure standards

### 2.1 List of participating institutes

There were totally 5 National Metrology Institutes (NMIs) participated in this comparison including the pilot and linkage institute. The participating institutes along with their addresses and contact person are listed in Table 1.

**Table 1:** List of participating institutes.

| No. | Participating Institutes |
|---|---|
| **1** | **Institute :** National Institute of Metrology (Thailand)<br>**Acronym :** NIMT (Pilot institute)<br>**Address :** 3/4 - 5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand<br>**Contact Person :** Dr. Padipat Wongthep, Mr. Likit Sainoo, Mr. Chaveng Khamnounsak and Mr. Tawat Changpan<br>**Phone :** +66-2577-5100 ext. 2106<br>**Fax :** +66-2577-3658<br>**E-mail :** tchangpan@yahoo.com, likit@nimt.or.th and patipat@nimt.or.th |
| **2** | **Institute :** Research Center for Metrology - LIPI<br>**Acronym :** RCM-LIPI<br>**Address :** Kompleks Puspiptek Gedung 420, Setu, Tangerang Selatan, Banten 15314<br>**Contact Person :** Mr. Adindra Vickar Ega and R. Rudi Anggoro Samodro<br>**Phone :** +62-21-7560533 ext. 3098<br>**Fax :** +62-21-7560568<br>**E-mail :** adindravickar@gmail.com and anggoro_rudi@yahoo.com |
| **3** | **Institute :** Vietnam Metrology Institute<br>**Acronym :** VMI<br>**Address :** No 8, Hoang Quoc Viet Str., Cau Giay Dst., Hanoi, Vietnam<br>**Contact Person :** Mr. Nguyen Nam Thang and Hoang Le Tuan<br>**Phone :** +84 438 361 136<br>**Fax :** +84 437 564 260<br>**E-mail :** thangnn@vmi.gov.vn and tuanhl@vmi.gov.vn |
| **4** | **Institute :** National Metrology Laboratory- Industrial Technology Development Institute (Philippines)<br>**Acronym :** NMLPHIL<br>**Address :** Metrology Bldg., Gen. Santos Ave., Bicutan, Taguig City, Metro Manila, Philippines<br>**Contact Person :** Mr. Radley F. Manalo and Ms. Maryness I Salazar<br>**Phone :** +63-2-837-2071 ext. 2264<br>**Fax :** +63-2-837-6150<br>**E-mail :** rfmanalo@itdi.dost.gov.ph, radleymanalo@yahoo.com and nhet28@yahoo.com |
| **5** | **Institute :** National Metrology Institute of Japan, AIST<br>**Acronym :** NMIJ/AIST<br>**Address :** AIST Tsukuba Central 3, 1-1, Umezono 1-Chome, Tsukuba, Ibaraki, 305-8563 Japan<br>**Contact Person :** Dr. Hiroaki Kajikawa and Dr. Tokihiko Kobata<br>**Phone :** +81-298-61-4064<br>**Fax :** +81-298-61-4181<br>**E-mail :** kajikawa.hiroaki@aist.go.jp and tokihiko.kobata@aist.go.jp |

## 2.2 Description of pressure standards

The pressure standards of all participating institutes were mostly pressure balances of different manufacture and model. All participating institutes provided the information of their pressure standards such as pressure balance base, the type and material of piston-cylinder unit (PCU), traceability, etc. as listed in Table 2.

All piston and cylinder materials and types of the pressure balances used by the participating institutes were tungsten carbide and simple type, respectively. All the institutes assumed linear pressure dependence for the effective area of piston-cylinder unit. The participants with primary pressure standards directly traced to base SI units were the following two NMIs: NIMT and NMIJ/AIST.

**Table 2:** Description of pressure standards of the participating institutes. All the uncertainties are expressed as the standard ones.

| *j* | Institute | Country | Pressure balance base | | Piston-cylinder unit | | Effective area, $A_0$ | | | Ref. temp., *t* | Distortion coefficient, $\lambda$ | | Traceability | Rotation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Manufacturer | Model | Type | Material | Value [m$^2$] | Unc. [m$^2$] | Unc. [ppm] | [ºC] | Value [MPa$^{-1}$] | Unc. [MPa$^{-1}$] | | Method | Speed [rpm] |
| 1 | NIMT | Thailand | Ruska | 2485-930D | Simple | WC/WC | 7.11100E-6 | 9.4E-11 | 13.4 | 20 | 7.48E-7 | 4.2E-8 | Independent | Hand | 20-25 |
| 2 | RCM-LIPI | Indonesia | DH Instruments | 7302-M | Simple | WC/WC | 4.902920E-6 | 1.1E-11 | 28.5 | 23 | 9.1E-7 | 3.0E-8 | KRISS | Motor | 30 |
| 3 | VMI | Vietnam | Ruska | 2485-930D | Simple | WC/WC | 9.809514E-6 | 2.0E-10 | 20.5 | 23 | 9.4E-7 | 9.4E-8 | KRISS | Hand | 30 |
| 4 | NMLPHIL | Philippines | DH-Budenberg | 5306 | Simple | WC/WC | 9.80495E-6 | 1.6E-10 | 16.3 | 20 | 8.86E-7 | 0.46E-7 | NIMT | Hand | 21-25 |
| 5 | NMIJ/AIST | Japan | DH Instruments | 5616-02 | Simple | WC/WC | 9.805620E-6 | 1.23E-10 | 12.5 | 23 | 8.38E-7 | 1.01E-7 | Independent | Hand | 20 |

## 3. The transfer standards

Two types of hydraulic pressure transducers [8,9] were borrowed from NMIJ/AIST to use as the transfer standards of this comparison. Major characteristics of the transfer standard were evaluated in APMP.M.P-K7 [3] and APMP.M.P-K7.1 [5], and the performance of the transfer standard during these comparisons was satisfactory. The long-term instability and performance were also checked at NMIJ/AIST before sending to the pilot institute. After re-checking of the performance of the transfer standard, the pilot institute changed parameters of the pressure transducers in secrecy. In addition, to observe the long-term instability during their travelling, the transfer standard unit was calibrated twice at the pilot institute before and after the circulation. The detail of the transfer standard is listed in Table 3 and shown in Figure 1. The Schematic drawing of transfer standard is shown in Figure 2.

**Table 3**: Two types of hydraulic pressure transducers used as transfer standard.

| Type | a | b |
|---|---|---|
| Manufacturer | DH Instruments, Inc. | Paroscientific, Inc. |
| Model | RPM3  A15000 | 785A15000 |
| Serial number | 1476 | 1668 (88609) |
| Specification | See RPM3's specification*1 | See 785's specification*2 |
| Range | Up to 100 MPa | |
| Power supply | 85 to 264 VAC and 47 to 440 Hz | |

*1 http://www.dhinstruments.com//prod1/pdfs/brorpm3a.pdf
*2 http://www.paroscientific.com/pdf/model785.pdf

**Figure 1:** Photographs of the transfer standard for the APMP.M.P-K7.3.

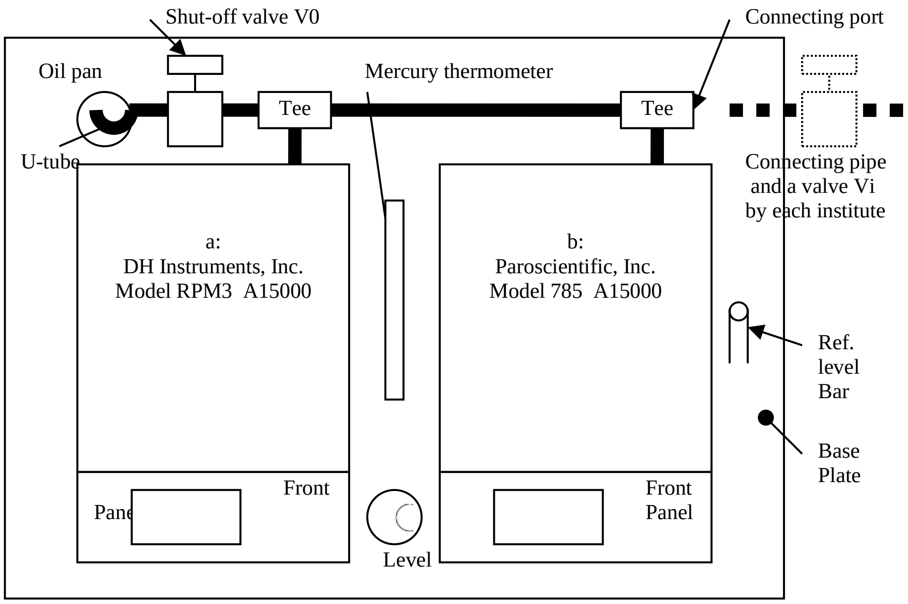


**Figure 2:** Schematic drawing of the transfer standard.

## 4. Circulation of the transfer standard

According to the protocol, the transfer standard unit was circulated during the period March 2016 through October 2017 with calibrations at the pilot institute (NIMT) at the start and the end of the comparison. While the circulation, ATA CARNET was prepared by NMIJ/AIST twice. When the package arrives and depart at the participating institutes, the transfer standard unit was checked and noted in the form prepared by pilot institute. Some difficulties occurred while circulating the transfer standard unit among the participants were different selection of logistic agencies by participants. Therefore, the comparison was delayed from the schedule described in the protocol.

The transfer standard was measured first by NIMT. Then it was carried to the participants for measuring by logistic agencies. After that, the transfer standard was calibrated again after returning to NIMT at the end of comparison in order to confirm that there is no significant drift occurred during its travelling. The actual chronology of measurements in this comparison is shown in Table 4.

The total time spent to complete the measurements of this comparison was nineteen months.

**Table 4:** Chronology of measurements in this comparison.

| Institute | Country | Date of calibration |
|---|---|---|
| NIMT | Thailand | 2016/03/29-31 |
| RCM-LIPI | Indonesia | 2016/08/03-04,08 |
| NMIM | Malaysia | 2016/09/27-29 |
| VMI | Viet-Nam | 2016/10/30-31, 2016/11/01 |
| NMLPHIL | Philippines | 2017/01/03-05 |
| NMIJ/AIST | Japan | 2017/03/22, 24, 28 |
| NPLI | India | 2017/07/07, 12-13 |
| NIMT | Thailand | 2017/10/18-20 |

NPL India and NMIM participated in the measurement, but after completing their measurements and sending back the TS to the pilot, they found some anomalies in their installation and deviations in measurement procedure from the protocol. Then, NPL India and NMIM finally decided to withdraw from the comparison.

## 5. Calibration

The general procedure which required each participating institute to calibrate the transfer standard unit for this comparison was described in the protocol.

### 5.1 Preparation

All participants were required to prepare clean Di(2)-ethyl-Hexyl-Sebacate (DHS) as a working fluid. The pressure standard of each participating institute was operated at the normal operating temperature of the institute. The environmental conditions, such as atmospheric pressure, ambient temperature, and ambient relative humidity during the calibration were measured using the participant's own devices. For the preparation of the calibration, the followings were recommended: (i) At least, twenty-four hours before starting the measurement procedure, pressure transducers should be connected to a power supply and should be turned on for warming up and stabilization. (ii) The power supply for the transfer standard should be maintained during all the calibrations at the participating institute. (iii) Setting parameters of the transfer standard should be set as the following:

- Range: 100 MPa
- Unit: kPa
- Mode: gauge
- Average measurement mode: twenty readings each twenty seconds
- Resolution: kPa
- Autozero function: ON

(iv) After the installation, the transfer standard system should be pressurized using the system of each participant up to 100 MPa and the function of each pressure transducer and the leak in the test system should be checked. (v) During twelve hours before the start of each calibration cycle, no gauge pressure should be applied to the transfer standard.

### 5.2 Head correction by height difference

The pressure generated by a pressure standard at the reference level of transfer standard, $P$, is represented by the following equation:

$$P = P_{std} + (\rho_f - \rho_a)\cdot g_l\cdot H \qquad (1)$$

Where $P_{std}$ is the pressure generated by the participant's pressure standard at its reference level; $(\rho_f - \rho_a)\cdot g_l\cdot H$, is the head correction, which $\rho_f$ is the density of the working fluid, $\rho_a$ is the air density, $g_l$ is the local acceleration due to gravity, and $H$ is the vertical distance between the reference levels of institute's standard and transfer standard. $H$ is positive if the level of the institute's standard is higher. Each participant should make appropriate corrections for the height difference between the reference levels of the applied pressure and the transfer standard, and include their contributions into the uncertainty of the applied pressure.

### 5.3 Calibration procedure

At nominal target pressures of 0 MPa, 10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, 70 MPa, 80 MPa, 90 MPa, and 100 MPa, the applied pressures and the readings of the transfer standard were measured. The values, together with the respective measurement uncertainties, were the main basis of the comparison.

### 5.3.1 Complete measurement cycle

One complete measurement cycle consists of pressure and temperature recordings obtained from the transfer standard and the pressure standard at twenty-three pressure data points of eleven set pressure points from 0 MPa to 100 MPa in step of 10 MPa in ascending order, one point 0 MPa, and eleven points from 100 MPa to 0 MPa in step of 10 MPa in descending order as shown in Figure 3. The ascending pressure measurement cycle must start from 0 MPa while the descending pressure measurement must start from 100 MPa. The results of the measurement were recorded on the measurement results sheet prepared by the pilot institute. One complete measurement cycle was performed in a day. A total of three calibration cycles were required, with each cycle being on a separate day.

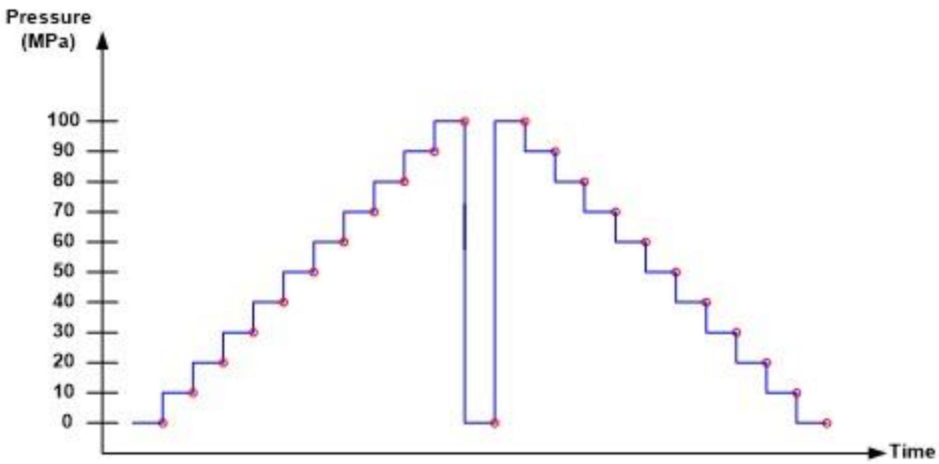


**Figure 3:** Pressure measurement cycle.

### 5.3.2 Calibration at 0 MPa

At the beginning, middle and end of each cycle, zero-pressure readings for the transfer standard were measured. These data were used to correct calibration data for zero-pressure offsets. To apply zero gauge pressure to the transfer standard unit, the valve V0 was opened and the valve Vi was closed (See Figure 2). After the waiting of ten minutes, within five minutes, the readings which were the resulting average for twenty measurements and its corresponding standard deviation, $\sigma$ of the transfer standard unit, were measured. The temperature on the base-plate, $t_b$, and the environmental condition were also measured. Those data were recorded on the forms prepared by the pilot institute as shown in Table 5.

**Table 5:** Example of data recording at 0 MPa.

| Nom. Pres. [MPa] | Local Time | Atmo Temp. [°C] | Atmo R.H. [%] | Atmo Pres. [kPa] | Temp. Base [°C] | Reading $R\_a$ [kPa] | | Reading $R\_b$ [kPa] | | Applied Pressure $P^{*1}$ [kPa] | $u(P)^{*2}$ [kPa] ($k$=1) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Average | σ | Average | σ | | |
| 0 | 9:30 | 23.0 | 45.0 | 101.2 | 23.1 | 3.5 | 0.2 | -5.5 | 0.1 | Not required | |

### 5.3.3 Calibration at 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 MPa

The pressure generated by the participant's standard was applied to the transfer standard by closing valve V0 and opening valve Vi. The position of the piston of the pressure balance was kept in the floating range to maintain the applied pressure. After the waiting time of ten minutes for stabilization of the pressure, within five minutes, the readings which were the resulting average for the twenty measurements and its corresponding standard deviation, $\sigma$ of transfer standard unit, were measured. Then, the applied pressure with the associated standard uncertainty at the reference level of the transfer standard unit was calculated. Any influence quantity for the institute system was taken into account in the uncertainty estimation appropriately by each participant. The correction by the differential height of the reference levels between the participating institute's standard and the transfer standard was considered. These data were recorded in the forms prepared by the pilot institute as presented in Table 6. In the table, $P$ is the pressure applied by the participant's standard at the local gravity $g_l$ and the local air density $\rho_a$ and calculated at the reference level of the transfer standard using equation (1) and $u(P)$ is the standard uncertainty of $P$.

**Table 6:** Example of data recording at target pressure except 0 MPa.

| Nom. Pres. [MPa] | Local Time | Atmo Temp. [°C] | Atmo R.H. [%] | Atmo Pres. [kPa] | Temp. Base [°C] | Reading $R\_a$ [kPa] | | Reading $R\_b$ [kPa] | | Applied Pressure $P^{*1}$ [kPa] | $u(P)^{*2}$ [kPa] ($k$=1) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Average | σ | Average | σ | | |
| 100 | 13:54 | 23.0 | 45.0 | 101.2 | 23.1 | 100041.1 | 0.3 | 99998.5 | 0.2 | 99999.8 | 5.6 |

### 5.3.4 Results to be reported

After the measurements were completed at the participating institute, the calibration results were transmitted to the pilot institute. The pilot institute, NIMT, collected the following data and information using the forms prepared at the pilot institute.

(i) Measured and calculated values at the nominal pressures specified, each with an uncertainty in the measurement and the dates on which calibration cycle was undertaken (three cycles).

(ii) Details of the participating institute's standards which used to calibrate the transfer standard unit, including the origin of its traceability to the SI (presented in Table 2).

(iii) Details of the parameters used for the comparison, which are local gravity, differential height of the reference levels between the participating institute's standard and the transfer standard, density of working fluid, the voltage and frequency applied to pressure monitors (presented in Table 7).

(iv) Uncertainty budget of the pressure generated, which shall be estimated and combined follow the GUM guide line under the responsibility of the participating institutes. The uncertainties were evaluated at a level of one standard uncertainty at the individual participating institute.

Also, the uncertainty estimation of the transfer standard was reported by several institutes optionally.

## 5.4 Parameters used by each participating institute

Details of the parameters used by each participating institute are listed in Table 7. The name of participating institute, the name of country, the local gravity, the height difference, the fluid density associated with standard uncertainties, the voltage and frequency applied to transfer standard unit are also presented.

**Table 7:** Details of the parameters used by each participating institute. All the uncertainties are expressed as the standard ones.

| $j$ | Institute | Country | Local gravity, $g_l$ | | | Hight diff.,$h$ | | $\rho_f$, (DHS) | | Voltage | Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Value [m/s$^2$] | Unc. [m/s$^2$] | Unc. [ppm] | Value [mm] | Unc. [mm] | Value [kg/m$^3$] | Unc.[(kg/m$^3$] | [VAC] | [Hz] |
| 1 | NIMT | Thailand | 9.7831243 | 5.6E-6 | 0.57 | 0 | 2.89 | Eq. (1) | 2.89% | 100 | 50 |
| 2 | RCM-LIPI | Indonesia | 9.78137 | 2.0E-5 | 2 | 0 | 1.4 | Eq. (2) | 26 | 110 | 50-60 |
| 3 | VMI | Viet-Nam | 9.786675 | 5.0E-6 | 0.51 | 0 | 1.0 | 912 | 10 | 110 | 50 |
| 4 | NMLPHIL | Philippines | 9.783551 | 2.0E-4 | 20 | 5 | 0.25 | 914 | 10 | 220 | 60 |
| 5 | NMIJ/AIST | Japan | 9.7994804 | 2.0E-6 | 0.2 | 0.5 | 0.5 | Eq. (2) | 0.5% | 100 | 50 |

Eq.(1): $\rho_f = 914\times[1-0.00078\times(t-20)]\times(1+0.00008\times P)$

where: $P$ in bar and $t$ is average room and PCU's temperature in $^0$C

Eq.(2): $\rho_f = 912.7+(0.752\times P)-(0.001645\times P^2)+[(0.000001456\times P^3)\times(1-0.00078\times(t_r-20))]$

where: $P$ in MPa and $t_r$ is room temperature in $^0$C

## 6. Analysis of the reported data

Data obtained from one complete measurement cycle consists of the recordings of the pressure and temperature obtained from the transfer standard unit, the pressure applied by a pressure standard and environmental parameters at twenty-three pressure data points of eleven set pressure points from 0 MPa to 100 MPa in step of 10 MPa in ascending order, one point 0 MPa, and eleven set points from 100 MPa to 0 MPa in step of 10 MPa in descending order. Therefore, the following data sets were obtained from the reported results,

$$\{R\ (j,m,y,w,i),\ P\ (j,y,w,i)\}$$

where the meanings of the parameters are as the following:

$R$ = Raw reading of transfer standard, [kPa]
$P$ = Applied pressure at the reference level of transfer standard by pressure standard $j$, [kPa]
$j$ = Index for participating institute,
$m$ = Index for transfer standard $a$ or $b$, $m$ = 1 or 2
$y$ = Index for measurement cycle,
$w$ = Index for indicating ascending or descending measurements, $w$ = 1 or 2
$i$ = Index for indicating pressure $i$×10 MPa, $i$ = 0 – 10.

In this section, the reduction and analysis of the data are described in the following sequence:

6.1 Correct by the zero-pressure offsets,
6.2 Correct by the difference between nominal pressure and actual pressure,
6.3 Correct to the reference temperature,
6.4 Calculate the expected mean pressure of participating institute,
6.5 Estimate the measurement uncertainty of participating institute,
6.6 Calculate the degree of equivalence

### 6.1 Correction for zero-pressure offsets

There were three 0 MPa pressure points in one measurement cycle. From calibration results performed at the pilot institute, and also in the APMP.M.P-K7.1, it was confirmed that the reproducibility of the readings of the transfer standard unit at an intermediate 0 MPa point was not better than those at first or last 0 MPa points. The reading at an intermediate 0 MPa point was susceptible to the history from the past pressure points. Therefore, in this analysis, the reading at an intermediate 0 MPa point was not used. The readings for ascending and descending pressure points of each cycle are offset by the readings at the first and the last 0 MPa points of each cycle, respectively. By subtracting the offset from the raw reading $R$, the corrected reading $R_{c0}$ can be obtained by:

$$R_{c0}\ (j,m,y,w,i) = R\ (j,m,y,w,i) - R\ (j,m,y,w,0). \qquad (2)$$

### 6.2 Correction for difference between nominal pressure and actual pressure

$R_{c0}$ is the reading of transfer standard unit corrected by the zero-pressure offset as mentioned above. Since the readings from the transfer standard unit are nominally linear and the ratio of the readings to the actual pressure are generally independent of pressure for the pressure range that the deviation of the actual pressure from the nominal target pressure is small.

As described in the protocol, the difference between the actual applied pressure and the nominal target pressure was adjusted to be within a thousandth of the nominal pressure. The ratios can be used to correct the readings for deviation of the pressure standard from the nominal pressure. When an exact nominal pressure $P_n$ is applied to the transfer standard, the predicted reading, $R_{c1}$, can be calculated by equation (3)

$$R_{c1}(j,m,y,w,i) = \frac{R_{c0}(j,m,y,w,i)}{P(j,y,w,i)} \cdot P_n(i), \tag{3}$$

where $R_{c0}$ and $P$ are the simultaneous readings of the transfer standard unit and the actual applied pressure, respectively. Then the ratio of each measurement point of each participant can be used to correct the reading for deviation of the pressure standard from the nominal pressure without significant effect.

### 6.3 Correction to reference temperature

$R_{c1}$ is the reading of the transfer standard unit when the base temperature is, $t_b$. Since the reading is affected by the temperature, the reading should be corrected. Therefore, in this comparison, the reading of the transfer standard was corrected by using the recent data from APMP.M.P-K7.1. The temperature coefficient of each pressure transducer at each target nominal pressure is shown in the Table 8 and Figure 4.

**Table 8:** Temperature coefficients of each pressure sensor for the transfer standard from APMP.M.P-K7.1.

| | | Temperature coefficient, $\beta$ [kPa/ºC] | |
|---|---|---|---|
| *m* | | 1 | 2 |
| Transfer standard | | *a* | *b* |
| *i* | [MPa] | average | average |
| 1 | 10 | 0.185 | 0.080 |
| 2 | 20 | 0.146 | 0.094 |
| 3 | 30 | 0.215 | 0.135 |
| 4 | 40 | 0.277 | 0.186 |
| 5 | 50 | 0.304 | 0.184 |
| 6 | 60 | 0.329 | 0.206 |
| 7 | 70 | 0.384 | 0.226 |
| 8 | 80 | 0.476 | 0.256 |
| 9 | 90 | 0.405 | 0.208 |
| 10 | 100 | 0.354 | 0.211 |

The standard uncertainty of the coefficient was estimated by $u\{\beta(m,i)\}$ = 0.03 kPa/ºC according to APMP.M.P-K7.1.

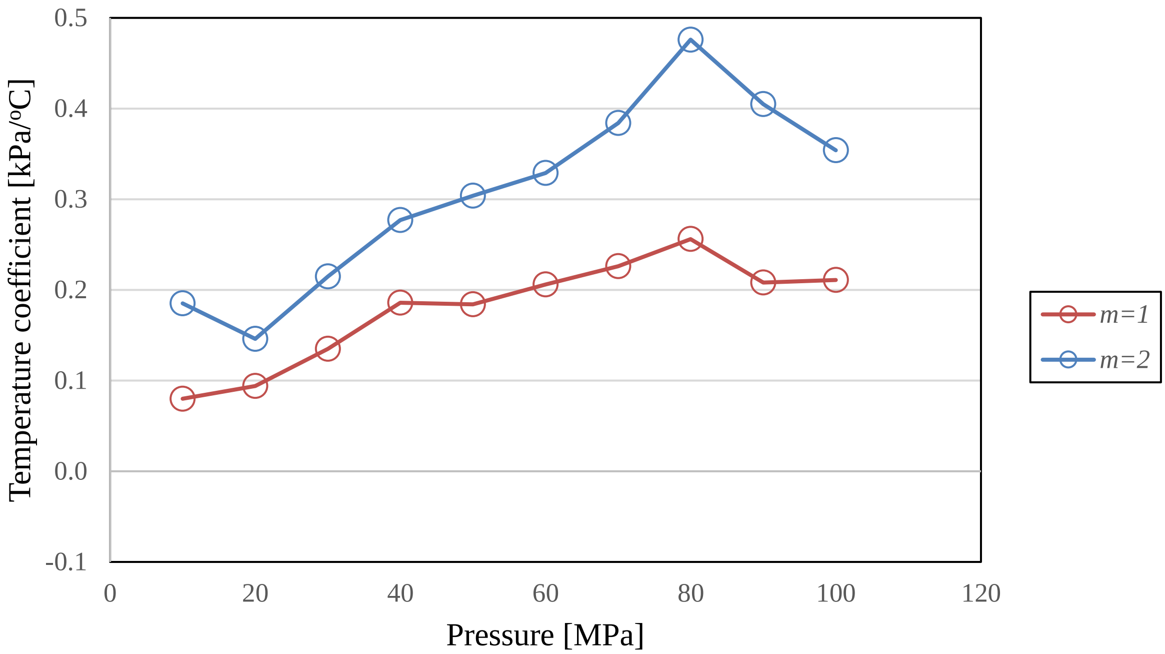


**Figure 4:** Calculated temperature coefficients of each the transfer standard as a function of nominal target pressure according to APMP.M.P-K7.1.

From the temperature coefficient in table 8, the reading corrected to a reference temperature, $R_{c2}$, can be calculated from,

$$R_{c2}(j,m,y,w,i) = R_{c1}(j,m,y,w,i) - \beta(m,i)\cdot\left[t_b(j,m,y,w,i) - t_r\right] \quad (4)$$

where $t_r$ is the reference temperature which is determined from the average of all participants. The average temperature measured on each transfer standard by a mercury thermometer by the participating institutes for nominal target pressure are shown in Table 9.

**Table 9:** Average temperatures measured on the transfer standard by the participating institutes for nominal target pressures.

| | | Average temperature [°C] | | | | | |
|---|---|---|---|---|---|---|---|
| *j* | | 1 | 2 | 3 | 4 | 5 | 6 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 0 | 0 | 21.00 | 19.12 | 22.48 | 20.37 | 23.17 | 21.33 |
| 1 | 10 | 21.00 | 19.14 | 22.48 | 20.28 | 23.17 | 21.33 |
| 2 | 20 | 21.00 | 19.19 | 22.48 | 20.30 | 23.18 | 21.33 |
| 3 | 30 | 21.00 | 19.25 | 22.48 | 20.35 | 23.18 | 21.33 |
| 4 | 40 | 21.00 | 19.26 | 22.48 | 20.45 | 23.18 | 21.38 |
| 5 | 50 | 21.00 | 19.29 | 22.48 | 20.38 | 23.15 | 21.38 |
| 6 | 60 | 21.00 | 19.31 | 22.48 | 20.37 | 23.15 | 21.38 |
| 7 | 70 | 21.00 | 19.32 | 22.48 | 20.45 | 23.17 | 21.33 |
| 8 | 80 | 21.00 | 19.33 | 22.48 | 20.38 | 23.15 | 21.38 |
| 9 | 90 | 21.00 | 19.35 | 22.48 | 20.30 | 23.17 | 21.38 |
| 10 | 100 | 21.00 | 19.35 | 22.48 | 20.33 | 23.17 | 21.42 |
| Average | | 21.27 | | | | | |

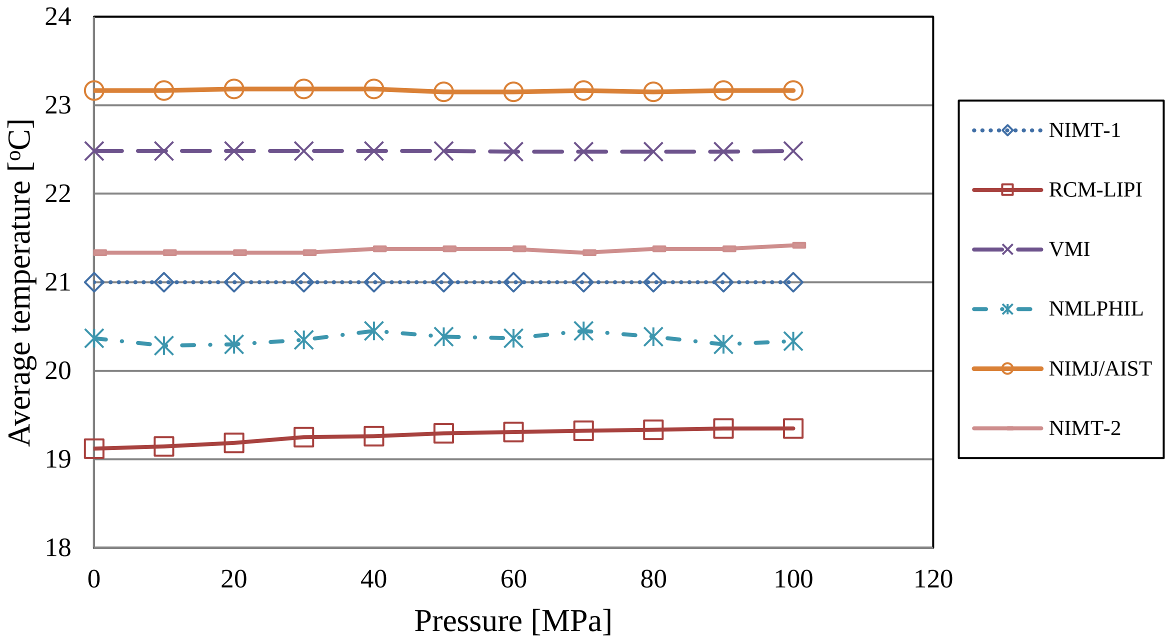


**Figure 5:** Average temperatures measured on the transfer standard by the participating institutes as a function of nominal target pressure.

The index number shown in Table 9 and Figure 5 is used for identifying the results of the pilot institute in the second calibration at the end of the comparison. The average of all the values in Table 9 is 21.27ºC. Therefore, the reference temperature of this comparison was defined as $t_r$= 21.27ºC.

Since calibrations of each participant were performed at different temperatures, the uncertainty due to the deviation from the reference temperature has been estimated as described later on subsection 6.5.3.

### 6.4 Calculation of expected mean pressure of participating institutes

By taking the average of $R_{c2}$ for ascending and descending pressures of 3 cycles, the pressure reading for the transfer standard unit, $R_{c3}$, can be calculated by:

$$R_{c3}(j,m,i)=\frac{1}{6}\sum_{w=1}^{2}\sum_{y=1}^{3}R_{c2}(j,m,y,w,i) \qquad (5)$$

There are two pressure transducers in the transfer standard unit. By taking the average of $R_{c3}$, values the expected mean pressure reading of the transfer standard unit for each participant institute, $p(j,i)$, can be calculated by:

$$p(j,i)=\frac{1}{2}\sum_{m=1}^{2}R_{c3}(j,m,i) \qquad (6)$$

The results for $p(j,i)$ from individual institutes are presented in Table 10.

**Table 10:** Expected mean pressures of the institutes for nominal target pressures.

| | | Expected mean pressure, *p*(*j*,*i*) [MPa] | | | | | |
|---|---|---|---|---|---|---|---|
| *j* | | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 9.99947 | 9.99953 | 9.99923 | 9.99907 | 9.99932 | 9.99935 |
| 2 | 20 | 19.99941 | 19.99923 | 19.99906 | 19.99880 | 19.99926 | 19.99918 |
| 3 | 30 | 29.99847 | 29.99766 | 29.99806 | 29.99722 | 29.99829 | 29.99813 |
| 4 | 40 | 39.99807 | 39.99715 | 39.99772 | 39.99651 | 39.99771 | 39.99764 |
| 5 | 50 | 49.99817 | 49.99663 | 49.99781 | 49.99635 | 49.99787 | 49.99757 |
| 6 | 60 | 59.99839 | 59.99675 | 59.99819 | 59.99628 | 59.99810 | 59.99783 |
| 7 | 70 | 69.99856 | 69.99625 | 69.99859 | 69.99610 | 69.99837 | 69.99791 |
| 8 | 80 | 80.00073 | 79.99813 | 80.00089 | 79.99833 | 80.00054 | 79.99996 |
| 9 | 90 | 90.00170 | 89.99768 | 90.00218 | 89.99949 | 90.00143 | 90.00076 |
| 10 | 100 | 100.00027 | 99.99737 | 100.00129 | 99.99767 | 100.00001 | 99.99938 |

### 6.5 Estimation of uncertainties

In this subsection, all the uncertainties are expressed as the standard ones. The relative combined standard uncertainty in the mean pressure of *j*-th participating institute, *p*(*j*,*i*), was estimated from the root-sum-square of four component uncertainties as equation (7),

$$u_c\{p(j,i)\} = \sqrt{u_{std}^2\{p(j,i)\} + u_{rdm}^2\{p(j,i)\} + u_{temp}^2\{p(j,i)\} + u_{lts}^2\{p(j,i)\}} \quad (7)$$

where $u_{std}\{p\}$ is the uncertainty due to systematic effects in pressure standard for each participant, $u_{rdm}\{p\}$ is the uncertainty due to combined effect of short-term random errors of transfer standard, $u_{temp}\{p\}$ is the uncertainty in correcting the readings to equivalent values at the reference temperature and $u_{lts}\{p\}$ is the uncertainty arising from long-term shift in the characteristics of the transfer standard calibrated at the pilot institute.

#### 6.5.1 Uncertainty due to systematic effect in pressure standard

The relative standard uncertainty due to systematic effect in pressure standard, $u_{std}\{p(j,i)\}$, can be estimated from equation (8),

$$u_{std}\{p(j,i)\} = \frac{u\{P_{std}(j,i)\}}{P_n(i)} \quad (8)$$

where $P_n(i)$ is the nominal target pressure.

Table 11 and Figure 6 present the estimated relative standard uncertainties arose from systematic effects in the pressure standards used in the comparison, as reported by the participating institutes for nominal target pressures. The uncertainty due to the hydrostatic head correction was considered as inclusion in the uncertainty of the pressure standard. The main contributions in this uncertainty came from the effective area and the pressure distortion coefficient of the pressure standard of the participating institutes except NMLPHIL came from acceleration due to gravity.

**Table 11:** Relative standard uncertainties, as claimed by the participants, due to systematic effects in their pressure standards. All the uncertainties are expressed as the standard ones.

| | | Relative standard uncertainty of applied pressure, $u_{std}\{p(j,i)\}$ [$\times10^{-6}$] | | | | | |
|---|---|---|---|---|---|---|---|
| | *j* | 1 | 2 | 3 | 4 | 5 | 6 |
| *i* | (MPa) | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 16.8 | 29.7 | 27.0 | 30.0 | 13.0 | 16.8 |
| 2 | 20 | 16.6 | 29.7 | 26.5 | 29.5 | 13.0 | 16.6 |
| 3 | 30 | 16.6 | 29.9 | 26.7 | 29.7 | 13.3 | 16.6 |
| 4 | 40 | 16.5 | 30.1 | 26.8 | 29.5 | 13.5 | 16.6 |
| 5 | 50 | 16.5 | 30.4 | 26.8 | 29.6 | 13.8 | 16.5 |
| 6 | 60 | 16.5 | 30.6 | 26.7 | 29.5 | 14.2 | 16.5 |
| 7 | 70 | 16.5 | 30.9 | 26.7 | 29.6 | 14.6 | 16.5 |
| 8 | 80 | 16.6 | 31.1 | 26.8 | 29.5 | 15.1 | 16.6 |
| 9 | 90 | 16.6 | 31.4 | 26.7 | 29.6 | 15.7 | 16.6 |
| 10 | 100 | 16.6 | 31.6 | 26.7 | 29.5 | 16.3 | 16.6 |

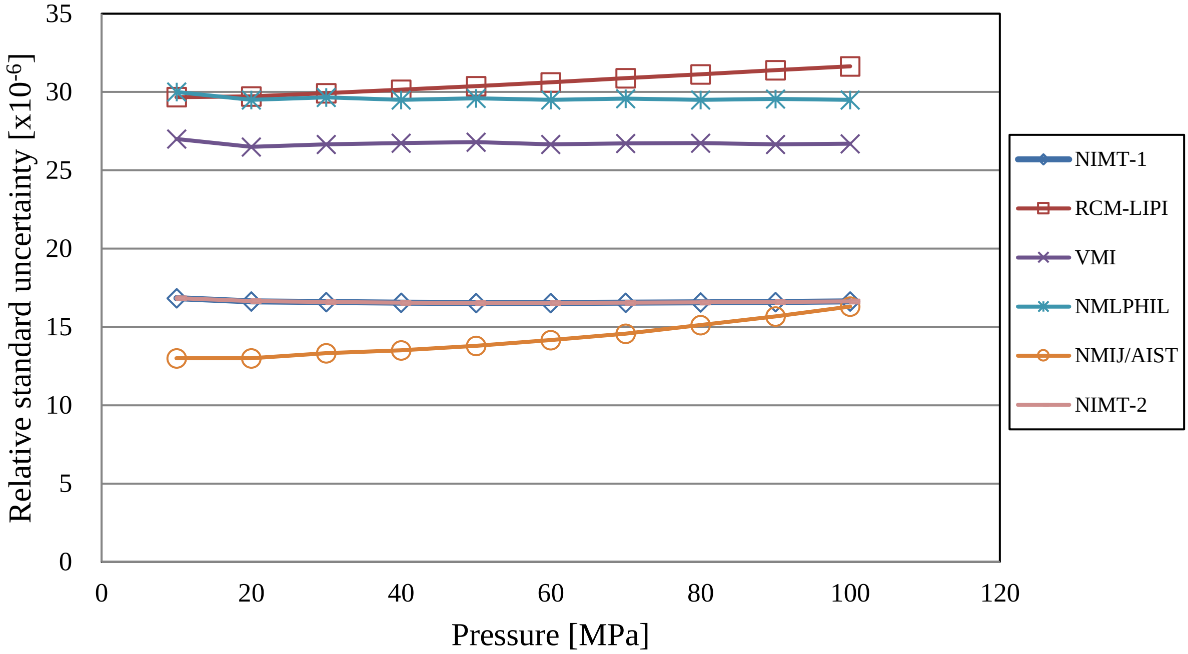


**Figure 6:** Relative standard uncertainties, as claimed by the participants, due to systematic effects in their pressure standards as a function of nominal target pressure.

### 6.5.2 Uncertainty due to combined effect of short-term random errors

The standard uncertainty in $p(j,i)$ due to combined effect of short-term random errors of the transfer standard, $u_{rdm}\{p(j,i)\}$, can be estimated on the basis of pool standard deviation as from equation below,

$$u_{rdm}\{p(j,i)\} = \frac{\sqrt{\frac{1}{24}\sum_{m=1}^{2}\left[\sigma^2\{R_{c2}(j,m,y,w,i)\}\right]}}{p_n(i)} \quad (9)$$

where $\sigma\{R_{c2}(j,m,y,w,i)\}$ is the standard deviation of 12 values of $R_{c2}(j,m,y,w,i)$ from its mean.

Table 12 and Figure 7 present the estimated standard uncertainties due to combined effect of short-term random errors calculated from equations (9).

**Table 12:** Standard uncertainties due to combined effects of short-term random errors. All the uncertainties are expressed as the standard ones.

| | | Standard uncertainty due to combined effects of short-term random effects, $u_{rdm}\{p(j,i)\}$[x $10^{-6}$] | | | | | |
|---|---|---|---|---|---|---|---|
| *j* | | 1 | 2 | 3 | 4 | 5 | 6 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 5.7 | 10.5 | 10.4 | 8.3 | 11.0 | 5.9 |
| 2 | 20 | 5.2 | 8.4 | 7.1 | 10.7 | 9.9 | 6.2 |
| 3 | 30 | 4.7 | 5.7 | 5.4 | 5.3 | 9.1 | 5.4 |
| 4 | 40 | 4.6 | 4.7 | 5.1 | 4.8 | 7.2 | 4.6 |
| 5 | 50 | 3.6 | 3.7 | 4.1 | 3.5 | 5.0 | 3.7 |
| 6 | 60 | 3.0 | 2.7 | 3.3 | 2.3 | 3.7 | 2.5 |
| 7 | 70 | 2.2 | 1.8 | 2.4 | 2.4 | 2.9 | 1.8 |
| 8 | 80 | 1.6 | 1.5 | 1.9 | 2.5 | 2.3 | 1.4 |
| 9 | 90 | 1.0 | 1.0 | 1.5 | 1.5 | 1.6 | 0.8 |
| 10 | 100 | 0.6 | 0.5 | 1.2 | 0.7 | 1.1 | 0.5 |

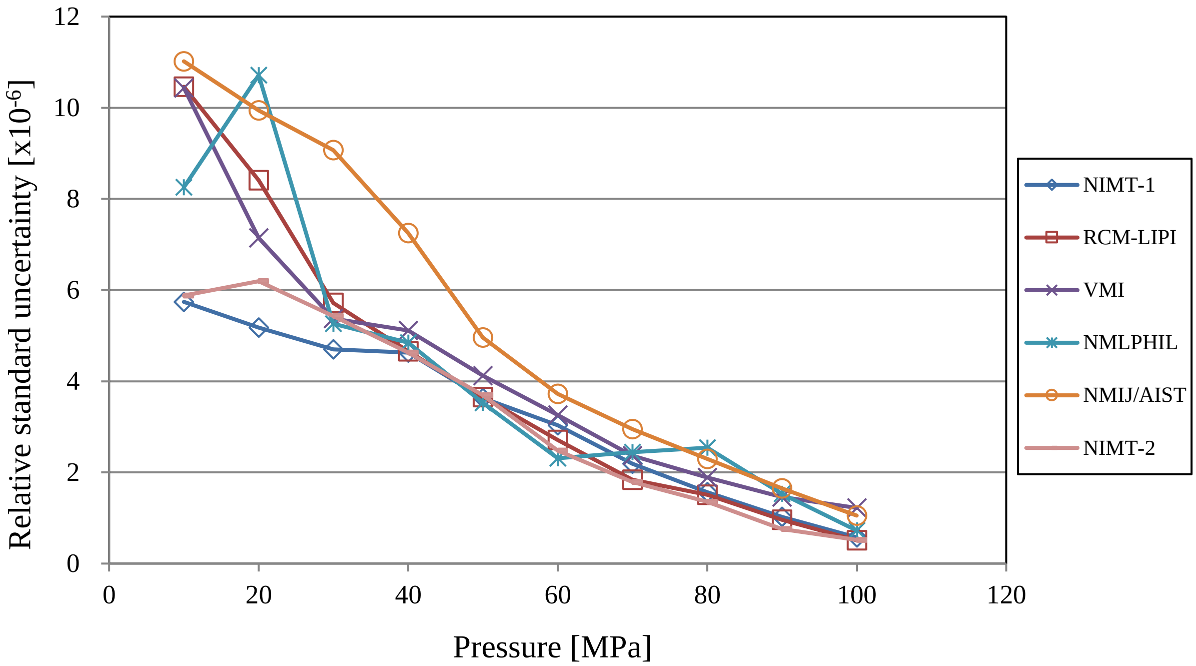


**Figure 7:** Standard uncertainties due to short-term random errors as a function of nominal target pressure.

### 6.5.3 Uncertainty due to deviation from reference temperature

The uncertainty in correcting the reading at the temperature realized at *j*-th participating institute to equivalent value at the reference temperature, $u_{temp}\{p(j,i)\}$, can be estimated from equation (10),

$$u_{temp}\{p(j,i)\} = \frac{u\{\beta(i)\}}{P_n(i)} \cdot \{\overline{t_b}(j,i) - t_r\} \tag{10}$$

where $u\{\beta(i)\}$ is the estimated standard uncertainty in the temperature coefficient according to APMP.M.P-K7.1, which was estimated as $u\{\beta(i)\}$ = 0.03 kPa/°C. $\overline{t_b}(j,i)$ is the average temperature measured on the transfer standard unit by the participating institutes for nominal target pressures, $t_r$ is the reference temperature of this comparison specified as $t_r$ = 21.27°C. The uncertainty in $\overline{t_b}(j,i)$ may also contribute an uncertainty to $u_{temp}\{p(j,i)\}$. However this systematic contribution was so small that the uncertainty made a negligible contribution to the uncertainty evaluated by equation (10). Table 13 and Figure 8 present the estimated standard uncertainties, $u_{temp}\{p(j,i)\}$.

**Table 13:** Standard uncertainties in correcting the readings to equivalent values at the reference temperature. All the uncertainties are expressed as the standard ones.

| | | Standard uncertainty due to deviation from reference temperature, $u_{temp}\{p(j,i)\}$[x $10^{-6}$] | | | | | |
|---|---|---|---|---|---|---|---|
| *j* | | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 0.8 | 6.4 | 3.6 | 3.0 | 5.7 | 0.2 |
| 2 | 20 | 0.4 | 3.1 | 1.8 | 1.5 | 2.9 | 0.1 |
| 3 | 30 | 0.3 | 2.0 | 1.2 | 0.9 | 1.9 | 0.1 |
| 4 | 40 | 0.2 | 1.5 | 0.9 | 0.6 | 1.4 | 0.1 |
| 5 | 50 | 0.2 | 1.2 | 0.7 | 0.5 | 1.1 | 0.1 |
| 6 | 60 | 0.1 | 1.0 | 0.6 | 0.5 | 0.9 | 0.1 |
| 7 | 70 | 0.1 | 0.8 | 0.5 | 0.4 | 0.8 | 0.0 |
| 8 | 80 | 0.1 | 0.7 | 0.5 | 0.3 | 0.7 | 0.0 |
| 9 | 90 | 0.1 | 0.6 | 0.4 | 0.3 | 0.6 | 0.0 |
| 10 | 100 | 0.1 | 0.6 | 0.4 | 0.3 | 0.6 | 0.0 |

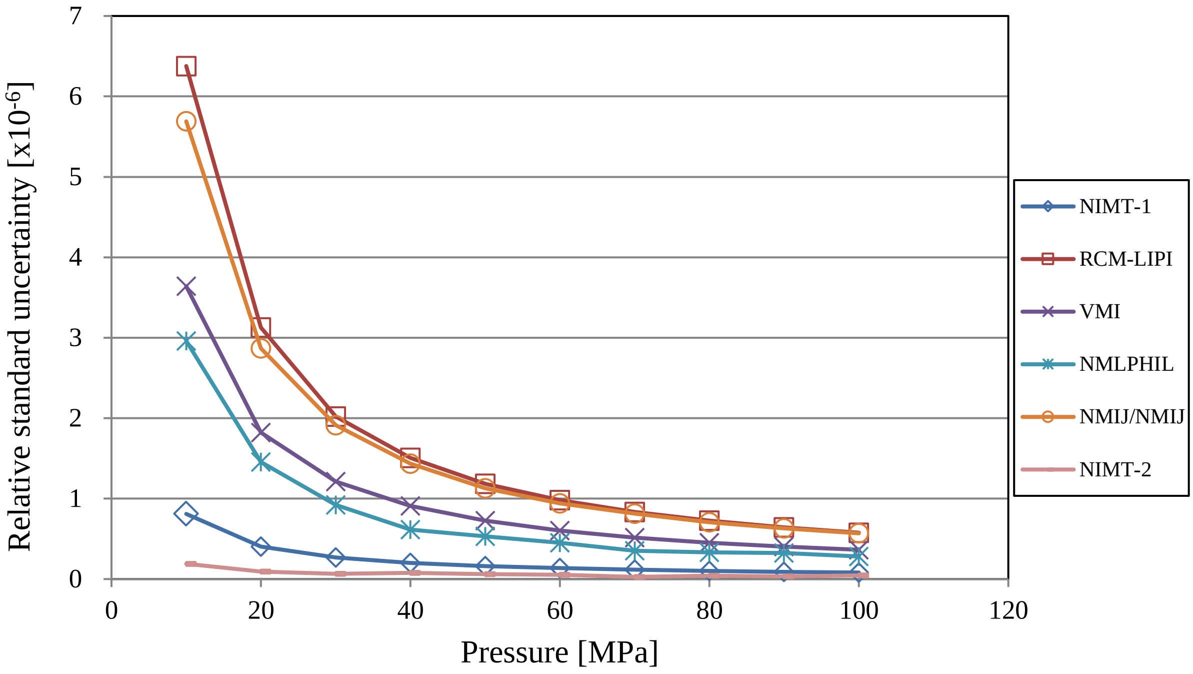


**Figure 8:** Standard uncertainties in correcting the readings to equivalent values at the reference temperature as a function of nominal target pressure.

### 6.5.4 Uncertainty due to long-term shift

The transfer standard was calibrated at pilot institute twice, before and after circulating the transfer standard to the participating institutes. The deviation between before and after the calibration results at the pilot institute was not significant, and hence the participating institute's results were not corrected according to the measurement date. In this comparison, the deviation was estimated as the uncertainty due to long-term instability for all participating institutes. The standard uncertainty due to instability of the transfer standard was estimated by equation (11) and shown in Table 14.

$$u_{lts}\{p(j,i)\} = \frac{1}{P_n(i)}\sqrt{\sum_{m=1}^{2}\left\{\frac{\left|R_{c3}(1,m,i) - R_{c3}(8,m,i)\right|}{2\cdot\sqrt{3}}\right\}^2} \quad (11)$$

**Table 14:** Standard uncertainty due to the long-term instability of the transfer standard.

| | | Standard uncertainty due to long-term instability of the transfer standard |
|---|---|---|
| *i* | [MPa] | $10^{-6}$ |
| 1 | 10 | 5.2 |
| 2 | 20 | 5.0 |
| 3 | 30 | 4.9 |
| 4 | 40 | 4.6 |
| 5 | 50 | 4.9 |
| 6 | 60 | 4.1 |
| 7 | 70 | 3.9 |
| 8 | 80 | 4.1 |
| 9 | 90 | 4.3 |
| 10 | 100 | 3.8 |

### 6.5.5 Combined uncertainty of the mean pressure for participating institutes

The combined standard uncertainty of the mean pressure of participating institutes, $u_c\{p(j,i)\}$, is calculated from equation (7) and presented in Table 15 and Figure 9.

**Table 15:** Combined standard uncertainties for the mean pressures of participant institutes, $u_c\{p(j,i)\}$. All the uncertainties are expressed as the standard ones.

| | | Combined standard uncertainty $u_c\{p(j,i)\}$[x $10^{-6}$] | | | | | |
|---|---|---|---|---|---|---|---|
| | $j$ | 1 | 2 | 4 | 5 | 6 | 7 |
| $i$ | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 18.6 | 32.5 | 29.6 | 31.7 | 18.7 | 18.6 |
| 2 | 20 | 18.1 | 31.5 | 28.0 | 31.8 | 17.4 | 18.5 |
| 3 | 30 | 17.9 | 30.9 | 27.7 | 30.5 | 17.0 | 18.1 |
| 4 | 40 | 17.8 | 30.9 | 27.6 | 30.3 | 16.1 | 17.8 |
| 5 | 50 | 17.6 | 31.0 | 27.6 | 30.2 | 15.5 | 17.6 |
| 6 | 60 | 17.3 | 31.0 | 27.2 | 29.9 | 15.2 | 17.2 |
| 7 | 70 | 17.1 | 31.2 | 27.1 | 29.9 | 15.4 | 17.1 |
| 8 | 80 | 17.1 | 31.4 | 27.1 | 29.9 | 15.8 | 17.1 |
| 9 | 90 | 17.2 | 31.7 | 27.1 | 29.9 | 16.3 | 17.2 |
| 10 | 100 | 17.1 | 31.9 | 27.0 | 29.8 | 16.8 | 17.1 |

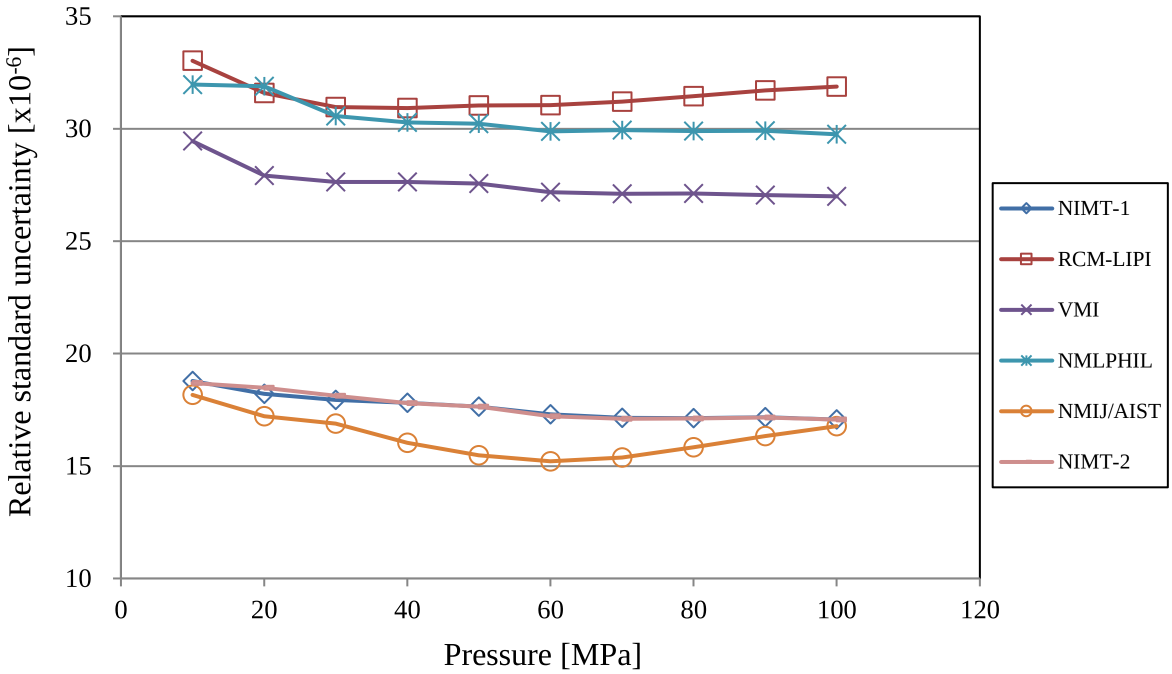


**Figure 9:** Combined standard uncertainty for the mean pressure of participant institutes as a function of nominal target pressure.

## 7. Linking key comparison APMP.M.P-K7.3 to key comparison CCM.P-K7

This APMP key comparison, APMP.M.P-K7.3, is linked to the corresponding CCM key comparison, CCM.P-K7 through the linkage institute, NMIJ/AIST. Therefore the deviation of the participating institutes from the linkage institute, NMIJ/AIST are shown in the Table 16.

**Table 16:** Relative deviation of participating institutes from the linkage institute, NMIJ/AIST, $y(i,j)$.

| | | Relative deviation from linkage institute, NMIJ/AIST, $y(j,i)$ [x $10^6$] | | | | | |
|---|---|---|---|---|---|---|---|
| *j* | | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 15.6 | 20.8 | -9.1 | -24.4 | 0.0 | 2.9 |
| 2 | 20 | 7.4 | -1.7 | -10.0 | -23.1 | 0.0 | -4.4 |
| 3 | 30 | 6.0 | -21.0 | -7.5 | -35.7 | 0.0 | -5.1 |
| 4 | 40 | 9.0 | -14.0 | 0.3 | -30.0 | 0.0 | -1.8 |
| 5 | 50 | 5.9 | -24.9 | -1.3 | -30.4 | 0.0 | -6.1 |
| 6 | 60 | 4.8 | -22.5 | 1.6 | -30.4 | 0.0 | -4.5 |
| 7 | 70 | 2.8 | -30.3 | 3.2 | -32.4 | 0.0 | -6.5 |
| 8 | 80 | 2.4 | -30.1 | 4.4 | -27.5 | 0.0 | -7.2 |
| 9 | 90 | 3.0 | -41.6 | 8.4 | -21.5 | 0.0 | -7.4 |
| 10 | 100 | 2.6 | -26.4 | 12.7 | -23.4 | 0.0 | -6.3 |

The linkage institute, NIMJ/AIST, participated in the both comparisons CCM.P-K7 and APMP.M.P-K7.3. The deviations from CCM KCRV of NMIJ/AIST, $x$(NMIJ,$i$),was listed in the Table 4 in the final report of CCM.P-K7.

The values used to link the results from APMP.M.P-K7.3 to CCM.P-K7 through the linkage institute, NMIJ/AIST are shown in the Table 17.

**Table 17.** Relative deviations obtained from the linking institute for CCM.P-K7.

| *i* | Pressure [MPa] | Results in CCM.P-K7 of NMIJ/AIST |
|---|---|---|
| | | $x$(NMIJ,$i$)[x $10^6$] |
| 1 | 10 | 0.0 |
| 2 | 20 | -1.6 |
| 3 | 30 | -0.7 |
| 4 | 40 | -1.1 |
| 5 | 50 | -0.5 |
| 6 | 60 | -1.3 |
| 7 | 70 | -0.6 |
| 8 | 80 | -0.5 |
| 9 | 90 | 0.0 |
| 10 | 100 | 0.0 |

Using the relationship of both quantities, the degree of equivalence of participating institutes in APMP.M.P-K7.3 comparison can be transferred to CCM.P-K7 comparison as follows:

$$D(j,i) = y(j,i) + x(\text{NMIJ},i) \qquad (12)$$

where $D(j,i)$ is the relative deviation from the CCM.P-K7 reference value of $j$-th institute that participated into APMP.M.P-K7.3, $y(j,i)$ is the relative deviation of $j$-th institute from the linkage institute NMIJ/AIST listed in Table 16, and $x$(NMIJ,$j$) is the deviation of NMIJ/AIST from CCM KCRV listed in Table 17.

The standard uncertainty of deviation from the CCM.P-K7 can be evaluated as follows

$$u\{D(j,i)\} = \sqrt{u_c^2(j,i) + u_{c,\text{CCM}}^2(\text{ref},i) + u_{A,\text{APMP}}^2(\text{NMIJ},i) + u_{A,\text{CCM}}^2(\text{NMIJ},i)} \qquad (13)$$

where $u_c(j,i)$ is the uncertainty for each participant listed in the Table 15, $u_{c,\mathrm{CCM}}(\mathrm{ref},i)$ was listed in the Table 13 of CCM.P-K7. Type A uncertainty $u_{A,\mathrm{APMP}}(\mathrm{NMIJ},i)$ and $u_{A,\mathrm{CCM}}(\mathrm{NMIJ},i)$ of NMIJ/AIST were listed in the Table 12, and Table 1 of CCM.P-K7.

The degrees of equivalent of the participants can be expressed by the normalize errors ($E_\mathrm{n}$). The equation of $E_\mathrm{n}$ for each pressure is shown below:

$$E_\mathrm{n} = \frac{|D(j,i)|}{U\{D(j,i)\}} \tag{14}$$

The relative expanded uncertainty of $D(j,i)$, for the institutes participated into APMP.M.P-K7 is estimated from

$$U\{D(j,i)\} = k \cdot u\{D(j,i)\} \tag{15}$$

where $k$ is the coverage factor and $k$ = 2 is adopted.

Table 18 presents respectively the relative deviations from the CCM KCRV, CCM.P-K7, $D(j,i)$, the expanded uncertainties ($k$ = 2) of the relative deviations, $U\{D(j,i)\}$, and the degrees of equivalence, $E_\mathrm{n}$ expressed by the ratios, $|D(j,i)|/U\{D(j,i)\}$, for individual participants at all nominal target pressure. A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $|D(j,i)|/U\{D(j,i)\} \leq 1$.

Figures 10 presents $D(j,i)$, with $U\{D(j,i)\}$, graphically for the participating institutes as a function of nominal target pressure.

**Table 18.** Deviations from the CCM KCRV, $D(j,i)$ [upper], the expanded ($k$=2) uncertainties of the deviations, $U\{D(j,i)\}$ [middle] and the degrees of equivalence as expressed by the $E_n$ ratios, $|D(j,i)|/U\{D(j,i)\}$ [lower].

| | | Relative deviation from CCM KCRV, $D(j,i)$ [x10$^6$] | | | | | |
|---|---|---|---|---|---|---|---|
| | *j* | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 15.6 | 20.8 | -9.1 | -24.4 | 0.0 | 2.9 |
| 2 | 20 | 5.8 | -3.3 | -11.6 | -24.7 | -1.6 | -6.0 |
| 3 | 30 | 5.3 | -21.7 | -8.2 | -36.4 | -0.7 | -5.8 |
| 4 | 40 | 7.9 | -15.1 | -0.8 | -31.1 | -1.1 | -2.9 |
| 5 | 50 | 5.4 | -25.4 | -1.8 | -30.9 | -0.5 | -6.6 |
| 6 | 60 | 3.5 | -23.8 | 0.3 | -31.7 | -1.3 | -5.8 |
| 7 | 70 | 2.2 | -30.9 | 2.6 | -33.0 | -0.6 | -7.1 |
| 8 | 80 | 1.9 | -30.6 | 3.9 | -28.0 | -0.5 | -7.7 |
| 9 | 90 | 3.0 | -41.6 | 8.4 | -21.5 | 0.0 | -7.4 |
| 10 | 100 | 2.6 | -26.4 | 12.7 | -23.4 | 0.0 | -6.3 |

| | | Expanded uncertainty, $U\{D(j,i)\}$ [x10$^6$] *(k=2)* | | | | | |
|---|---|---|---|---|---|---|---|
| | *j* | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 43.5 | 68.9 | 63.5 | 67.3 | 43.8 | 43.6 |
| 2 | 20 | 41.5 | 66.0 | 59.4 | 66.7 | 40.1 | 42.0 |
| 3 | 30 | 40.2 | 64.5 | 58.3 | 63.8 | 38.5 | 40.6 |
| 4 | 40 | 38.5 | 63.5 | 57.2 | 62.3 | 35.3 | 38.5 |
| 5 | 50 | 36.8 | 62.9 | 56.1 | 61.4 | 32.8 | 36.8 |
| 6 | 60 | 35.8 | 62.7 | 55.1 | 60.4 | 31.8 | 35.6 |
| 7 | 70 | 35.1 | 62.8 | 54.7 | 60.3 | 31.7 | 35.0 |
| 8 | 80 | 35.0 | 63.3 | 54.8 | 60.2 | 32.6 | 35.0 |
| 9 | 90 | 35.2 | 63.9 | 54.6 | 60.3 | 33.6 | 35.2 |
| 10 | 100 | 35.1 | 64.3 | 54.6 | 60.1 | 34.5 | 35.1 |

| | | $\lvert D(j,i)\rvert/U\{D(j,i)\}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | *j* | 1 | 2 | 4 | 5 | 6 | 7 |
| *i* | [MPa] | NIMT-1 | RCM-LIPI | VMI | NMLPHIL | NMIJ/AIST | NIMT-2 |
| 1 | 10 | 0.4 | 0.3 | 0.1 | 0.4 | 0.0 | 0.1 |
| 2 | 20 | 0.1 | 0.0 | 0.2 | 0.4 | 0.0 | 0.1 |
| 3 | 30 | 0.1 | 0.3 | 0.1 | 0.6 | 0.0 | 0.1 |
| 4 | 40 | 0.2 | 0.2 | 0.0 | 0.5 | 0.0 | 0.1 |
| 5 | 50 | 0.1 | 0.4 | 0.0 | 0.5 | 0.0 | 0.2 |
| 6 | 60 | 0.1 | 0.4 | 0.0 | 0.5 | 0.0 | 0.2 |
| 7 | 70 | 0.1 | 0.5 | 0.0 | 0.5 | 0.0 | 0.2 |
| 8 | 80 | 0.1 | 0.5 | 0.1 | 0.5 | 0.0 | 0.2 |
| 9 | 90 | 0.1 | 0.7 | 0.2 | 0.4 | 0.0 | 0.2 |
| 10 | 100 | 0.1 | 0.4 | 0.2 | 0.4 | 0.0 | 0.2 |

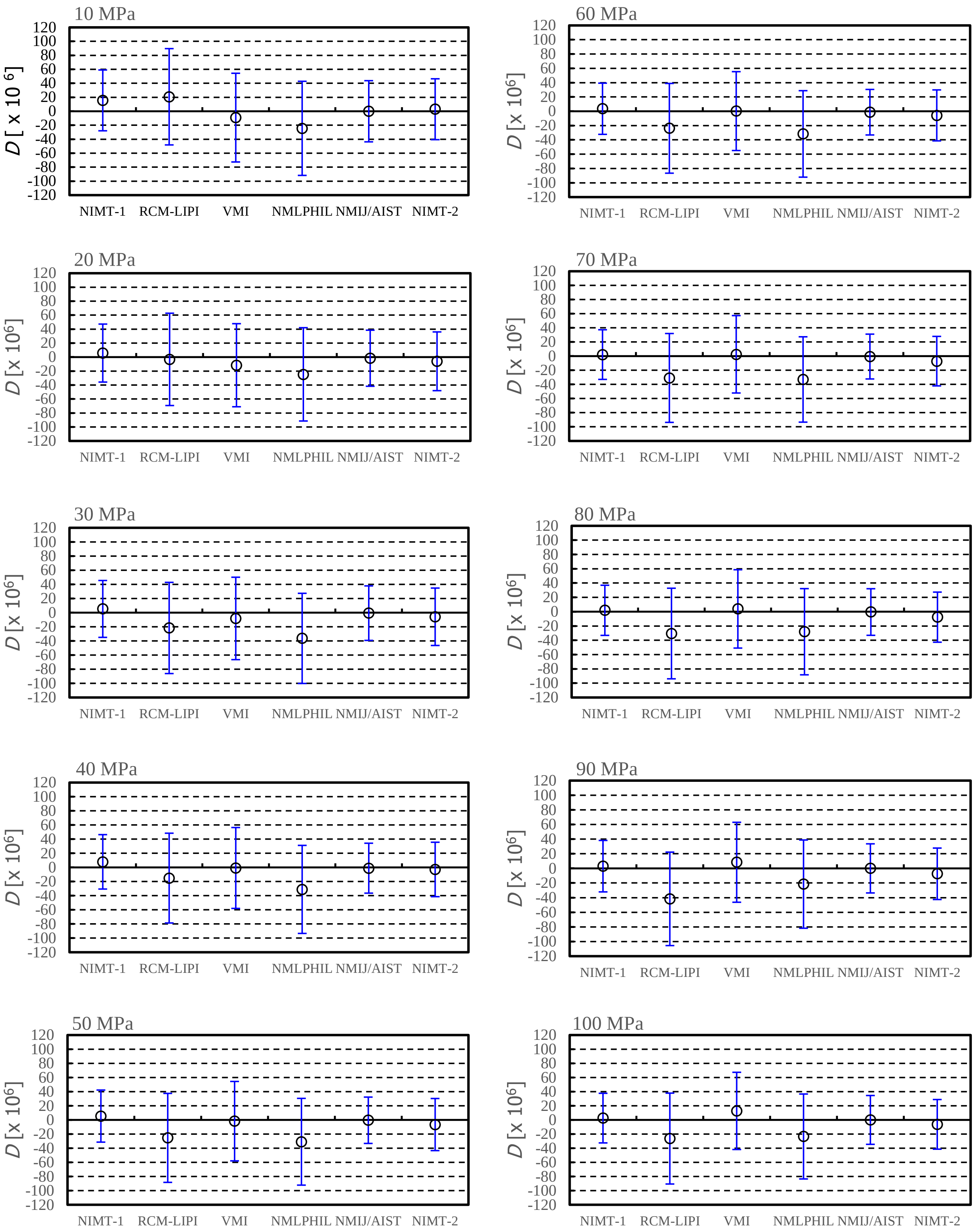


**Figure 10.** Deviations from the CCM KCRV, $D(j,i)$ and the expanded ($k$=2) uncertainties of the deviations, $U\{D(j,i)\}$.

## 8. Discussions

The results presented in this report are based on data originally submitted by participants to pilot institute for preparation of the draft A report. The expected mean pressures and associated measurement uncertainties for each participant were calculated. All the participating institutes calibrated two pressure transducers in the transfer standard against the pressure balance by following the protocol. Since one linkage institute withdrew from the comparison, the results in this comparison were linked to CCM.P-K7 through the results of the linkage institute NMIJ/AIST.

A comment from RCM-LIPI about the reference temperature and temperature coefficient as well as the uncertainty due to the temperature effect on the transfer standard was considered in this report and next key comparison. The results of this report were prepared by pilot institute, NIMT and linkage institute, NMIJ/AIST.

Finally, the results of the participants in APMP.M.P-K7.3 were linked to CCM KCRV of CCM.P-K7.

## 9. Conclusions

Seven National Metrology Institutes (NMIs) participated in this APMP key comparison for hydraulic high pressure standards from 10 MPa to 100 MPa for gauge mode. Two NMIs decided to withdraw the results from this comparison because of their hydraulic pressure standards were not functioning. Two high-precision electronic pressure transducers were circulated to each participant as the transfer standard for the comparison. The performance of the transfer standard was checked at the pilot institute, NIMT, and the linkage institute, NMIJ/AIST. The parameters of the pressure transducers were changed in secrecy by the pilot institute. The transfer standard was calibrated at the pilot institute before and after circulating in order to investigate the long-term instability. The deviations between two measurements were taken into account for evaluating the uncertainties.

The degrees of equivalence were expressed by two terms, deviations from the key comparison reference values and normalize error ratio, $E_n$. The hydraulic pressure standards of the five participating NMIs (NIMT, RCM-LIPI, VMI, NMLPHIL and NMIJ/AIST) in this comparison were transferred to CCM.P-K7. The results showed that the hydraulic pressure standards in the range from 10 MPa to 100 MPa, for gauge mode, of the participating NMIs were found to be fully equivalent within their claimed uncertainties.

## References

1. Padipat Wongthep, Technical Protocol of ASIA-Pacific Metrology Programme 100 MPa Hydraulic Pressure Inter laboratory Comparison (APMP.M.P-K7.3), March 2016
2. Tokihiko Kobata, Technical Protocol of ASIA-Pacific Metrology Programme 100 MPa Hydraulic Pressure Inter laboratory Comparison (APMP.M.P-K7), 2002.
3. Tokihiko Kobata, etc., Final Report on Key Comparison APMP.M.P-K7 in Hydraulic Gauge Pressure from 10 MPa to 100 MPa, March 2005.

4. Likit Sainoo, Technical Protocol of ASIA-Pacific Metrology Programme 100 MPa Hydraulic Pressure Inter laboratory Comparison (APMP.M.P-K7.2), September 2015
5. Tokihiko Kobata, etc., Final Report on Key Comparison APMP.M.P-K7.1 in Hydraulic Gauge Pressure from 10 MPa to 100 MPa, July 2009.
6. Wladimir Sabuga, etc., Final Report on Key Comparison CCM.P-K7 in the Range 10 MPa to 100 MPa of Hydraulic Gauge Pressure, Version 1 of 19.01.2005.
7. Mutual recognition of national measurements standards and of calibration and measurement certificates issued by national metrology institutes (MRA), Technical Report, International Committee for Weights and Measures, 1999 (http://www.bipm.org/pdf/mra.pdf)
8. DH Instruments, Inc., RPM4™ Reference Pressure Monitor Operation and Maintenance Manual.
9. Paroscientific, Inc., Digiquartz® Pressure Instrumentation User's Manual.