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ASIA-PACIFIC METROLOGY PROGRAMME
100 MPa HYDRAULIC PRESSURE INTERLABORATORY COMPARISON
Comparison Identifier: **APMP.M.P-K7.1**

Final Report on Key Comparison APMP.M.P-K7.1 in Hydraulic Gauge Pressure from 10 MPa to 100 MPa

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Abstract

This report describes the results of a key comparison of hydraulic high-pressure standards at three National Metrology Institutes (NMIs: NMIJ/AIST, MSL, and NML-SIRIM), which was carried out during the period June 2007 to February 2008 within the framework of the Asia-Pacific Metrology Programme (APMP) in order to determine their degrees of equivalence at pressures in the range from 10 MPa to 100 MPa for gauge mode. The pilot institute was the National Metrology Institute of Japan (NMIJ/AIST). All participating institutes used hydraulic pressure balances as their pressure standards. High-precision pressure transducers were used as a transfer standard. The sensing element of the transducer was a precision quartz crystal resonator. To ensure the reliability of the transfer standard, two pressure transducers were used in the transfer standard unit. During this comparison, the transfer standard was calibrated at the pilot institute five times in total. These results show that the transfer standard was sufficiently stable to meet the requirements of the comparison. The degrees of equivalence of each national measurement standard were expressed quantitatively by two terms, deviations from the key comparison reference values and pair-wise differences of their deviations. The hydraulic pressure standards in the range from 10 MPa to 100 MPa, for gauge mode, of the three participating NMIs were found to be fully equivalent within their claimed uncertainties. The degrees of equivalence in this comparison were also transferred to the corresponding CCM key comparison, CCM.P-K7, and it is shown that the values of the participating NMIs were equivalent to the CCM KCRV within the claimed uncertainties.

Contents:

1. Introduction

The National Metrology Institute of Japan (NMIJ/AIST), Japan, has successfully participated in the CCM comparison, CCM.P-K7, in the pressure range from 10 MPa to 100 MPa using a pressure balance. The Measurement Standards Laboratory (MSL) of New Zealand and the National Metrology Laboratory, SIRIM Berhad (NML-SIRIM), Malaysia, have developed a hydraulic pressure standard ranging from 10 Pa to 100 MPa for gauge mode using pressure balances. A trilateral comparison was planned by the three laboratories using high-resolution pressure transducers as a transfer standard.

NMIJ/AIST has been approved by the Technical Committee for Mass and Related Quantities (TCM) in the Asia-Pacific Metrology Programme (APMP) to coordinate an interlaboratory comparison program for hydraulic high-pressure as a pilot institute. The comparison has been identified as **APMP.M.P-K7.1** 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 the comparison is to determine the relative agreement between hydraulic pressure standards of the participating National Metrology Institutes (NMIs) in the pressure range from 10 MPa to 100 MPa for gauge mode according to the protocol guidelines[1,2,3] using Di(2)-ethyl-Hexyl-Sebacate (DHS) as a transmitting fluid. To gain international acceptance for the pressure standards APMP.M.P-K7.1 is linked to the CCM and APMP key comparisons, CCM.P-K7[4] and APMP.M.P-K7[5], which has a similar pressure range as APMP.M.P-K7.1. The results of this comparison will be submitted to the Key Comparison Database (KCDB) of BIPM following the rules of CCM and can then be used to establish the degree of equivalence of national measurement standard by NMIs[6]. This will provide the essential supporting evidence for hydraulic pressure calibration and measurement capabilities (CMCs) of the NMIs for the Mutual Recognition Arrangement (MRA)[1].

Similar to APMP.M.P-K7[5], high-precision electronic pressure transducers were circulated as the transfer standard for the whole comparison. To ensure the reliability of the transfer standard, two high-precision pressure transducers were used on a transfer standard unit. During the comparison, the transfer standard was calibrated at the pilot institute five times in total. From the calibration results, the behavior of the transfer standard during the comparison period was well characterized.

A protocol[8,9] was prepared by the pilot institute (NMIJ/AIST) in cooperation with MSL and NML-SIRIM with reference to the protocol of APMP.M.P-K7[5]. The first edition was distributed on May 2007. After the revised protocol was approved by the participating institutes, the transfer standard was circulated from June 2007 to February 2008. During this comparison, the transfer standard was calibrated at the pilot institute (NMIJ/AIST) five times in total. From the calibration results, the stability of the transfer standard during the comparison period was evaluated. The three NMIs used hydraulic pressure balances as their pressure standards and calibrated the transfer standard against the pressure balances following the protocol[8,9]. The calibration results obtained by each participating institute were submitted to the pilot institute (NMIJ/AIST) for analysis. The preparation of a report on the comparison and the analysis of data on the basis of the results from the participants have been done by the pilot institute to ensure uniform treatment for all participants according to the guidelines[1,2,3].

This report gives the calibration results of the transfer standard carried out at the three NMIs. The following sections provide descriptions of the participating institutes and their pressure standards, 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 their pressure standards

2.1 List of participating institutes

Three National Metrology Institutes (NMIs) participated into this comparison including the pilot institute. The participating institutes along with addresses for contacts are listed in Table 2.1. The index number in column one is used to identify the participating institute in this report.

Table 2.1: List of participating institutes.

	Participating Institutes
1	**Country:** Japan **Acronym:** NMIJ/AIST (Pilot institute) **Institute:** National Metrology Institute of Japan, AIST **Address:** AIST Tsukuba Central 3, 1-1, Umezono 1-Chome, Tsukuba, Ibaraki, 305-8563 Japan
2	**Country:** New Zealand **Acronym:** MSL **Institute:** Measurement Standards Laboratory of New Zealand, Industrial Research Ltd **Courier Address:** 69 Gracefield Rd, Lower Hutt, New Zealand **Postal address:** P O Box 31310, Lower Hutt, New Zealand
3	**Country:** Malaysia **Acronym:** NML-SIRIM **Institute:** National Metrology Laboratory, SIRIM Berhad **Address:** Lot PT 4803, Bandar Baru Salak Tinggi, 43900 Sepang, Selangor, Malaysia

2.2 Pressure standards of participating institutes

The pressure standards of all the participating institutes were pressure balances of different manufacture and model. They were equipped with a simple type or a re-entrant type piston-cylinder assembly. Each institute provided the pilot institute with information about their standard that was used to calibrate the transfer standard, including the pressure balance base, the type and material of piston-cylinder assembly, the effective area with associated standard uncertainty, the reference temperature, the pressure distortion coefficient with associated standard uncertainty, the method and rotation rate of the piston as listed in Table 2.2. All piston and cylinder materials of the pressure balances used by the participating institutes were tungsten carbide. All the institutes assumed linear pressure dependence for the effective area of piston-cylinder assembly. The participants with primary pressure standards directly linked to base SI units were NMIJ/AIST and MSL.

Table 2.2: Details of the pressure standards of the participating institutes. All the uncertainties are expressed as the standard ones.

j	Institute	Country	Pressure balance base		Piston-cylinder		Rotation	
			Manufacturer	Model	Type	Material	Method	rpm
1	NMIJ/AIST	Japan	DH	5316-02	Simple	WC/WC	Hand	10 - 30
2	MSL	New Zealand	Ruska	2450-700-00	Re-entrant	WC/WC	Hand	20 ± 10
3	NML-SIRIM	Malaysia	Desgranges Et Huot	5301	Simple	WC/WC	Motor	20

j	Institute	Country	Effective area A_{tr}			Ref. temp	Distortion coefficient λ / MPa^{-1}	
			Value / m^2	Unc. / m^2	Unc. / 10^{-6}	t_r / °C	Value / MPa^{-1}	Unc. / MPa^{-1}
1	NMIJ/AIST	Japan	9.805620E-06	1.24E-10	12.6	23	8.38E-07	1.01E-07
2	MSL	New Zealand	1.67993E-05	2.00E-10	11.9	20	-1.62E-06	1.80E-07
3	NML-SIRIM	Malaysia	5.688426E-06	3.7E-11	6.5	20	1.03E-06	5.3E-08

3. Transfer standard

In this APMP comparison, high-precision electronic pressure transducers were circulated as the transfer standard for the whole comparison. To ensure the reliability, two transducers were used in the transfer standard.

3.1 Pressure monitors

Two commercially available pressure monitors, which are listed in Table 3.1, were used in the transfer standard. One type is from DH Instruments, Inc. and another type is from Paroscientific Inc. (in alphabetical order)[10,11]. The pressure range of these pressure monitors were up to 100 MPa. Each pressure monitor included a high-precision electronic pressure transducer inside the body. The sensing element of the transducer was a precision quartz crystal resonator and the frequency of oscillation varied with pressure induced stress. The resolution of the transducer was 0.1 kPa.

Table 3.1: Two types of pressure monitors.

Type	a	b
Manufacturer	DH Instruments, Inc.	Paroscientific, Inc.
Model	RPM3 A15000	785 A15000
Specification	See RPM3's specification*1	See 785's specification*2
Serial number	1476	1668 (88609)
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

Some general information concerning the characteristics of these pressure monitors are given in the operation and maintenance manuals[10,11] which were enclosed in a transfer package.

To perform a reliable comparison, the effects on the readings of the monitors by setting parameter and environmental condition were evaluated at the pilot institute during the comparison. The important characteristics for the transfer standard such as the long-term stability and the temperature coefficient of the span reading are evaluated quantitatively in section 6.

3.2 Structure of transfer standard

For this APMP comparison, two pressure monitors were used in the transfer standard to ensure the reliability. As shown in Figure 3.1, the transfer standard consisted of two types of pressure monitors, a base-plate, a mercury thermometer, a sensitive bubble level, a reference level bar, an oil pan, a shut-off valve and connecting parts. A mercury thermometer was used to measure the temperature on the base-plate. The tilt orientation of the base-plate was checked using a sensitive bubble level mounted on the base plate and any observed changes were corrected using the leveling screws. The reference level of the transfer standard was represented by a reference level bar on the base-plate. The height of the reference level bar from the top surface of the base-plate was 48 mm. The height of one end of a U-tube was adjusted to the same height as the reference level bar. Two electric thermometers were installed in the transfer standard to check the temperature change during the comparison including the transportation. The temperature measured by the thermometer was recorded into the memory automatically. The data was extracted from the memory at the pilot institute using a special device, which was presented in section 4.2. Through a specified connecting port of the transfer standard, the transfer standard was connected to a participant's pressure balance. A shut-off valve Vi, which was prepared by the participant, was used between the specified connecting port and the participant's pressure balance at the same level of the transfer standard as shown in Figure 3.1. The dimensions of the transfer standard were approximately 600 mm × 360 mm × 150 mm, the total weight was about 18 kg.

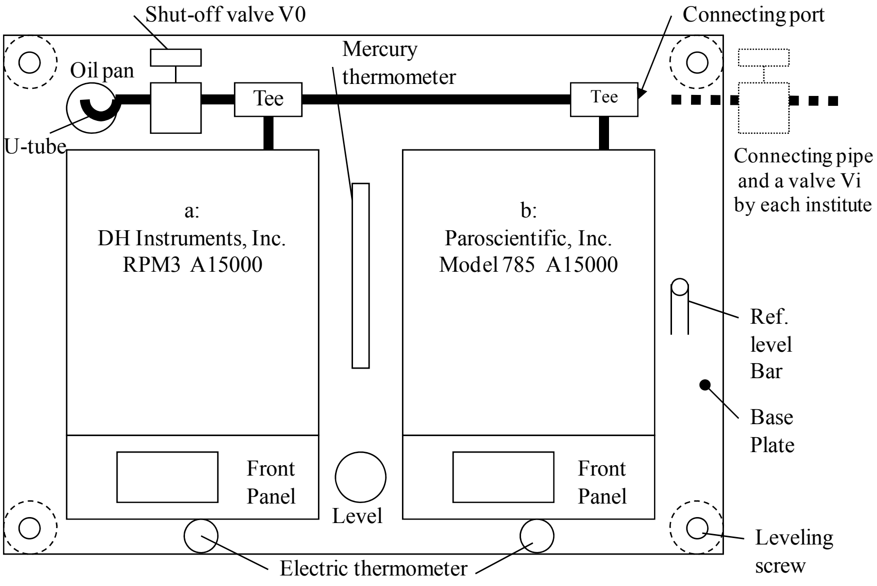

Figure 3.1: Schematic drawing of transfer standard.

3.3 Transfer package

A single commercial container, which was resistant to mechanical shock and vibration, was used for carrying the transfer standard. The transfer standard was put in the container when it was transferred. The dimensions of the container were approximately 850 mm × 570 mm × 360 mm, the total weight was about 34 kg. Shock meter were attached in the box for measuring the condition during transportation.

The contents of the transfer package were a transfer standard, two power cables for both pressure monitors, reserve parts, copies of the manual and the protocol for this comparison as listed in Table 3.2.

Table 3.2: Contents of the transfer package.

Carrying container	(1)	
Transfer standard	(1)	
Power cable	(2) For both pressure monitors	
Oil pan	(2)	
Reserve parts	Tee	CT4440, Number of stock: (1)
	Shut-off valve	60VM4071, Number of stock: (1)
	Color	ACL40, Number of stock: (3)
	Grand nut	AGL40, Number of stock: (3)
Manual	(2) For both pressure monitors[10,11]	
Protocol	(1) Document[8,9]	

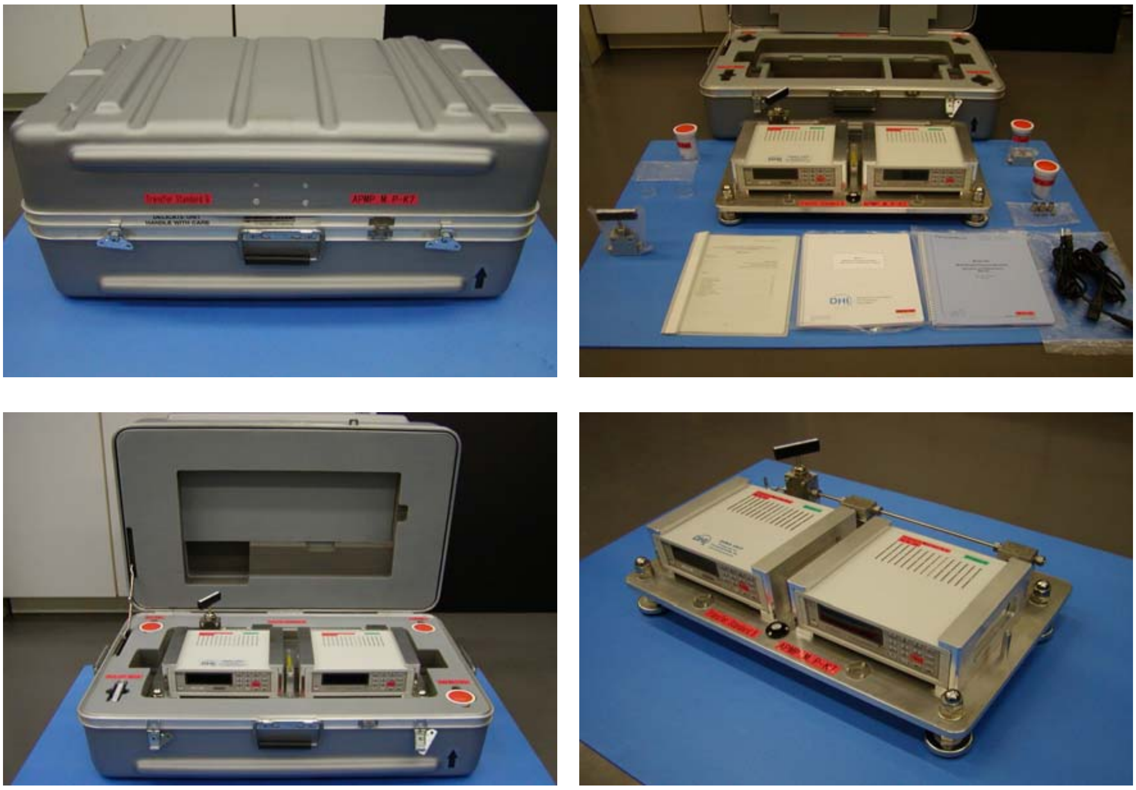

Figure 3.2: Photographs of transfer standard for APMP.M.P-K7.1.

4. Circulation of the transfer standard

4.1 Chronology of measurements

According to the protocol[8,9], the transfer package was circulated during the period June 2007 to February 2008 with calibrations at the pilot institute (NMIJ/AIST).

For each circulation, ATA CARNET was prepared by the pilot institute. When the package arrived at the participating institute, the followings procedure was required. The package was unpacked, and an inspection of the appearance was made. Then, the function of the devices was checked. The results were noted on the corresponding paper sheets attached in appendix[9]. The pilot institute (NMIJ/AIST) was informed about the arrival time and about the result of the inspection. When the package departed from the participating institute, all parts were required to be put in the original package appropriately. An inspection of the appearance was made, and the function of the devices was checked. The results were noted on the corresponding paper sheets attached in appendix[9]. The pilot institute (NMIJ/AIST) was informed about the departure time and about the result of the inspection.

Table 4.1 presents the actual chronology of measurements in the comparison loop with the transfer standard. Figure 4.1 shows the transportations of the transfer standard on a world map. The arrival and departure dates, and dates during which calibration data was taken at each participating institute are listed. The comparison was organized on a petal basis with the transfer packages returning periodically to the pilot institute (NMIJ/AIST) for calibrations. Throughout the comparison the transfer standard was calibrated simultaneously five times at the pilot institute. The actual sequence of the simultaneous calibrations of the transfer standard at the pilot institute is listed in Table 4.2. The total time required to complete the measurements phase of this comparison was nine months.

Table 4.1: Chronology of measurements in comparison loop with transfer package.

Petal	Institute	Country	Arrival	Departure	Dates for calibrations
Petal 1	NMIJ/AIST	Japan	---	2007/7/17	---
	MSLNZ	New Zealand	2007/8/1	2007/9/11	2007/9/5, 6, 7
	NMIJ/AIST	Japan	2007/9/20	2007/11/22	---
Petal 2	NML-SIRIM	Malaysia	2007/11/28	2008/1/18	2007/12/31, 2008/1/2, 9
	NMIJ/AIST	Japan	2008/1/25	---	---

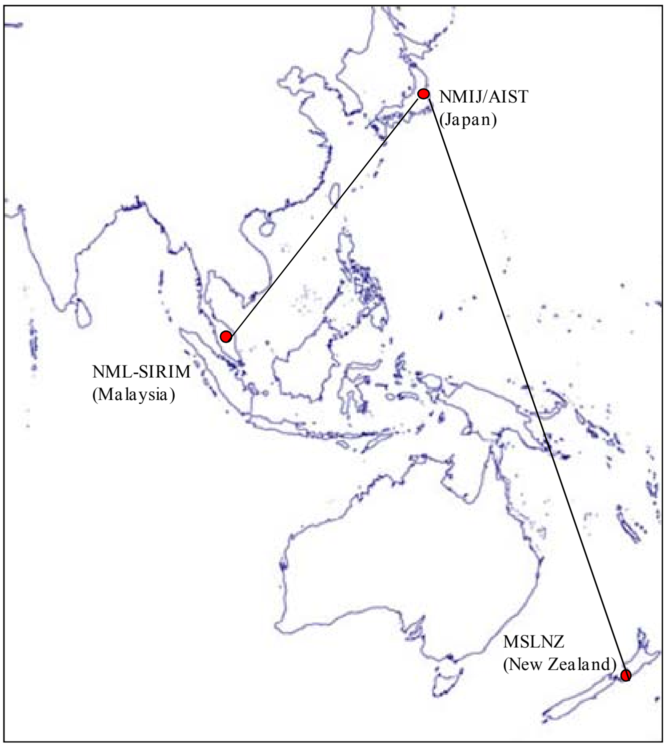

Figure 4.1: Circulation in comparison loop.

Table 4.2: Simultaneous calibrations performed at the pilot institute (NMIJ/AIST).

Index	Dates for calibrations
1	2007/6/18, 6/20, 6/21
2	2007/7/9, 7/12, 7/13
Petal 1	
3	2007/10/3, 10/10, 10/12
4	2007/11/12, 11/16, 11/19
Petal 2	
5	2008/1/30, 2/1, 2/6

4.2 Temperature change on the transfer standard during comparison

As explained in section 3, two electric thermometers were installed in the transfer standard to check the temperature change during the whole comparison including the transportation. From outputs obtained from two thermometers, the average temperature on the transfer standard every hour was obtained as shown in Figure 4.2. The results indicate that the temperature range measured by the thermometers was approximately from in the range from 4 ℃ to 30 ℃ during the whole comparison including the transportation. The temperature range was almost the same as the manufacturer’s recommended operating temperature range of 5 ℃ to 35 ℃. Therefore, it can be stated that the temperature of the transfer standard was maintained in the normal operating range during the whole comparison.

The temperature measured on the transfer standard reported by each participating institute was compared with the temperature described above. There was no clear systematic difference. Therefore, the temperature reported by each participant was used to make a temperature correction on the reading of each pressure monitor.

The shock acceleration suffered during the transportation was also measured by a shock recorder. The maximum acceleration was found to be about 140 m/s^2 (14 G) and was within the permissible range according to the manufacturer’s specification.

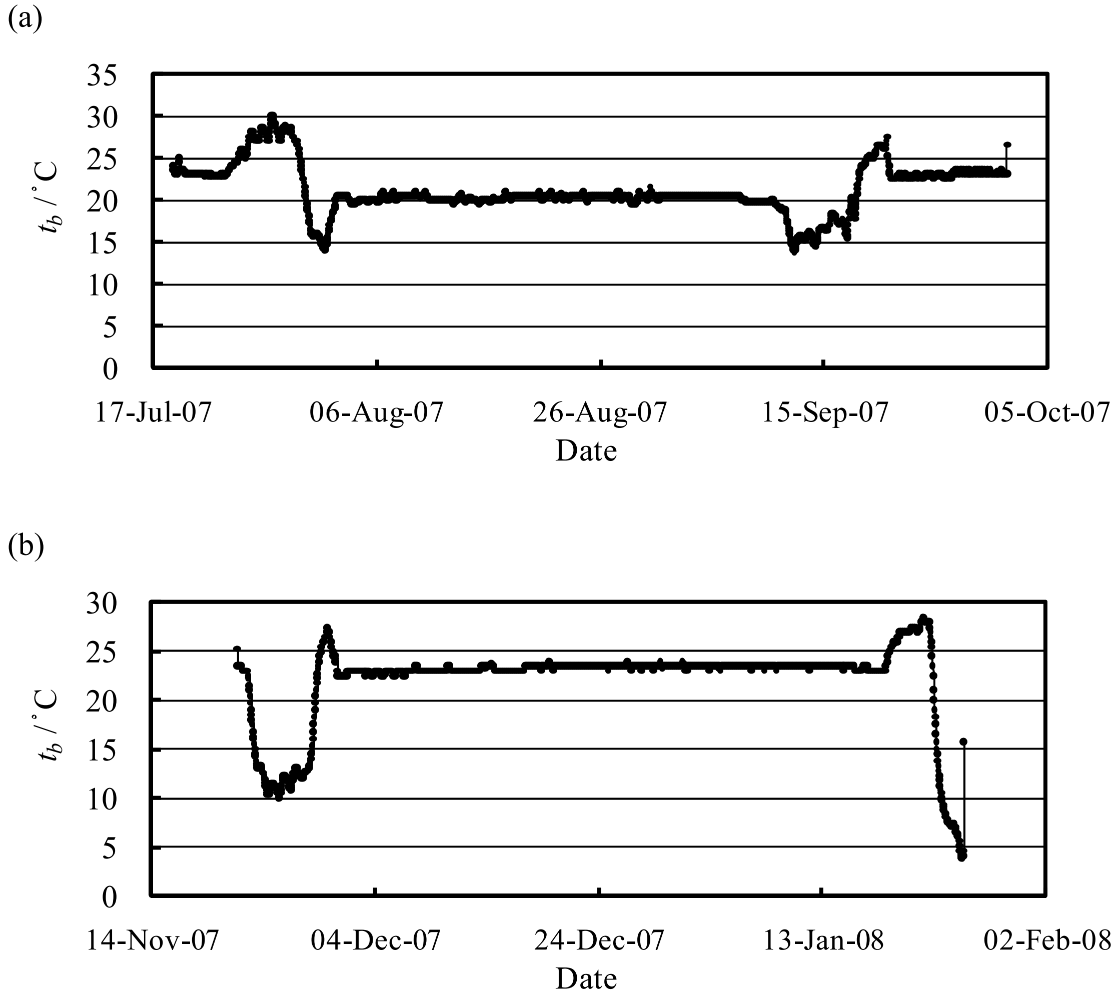

Figure 4.2: Temperature changes on transfer standard,
(a) Loop [NMIJ/AIST <-> MSL], (b) Loop [NMIJ/AIST <-> NML-SIRIM].

5. Calibration

The general procedure required that each participant calibrated the transfer standard for this comparison was described in the protocol[8,9].

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 condition, such as atmospheric pressure, ambient temperature and relative humidity, during the calibration was measured using the participant's own devices.

For the preparation of the calibration, the followings were recommended: (i) At latest, twenty-four hours before starting the measurement procedure, pressure monitors should be connected to a power supply and be turned on for warming up and stabilization. (ii) The power supply for the pressure monitors should be maintained during all the calibrations at the participating institute. (iii) Setting parameters of each pressure monitor should be set as follows:

- Range of 100 MPa
- kPa unit
- Gauge mode
- Average measurement mode for twenty readings each twenty seconds
- kPa resolution
- 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 monitor 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 both pressure monitors.

5.2 Head correction by height difference

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

$$P = P_{std} + (\rho_f - \rho_a)\cdot g_l\cdot H \tag{5.1}$$

where, P_{std} is the pressure generated by the participant's pressure standard at its reference level; $(\rho_f - \rho_a)\cdot g\cdot H$, is the head correction, with ρ_f the density of the working fluid, ρ_a the air density, g_l the local acceleration due to gravity, and H the vertical distance between the reference levels of the two intercompared standards (institute 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 on the applied pressure and the reference level of the transfer standard, and include their contributions into the uncertainty of the applied pressure.

5.3 Calibration procedure

At nominal target pressures of 0, 10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, 70 MPa, 80 MPa, 90 MPa, and 100 MPa, the pressure applied and the readings of the pressure monitors 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 points of eleven pressure points from 0 MPa to 100 MPa in steps of 10 MPa in ascending order, one point 0 MPa, and eleven points from 100 MPa to 0 MPa in steps of 10 MPa in descending order as shown in Figure 5.1. 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 in appendix[9]. 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.

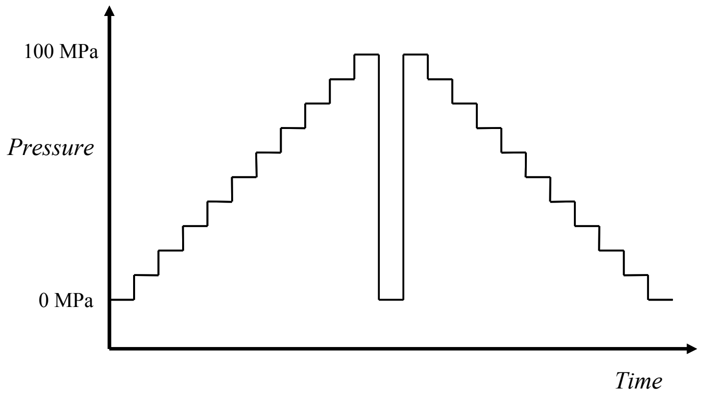

Figure 5.1: One complete measurement cycle.

5.3.2 Calibration at 0 MPa

At the beginning, middle and end of each cycle, zero-pressure readings for the pressure monitors were measured. These data were used to correct calibration data for zero-pressure offsets. To apply zero gauge pressure to the pressure monitors, the valve V0 was opened and the valve Vi was closed. (See Figure 3.1) After waiting ten minutes the readings of each pressure monitor were recorded within the following five minutes. Each reading was an average of twenty successive measurements with a corresponding standard deviation σ. The temperature on the base-plate, t_b, and the environmental conditions were also measured. This data was recorded in the cells on the forms annexed to the protocol[8,9] as shown in Table 5.1.

Table 5.1: Example of data recording at 0 MPa.

Nom. Pres. [MPa]	Local Time	Atmo Temp. [°C]	Atmo R.H. [%]	Atmo Pres. [kPa]	Temp. Base t_b [°C]	Reading *R_a* [kPa]		Reading *R_b* [kPa]		Applied Pressure *P* [kPa]	*u*(*P*) [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	---	

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 pressure balance piston position was kept in the floating range to maintain the pressure by using a hand pump. The difference between the actual pressure realized at the transfer standard by the participant's pressure standard and the target pressure was required to be within one thousandth of the target pressure. After waiting ten minutes for the pressure to stabilize, each pressure monitor was read within the following five minutes. Each reading was the average of twenty measurements with a corresponding standard deviation σ. Then the applied pressure with the associated standard uncertainty at the reference level of the transfer standard was calculated. All influence quantities for the institute system were taken into account in the uncertainty estimation by each participant. The correction of the height differential between the reference level of the participating institute's standard and the transfer standard was considered. This data was recorded in the forms annexed to the protocol[8,9] as presented in Table 5.2. In the table, P is the pressure applied by the participant's standard at the local gravity g_l and the local air density ρ_a and calculated at the reference level of the transfer standard using equation (5.1) and *u*(*P*) is the standard uncertainty of *P*.

Table 5.2: 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 t_b [°C]	Reading R_a [kPa]		Reading R_b [kPa]		Applied Pressure *P* [kPa]	*u*(*P*) [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, NMIJ/AIST, collected the following data and information using the sheets annexed to the protocol[8,9].

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

(ii) Details of the participating institute's standard(s) against which the transfer standard was calibrated, including the origin of its traceability to the SI (presented in Table 2.2).

(iii) Details of the parameters used for the comparison. These were 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 5.3).

(iv) Uncertainty budget of the pressure generated, which were estimated and combined following GUM[6] under the responsibility of the participating institute. The uncertainties were evaluated at a level of one standard uncertainty at the participating institute.

Also, the uncertainty estimation of each pressure monitor calibrated was reported by the institutes optionally.

5.4 Parameters used by each participating institute

Details of the parameters used by each participating institute are listed in Table 5.3. The name of participating institute, the name of country, the local gravity, the height difference, the fluid density with associated standard uncertainties, the voltage and frequency applied to pressure monitors are presented.

Table 5.3: 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			Height diff. H		ρ_f (DHS)		Voltage / VAC	Frequency / Hz
			Value / m/s^2	Unc. / m/s^2	Unc. / 10^{-6}	Value / mm	Unc. / mm	Value / kg/m^3	Unc. / kg/m^3		
1	NMIJ/AIST	Japan	9.7994804	2.0E-06	0.20	0.0	0.5	Eq.(1)	1%	100	50
2	MSL	New Zealand	9.80279	1.0E-05	1.02	1	0.5	912	3	100	50
3	NML-SIRIM	Malaysia	9.78060	1.0E-05	1.02	0	1.0	912.7	12.5	100	50

Eq.(1) $\rho_f = [912.7 + 0.752\,(p/\mathrm{MPa}) - 1.645\cdot10^{-3}\,(p/\mathrm{MPa})^2 + 1.456\cdot10^{-6}\,(p/\mathrm{MPa})^3] \times [1 - 7.8 \times 10^{-4}\,(t/°\mathrm{C} - 20)]\ \mathrm{kg/m^3}$.

ρ_f: density of Di(2)-ethyl-Hexyl-Sebacate (DHS), p : pressure, t : temperature

6. Analysis of reported data

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

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

where the meanings of the parameters are as follows:

R [kPa]: Raw reading of pressure monitor,

P [kPa]: Applied pressure at the reference level of the transfer standard by pressure standard j,

t_b [℃]: Temperature measured on the transfer standard,

j : Index for participating institute,

m : Index for pressure monitor 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, $i \times 10$ MPa, $i = 0 – 10$,

n : Number of days from the beginning date, 1 June 2007, which was defined for purpose of evaluating a long-term shift with time, to the date which the calibration was performed.

In this section, the reduction and analysis of the data are performed by the following procedure:

6.1 Correction for zero-pressure offsets,

6.2 Correction for difference between nominal pressure and actual pressure,

6.3 Correction to reference temperature,

6.4 Correction for long-term shift in characteristics of transducer,

6.5 Normalization of mean ratio of transfer standard,

6.6 Calculation of normalized mean ratio of participating institute,

6.7 Calculation of expected mean pressure of participating institute,

6.8 Estimation of uncertainties.

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, it was confirmed that the reproducibility of the reading of pressure monitor 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 suffered at 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 first and last 0 MPa points of each cycle, respectively. By subtracting the offset from the raw reading R, the corrected reading R_{c0} is obtained as follows:

$$R_{c0}(j,m,y,w,i,n) = R(j,m,y,w,i,n) - R(j,m,y,w,0,n) \tag{6.1}$$

6.2 Correction for difference between nominal pressure and actual pressure

R_{c0} is the reading of pressure monitor when the actual pressure realized at the transfer standard by the participant's pressure standard, P, is applied. Since the readings of pressure monitors are nominally linear and the ratios of the readings of pressure monitors 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[8], the difference between actual pressure applied and the nominal target pressure was adjusted to be within one thousandth of the nominal pressure. The ratios can be used to correct the readings for deviations of the pressure standard from the nominal pressure. When an exact nominal pressure P_n is applied to the pressure monitor, the predicted reading, R_{c1}, is calculated by

$$R_{c1}(j,m,y,w,i,n) = \frac{R_{c0}(j,m,y,w,i,n)}{P(j,y,w,i)} \cdot P_n(i), \tag{6.2}$$

where R_{c0} and P are the simultaneous readings of pressure monitor and the actual pressure applied, respectively.

6.3 Correction to reference temperature

R_{c1} is the reading of each pressure monitor when the base temperature is t_b. Since the reading is affected by the temperature, the reading should be corrected. During the comparison, the effect on the reading by the temperature was evaluated by the pilot institute. Here, the temperature coefficient of each pressure monitor at each target nominal pressure, $\beta(m,i)$ [kPa/℃], is calculated by the following equation from calibration data obtained at the pilot institute $j = 1$:

$$\beta(m,i) = \frac{1}{12} \cdot \sum_{q=1}^{2} \sum_{w=1}^{2} \sum_{y=1}^{3} \frac{R_{c1}^{q}(1,m,y,w,i,n) - R_{c1}^{0}(1,m,y,w,i,n)}{t_b^{q}(1,y,w,i) - t_b^{0}(1,y,w,i)} \tag{6.3}$$

where t_b^q is the measured temperature on the transfer standard obtained from the calibration results performed at around 23 ℃ for $q = 0$, 20 ℃ for $q = 1$ and 26 ℃ for $q = 2$, respectively, and R_{c1}^q is the corresponding reading of each pressure monitor. The standard uncertainty of the coefficient was estimated as $u\{\beta(k,m,i)\} = u\{\beta(i)\} = 0.03$ kPa/℃.

Table 6.1 and Figure 6.1 present the calculated temperature coefficients of each pressure monitor for nominal target pressures. It has been confirmed that the reading of pressure monitor can be corrected sufficiently using the temperature coefficient.

Table 6.1: Temperature coefficients of each pressure monitor.

		Temperature coefficient, β / kPa/℃	
m		1	2
Monitor		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

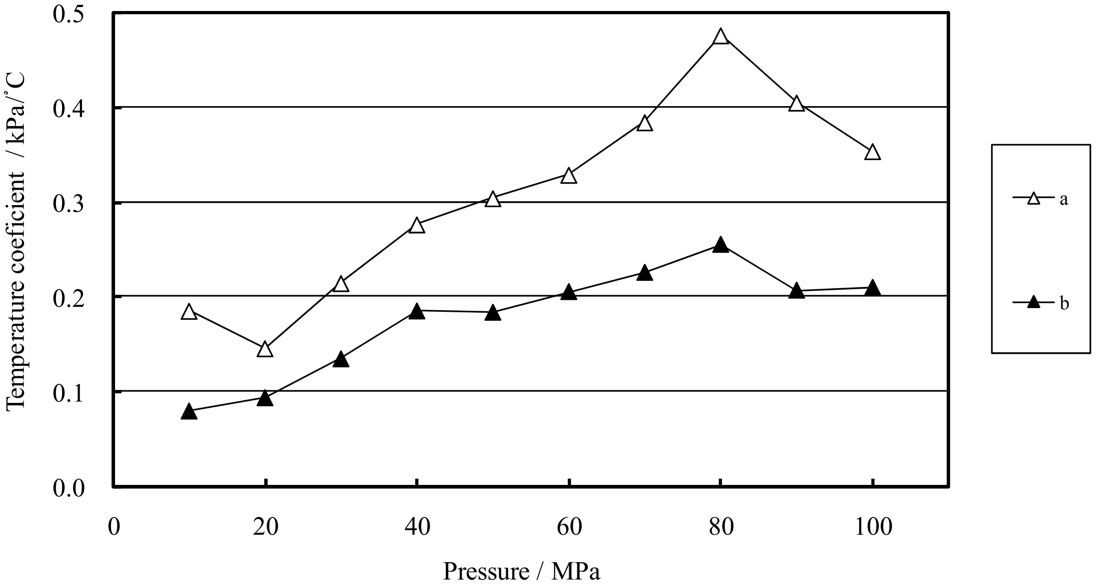

Figure 6.1: Calculated temperature coefficients of each pressure monitor as a function of nominal target pressure.

From the temperature coefficient calculated by equation (6.3), the reading corrected to a reference temperature, R_{c2}, can be calculated as

$$R_{c2}(j,m,y,w,i,n) = R_{c1}(j,m,y,w,i,n) - \beta(m,i)\cdot\left[t_b(j,y,w,i) - t_r\right]. \tag{6.4}$$

where t_r is the reference temperature which is determined as stated in the followings.

The average temperature measured on the transfer standard by a mercury thermometer by the participating institutes for nominal target pressure, $\overline{t_b}(j,i)$, is calculated from

$$\overline{t_b}(j,i) = \frac{1}{6}\cdot\sum_{w=1}^{2}\sum_{y=1}^{3} t_b(j,y,w,i) \tag{6.5}$$

For the pilot institute, $j = 1$, the average temperature is calculated from

$$\overline{t_b}(1,i) = \frac{1}{30}\cdot\sum_{l=1}^{5}\sum_{w=1}^{2}\sum_{y=1}^{3} t_b^l(1,y,w,i) \tag{6.6}$$

where t_b^l is the temperature on the transfer standard obtained from l-th simultaneous calibration data set (five data sets in total) performed at the pilot institute. Table 6.2 and Figure 6.2 present the average temperatures calculated from equations (6.5) and (6.6). Since the reference temperature was not described in the protocol[8], it should be determined to be fair for all participants. The average of all the values in Table 6.2 is 22.99 ℃. Therefore, by rounding the value up slightly, the reference temperature of this comparison was determined as $\underline{t_r} = 23.0$ ℃ so that the maximum temperature deviation of the participating institutes from the reference temperature was minimized. Since calibrations were performed at different temperatures, the uncertainty due to the deviation from the reference temperature has been estimated as described in later subsection.

Table 6.2: Average temperatures measured on the transfer standard by the participating institutes for nominal target pressures.

		Average temperature / ˚C		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
0	0	23.85	20.90	24.20
1	10	23.88	20.90	24.20
2	20	23.88	20.90	24.20
3	30	23.88	20.90	24.20
4	40	23.88	20.90	24.20
5	50	23.86	20.90	24.20
6	60	23.87	20.90	24.20
7	70	23.86	20.90	24.23
8	80	23.82	20.90	24.23
9	90	23.83	20.90	24.23
10	100	23.82	20.90	24.23
Average		23.86	20.90	24.21

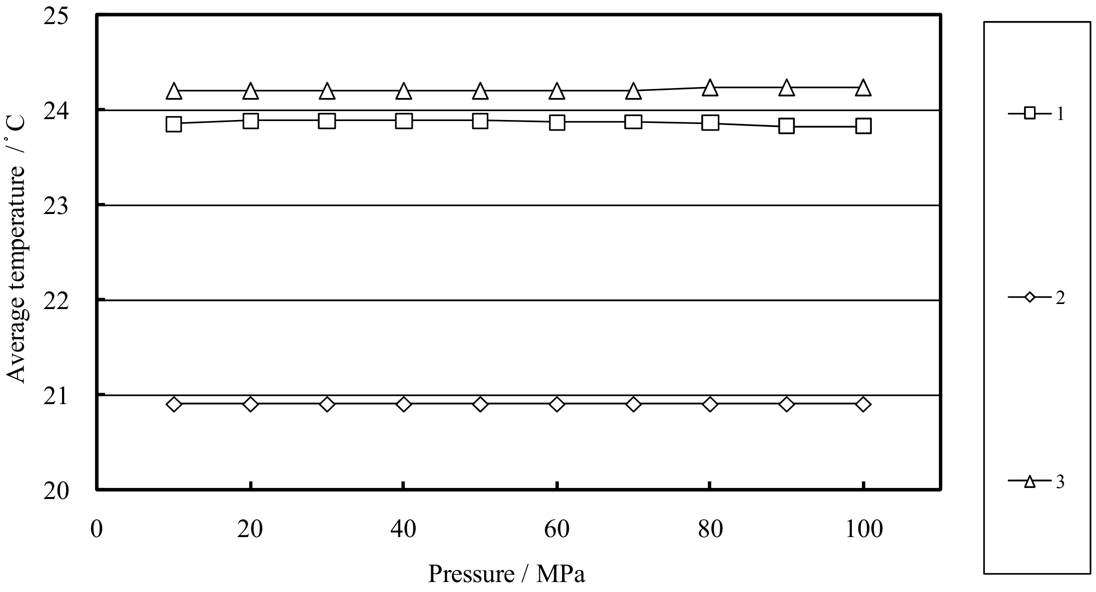

Figure 6.2: Average temperatures measured on the transfer standard by the participating institutes as a function of nominal target pressure.

6.4 Correction for long-term shift in characteristics of transducer

At the pilot institute, the transfer standard was calibrated by a primary pressure standard. A calibration set of three cycle measurements was repeated five times during the comparison. A long-term shift was observed as a monotonic drift with time in the characteristics of each transducer. It has been confirmed that the shifts were due to the characteristics of the transducers and were not the pressure standard at the pilot institute. The stability of the pressure standard of the pilot institute had been checked by cross-float comparison against other standard pressure balances during the period of this comparison and it was confirmed that there was no systematic shift in the primary pressure standard.

In this analysis, the shift was fitted by a least-squares-best-fitting straight line using R_{c2} taken during simultaneous calibrations against the pressure standard at the pilot institute.

$$R_e(m,w,i,n) = \alpha_0(m,w,i) \cdot n + \alpha_1(m,w,i). \tag{6.7}$$

where R_e is the predicted reading at the date which the calibration cycle was performed after n days from the beginning date, 1 June 2007. The predicted reading, once determined by the simultaneous calibrations, could be used to convert all comparison data. Table 6.3 lists the coefficients α_0 and α_1 calculated with the least-squares fit for the long-term shift obtained from five simultaneous calibrations at the pilot institute during this comparison. The relationships between the readings of two pressure monitors in the transfer standard can be known using equation (6.7) and the coefficients listed in Table 6.3. Figure 6.3 shows the coefficients α_0 obtained from the ascending sequence.

Table 6.3: Coefficients α_0 and α_1 calculated from the least-squares fit for pressure monitors.

			Coefficients for long-term shift, α0 / kPa/day, α1 / kPa			
m			1		2	
Monitor			a		b	
w	*i*	MPa	α_0	α_1	α_0	α_1
1	1	10	-7.044173E-05	1.000081E+04	-6.545008E-04	9.999870E+03
1	2	20	-3.255178E-05	2.000190E+04	2.036222E-04	2.000004E+04
1	3	30	-1.302681E-04	3.000197E+04	5.261242E-04	2.999952E+04
1	4	40	7.352479E-04	4.000311E+04	1.198809E-03	3.999912E+04
1	5	50	4.861685E-04	5.000464E+04	1.011798E-03	4.999936E+04
1	6	60	-1.383188E-04	6.000649E+04	6.606104E-04	5.999950E+04
1	7	70	5.717544E-04	7.000829E+04	2.661965E-03	6.999954E+04
1	8	80	1.251813E-03	8.001341E+04	3.694761E-03	7.999965E+04
1	9	90	1.294118E-03	9.001537E+04	3.967992E-03	9.000121E+04
1	10	100	7.033619E-05	1.000150E+05	2.728910E-03	1.000005E+05
2	10	100	1.593466E-03	1.000156E+05	4.203773E-03	1.000009E+05
2	9	90	1.337792E-03	9.001619E+04	4.112962E-03	9.000190E+04
2	8	80	1.199342E-03	8.001436E+04	3.687610E-03	8.000046E+04
2	7	70	2.090855E-03	7.000912E+04	4.161355E-03	7.000028E+04
2	6	60	2.165317E-03	6.000735E+04	3.516433E-03	6.000018E+04
2	5	50	1.637116E-03	5.000554E+04	2.593332E-03	5.000014E+04
2	4	40	1.240554E-03	4.000392E+04	1.878931E-03	3.999990E+04
2	3	30	1.123396E-03	3.000256E+04	1.428992E-03	3.000014E+04
2	2	20	4.214546E-04	2.000234E+04	5.064342E-04	2.000043E+04
2	1	10	2.779561E-04	1.000105E+04	4.748146E-05	9.999967E+03

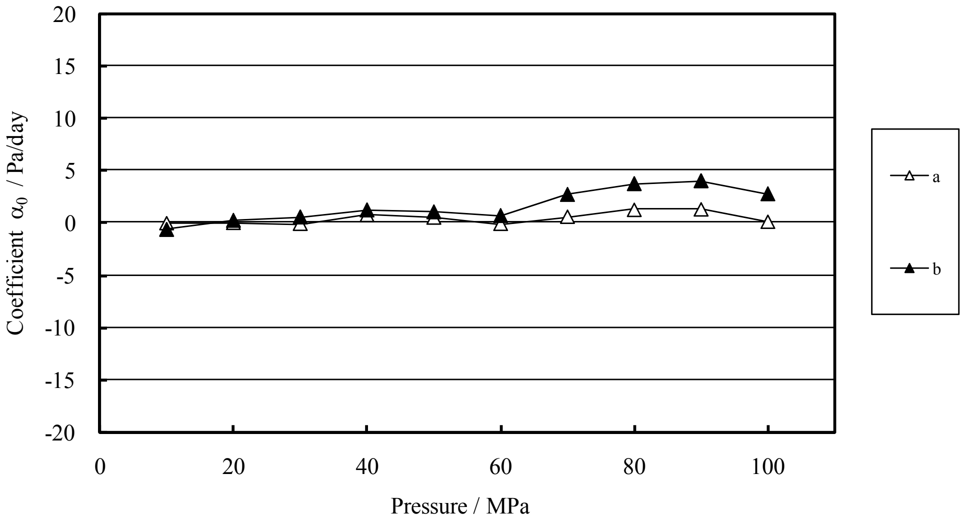

Figure 6.3: Coefficients $\alpha_0(m,1,i)$ calculated with the least-squares fit for the long-term shifts as a function of nominal target pressure.

6.5 Normalization of mean ratio of transfer standard

By taking the ratios of R_{c2} to R_e, the normalized mean ratio for each calibration point, s_0, is calculated as

$$s_0(j,m,y,w,i)=\frac{R_{c2}(j,m,y,w,i,n)}{R_e(m,w,i,n)} \tag{6.8}$$

By taking the average of s_0 for ascending and descending pressures of three cycles, the normalized mean ratio of each pressure monitor, s_1, is calculated as

$$s_1(j,m,i)=\frac{1}{6}\cdot\sum_{w=1}^{2}\sum_{y=1}^{3}s_0(j,m,y,w,i) \tag{6.9}$$

There were two pressure monitors in the transfer standard. By taking the average of s_1 for the pressure monitors, the normalized mean ratio of the transfer standard, s_2, is calculated as

$$s_2(j,i)=\frac{1}{2}\cdot\sum_{m=1}^{2}s_1(j,m,i) \tag{6.10}$$

From l-th calibration at the pilot institute $j = 1$, the normalized mean ratios, $s_1^l(1,m,i)$ and $s_2^l(1,i)$, were obtained using equations (6.9) and (6.10). Figures 6.4 presents the instabilities of the transfer standard expressed as the deviations of $s_2^l(1,i)$ from unity, respectively.

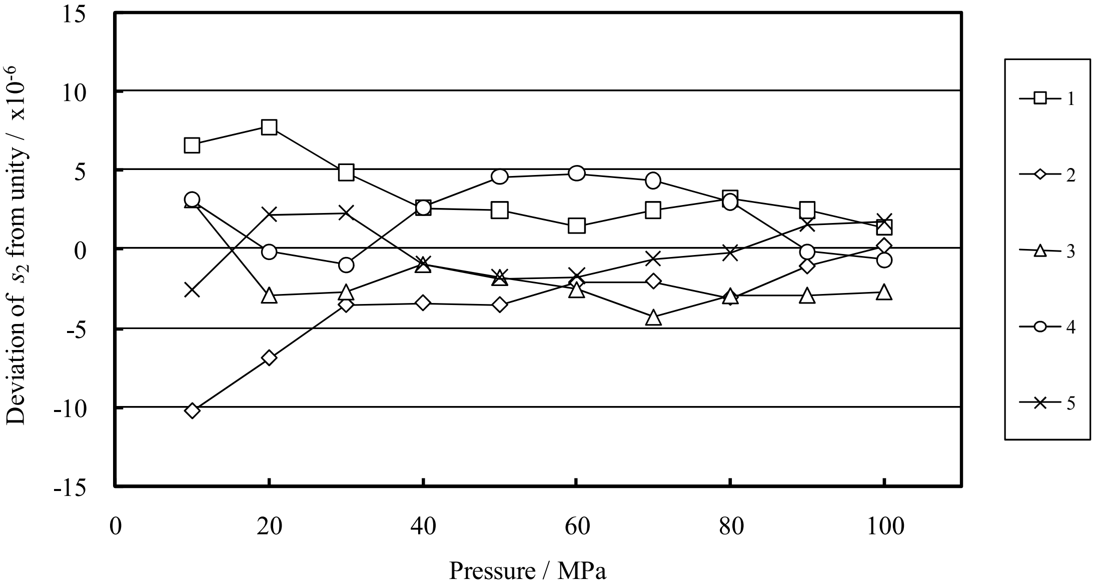

Figure 6.4: Instability of the transfer standard expressed as the deviations of $s_2^l(1,i)$ from unity.

Table 6.4 and Figure 6.5 present the instabilities of the transfer standard expressed as the standard deviations, $\sigma\{s_1^l(1,m,i)\}$ and $\sigma\{s_2^l(1,i)\}$, calculated from five values of $s_1^l(1,m,i)$ and $s_2^l(1,i)$ about their mean, respectively. The standard deviations at each pressure are generally less than 5×10^{-6} in the pressure ranges between 30 MPa and 100 MPa and 10×10^{-6} at maximum for the transfer standard. From these results, it can be stated that the stability of the transfer standard was capable of comparing the pressure standards established by the participating institutes. The instabilities of the transfer standard have been incorporated into the uncertainty evaluation as described in the later subsection.

Table 6.4: Instabilities of the transfer standard expressed as the standard deviations, $\sigma\{s_1^l(1,m,i)\}$ and $\sigma\{s_2^l(1,i)\}$, which are the standard deviations of five values of $s_1^l(1,m,i)$ and $s_2^l(1,i)$ about their mean, respectively. $s_1^l(1,m,i)$ and $s_2^l(1,i)$ are the normalized mean ratios obtained from *l*-th simultaneous calibration data set (five sets in total) performed at the pilot institute.

		Standard deviations of normalized mean ratios, $\sigma(s_1^{\,l})$ and $\sigma(s_2^{\,l})$ / $\times 10^{-6}$		
$\sigma(s^l)$		$\sigma(s_1^{\,l})$	$\sigma(s_1^{\,l})$	$\sigma(s_2^{\,l})$
m		1	2	
i	MPa	a	b	Aver.
1	10	10.7	12.7	11.7
2	20	7.4	9.4	8.5
3	30	4.7	6.7	5.8
4	40	2.8	4.3	3.6
5	50	2.5	4.7	3.8
6	60	2.3	3.8	3.2
7	70	2.7	4.2	3.5
8	80	2.6	4.0	3.3
9	90	2.1	2.8	2.4
10	100	1.7	2.2	2.0

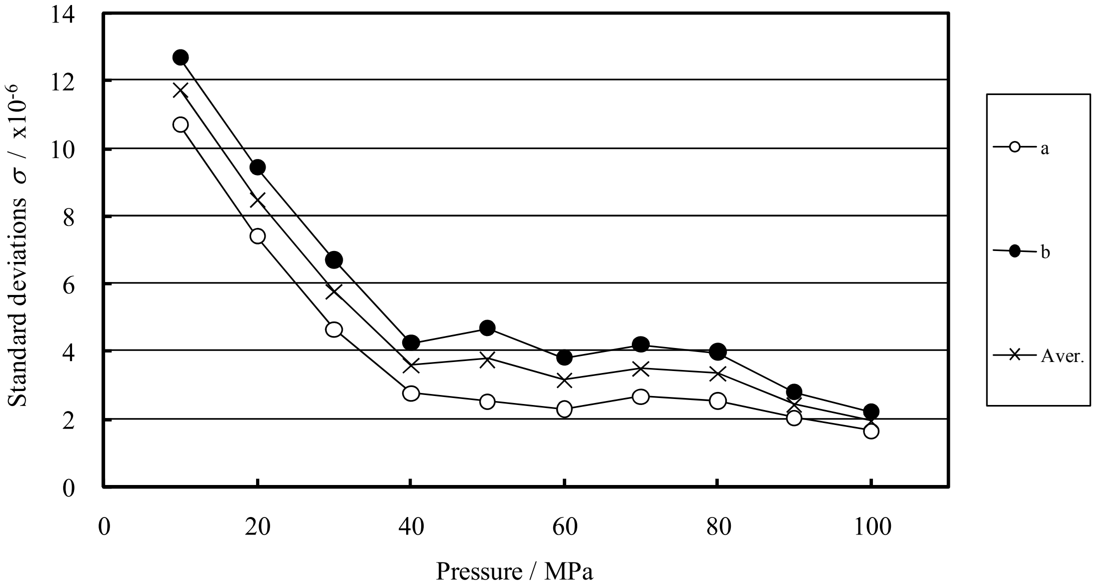

Figure 6.5: Instabilities of the transfer standard expressed as the standard deviations, $\sigma\{s_1^l(1,m,i)\}$ and $\sigma\{s_2^l(1,i)\}$, as a function of nominal target pressure.

6.6 Calculation of normalized mean ratio of participating institute

Since the predicted reading R_e was determined by the least-squares method using data obtained from five simultaneous calibrations at the pilot institute j = 1, the following relation can be derived for the transfer standard,

$$\frac{1}{5}\cdot\sum_{l=1}^{5}\left[s_2^l(1,i)\right]=1$$

(6.11)

where s_2^l is the normalized mean ratio of the transfer standard obtained from l-th calibration performed at the pilot institute. Therefore, the relationships between the normalized mean ratios obtained from two pressure monitors in the transfer standard were already compensated to compare pressure standards used to calibrate different transfer standard.

For j-th non-pilot participating institute, the normalized mean ratio of the institute, S, is obtained from

$$S(j,i)=s_2(j,i).$$

(6.12)

Ratio S provides a common basis for comparing the results reported by participants.

For the pilot institute j = 1, S is calculated from

$$S(1,i)=\frac{1}{5}\cdot\sum_{l=1}^{5}\left[s_2^l(1,i)\right].$$

(6.13)

As understood from equation (6.11), $S(1,i) = 1$.

Table 6.5 and Figure 6.6 present the deviations from the normalized mean ratios of the institutes from unity, $S(j,i)-1$, obtained from calibrations at the pilot institute and other participating institutes as a function of nominal target pressure.

Table 6.5: Deviations of the normalized mean ratios of the institutes from unity, $S-1$, for nominal target pressures.

		Deviation of normalized mean ratio from unity, $\{S(j,i)-1\}$ / $\times 10^{-6}$		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	0.0	9.4	-28.5
2	20	0.0	-6.3	-25.5
3	30	0.0	-6.3	-25.7
4	40	0.0	-5.4	-25.6
5	50	0.0	-3.9	-22.5
6	60	0.0	4.0	-21.3
7	70	0.0	12.3	-21.1
8	80	0.0	21.3	-21.1
9	90	0.0	30.4	-19.8
10	100	0.0	38.6	-18.7

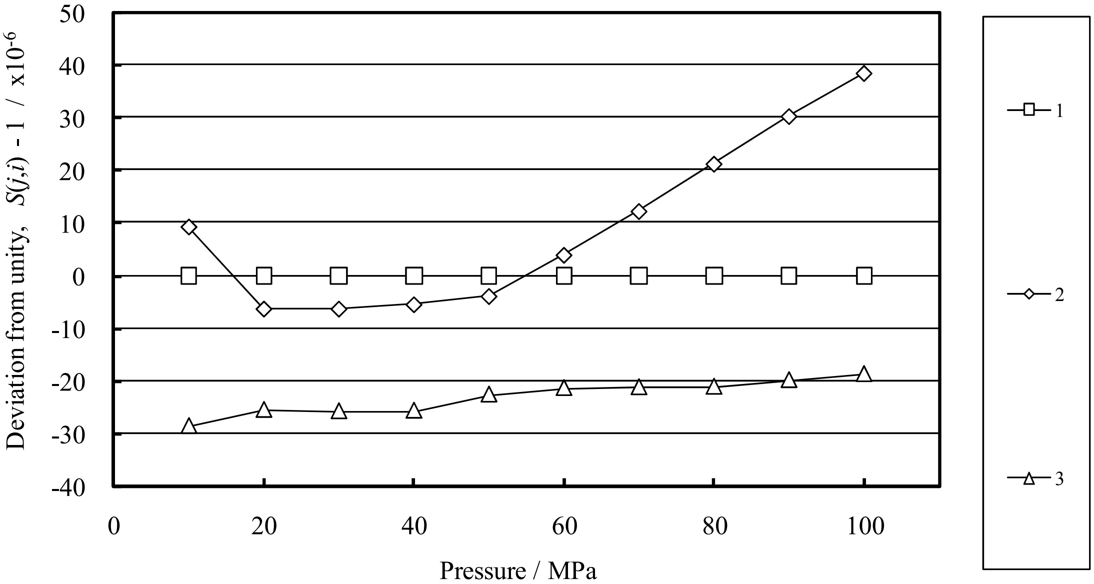

Figure 6.6: Deviations of the normalized mean ratios of the institutes from unity, $S-1$, as a function of nominal target pressure.

6.7 Calculation of expected mean pressure of participating institute

Expected mean pressure of participating institute, $p(j,i)$, is calculated by

$$p(j,i) = S(j,i) \cdot P_n(i). \tag{6.14}$$

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

$p(j,i)$ is taken as an indicator of the expected pressure actually generated by the pressure standard of the participating institute when the institute claims to generate the nominal target pressure. The results for $p(j,i)$ from individual institutes are presented in Table 6.6.

Table 6.6: Expected mean pressures of the institutes for nominal target pressures.

		Mean pressure, $p(j,i)$ / MPa		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	10.00000	10.00009	9.99971
2	20	20.00000	19.99987	19.99949
3	30	30.00000	29.99981	29.99923
4	40	40.00000	39.99978	39.99898
5	50	50.00000	49.99981	49.99887
6	60	60.00000	60.00024	59.99872
7	70	70.00000	70.00086	69.99852
8	80	80.00000	80.00170	79.99832
9	90	90.00000	90.00273	89.99822
10	100	100.00000	100.00386	99.99813

6.8 Estimation of uncertainties

In this subsection, all the uncertainties are expressed as the standard ones. The relative combined standard uncertainty in the normalized mean ratio of *j*-th participating institute, *S*(*j*,*i*), may be estimated from the root-sum-square of four component uncertainties.

$$u_c\{S(j,i)\} = \sqrt{u_{std}^2\{S(j,i)\} + u_{tem}^2\{S(j,i)\} + u_{rdm}^2\{S(j,i)\} + u_{lts}^2\{S(j,i)\}}$$

(6.15)

where $u_{std}\{S\}$ is the uncertainty in *S* due to systematic effects in pressure standard *j*, $u_{tem}\{S\}$ is the uncertainty in correcting the readings to equivalent values at the reference temperature, $u_{rdm}\{S\}$ is the uncertainty due to combined effect of short-term random errors of transfer standard used and pressure standard *j* during calibration and $u_{lts}\{S\}$ is the uncertainty arising from long-term shift in the characteristics of the transducers in the transfer standard calibrated at *j*-th institute.

6.8.1 Uncertainty due to systematic effect in pressure standard

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

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

(6.16)

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

Table 6.7 and Figure 6.7 present the estimated relative standard uncertainties arising from systematic effects in the pressure standards used in the comparison, as reported by the participating institutes for the nominal target pressures. The uncertainty due to the hydrostatic head correction was assumed to be included 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 each participating institute.

Table 6.7: Relative standard uncertainties, as claimed by the participants, due to systematic effects in their pressure standards.

		Relative standard uncertainty of applied pressure reported by participating institute, $u_{std}\{S(j,i)\}$ / ×10^{-6}		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	13.1	28.0	18.0
2	20	13.0	23.0	16.0
3	30	13.2	22.3	15.3
4	40	13.4	23.3	15.3
5	50	13.8	24.8	15.6
6	60	14.2	26.3	15.3
7	70	14.6	28.1	15.3
8	80	15.1	30.1	15.3
9	90	15.7	32.0	15.1
10	100	16.3	34.0	15.3

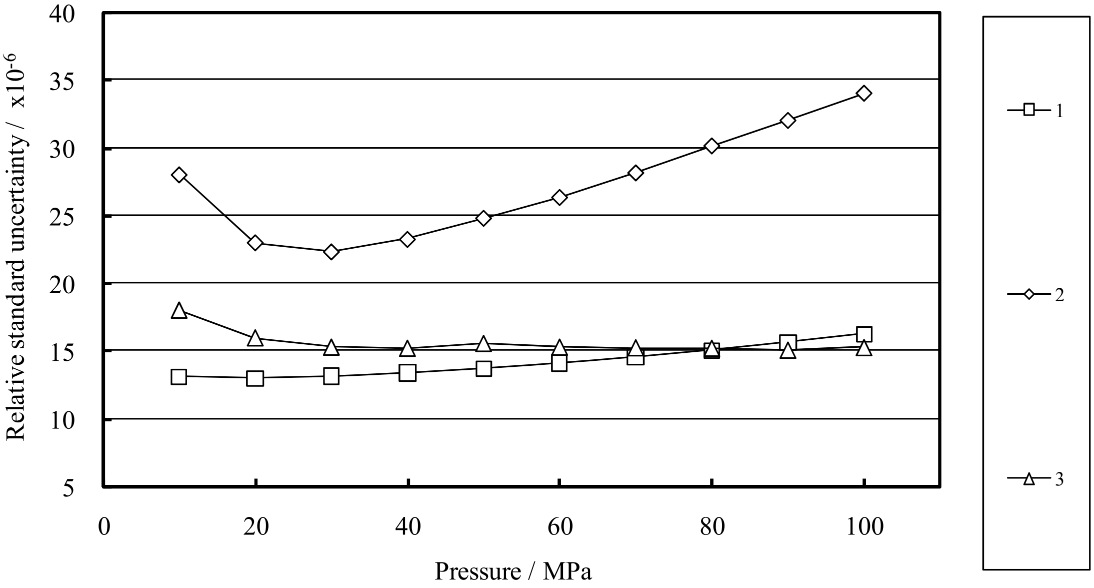

Figure 6.7: Relative standard uncertainties, as claimed by the participants, due to systematic effects in their pressure standards as a function of nominal target pressure.

6.8.2 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, $u\{S_{tem}\}$, can be estimated from

$$u_{tem}\{S(j,i)\} = \frac{u\{\beta(i)\}}{P_n(i)} \cdot \left| \overline{t_b}(j,i) - t_r \right|$$

(6.17)

where $u\{\beta(i)\}$ is the calculated standard uncertainty in the temperature coefficient, which was estimated as $u\{\beta(i)\}$= 0.03 kPa/℃ in the previous subsection. $\overline{t_b}(j,i)$ is the average temperature measured on the transfer standard by the participating institutes for nominal target pressures calculated from equations (6.5) or (6.6), t_r is the reference temperature of this comparison determined as t_r = 23.0 ℃. The uncertainty in $\overline{t_b}(j,i)$ may also contribute an uncertainty to $u_{tem}\{S\}$. However this systematic contribution was so small that the uncertainty made a negligible contribution to the uncertainty evaluated by equation (6.17). Table 6.8 and Figure 6.8 present the estimated standard uncertainties, $u_{tem}\{S\}$, calculated from equations (6.17).

Table 6.8: Relative standard uncertainties in correcting the readings to equivalent values at the reference temperature.

		Relative standard uncertainty due to deviation from reference temperature, $u_{tem}\{S(j,i)\}$ / ×10^{-6}		
	j	1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	2.6	6.3	3.6
2	20	1.3	3.2	1.8
3	30	0.9	2.1	1.2
4	40	0.7	1.6	0.9
5	50	0.5	1.3	0.7
6	60	0.4	1.1	0.6
7	70	0.4	0.9	0.5
8	80	0.3	0.8	0.5
9	90	0.3	0.7	0.4
10	100	0.2	0.6	0.4

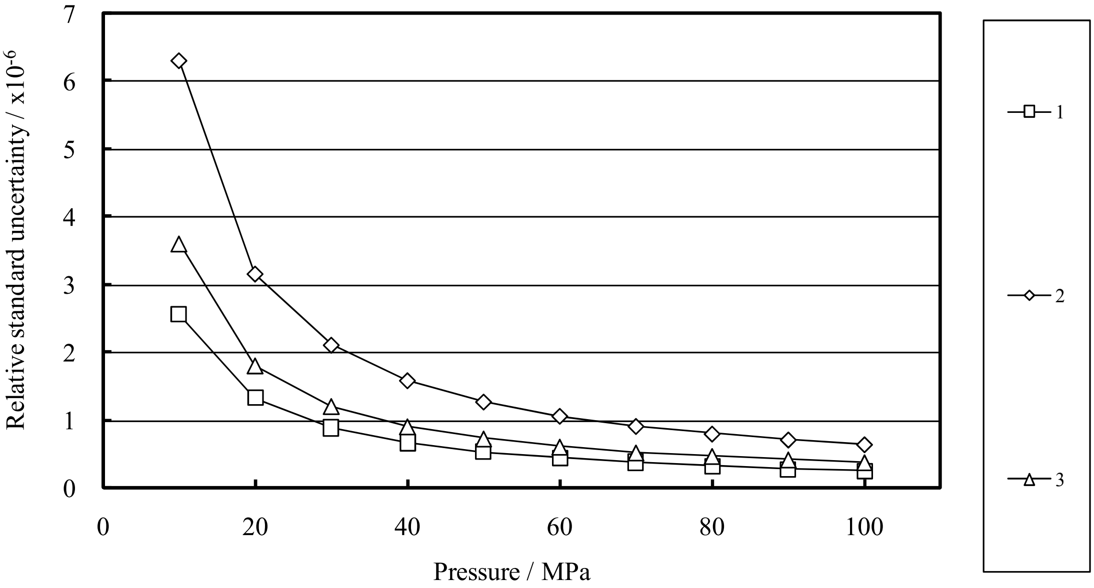

Figure 6.8: Relative standard uncertainties in correcting the readings to equivalent values at the reference temperature as a function of nominal target pressure.

6.8.3 Uncertainty due to combined effect of short-term random errors

The standard uncertainty in S due to combined effect of short-term random errors of the transfer standard calibrated, $u_{rdm}\{S\}$, can be estimated from the corresponding uncertainties in the normalized mean ratios by statistical methods.

For j-th non-pilot participating institute, the uncertainty is obtained from

$$u_{rdm}^2\{S(j,i)\} = \sigma^2\{s_0(j,m,y,w,i)\}/12 \tag{6.18}$$

where $\sigma\{s_0(j,m,y,w,i)\}$ is the standard deviation of twelve values of $s_0(j,m,y,w,i)$ about its mean.

For the pilot institute $j = 1$, the uncertainty is calculated from

$$u_{rdm}^2\{S(1,i)\} = \frac{1}{5}\cdot\sum_{l=1}^{5}\left[\sigma^2\{s_0^l(1,m,y,w,i)\}/12\right] \tag{6.19}$$

where $s_0^l(1,m,y,w,i)$ is the normalized mean ratio obtained from l-th simultaneous calibration set (five sets in total) performed at the pilot institute, $\sigma\{s_0^l(1,m,y,w,i)\}$ is the standard deviation of twelve values of $s_0^l(1,m,y,w,i)$ about its mean. The multiple calibrations at the pilot institute tend to reduce the influence of uncorrelated uncertainties arising from short-term variability for the pilot institute[12].

Table 6.9 and Figure 6.9 present the estimated standard uncertainties due to combined effect of short-term random errors calculated from equations (6.18) and (6.19).

Table 6.9: Relative standard uncertainties in the normalized mean ratios due to combined effects of short-term random errors.

		Standard uncertainty due to combined effects of short-term random effects, $u_{rdm}\{S(j,i)\}$ / $\times10^{-6}$		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	5.4	4.0	4.7
2	20	3.3	2.8	3.4
3	30	3.1	1.8	2.2
4	40	2.7	1.8	2.0
5	50	2.1	1.6	1.9
6	60	1.8	1.1	1.8
7	70	1.7	0.7	1.2
8	80	1.4	0.7	1.4
9	90	1.4	0.6	1.2
10	100	1.2	0.7	1.0

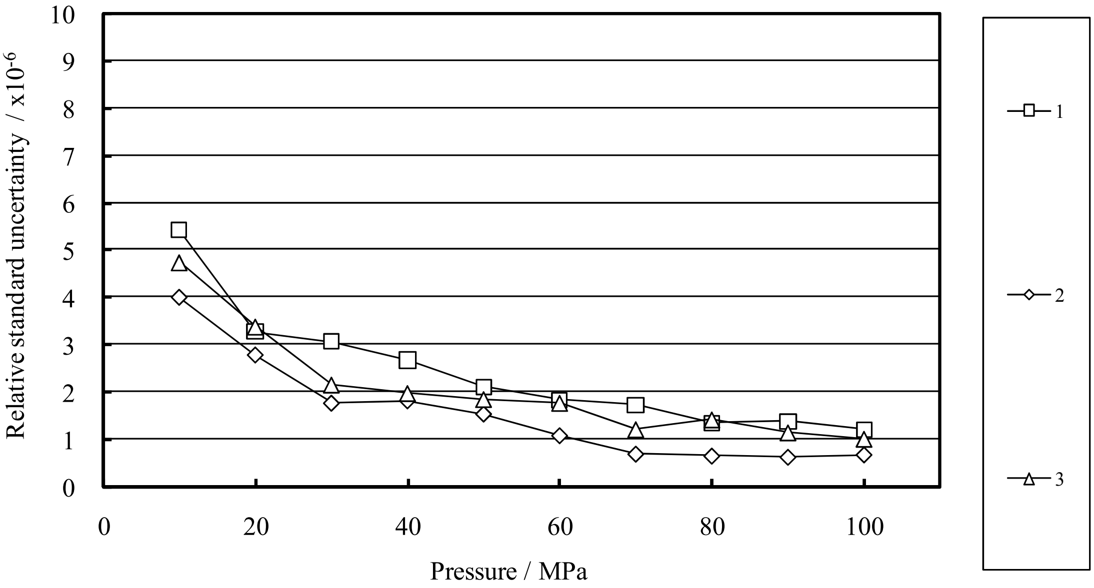

Figure 6.9: Relative standard uncertainties in the normalized mean ratios due to short-term random errors as a function of nominal target pressure.

6.8.4 Uncertainty arising from the long-term shift

The long-term shift of a pressure transducer between calibrations should be considered in the uncertainties. The deviations from unity of $s_1(j,m,i)$ and $s_2(j,i)$ obtained from the five calibrations seemed to be almost random at each nominal target pressure as presented in Figures 6.4 and 6.5. Therefore, the relative standard uncertainty in the normalized mean ratio of *j*-th participating institute due to long-term shift, $u_{lts}\{S(j,i)\}$, was estimated as follows:

In the case that two monitors in the transfer standard were calibrated at *j*-th participating institute,

$$u_{lts}^2\{S(j,i)\} = \sigma^2\{s_2^l(1,i)\} \tag{6.20}$$

where $\sigma\{s_2^l(1,i)\}$ is the standard deviation of five values of $s_2^l(1,i)$ about its mean, which is listed in Table 6.4.

At the pilot institute *j* = 1, the transfer standard was calibrated five times. The relative uncertainty arising from long-term shifts of the transfer standard for the pilot institute, $u_{lts}\{S(1,i)\}$, is estimated as follows:

$$u_{lts}^2\{S(1,i)\} = \frac{1}{5}\cdot\sigma^2\{s_2^l(1,i)\} \tag{6.21}$$

6.8.5 Combined uncertainty in normalized mean ratio of institute

The combined standard uncertainty in the normalized mean ratio of the institute is estimated by combining the component uncertainties using the "root-sum-squares" method according to equation (6.15) and is presented in Table 6.10 and Figure 6.10.

Table 6.10: Combined standard uncertainties in normalized mean ratios of institutes, $u_c\{S\}$.

		Combined standard uncertainty, $u_c\{S(j,i)\}$ / ×10^{-6}		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	15.3	31.3	22.3
2	20	14.0	24.9	18.5
3	30	13.8	23.2	16.6
4	40	13.8	23.6	15.8
5	50	14.0	25.2	16.2
6	60	14.3	26.6	15.8
7	70	14.8	28.4	15.7
8	80	15.3	30.3	15.7
9	90	15.8	32.1	15.4
10	100	16.3	34.1	15.5

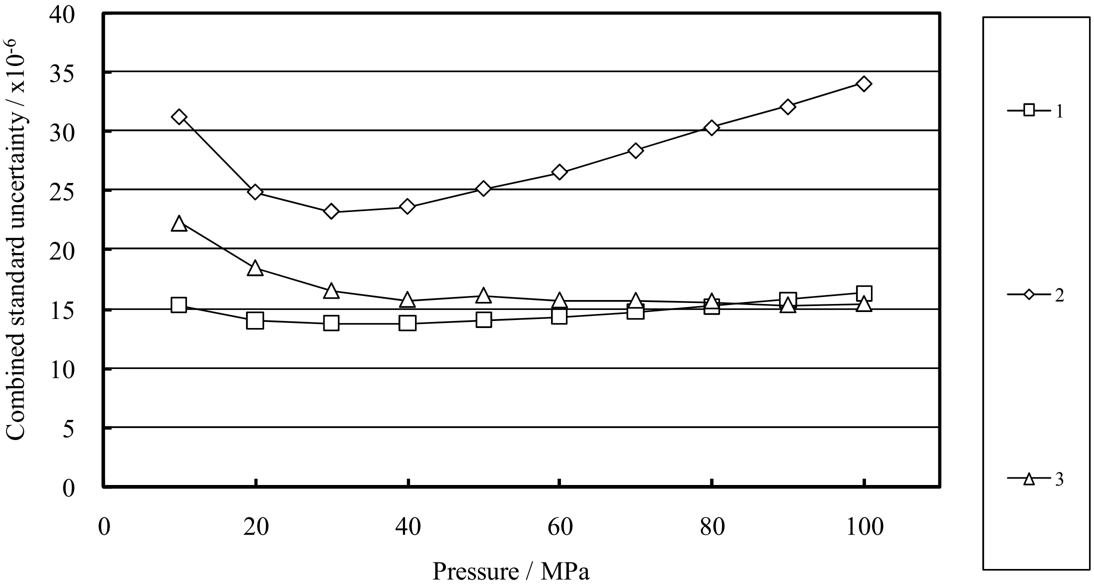

Figure 6.10: Combined standard uncertainties in normalized mean ratios of institutes as a function of nominal target pressure.

6.8.6 Combined uncertainty in expected mean pressure of institute

The combined standard uncertainty of the expected mean pressure of participating institute, $u_c\{p(j,i)\}$, is calculated from $u_c\{S(j,i)\}$ by

$$u_c\{p(j,i)\} = u_c\{S(j,i)\} \cdot P_n(i). \tag{6.22}$$

where $P_n(i)$ is the nominal target pressure. $u_c\{p(j,i)\}$ is presented in Table 6.11 and Figure 6.11.

Table 6.11: Combined standard uncertainties in expected mean pressures of institutes, $u_c\{p\}$.

		Combined standard uncertainty, $u_c\{p(j,i)\}$ / kPa		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	0.153	0.313	0.223
2	20	0.280	0.497	0.370
3	30	0.414	0.697	0.497
4	40	0.552	0.946	0.633
5	50	0.701	1.258	0.809
6	60	0.861	1.594	0.946
7	70	1.036	1.987	1.102
8	80	1.220	2.426	1.255
9	90	1.420	2.890	1.382
10	100	1.635	3.407	1.546

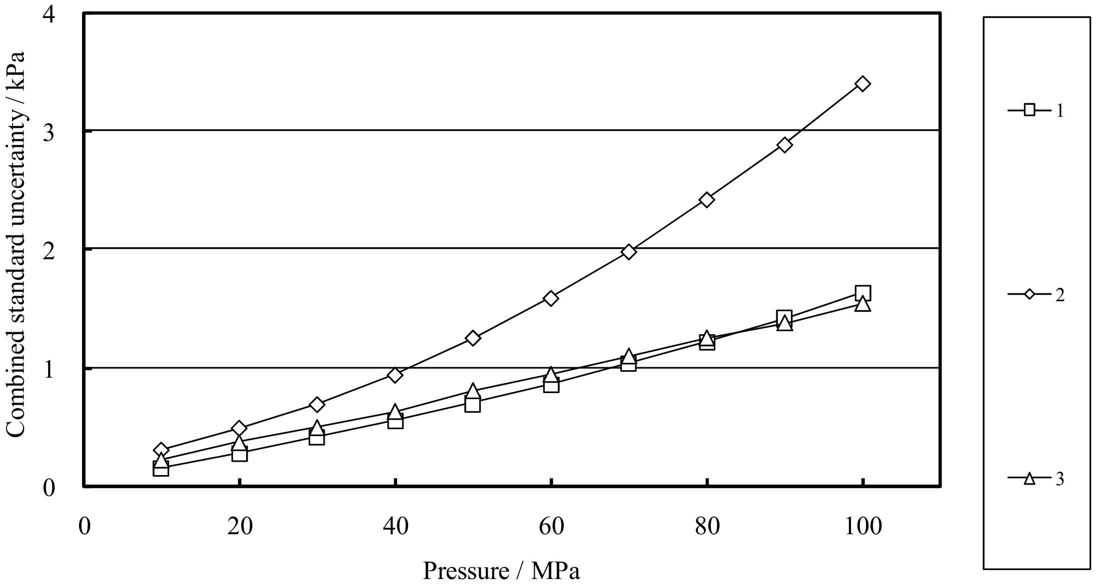

Figure 6.11: Combined standard uncertainties in expected mean pressures of institutes as a function of nominal target pressure.

7. Results for key comparison APMP.M.P-K7.1

The results for key comparison APMP.M.P-K7.1 are processed by the following procedure:

7.1 Calculation of Key Comparison Reference Values (KCRVs),

7.2 Evaluation of degrees of equivalence.

7.1 Calculation of APMP Key Comparison Reference Values

The key comparison reference value (KCRV) is interpreted as an estimate of the measurand on the basis of the measurements provided by the participating institutes. In the guidelines[2], it is described that "In calculating the KCRV, the pilot institute will use the method considered most appropriate for the particular comparison." Several methods for defining a KCRV have been proposed[13]. The typical methods are (i) the simple mean method, (ii) the weighted mean method and (iii) the median method. Each method has some advantages and disadvantages. However, the simple mean values are known to lack stability against the effect of "outliers" [14].

For the APMP comparison, the median value of the expected mean pressure obtained from all participating institutes is calculated at the nominal target pressure as the KCRV for this key comparison, $p(KCRV, i)$, using similar ways as given in the key comparison APMPM.P-K7[5].

According to the method of Müller[14], the uncertainty of the median can be estimated by taking *MAD*, which is the median of absolute deviations from the median of the results, multiplying by 1.858 and dividing the square root of one less than the number of participating institute contributing to the reference value [14].

$$u\{p(KCRV,i)\} = \frac{1.858 \cdot MAD}{\sqrt{n-1}} \tag{7.1}$$

where $u\{p(KCRV,i)\}$ is the standard uncertainty of $p(KCRV,i)$.

Table 7.1 presents the KCRVs and their combined standard uncertainties calculated for the expected mean pressures.

Table 7.1: APMP Key comparison reference values and their standard uncertainties calculated for the expected mean pressures.

i	Nom. Tar. Pressure / MPa	$p(KCRV,i)$ / MPa	$u\{p(KCRV,i)\}$ / MPa
1	10	10.000000	0.123
2	20	19.999875	0.165
3	30	29.999812	0.247
4	40	39.999783	0.286
5	50	49.999807	0.254
6	60	60.000000	0.313
7	70	70.000000	1.131
8	80	80.000000	2.213
9	90	90.000000	2.341
10	100	100.000000	2.450

7.2 Evaluation of degrees of equivalence

In the MRA the term “degree of equivalence of the measurement standards” is taken to mean the degree to which a standard is consistent with a Key Comparison Reference Value (KCRV) or with a measurement standard at another institute[1].

Therefore, the degrees of equivalence of the pressure standards for this comparison are expressed using the expected mean pressures quantitatively in two ways:

(1) Deviations of participating institute’s values from KCRVs,

(2) Differences between deviations for pairs of participating institutes.

7.2.1 Deviation of institute’s value from APMP KCRV

By comparing the expected mean pressure of j-th participating institute relative to a KCRV, the relative deviation from the reference value, $\Delta(j,i)$, is calculated by the following equation:

$$\Delta(j,i) = \frac{p(j,i) - p(KCRV,i)}{p(KCRV,i)} \tag{7.2}$$

and the relative expanded uncertainty of $\Delta(j,i)$, $U\{\Delta(j,i)\}$, is estimated from

$$U\{\Delta(j,i)\} = k \cdot u_c\{\Delta(j,i)\} = k \cdot \frac{\sqrt{u^2\{p(j,i)\} + u^2\{p(KCRV,i)\}}}{p(KCRV,i)} \tag{7.3}$$

where $u_c\{\Delta(j,i)\}$ is the combined standard uncertainty of the relative deviation, k is the coverage factor and k = 2 is adopted, $u\{p(j,i)\}$ and $u\{p(KCRV,i)\}$ are the combined uncertainties in the expected mean pressure of the institute and the reference value.

Table 7.2 presents the relative deviations from reference values, $\Delta(j,i)$, the expanded (k = 2) uncertainties of the relative deviations, $U\{\Delta(j,i)\}$, and the degrees of equivalence expressed by the ratios, $\Delta(j,i)/U\{\Delta(j,i)\}$, for individual NMIs. Figure 7.1 provides a measure of the degree of equivalence by the relative magnitude of the deviation, $\Delta(j,i)/U\{\Delta(j,i)\}$. For the present comparison, the condition $|\Delta(j,i)/U\{\Delta(j,i)\}| \leq 1$ was established for all the participating institutes at all nominal target pressures.

Table 7.2: Deviations from the APMP KCRVs, $\Delta(j,i)$ [upper], the expanded (k = 2) uncertainties of the deviations, $U\{\Delta(j,i)\}$ [middle] and the degrees of equivalence as expressed by the ratios, $\Delta(j,i)/U\{\Delta(j,i)\}$ [lower].

		$\Delta(j,i) = \{p(j,i) - p(KCRV,i)\} / p(KCRV,i)$ / $\times 10^{-6}$		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	0.0	9.4	-28.5
2	20	6.3	0.0	-19.2
3	30	6.3	0.0	-19.5
4	40	5.4	0.0	-20.2
5	50	3.9	0.0	-18.7
6	60	0.0	4.0	-21.3
7	70	0.0	12.3	-21.1
8	80	0.0	21.3	-21.1
9	90	0.0	30.4	-19.8
10	100	0.0	38.6	-18.7

		Expanded uncertainty, $U\{\Delta(j,i)\}$ / $\times 10^{-6}$ ($k = 2$)		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	39.3	67.2	50.9
2	20	32.5	52.4	40.5
3	30	32.1	49.3	37.0
4	40	31.1	49.4	34.7
5	50	29.8	51.3	33.9
6	60	30.5	54.1	33.2
7	70	43.8	65.3	45.1
8	80	63.2	82.1	63.6
9	90	60.8	82.6	60.4
10	100	58.9	83.9	57.9

		$\Delta(j,i) / U\{\Delta(j,i)\}$		
j		1	2	3
i	MPa	NMIJ/AIST	MSL	NML-SIRIM
1	10	0.00	0.14	-0.56
2	20	0.19	0.00	-0.47
3	30	0.19	0.00	-0.53
4	40	0.17	0.00	-0.58
5	50	0.13	0.00	-0.55
6	60	0.00	0.07	-0.64
7	70	0.00	0.19	-0.47
8	80	0.00	0.26	-0.33
9	90	0.00	0.37	-0.33
10	100	0.00	0.46	-0.32

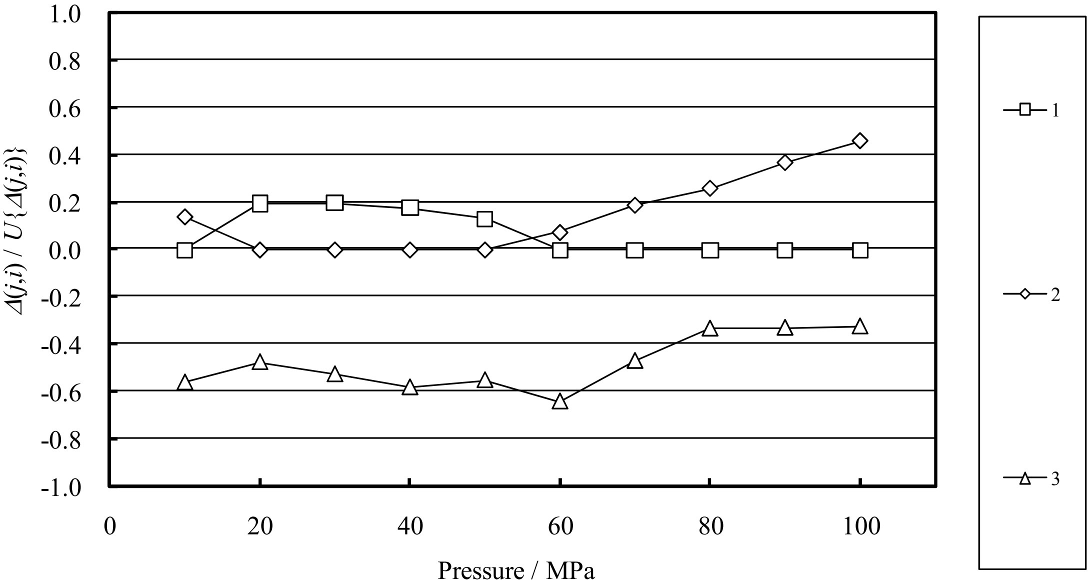

Figure 7.1: Degrees of equivalence of the participating institutes with respect to key comparison reference values. Ratios $\Delta(j,i)/U\{\Delta(j,i)\}$ for the participating institutes are plotted as a function of nominal target pressure.

7.2.2 Difference between deviations for pairs of institutes

The degree of equivalence between pairs of pressure standards *j* and *j'* is calculated by the following equation:

$$\delta(j,j',i)=\Delta(j,i)-\Delta(j',i)=\frac{p(j,i)-p(j',i)}{p(KCRV,i)}$$

(7.4)

where $\delta(j,j',i)$ is the relative difference of their deviations from the reference values, and the relative expanded uncertainty of the difference, $U\{\delta(j,j',i)\}$, is estimated from

$$U\{\delta(j,j',i)\}=k\cdot u_c\{\delta(j,j',i)\}=k\cdot\frac{\sqrt{u^2\{p(j,i)\}+u^2\{p(j',i)\}}}{p(KCRV,i)}$$

(7.5)

where $u_c\{\delta(j,j',i)\}$ is the combined standard uncertainty of the difference, *k* is the coverage factor and *k* = 2 is adopted, $u\{p(j,i)\}$ and $u\{p(j',i)\}$ are the combined uncertainties in the expected mean pressure of *j*-th and *j'*-th institutes, respectively.

Tables 7.3, 7.4 and 7.5 present a summary of results of the differences, $\delta(j,j',i)$, the expanded (*k* = 2) uncertainties of the differences, $U\{\delta(j,j',i)\}$, and the degrees of equivalence expressed by the ratios, $\delta(j,j',i)/U\{\delta(j,j',i)\}$, for the participating institutes. A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $\delta(j,j',i)/U\{\delta(j,j',i)\}\leq 1$. For the present comparison, the condition was established for all the pairs of the participating institutes at all nominal target pressures.

Table 7.3: Differences, $\delta(j, j', i) = \Delta(j,i) - \Delta(j',i)$.

j	Institute			Differences between deviations, $\delta(j,j',i) = \Delta(j,i) - \Delta(j',i)$ / $\times 10^{-6}$		
		j'		1	2	3
1	NMIJ/AIST	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10		-9.4	28.5
		2	20		6.3	25.5
		3	30		6.3	25.7
		4	40		5.4	25.6
		5	50		3.9	22.5
		6	60		-4.0	21.3
		7	70		-12.3	21.1
		8	80		-21.3	21.1
		9	90		-30.4	19.8
		10	100		-38.6	18.7
2	MSL	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	9.4		37.9
		2	20	-6.3		19.2
		3	30	-6.3		19.5
		4	40	-5.4		20.2
		5	50	-3.9		18.7
		6	60	4.0		25.3
		7	70	12.3		33.4
		8	80	21.3		42.4
		9	90	30.4		50.2
		10	100	38.6		57.2
3	NML-SIRIM	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	-28.5	-37.9	
		2	20	-25.5	-19.2	
		3	30	-25.7	-19.5	
		4	40	-25.6	-20.2	
		5	50	-22.5	-18.7	
		6	60	-21.3	-25.3	
		7	70	-21.1	-33.4	
		8	80	-21.1	-42.4	
		9	90	-19.8	-50.2	
		10	100	-18.7	-57.2	

Table 7.4: Expanded ($k = 2$) uncertainties of differences, $U\{\delta(j, j', i)\}$.

j	Institute			Expanded uncertainty of δ, $U\{\delta(j, j', i)\}$ / $\times 10^{-6}$		
		j'		1	2	3
1	NMIJ/AIST	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10		69.6	54.1
		2	20		57.1	46.4
		3	30		54.0	43.1
		4	40		54.8	42.0
		5	50		57.6	42.8
		6	60		60.4	42.6
		7	70		64.0	43.2
		8	80		67.9	43.8
		9	90		71.5	44.0
		10	100		75.6	45.0
2	MSL	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	69.6		76.8
		2	20	57.1		62.0
		3	30	54.0		57.1
		4	40	54.8		56.9
		5	50	57.6		59.8
		6	60	60.4		61.8
		7	70	64.0		64.9
		8	80	67.9		68.3
		9	90	71.5		71.2
		10	100	75.6		74.8
3	NML-SIRIM	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	54.1	76.8	
		2	20	46.4	62.0	
		3	30	43.1	57.1	
		4	40	42.0	56.9	
		5	50	42.8	59.8	
		6	60	42.6	61.8	
		7	70	43.2	64.9	
		8	80	43.8	68.3	
		9	90	44.0	71.2	
		10	100	45.0	74.8	

Table 7.5: Degrees of equivalence expressed by ratios, $\delta(j, j', i)/U\{\delta(j, j', i)\}$.

j	Institute			$\delta(j,j',i)$ / $U\{\delta(j,j',i)\}$		
		j'		1	2	3
1	NMIJ/AIST	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10		-0.13	0.53
		2	20		0.11	0.55
		3	30		0.12	0.60
		4	40		0.10	0.61
		5	50		0.07	0.53
		6	60		-0.07	0.50
		7	70		-0.19	0.49
		8	80		-0.31	0.48
		9	90		-0.42	0.45
		10	100		-0.51	0.41
2	MSL	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	0.13		0.49
		2	20	-0.11		0.31
		3	30	-0.12		0.34
		4	40	-0.10		0.35
		5	50	-0.07		0.31
		6	60	0.07		0.41
		7	70	0.19		0.52
		8	80	0.31		0.62
		9	90	0.42		0.70
		10	100	0.51		0.76
3	NML-SIRIM	i	MPa	NMIJ/AIST	MSL	NML-SIRIM
		1	10	-0.53	-0.49	
		2	20	-0.55	-0.31	
		3	30	-0.60	-0.34	
		4	40	-0.61	-0.35	
		5	50	-0.53	-0.31	
		6	60	-0.50	-0.41	
		7	70	-0.49	-0.52	
		8	80	-0.48	-0.62	
		9	90	-0.45	-0.70	
		10	100	-0.41	-0.76	

8. Linking key comparison APMP.M.P-K7.1 to key comparison CCM.P-K7

According to the MRA the linking should be established by means of the linking institutes taking part in both the International Committee for Weights and Measures (CIPM) and the Regional Metrology Organization (RMO) key comparisons[1]. A procedure for linking the results of a RMO key comparison to those of a related CIPM key comparison has been proposed[15,16].

This APMP key comparison, APMP.M.P-K7.1, is linked to the corresponding CCM key comparison, CCM.P.K-7, which has the same pressure range as APMP.M.P-K7.1. The final report of CCM.P.K-7 has been approved[4]. Although the type of transfer standards for both comparisons were different since the transfer standard of CCM.P.K-7 was a complete pressure balance, the pressure points at which both comparisons were carried out were the same within one thousandth of the target nominal pressure.

8.1 Value used for linkage

The linking institute, NMIJ, participated into both comparisons CCM.P.K-7 and APMP.M.P-K7.1. The values for the linkage are obtained by using the results of the corresponding differences of the linking institute, NMIJ, in the both comparisons CCM.P.K-7 and APMP.M.P-K7.1, in the same way as given in the linkage between the key comparisons, CCM.P-K7[4] and APMP.M.P-K7[5]. The value obtained from the linking institute for CCM.P-K7, $X_{CCM}(i)$, is

$$X_{CCM}(i) = x(NMIJ, i) \tag{8.1}$$

where $x(NMIJ, i)$ is the relative deviation of NMIJ from the reference values calculated from the claimed effective area related to the CCM comparison.

In the same way, the value obtained from the linking institute for APMP.M.P-K7.1, $Y_{APMP}(i)$, is

$$Y_{APMP}(i) = y(NMIJ, i) \tag{8.2}$$

where $y(NMIJ, i)$ is the relative deviation of NMIJ from the reference values calculated from the expected mean pressure related to the APMP comparison.

Table 8.1 presents the results of the linking institute for CCM.P-K7 and

APMP.M.P-K7.1 as a function of nominal target pressure. $u_c\{x(NMIJ,i)\}$ and $u_c\{y(NMIJ,i)\}$ are the combined standard uncertainties of the relative deviations from the reference values calculated from the claimed effective area related to the CCM comparison and the expected mean pressure related to the APMP comparison respectively. Table 8.1 also shows the differences of the relative deviations, $X_{CCM}(i)-Y_{APMP}(i)$, calculated from equations (8.1) and (8.2) as a function of nominal target pressure.

Table 8.1: Relative deviations obtained from the linking institute for CCM.P-K7 and APMP.M.P-K7.1 and differences of the relative deviations, $X_{CCM}(i)-Y_{APMP}(i)$.

		Results in CCM.P-K7			Results in APMP.M.P-K7.1			
		NMIJ/AIST		Rel. Devi.	NMIJ/AIST		Rel. Devi.	Difference
i	Pressure / MPa	x (NMIJ,i) / 10^{-6}	$u\{x(\mathrm{NMIJ},i)\}$ / 10^{-6}	$X_{\mathrm{CCM}}(i)$ / 10^{-6}	y (NMIJ,i) / 10^{-6}	$u\{y(\mathrm{NMIJ},i)\}$ / 10^{-6}	$Y_{\mathrm{APMP}}(i)$ / 10^{-6}	$X_{CCM}(i)$-$Y_{\mathrm{APMP}}(i$ / 10^{-6}
1	10	0.0	13.5	0.0	0.0	19.7	0.0	0.0
2	20	-1.6	13.5	-1.6	6.3	16.2	6.3	-7.9
3	30	-0.7	13.5	-0.7	6.3	16.1	6.3	-7.0
4	40	-1.1	13.5	-1.1	5.4	15.5	5.4	-6.5
5	50	-0.5	14.0	-0.5	3.9	14.9	3.9	-4.4
6	60	-1.3	14.5	-1.3	0.0	15.3	0.0	-1.3
7	70	-0.6	15.0	-0.6	0.0	21.9	0.0	-0.6
8	80	-0.5	15.5	-0.5	0.0	31.6	0.0	-0.5
9	90	0.0	16.5	0.0	0.0	30.4	0.0	0.0
10	100	0.0	17.0	0.0	0.0	29.5	0.0	0.0

8.2 Evaluation of degrees of equivalence

8.2.1 Deviation of institute's value from CCM KCRV

As mentioned above, the measurands in CCM.P-K7 and APMP.M.P-K7.1 were the claimed effective area and the expected mean pressure, respectively. The following relationship is established:

(Claimed effective area)/(Actual effective area)
≈ (Expected mean pressure)/(Claimed pressure).

By considering the relationship of both quantities, the degrees of equivalence of participating institutes in APMP.M.P-K7.1 comparison can be transferred to CCM.P-K7 comparison as follows:

$$D(J,i) = X_{CCM}(i) - Y_{APMP}(i) + y(j,i) \tag{8.3}$$

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-K7.1 and $y(j,i)$ is the relative deviation from the APMP.M.P-K7.1 reference value of j-th participating institute.

The relative deviation from the CCM.P-K7 reference value for the institutes who participated in CCM.P-K7, $D(J,i)$, is simply transferred for convenience as follows:

$$D(J,i) = x(J,i) \tag{8.4}$$

The differences listed in Table 8.1 are considerably smaller than the expanded uncertainties claimed by the participating institutes in APMP.M.P-K7.1 and the results of the linking institute in both comparisons are comparable. Therefore, in the same way as given in the linkage between the key comparisons, CCM.P-K7[4] and APMP.M.P-K7[5], the relative expanded uncertainty of $D(J,i)$ for the institutes participated into APMP.M.P-K7.1 is estimated from

$$U\{D(J,i)\} = k \cdot u_c\{y(j,i)\} \tag{8.5}$$

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

The relative expanded uncertainty for the institute who participated in CCM.P-K7 is simply transferred for convenience as follows:

$$U\{D(J,i)\} = k \cdot u_c\{x(J,i)\} \tag{8.6}$$

Table 8.2 presents respectively the relative deviations from the CCM KCRVs, $D(J,i)$, the expanded ($k = 2$) uncertainties of the relative deviations, $U\{D(J,i)\}$, and the degrees of equivalence expressed by the ratios, $D(J,i)/U\{D(J,i)\}$, for individual NMIs at all nominal target pressures. A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $|D(J,i)/U\{D(J,i)\}| \leq 1$.

Figure 8.1 presents $D(J,i)$ with $U\{D(J,i)\}$ graphically for the participating institutes as a function of nominal target pressure.

Table 8.2: Deviations from the CCM KCRVs, $D(J,i)$ [upper], the expanded (k = 2) uncertainties of the deviations, $U\{D(J,i)\}$ [middle] and the degrees of equivalence as expressed by the ratios, $D(J,i)/U\{D(J,i)\}$ [lower].

		Relative deviation from CCM KCRV, $D(J,i)$ / $\times 10^{-6}$										
J		1	2	3	4	5	6	7	8	9	10	11
i	MPa	PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	10	2.5	8.5	-3.7	-3.5	5.3	31.9	-1.6	0.0	-11.5	9.4	-28.5
2	20	1.1	1.1	-5.0	-1.7	3.3	20.9	0.0	-1.6	-9.7	-7.9	-27.1
3	30	0.3	0.0	-5.5	-1.6	1.9	15.1	0.3	-0.7	-7.9	-7.0	-26.4
4	40	0.0	0.5	-6.2	-1.3	0.0	9.6	2.2	-1.1	-7.6	-6.5	-26.7
5	50	0.6	2.4	-5.3	0.0	-2.8	7.0	4.6	-0.5	-5.2	-4.4	-23.0
6	60	0.0	2.1	-6.0	0.4	-4.5	4.1	5.9	-1.3	-4.5	2.7	-22.6
7	70	0.0	4.3	-5.7	2.6	-6.2	3.5	7.6	-0.6	-3.2	11.7	-21.7
8	80	0.0	4.5	-5.9	4.5	-7.0	3.6	7.8	-0.5	-1.8	20.8	-21.6
9	90	-0.1	5.2	-5.9	6.5	-8.5	4.4	8.0	0.0	-0.8	30.4	-19.8
10	100	-0.1	7.2	-5.9	8.3	-9.5	4.7	7.2	0.0	-0.8	38.6	-18.7

		Expanded uncertainty, $U\{D(J,i)\}$ / $\times 10^{-6}$ (k = 2)										
J		1	2	3	4	5	6	7	8	9	10	11
i	MPa	PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	10	22.0	23.0	16.0	23.0	32.0	39.0	35.0	27.0	61.0	67.2	50.9
2	20	22.0	22.0	14.0	22.0	31.0	38.0	36.0	27.0	57.0	52.4	40.5
3	30	22.0	22.0	14.0	23.0	32.0	37.0	37.0	27.0	49.0	49.3	37.0
4	40	23.0	22.0	14.0	23.0	32.0	37.0	37.0	27.0	49.0	49.4	34.7
5	50	25.0	22.0	15.0	23.0	33.0	37.0	39.0	28.0	49.0	51.3	33.9
6	60	27.0	23.0	16.0	24.0	34.0	38.0	41.0	29.0	49.0	54.1	33.2
7	70	29.0	22.0	16.0	24.0	35.0	38.0	42.0	30.0	49.0	65.3	45.1
8	80	31.0	23.0	17.0	24.0	36.0	38.0	43.0	31.0	49.0	82.1	63.6
9	90	33.0	23.0	18.0	25.0	37.0	38.0	45.0	33.0	49.0	82.6	60.4
10	100	36.0	23.0	19.0	25.0	38.0	38.0	46.0	34.0	49.0	83.9	57.9

		$D(J,i)$ / $U\{D(J,i)\}$										
J		1	2	3	4	5	6	7	8	9	10	11
i	MPa	PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	10	0.11	0.37	-0.23	-0.15	0.17	0.82	-0.05	0.00	-0.19	0.14	-0.56
2	20	0.05	0.05	-0.36	-0.08	0.11	0.55	0.00	-0.06	-0.17	-0.15	-0.67
3	30	0.01	0.00	-0.39	-0.07	0.06	0.41	0.01	-0.03	-0.16	-0.14	-0.71
4	40	0.00	0.02	-0.44	-0.06	0.00	0.26	0.06	-0.04	-0.16	-0.13	-0.77
5	50	0.02	0.11	-0.35	0.00	-0.08	0.19	0.12	-0.02	-0.11	-0.09	-0.68
6	60	0.00	0.09	-0.38	0.02	-0.13	0.11	0.14	-0.04	-0.09	0.05	-0.68
7	70	0.00	0.20	-0.36	0.11	-0.18	0.09	0.18	-0.02	-0.07	0.18	-0.48
8	80	0.00	0.20	-0.35	0.19	-0.19	0.09	0.18	-0.02	-0.04	0.25	-0.34
9	90	0.00	0.23	-0.33	0.26	-0.23	0.12	0.18	0.00	-0.02	0.37	-0.33
10	100	0.00	0.31	-0.31	0.33	-0.25	0.12	0.16	0.00	-0.02	0.46	-0.32

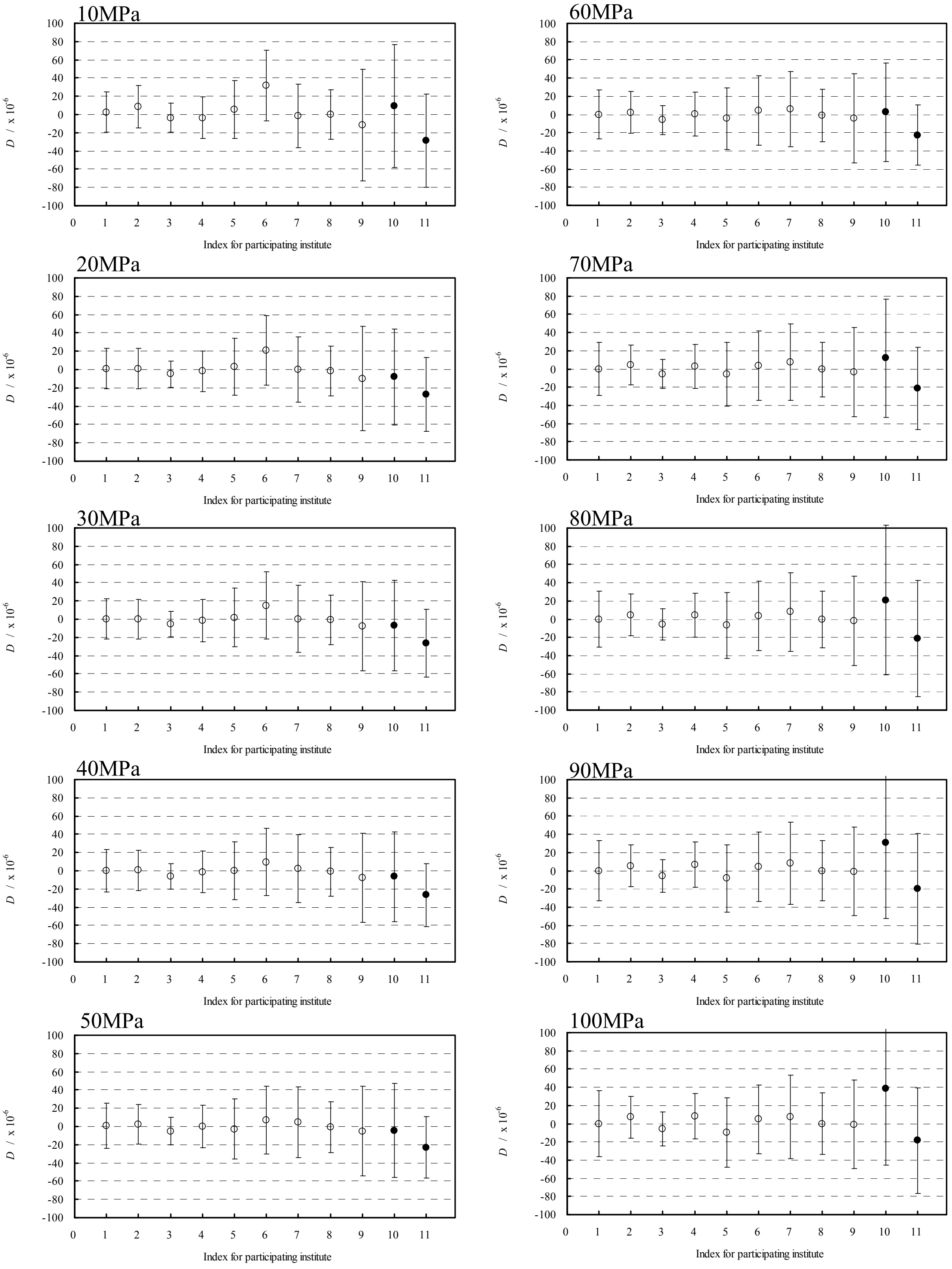

Figure 8.1: Deviations from the CCM KCRVs, $D(J,i)$, and the expanded uncertainties of $D(J,i)$, $U\{D(J,i)\}$. The black points show deviations $D(J,i)$ and the error bars refer to expanded ($k = 2$) uncertainties $U\{D(J,i)\}$.

8.2.2 Difference between deviations for pairs of institutes

The degree of equivalence between pairs of pressure standards *J* and *J'* is calculated by the following equation:

$$d(J,J',i) = D(J,i) - D(J',i) \tag{8.7}$$

where $d(J,J',i)$ is the relative difference of their deviations, and the relative expanded uncertainty of the difference, $U\{d(J,J',i)\}$, is estimated from

$$U\{d(J,J',i)\} = \sqrt{U^2\{D(J,i)\} + U^2\{D(J',i)\}} \tag{8.8}$$

where $U\{D(J,i)\}$ and $U\{D(J',i)\}$ are the expanded (k = 2) uncertainties of the relative deviation of *J*-th and *J'*-th institutes, respectively.

Tables 8.3, 8.4 and 8.5 present the results of the differences, $d(J,J',i)$, the expanded (k = 2) uncertainties of the differences, $U\{d(J,J',i)\}$, and the degrees of equivalence expressed by the ratios, $D(J,J',i)/U\{D(J,J',i)\}$, for the participating institutes in CCM.P-K7 and APMP.M.P-K7.1 at 10 MPa, 50 MPa and 100 MPa, respectively.

A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $D(J,J',i)/U\{D(J,J',i)\} \le 1$.

Table 8.3: Results of the differences, $d(J,J',i)$ [upper], the expanded (k = 2) uncertainties of the differences, $U\{d(J,J',i)\}$ [middle], and the degrees of equivalence expressed by the ratios, $D(J,J',i)/U\{D(J,J',i)\}$ [lower] at 10 MPa.

$i = 1$		Differences between deviations, $d(J,J',i) = D(J,i) - D(J',i)$ / $\times 10^{-6}$											
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11	$D(J,i)$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		-6.0	6.2	6.0	-2.8	-29.4	4.1	2.5	14.0	-6.9	31.0	2.5
2	IMGC-CNR	6.0		12.2	12.0	3.2	-23.4	10.1	8.5	20.0	-0.9	37.0	8.5
3	BNM-LNE	-6.2	-12.2		-0.2	-9.0	-35.6	-2.1	-3.7	7.8	-13.1	24.8	-3.7
4	NPL	-6.0	-12.0	0.2		-8.8	-35.4	-1.9	-3.5	8.0	-12.9	25.0	-3.5
5	CENAM	2.8	-3.2	9.0	8.8		-26.6	6.9	5.3	16.8	-4.1	33.8	5.3
6	NIST	29.4	23.4	35.6	35.4	26.6		33.5	31.9	43.4	22.5	60.4	31.9
7	INMS/NRC	-4.1	-10.1	2.1	1.9	-6.9	-33.5		-1.6	9.9	-11.0	26.9	-1.6
8	NMIJ/AIST	-2.5	-8.5	3.7	3.5	-5.3	-31.9	1.6		11.5	-9.4	28.5	0.0
9	NPLI	-14.0	-20.0	-7.8	-8.0	-16.8	-43.4	-9.9	-11.5		-20.9	17.0	-11.5
$D(J',i)$		2.5	8.5	-3.7	-3.5	5.3	31.9	-1.6	0.0	-11.5	9.4	-28.5	

$i = 1$		Expanded uncertainty of d, $U\{d(J,J',i)\}$ / $\times 10^{-6}$											
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11	$U\{D(J,i)\}$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		31.8	27.2	31.8	38.8	44.8	41.3	34.8	64.8	70.7	55.5	22.0
2	IMGC-CNR	31.8		28.0	32.5	39.4	45.3	41.9	35.5	65.2	71.0	55.9	23.0
3	BNM-LNE	27.2	28.0		28.0	35.8	42.2	38.5	31.4	63.1	69.1	53.4	16.0
4	NPL	31.8	32.5	28.0		39.4	45.3	41.9	35.5	65.2	71.0	55.9	23.0
5	CENAM	38.8	39.4	35.8	39.4		50.4	47.4	41.9	68.9	74.4	60.1	32.0
6	NIST	44.8	45.3	42.2	45.3	50.4		52.4	47.4	72.4	77.7	64.1	39.0
7	INMS/NRC	41.3	41.9	38.5	41.9	47.4	52.4		44.2	70.3	75.8	61.8	35.0
8	NMIJ/AIST	34.8	35.5	31.4	35.5	41.9	47.4	44.2		66.7	72.4	57.6	27.0
9	NPLI	64.8	65.2	63.1	65.2	68.9	72.4	70.3	66.7		90.7	79.5	61.0
$U\{D(J',i)\}$		22.0	23.0	16.0	23.0	32.0	39.0	35.0	27.0	61.0	67.2	50.9	

$i = 1$		$d(J,J',i) / U\{d(J,J',i)\}$										
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	PTB		-0.19	0.23	0.19	-0.07	-0.66	0.10	0.07	0.22	-0.10	0.56
2	IMGC-CNR	0.19		0.44	0.37	0.08	-0.52	0.24	0.24	0.31	-0.01	0.66
3	BNM-LNE	-0.23	-0.44		-0.01	-0.25	-0.84	-0.05	-0.12	0.12	-0.19	0.47
4	NPL	-0.19	-0.37	0.01		-0.22	-0.78	-0.05	-0.10	0.12	-0.18	0.45
5	CENAM	0.07	-0.08	0.25	0.22		-0.53	0.15	0.13	0.24	-0.05	0.56
6	NIST	0.66	0.52	0.84	0.78	0.53		0.64	0.67	0.60	0.29	0.94
7	INMS/NRC	-0.10	-0.24	0.05	0.05	-0.15	-0.64		-0.04	0.14	-0.14	0.44
8	NMIJ/AIST	-0.07	-0.24	0.12	0.10	-0.13	-0.67	0.04		0.17	-0.13	0.50
9	NPLI	-0.22	-0.31	-0.12	-0.12	-0.24	-0.60	-0.14	-0.17		-0.23	0.21

Table 8.4: Results of the differences, $d(J,J',i)$ [upper], the expanded (k = 2) uncertainties of the differences, $U\{d(J,J',i)\}$ [middle], and the degrees of equivalence expressed by the ratios, $D(J,J',i)/U\{D(J,J',i)\}$ [lower] at 50 MPa.

$i = 5$		Differences between deviations, $d(J, J', i) = D(J, i) - D(J', i)$ / $\times 10^{-6}$											
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11	$D(J, i)$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		-1.8	5.9	0.6	3.4	-6.4	-4.0	1.1	5.8	5.0	23.6	0.6
2	IMGC-CNR	1.8		7.7	2.4	5.2	-4.6	-2.2	2.9	7.6	6.8	25.4	2.4
3	BNM-LNE	-5.9	-7.7		-5.3	-2.5	-12.3	-9.9	-4.8	-0.1	-0.9	17.7	-5.3
4	NPL	-0.6	-2.4	5.3		2.8	-7.0	-4.6	0.5	5.2	4.4	23.0	0.0
5	CENAM	-3.4	-5.2	2.5	-2.8		-9.8	-7.4	-2.3	2.4	1.6	20.2	-2.8
6	NIST	6.4	4.6	12.3	7.0	9.8		2.4	7.5	12.2	11.4	30.0	7.0
7	INMS/NRC	4.0	2.2	9.9	4.6	7.4	-2.4		5.1	9.8	9.0	27.6	4.6
8	NMIJ/AIST	-1.1	-2.9	4.8	-0.5	2.3	-7.5	-5.1		4.7	3.9	22.5	-0.5
9	NPLI	-5.8	-7.6	0.1	-5.2	-2.4	-12.2	-9.8	-4.7		-0.8	17.8	-5.2
$D(J', i)$		0.6	2.4	-5.3	0.0	-2.8	7.0	4.6	-0.5	-5.2	-4.4	-23.0	

$i = 5$		Expanded uncertainty of d, $U\{d(J, J', i)\}$ / $\times 10^{-6}$											
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11	$U\{D(J, i)\}$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		33.3	29.2	34.0	41.4	44.7	46.3	37.5	55.0	57.1	42.1	25.0
2	IMGC-CNR	33.3		26.6	31.8	39.7	43.0	44.8	35.6	53.7	55.9	40.4	22.0
3	BNM-LNE	29.2	26.6		27.5	36.2	39.9	41.8	31.8	51.2	53.5	37.1	15.0
4	NPL	34.0	31.8	27.5		40.2	43.6	45.3	36.2	54.1	56.3	41.0	23.0
5	CENAM	41.4	39.7	36.2	40.2		49.6	51.1	43.3	59.1	61.0	47.3	33.0
6	NIST	44.7	43.0	39.9	43.6	49.6		53.8	46.4	61.4	63.3	50.2	37.0
7	INMS/NRC	46.3	44.8	41.8	45.3	51.1	53.8		48.0	62.6	64.5	51.7	39.0
8	NMIJ/AIST	37.5	35.6	31.8	36.2	43.3	46.4	48.0		56.4	58.5	44.0	28.0
9	NPLI	55.0	53.7	51.2	54.1	59.1	61.4	62.6	56.4		71.0	59.6	49.0
$U\{D(J', i)\}$		25.0	22.0	15.0	23.0	33.0	37.0	39.0	28.0	49.0	51.3	33.9	

$i = 5$		$d(J, J', i) / U\{d(J, J', i)\}$										
$J \backslash J'$		1	2	3	4	5	6	7	8	9	10	11
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	PTB		-0.05	0.20	0.02	0.08	-0.14	-0.09	0.03	0.11	0.09	0.56
2	IMGC-CNR	0.05		0.29	0.08	0.13	-0.11	-0.05	0.08	0.14	0.12	0.63
3	BNM-LNE	-0.20	-0.29		-0.19	-0.07	-0.31	-0.24	-0.15	0.00	-0.02	0.48
4	NPL	-0.02	-0.08	0.19		0.07	-0.16	-0.10	0.01	0.10	0.08	0.56
5	CENAM	-0.08	-0.13	0.07	-0.07		-0.20	-0.14	-0.05	0.04	0.03	0.43
6	NIST	0.14	0.11	0.31	0.16	0.20		0.04	0.16	0.20	0.18	0.60
7	INMS/NRC	0.09	0.05	0.24	0.10	0.14	-0.04		0.11	0.16	0.14	0.53
8	NMIJ/AIST	-0.03	-0.08	0.15	-0.01	0.05	-0.16	-0.11		0.08	0.07	0.51
9	NPLI	-0.11	-0.14	0.00	-0.10	-0.04	-0.20	-0.16	-0.08		-0.01	0.30

Table 8.5: Results of the differences, $d(J,J',i)$ [upper], the expanded (k = 2) uncertainties of the differences, $U\{d(J,J',i)\}$ [middle], and the degrees of equivalence expressed by the ratios, $D(J,J',i)/U\{D(J,J',i)\}$ [lower] at 100 MPa.

i = 10		Differences between deviations, $d(J,J',i) = D(J,i) - D(J',i)$ / $\times 10^{-6}$											
$J \setminus J'$		1	2	3	4	5	6	7	8	9	10	11	$D(J,i)$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		-7.3	5.8	-8.4	9.4	-4.8	-7.3	-0.1	0.7	-38.7	18.6	-0.1
2	IMGC-CNR	7.3		13.1	-1.1	16.7	2.5	0.0	7.2	8.0	-31.4	25.9	7.2
3	BNM-LNE	-5.8	-13.1		-14.2	3.6	-10.6	-13.1	-5.9	-5.1	-44.5	12.8	-5.9
4	NPL	8.4	1.1	14.2		17.8	3.6	1.1	8.3	9.1	-30.3	27.0	8.3
5	CENAM	-9.4	-16.7	-3.6	-17.8		-14.2	-16.7	-9.5	-8.7	-48.1	9.2	-9.5
6	NIST	4.8	-2.5	10.6	-3.6	14.2		-2.5	4.7	5.5	-33.9	23.4	4.7
7	INMS/NRC	7.3	0.0	13.1	-1.1	16.7	2.5		7.2	8.0	-31.4	25.9	7.2
8	NMIJ/AIST	0.1	-7.2	5.9	-8.3	9.5	-4.7	-7.2		0.8	-38.6	18.7	0.0
9	NPLI	-0.7	-8.0	5.1	-9.1	8.7	-5.5	-8.0	-0.8		-39.4	17.9	-0.8
$D(J',i)$		-0.1	7.2	-5.9	8.3	-9.5	4.7	7.2	0.0	-0.8	38.6	-18.7	

i = 10		Expanded uncertainty of d, $U\{d(J,J',i)\}$ / $\times 10^{-6}$											
$J \setminus J'$		1	2	3	4	5	6	7	8	9	10	11	$U\{D(J,i)\}$
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM	
1	PTB		42.7	40.7	43.8	52.3	52.3	58.4	49.5	60.8	91.3	68.2	36.0
2	IMGC-CNR	42.7		29.8	34.0	44.4	44.4	51.4	41.0	54.1	87.0	62.3	23.0
3	BNM-LNE	40.7	29.8		31.4	42.5	42.5	49.8	38.9	52.6	86.1	61.0	19.0
4	NPL	43.8	34.0	31.4		45.5	45.5	52.4	42.2	55.0	87.6	63.1	25.0
5	CENAM	52.3	44.4	42.5	45.5		53.7	59.7	51.0	62.0	92.1	69.3	38.0
6	NIST	52.3	44.4	42.5	45.5	53.7		59.7	51.0	62.0	92.1	69.3	38.0
7	INMS/NRC	58.4	51.4	49.8	52.4	59.7	59.7		57.2	67.2	95.7	74.0	46.0
8	NMIJ/AIST	49.5	41.0	38.9	42.2	51.0	51.0	57.2		59.6	90.6	67.2	34.0
9	NPLI	60.8	54.1	52.6	55.0	62.0	62.0	67.2	59.6		97.2	75.9	49.0
$U\{D(J',i)\}$		36.0	23.0	19.0	25.0	38.0	38.0	46.0	34.0	49.0	83.9	57.9	

i = 10		$d(J,J',i) / U\{d(J,J',i)\}$										
$J \setminus J'$		1	2	3	4	5	6	7	8	9	10	11
		PTB	IMGC-CNR	BNM-LNE	NPL	CENAM	NIST	INMS/NRC	NMIJ/AIST	NPLI	MSL	NML-SIRIM
1	PTB		-0.17	0.14	-0.19	0.18	-0.09	-0.12	0.00	0.01	-0.42	0.27
2	IMGC-CNR	0.17		0.44	-0.03	0.38	0.06	0.00	0.18	0.15	-0.36	0.41
3	BNM-LNE	-0.14	-0.44		-0.45	0.08	-0.25	-0.26	-0.15	-0.10	-0.52	0.21
4	NPL	0.19	0.03	0.45		0.39	0.08	0.02	0.20	0.17	-0.35	0.43
5	CENAM	-0.18	-0.38	-0.08	-0.39		-0.26	-0.28	-0.19	-0.14	-0.52	0.13
6	NIST	0.09	-0.06	0.25	-0.08	0.26		-0.04	0.09	0.09	-0.37	0.34
7	INMS/NRC	0.12	0.00	0.26	-0.02	0.28	0.04		0.13	0.12	-0.33	0.35
8	NMIJ/AIST	0.00	-0.18	0.15	-0.20	0.19	-0.09	-0.13		0.01	-0.43	0.28
9	NPLI	-0.01	-0.15	0.10	-0.17	0.14	-0.09	-0.12	-0.01		-0.41	0.24

9. Discussions

All the participating institutes had an almost equal opportunity to participate in this key comparison. It was entirely thanks to all the participating institutes that the circulations were successful. The results presented in this report are based on data originally submitted to the pilot institute for preparation of the draft A report. The expected mean pressures and associated uncertainties for each participating institute were calculated from the calibration data supplied by each participating institute.

All the participants calibrated two pressure monitors in the transfer standard against the pressure balance following the protocol[8,9].

In this report, the APMP.M.P-K7.1 reference values were calculated using the median method. The degrees of equivalence with respect to the APMP.M.P-K7.1 reference values and the degrees of equivalence between pairs of participating institutes in APMP.M.P-K7.1 were presented first.

Finally the results of the participating institutes in APMP.M.P-K7.1 were linked to CCM.P-K7 and the degrees of equivalence with respect to the CCM.P-K7 reference values and the degrees of equivalence between pairs of participating institutes in APMP.M.P-K7.1 and CCM.P-K7 were presented at 10 MPa, 50 MPa and 100 MPa.

10. Conclusions

Three National Metrology Institutes (NMIs) participated in this APMP key comparison of hydraulic high-pressure standards from 10 MPa to 100 MPa for gauge mode. High-precision electronic pressure transducers were circulated as the transfer standard for the comparison. Two high-precision pressure transducers were used in the transfer standard unit to ensure its reliability.

The transfer standard was calibrated at the pilot institute five times in total during this comparison. From the calibration results, the behavior of the transfer standard during the comparison period was well characterized and it was confirmed that the capabilities of the transfer standard were sufficiently stable for the requirements of this key comparison.

The degrees of equivalence of the national hydraulic pressure standards at the three participating NMIs were obtained. They were expressed quantitatively by two terms, deviations from the key comparison reference values and pair-wise differences between deviations of participating institutes. The hydraulic pressure standards in the range from 10 MPa to 100 MPa, for gauge mode, of the three participating NMIs (NMIJ/AIST, MSL, and NML-SIRIM) were found to be equivalent compared with their claimed expanded uncertainties. The results of this APMP comparison were satisfactory.

The degrees of equivalence in this comparison were also transferred to the corresponding CCM key comparison, CCM.P-K7. 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.

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