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ASIA-PACIFIC METROLOGY PROGRAMME
1 Pa – 5,000 Pa SMALL DIFFERENTIAL PRESSURE INTERLABORATORY COMPARISON
Comparison Identifier: **APMP.M.P-K5**

Final Report on Key Comparison APMP.M.P-K5 in Differential Pressure from 1 Pa to 5000 Pa

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Abstract

This report describes the results of a key comparison of small differential pressure standards at two National Metrology Institutes (NMIs: NMIJ/AIST and MSL) that was carried out during the period May 2005 to October 2005 within the framework of the Asia-Pacific Metrology Programme (APMP) in order to determine their degrees of equivalence at pressures in the range 1 Pa to 5000 Pa. The differential pressures were compared at a line pressure of about 100 kPa (absolute). The pilot institute was the National Metrology Institute of Japan (NMIJ)/AIST. Both participating institutes used double pressure balances as their primary pressure standards. The transfer standard package consisted of three high-precision pressure transducers; one capacitance diaphragm gauge to provide high resolution at low differential pressures, and two resonant silicon gauges to provide the required calibration stability. The transfer standard was calibrated at the pilot institute (NMIJ/AIST) at the beginning and the end of the comparison. These results show that the transfer standard was sufficiently stable to meet the requirements of the comparison. The degrees of equivalence of the measurement standards were expressed quantitatively by two terms, deviations from the key comparison reference values and pair-wise differences of their deviations. The differential pressure standards in the range 1 Pa to 5000 Pa of the two 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-K5, and it is shown that the NMIJ values were equivalent to the CCM KCRV within the claimed uncertainties.

Contents:

1. Introduction

The National Metrology Institute of Japan (NMIJ)/AIST, Japan, has developed a differential pressure standard ranging from 1 Pa to 10 k Pa with a line pressure of 100 kPa ± 10 kPa in absolute mode using double pressure balances. Measurement Standards Laboratory (MSL) of New Zealand has successfully participated in the CCM comparison, CCM.P-K5, in the pressure range 1 Pa to 1000 Pa using double pressure balances. A bilateral comparison was planned by the both 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 differential pressure as a pilot institute. The comparison has been identified as **APMP.M.P-K5** 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 differential pressure standards of the participating National Metrology Institutes (NMIs) in the pressure range of 1 Pa to 5000 Pa according to the protocol guidelines[1,2,3] using pure nitrogen (N_2) as a transmitting fluid. To gain international acceptance for the pressure standards APMP.M.P-K5 is linked to the CCM key comparison, CCM.P-K5[4,5], which has a similar pressure range as APMP.M.P-K5. 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[7]. This will provide the essential supporting evidence for differential pressure calibration and measurement capabilities (CMCs) of the NMIs for the Mutual Recognition Arrangement (MRA)[1].

Similar to CCM.P-K5[4,5], high-precision electronic differential pressure transducers were circulated as the transfer standard for the whole comparison. To ensure the reliability of the transfer standard, three high-precision pressure transducers with the following ranges; 133 Pa, 2,000 Pa, 10,000 Pa were used on a transfer standard. The three transducers were selected for reasons of redundancy and resolution to cover the four decades of pressure.

A protocol[8] was prepared by the pilot institute (NMIJ/AIST) in cooperation with MSL with reference to the protocol of CCM.P-K5[4,5]. The first edition was distributed on 16 March 2005. After the revised protocol was approved by the participating institutes, the transfer standard was circulated from May 2005 to October

2005. At the beginning and end of this comparison, the transfer standard was calibrated at the pilot institute (NMIJ/AIST). From the calibration results, the stability of the transfer standard during the comparison period was evaluated. Both NMIs used double pressure balances as their pressure standards and calibrated the transfer standard against the pressure balances following the protocol[8]. The calibration results obtained from each participating institute were submitted to the chair of APMP TCM and were held by the chair until all measurements were completed. Then the calibration results were released by the chair and were sent 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 two NMIs. The following sections provide descriptions of the participating institutes and their pressure standards, the transfer standards, the circulation of the transfer standards, 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

Two National Metrology Institutes (NMIs) participated into this comparison including the pilot institute. The participating institutes along with coordinators for contacts are listed in Table 2.1.

Table 2.1: List of participating institutes.

Participating Institutes
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
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

2.2 Pressure standards of participating institutes

The pressure standards of both participating institutes were double pressure balances that are used to generate the small differential pressures. Each institute provided information about their standard against which the transfer standard was calibrated, including the pressure balance base, the type and material of piston-cylinder assembly and the effective area with its associated standard uncertainty at the reference temperature, see Table 2.2. Details of the parameters used by each participating institute such as the local gravity, differential height of the reference levels between the participating institute's standard and the transfer standard and power supply voltage used for the transfer standard are also listed in Table 2.2. The pressure standard of each participating institute was operated at the normal operating temperature of the institute.

Table 2.2: Details of the pressure standards of the participating institutes. All the uncertainties are expressed as standard uncertainties. To change differential pressure, additional mass was loaded on pressure balance 1 (PB1). Pressure balance 2 (PB2) was used to generate reference pressure.

Institute	NMIJ			MSLNZ		
Country	Japan			New Zealand		
Description of standard	PB1	PB2		PB1	PB2	
PG Base Unit	DHI PG7607 No.112	DHI PG7607 No.305		MSLNZ twin-pressure-balance	MSLNZ twin-pressure-balance	
PG P/C assy.	No.204	No.337		P2-662 C2-1369	P2-637 C2-1368	
Material of piston	Tungsten carbide	Tungsten carbide		Stainless steel	Stainless steel	
Material of cylinder	ceramic	Tungsten carbide		Stainless steel	Stainless steel	
type	Floating cylinder	Floating cylinder		CEC 6-201	CEC 6-201	
Parameters used for the compariton	Value	ui	relative ui	Value	ui	relative ui
Local gravity [m/s2]	9.7994808	1.96×10^{-6}	2×10^{-7}	9.802789	6×10^{-6}	6×10^{-7}
Differential height of reference levels [mm]	109.95	0.50	5.0×10^{-3}	79.0	0.5	6.3×10^{-3}
Power supply	100V 50Hz			100.0	0.5	5×10^{-3}
Standard	Value	ui	relative ui	Value	ui	relative ui
λ [1/MPa]	4.54×10^{-6}	2.3×10^{-7}	0.05	0	0	0
α [℃$^{-1}$]	1.0×10^{-5}	2.5×10^{-6}	0.25	21.6×10^{-6}	4×10^{-6}	0.20
A_0 [m2]	1.961152×10^{-3} at 23 ℃	1.3×10^{-8}	6.6E-06	8.06362×10^{-5} at 20 ℃	8.1×10^{-10}	1×10^{-5}
Trim mass	Value [g]	ui [mg] (k=1)	relative ui	Value [g]	ui [mg]	relative ui
1 Pa	0.2007	0.08	3.9×10^{-4}	0.0081413	0.0023	2.9×10^{-4}
3 Pa	0.6088	0.07	1.2×10^{-4}	0.0246865	0.0006	2.6×10^{-5}
10 Pa	2.0110	0.13	6.6×10^{-5}	0.0822759	0.0008	9.2×10^{-6}
30 Pa	5.9114	0.24	4.1×10^{-5}	0.2468050	0.0010	4.2×10^{-6}
100 Pa	19.9086	0.13	6.4×10^{-6}	0.8228001	0.0037	4.5×10^{-6}
300 Pa	59.7004	0.23	3.9×10^{-6}	2.4678365	0.0038	1.6×10^{-6}
1000 Pa	198.6168	0.14	0.7×10^{-6}	8.223996	0.002	0.2×10^{-6}
3000 Pa	596.8658	0.25	0.4×10^{-6}	24.671851	0.006	0.2×10^{-6}
5000 Pa	996.9477	0.14	0.1×10^{-6}	41.119747	0.010	0.2×10^{-6}
Transfer Standard	Value	ui		Value	ui	
Reference level [mm]	161.33	0.10		79.0	0.5	

2.2.1 Description of the NMIJ/AIST differential pressure primary standard

The NMIJ/AIST differential standard is based on two nominally identical piston-cylinder assemblies mounted in two commercial bases PG7607s manufactured by the DH Instruments, Inc[9]. The piston-cylinder assemblies are floating cylinder type with a nominal effective area of 1961 mm^2. The piston and cylinder of Pressure Balance 1 (PB1) are made of tungsten carbide and ceramic, respectively, and those of PB2 are made of tungsten carbide. Each base allows the piston-cylinder assembly to operate in absolute mode while the region above each assembly is evacuated to 1 Pa or less. A connecting manifold equalizes the pressures above the assemblies. In operation each piston-cylinder unit is first loaded to generate an absolute pressure of 100 kPa and the loads are trimmed so that the pressures are approximately equal. The differential pressures, in the range 1 Pa to 5000 Pa, are then generated by adding small masses (201 mg up to 996 948 mg) on PB1. These small masses are added or removed by a mechanical mass loader while the region above the piston-cylinder units remains evacuated. The piston-cylinder assembly of PB1 is the NMIJ/AIST primary pressure standard. The effective area of the piston-cylinder assembly had been evaluated by comparison directly against the NMIJ/AIST primary mercury manometer and the calculation from diameter measurements. All mass calibrations are traceable to NMIJ/AIST mass standards.

2.2.2 Description of the MSLNZ differential pressure primary standard

The MSLNZ differential standard is based on two nominally identical piston-cylinder assemblies mounted in a common base[10]. The piston-cylinder assemblies are type 6-201 units, manufactured by the Consolidated Electrodynamics Corporation, with a nominal effective area of 80.6 mm^2 and both the piston and cylinder are made of stainless steel. The base was designed and constructed by MSLNZ and allows the two piston-cylinder assemblies to operate in absolute mode while the region above each assembly is evacuated to 10 Pa or less. The pressures above the assemblies are equalized by a large connecting manifold. Both cylinders are mounted on the same 25 mm thick aluminum plate to reduce temperature gradients between each assembly. In operation each piston-cylinder unit is first loaded to generate an absolute pressure of about 101 kPa and the loads are trimmed so that the pressures are equal to better than 0.1 Pa. The gauge differential pressures, in the range 1 Pa to 5000 Pa, are then generated by adding small masses (16 mg up to 41 000 mg) to one of the instruments. These small masses are added or removed by a mechanical mass loader while the region above the piston-cylinder units remains evacuated. The effective area of the piston-cylinder assembly was found by comparison directly against the MSLNZ primary gas pressure balance P1 703 – C1 729. The effective area of our primary balance P1 703 – C1 729 is calculated from diameter measurements made by MSL length standards. All mass calibrations are made by and traceable to MSL mass standards.

3. Transfer standard

3.1 Description of pressure transducers

In this comparison two types of pressure transducers were used in the transfer standard, see Table 3.1. These were resonant silicon gauges[11,12] (RSGs) from Yokogawa Electric Corporation used for their good long-term stability and a capacitance diaphragm gauge[13,14] (CDG) from MKS Instruments used for its high-resolution. The advantages and disadvantages of those pressure transducers were summarized in the final report of CCM.P-K5[5]. The transfer standard package was developed using both types of gauges, one CDG to provide redundancy and high resolution at low pressures, and two RSGs to provide redundancy and excellent calibration stability. Good calibration stability was accomplished over the entire pressure range by re-scaling the CDG response to that of the RSGs at an overlapping pressure.

The two RSGs selected for the comparison had full-scale ranges of 2000 Pa and 10,000 Pa and were combined with one CDG with a full-scale range of 133 Pa. The serial number of each pressure transducer was also listed in Table 3.1.

Table 3.1: Specification of pressure transducers
(Description of instruments in the transfer standard)

Transducer Identifier	CDG	RSG1	RSG2
Sensor Type	Capacitance Diaphragm Gauge	Resonant Silicon Gauge	Resonant Silicon Gauge
Manufacturer	MKS Instruments	Yokogawa	Yokogawa
Transducer Model	698A	2653-S8	MT110 265251
Transducer S/N	000322024	12WC02556M	26DU0014E
Range (Pa)	133	2,000	10,000
Resolution	1×10^{-6} of full scale	0.01 Pa	0.1 Pa
Max. allowable input	310 kPa (Px > Pr), 166 Pa (Px < Pr)	50 kPa	500 kPa
Max. line pressure	1034 kPa (gauge)		
External dimensions	110 x 200 x 105	115 x 125 x 225	132 x 213 x 350
Weight	2.5 kg	5 kg	7.8 kg
Signal Conditioner Model	270D-0		
Signal Conditioner S/N	000787584		
Power Consumption (W)	40	< 1	< 1
Power Supply	100 VAC (50Hz)	6 to 27 DC	100 VAC (50Hz)

The internal volume of CDG, RSG1 and RSG2 is about 30 cm^3, 100 cm^3, and 20 cm^3, respectively. The internal volume of fittings and plumbing is about 42 cm^3. Some general information concerning the pressure transducers is given in the operation and maintenance manuals[11-14], which were enclosed in a transfer package.

The performance and sensitivity of the pressure transducers to changing environmental and operating conditions was evaluated by the pilot institute (NMIJ/AIST) during the comparison[15].

Effect of power supply voltage

The effect on the reading of RSG1 due to power supply variation was evaluated by changing the input voltage. No systematic effect on the reading by the voltage of power source was found So this effect was considered to be negligible. The input voltage of RSG1 during the comparison was determined as 10 V.

Zero-shift by tilt

The shift in the zero-readings due to changing the tilt of each pressure transducer was evaluated. The tilt change was monitored with the bubble levels on the base-plate, which were calibrated using a digital tilt-meter. It was found that the readings of RSGs were sensitive to tilting in the side-to-side direction, while there was only a very small zero-shift for CDG. The sensitivity of the readings to a change in tilt of RSG1 and RSG2 in a side-to-side direction were estimated to about 360 mPa/mrad and 480 mPa/mrad, respectively[15]. These results are in good agreement with those of Miiller[16], who found a change of 300–400 mPa/mrad for RSGs. On the other hand, no significant sensitivity was seen for a front-to-back tilt for all the transducers.

Consequently, the horizontal level of the transfer standard base-plate was adjusted carefully before the start of each measurement run to reduce the effect related to tilt. Using a sensitive bubble level, whose resolution was 0.05 (mm/m)/division, the zero-shift by tilt could be reduced to be less than the resolution of the transducers.

Shift of zero-reading by temperature

To evaluate the dependency on temperature or humidity, the pressure transducers of the transfer standard were installed in a thermostat and humidistat chamber. Two test sequences were performed to change the temperature and humidity: (1) the temperature was changed by three steps at 20 ˚C, 23 ℃ and 26 ℃ with the relative humidity fixed to 50 %, and (2) the relative humidity was changed by three steps at 20 %, 50 % and 80 % with temperature fixed to 23 ℃. Each zero-reading was obtained by averaging the readings over 30 minutes after the temperature inside chamber was sufficiently stabilized. The standard deviations of the temperature during 30 minutes were approximately 0.02 K at every temperature point. Table 3.2 shows the averaged temperature coefficients of zero-readings of each pressure transducer, which were calculated from the results at three temperature points (20 ℃, 23 ℃ and 26 ℃). The temperature coefficients in the table can be used to estimate the uncertainty of zero-shift caused by temperature change in the environmental condition. If the temperature fluctuation during each measurement is kept within 0.2 K, the uncertainty by the temperature change can be negligible because the shift in readings is smaller than the resolution. Changing the relative humidity had negligible effect on the zero-readings of any pressure transducers.

Table 3.2: Temperature coefficient of zero-readings of pressure transducers

Pressure Transducer	CDG	RSG1	RSG2
Temperature coefficient [mPa/K]	0.43	-19.5	18.7
Resolution [mPa]	0.1	10	100

Shift of span-reading by temperature

During the comparison, the shift of span-reading of each transducer was evaluated at the pilot institute by changing the calibration room temperature from approximately 20 ℃ to 26 ℃. Table 3.3 shows the averaged temperature coefficients of span-reading of three pressure transducers, which were calculated from the results obtained by changing the room temperature. Each temperature coefficient was obtained by taking the ratio of the difference of span-readings to the difference of room temperature. As listed in the table, each temperature coefficient was smaller than its standard deviation in the temperature range evaluated. Therefore, the correction for the span-reading shift by temperature of each transducer was not made in this comparison and the uncertainty relating to this effect was considered to be included in the uncertainties of short-term and long-term instabilities in Section 6.

Table 3.3: Temperature coefficient of span-readings of pressure transducers

Pressure Transducer	CDG	RSG1	RSG2
Temperature coefficient [mPa/K]	-1.5	-0.1	-1.6
Standard deviation [mPa/K]	2.1	1.6	5.1
Pressure range evaluated [Pa]	1 - 30	100-1000	100-5000

3.2 Structure of transfer standard

For this comparison, three pressure transducers have been selected for reasons of redundancy and resolution to cover the pressure range from 1 Pa to 5 kPa. The schematic drawing of the transfer standard is shown in Figure 3.1. The transfer standard package consisted of the pressure transducer part (PTP), the support electronics part (SEP) and a laptop computer.

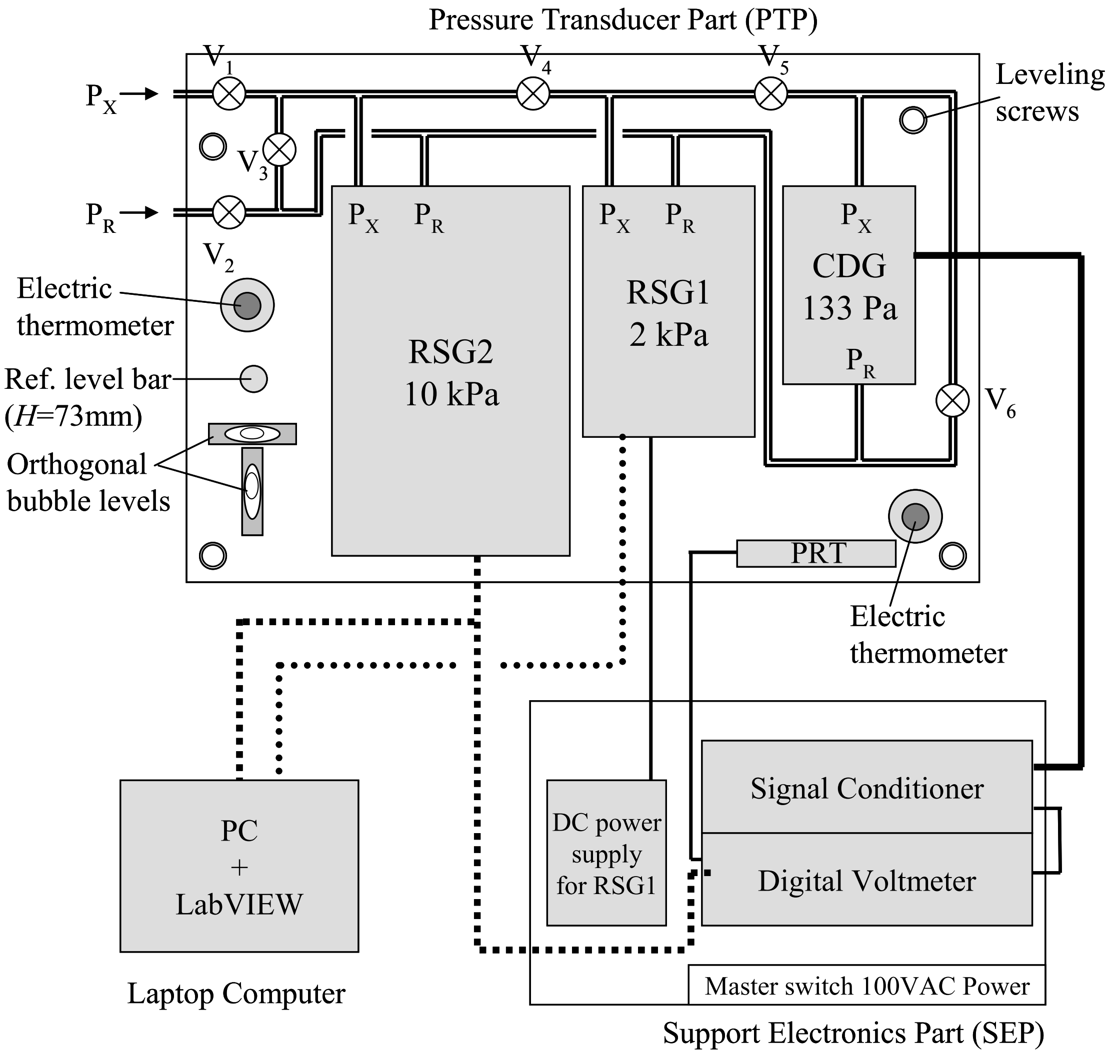


Figure 3.1: Schematic drawing of transfer standard.

Pressure Transducer Part (PTP)

The pressure transducer part composed of three transducers, thermometers, a base-plate, two orthogonal bubble levels, a reference level bar, valves and connecting parts. A calibrated platinum resistance type thermometer (PRT) was used to measure the temperature on the base-plate. The tilt orientation of the PTP during calibration of the RSGs was monitored by means of two orthogonal bubble levels mounted on the PTP base-plate and any observed changes were corrected using four 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 73 mm. The pressure connecting ports are 1/4” pipe fittings made by Swagelok Company. 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, and the results are presented in section 4.2. The valves included external isolation valves, internal isolation valves for CDG and RSGs, and internal bypass valves between pressure and reference side of the gauges. The gauges and internal plumbing were maintained under atmospheric pressure during shipment or storage, but with all internal valves open to avoid over-pressurization of the gauges.

The transfer standard was connected to the participant’s pressure standard through the ports P_X and P_R shown in figure 3.1,. The dimensions of the transfer standard are approximately 650 mm x 450 mm x 240 mm, the total weight is about 32.6 kg.

Support Electronics Part (SEP)

The electronics part composed of an aluminum mainframe, a signal conditioner for the CDG, a digital voltmeter (DMM) for digitizing analog signals from the output of the signal conditioner and the resistance of the PRT, a DC power supply for RSG1 (2 kPa) and 100 VAC plug sockets (ICE 320). All the electronics devices were installed in the mainframe. The dimensions of the mainframe are approximately 340 mm x 420 mm x 250 mm, the total weight is about 14 kg.

Laptop computer

A laptop computer (HP Compaq nx9040) was used for controlling the acquisition of data from the RSGs and the DMM during calibration. The computer had one serial port and PCMCIA-GPIB manufactured by National Instruments Corporation. The operating system was Windows^R XP Professional. The measurement program for this comparison was developed at the pilot institute using LabVIEW Ver. 6.0. The details of the software was described in the protocol[8].

A schematic of the proper connections between the SEP and the PTP are given in Figure 3.2.

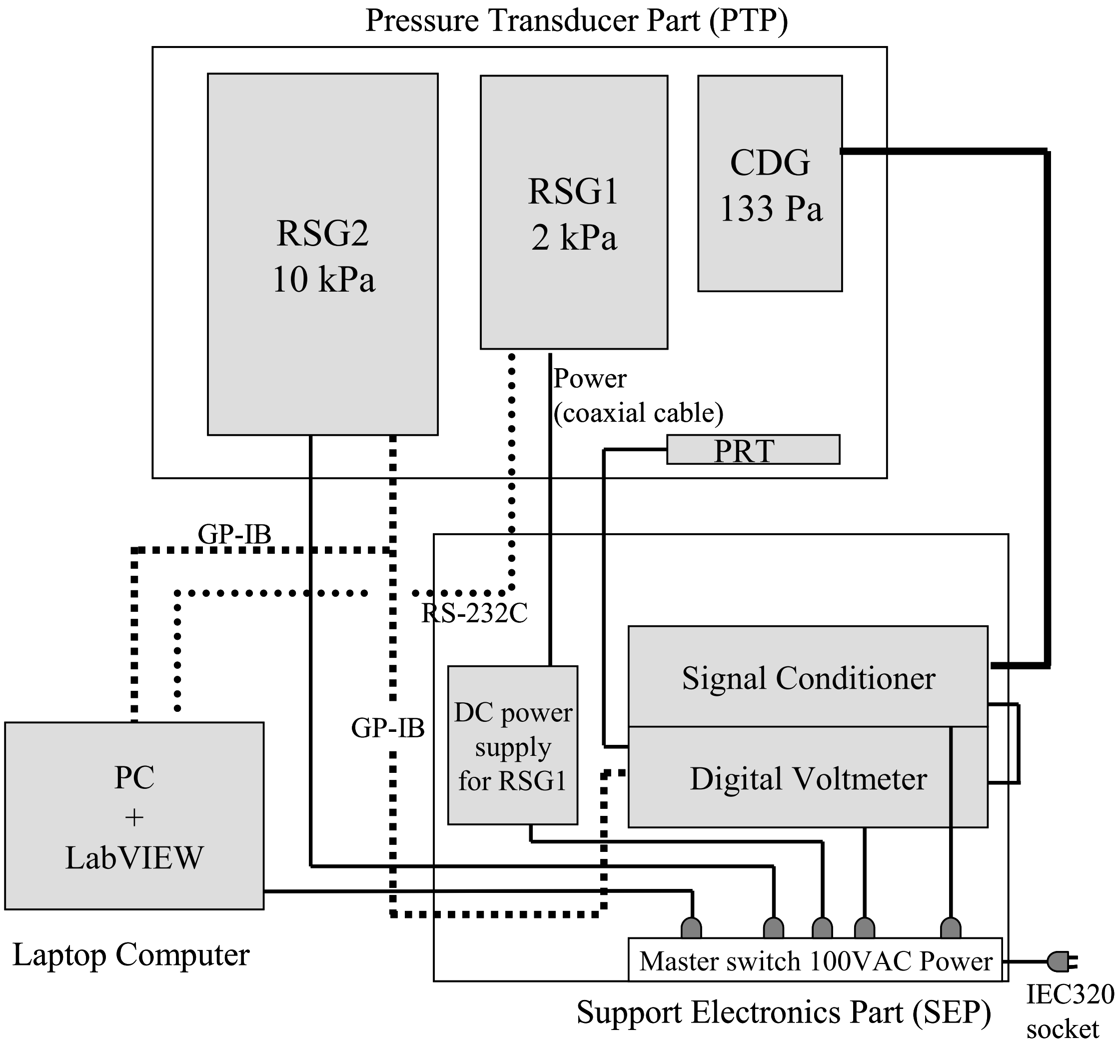


Figure 3.2: Cable interconnections between the pressure transducer part (PTP) and the support electronics part (SEP)

3.3 Transfer package

For interlaboratory shipment, the PTP and SEP (with the laptop) were packed in two carrying cases that were specially designed for vibration and shock isolation. The dimensions of each case are approximately 850 mm x 570 mm x 360 mm, the total weight of the first case (for PTP) was about 50 kg. The total weight of the second case (for SEP and a computer) was about 30 kg. Shock meter seals were attached to the respective cases to record the conditions during transportation. Power cables, connecting cables, spare parts, copies of the manual[11-14] and the protocol[8] were packed in the transfer cases. Figures 3.3 and 3.4 show the photograph of the pressure transducer part (PTP) package and the support electronics part (SEP) package, respectively.

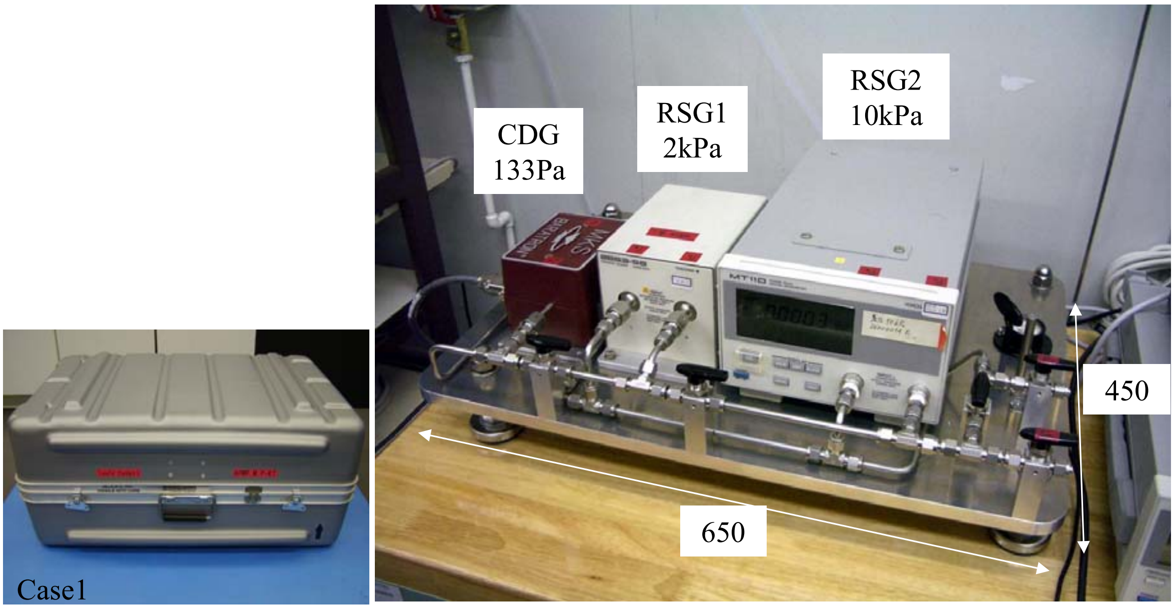


Figure 3.3: Photographs of the pressure transducer part (PTP) and packing case. The three different pressure transducers are mounted on the base-plate.

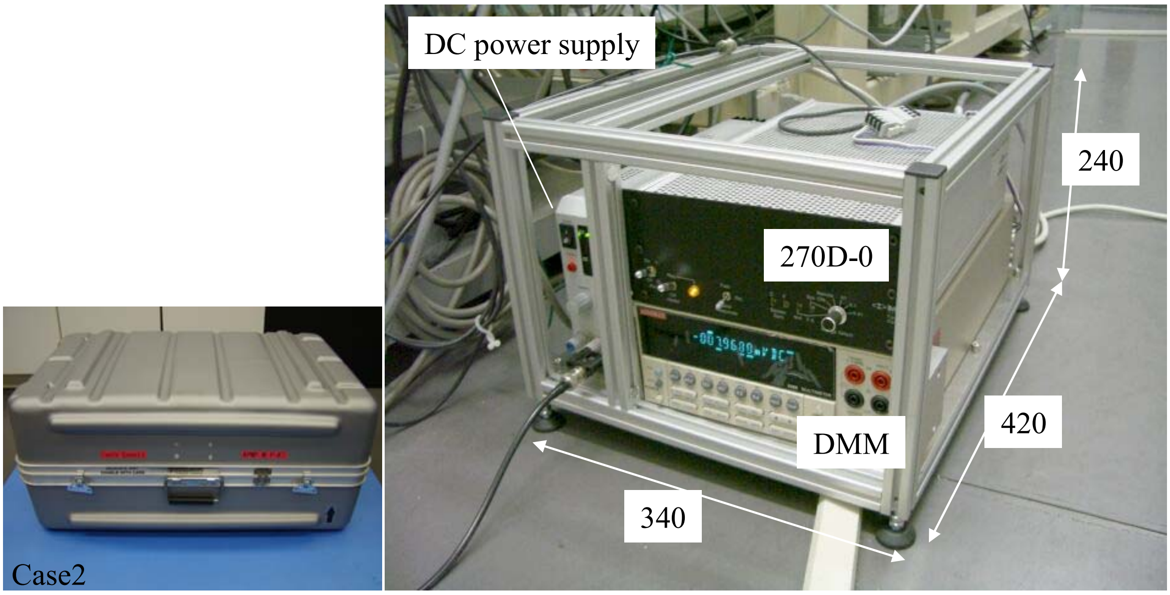


Figure 3.4: Photographs of the support electronics part (SEP) and packing case. The SEP includes a signal conditioner for the CDG, a DMM and a DC power supply within an aluminum mainframe.

4. Circulation of the transfer standards

According to the protocol[8], the transfer standard was circulated during the period May 2005 to October 2005 with calibrations at the pilot institute (NMIJ/AIST) at the start and end of the comparison. An ATA CARNET was prepared by the pilot institute to enable the circulation of the package. An inspection of the appearance and function of the devices was made when the package first arrived at and before the package departed from each participating institute.

4.1 Chronology of measurements

Table 4.1 presents the chronology of the measurements made with the transfer standard during the comparison loop. The arrival and departure dates, and dates during which calibration data was taken at each participating institute are listed. The total time required to complete the measurements phase of this comparison was about four months. There was no serious problem regarding the transportation during the course of the comparison.

Table 4.1: Chronology of measurements during key comparison.

Institute	Country	Arrival	Departure	Dates for calibrations
NMIJ/AIST	Japan	---	2005/6/23	2005/6/10, 14, 15, 16, 17
MSL	New Zealand	2005/7/1	2005/8/26	2005/8/10, 12, 15, 16, 17
NMIJ/AIST	Japan	2005/9/5	---	2005/9/9, 13, 14, 15, 16

4.2 Temperature change of the transfer standard during comparison

As described in section 3, electric thermometers were installed in the transfer standard to monitor the temperature change during the transportation. The temperature of the transfer standard during the comparison, sampled in intervals of two hours, is shown in Figure 4.1. The result indicates that the temperature range measured by the thermometer was approximately within the range 12 ℃ to 33 ℃ during the whole comparison including the transportation. This temperature range is within the manufacturer’s recommended operating range. Therefore, it can be stated that the temperature of the transfer standards was maintained in the normal operating range during the whole comparison.

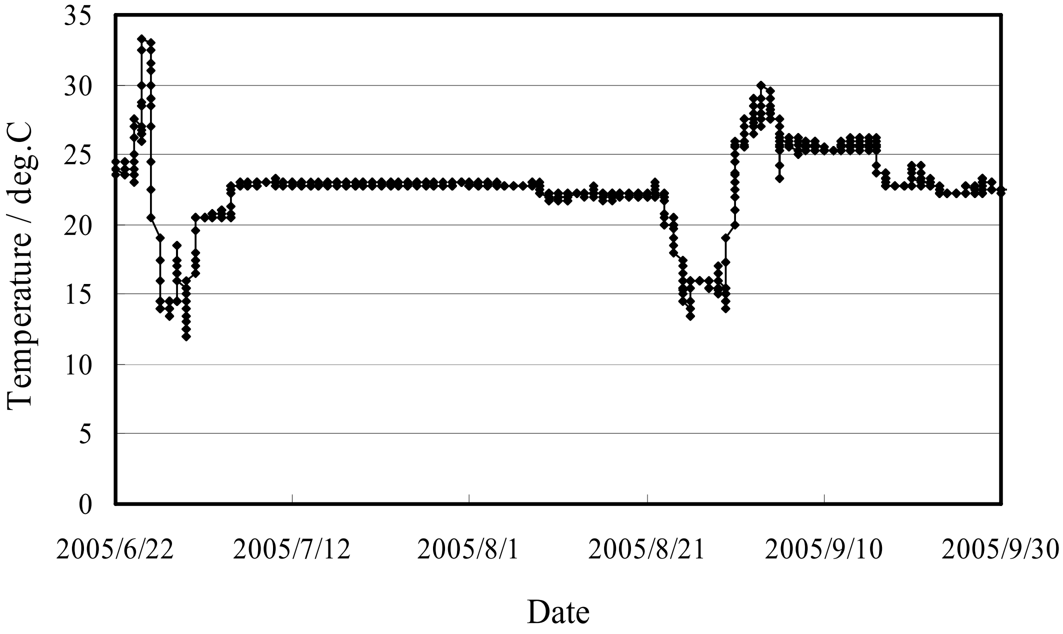


Figure 4.1: Temperature of transfer standard during the comparison.

5. General Calibration Procedure

The general procedure for the key comparison required each participant to calibrate the transfer standard (with nitrogen gas) at the following nominal differential pressures in ascending order: 1 Pa, 3 Pa, 10 Pa, 30 Pa, 100 Pa, 300 Pa, 1000 Pa, 3000 Pa and 5000 Pa (9 pressure points). The details of the procedure for this comparison are described in the protocol[8]. The reference and baseline pressure was required to be nominally between 95 kPa and 105 kPa absolute. An external pressure gauge supplied by the participating institute was used for this purpose. The actual differential pressures realized at the transfer standard gauges by the participant's pressure standards were required to be within 2 parts in 100 of the target pressures.

A total of five calibration runs were required, with each run taken on a different day. Within a calibration run, five sets of pressure and temperature readings of the transfer standard and primary standard were required at each target pressure. These five sets of readings are the ABABA sequence described below. Each set of data was obtained by averaging 12 instrument readings sampled every 5 seconds. The program required approximately 60 seconds to perform one measurement sequence.

At the beginning of each calibration run, ten repeat sets of zero-pressure readings for the transfer standard gauges were required to be taken with the PTP isolated from the participant's calibration system and with internal isolation valves and bypass valves open. An additional ten repeat sets of zero-pressure readings were to be taken at the end of each run in order to monitor zero drift in the three transducers during calibration.

At each target pressure, the following measurement procedure was performed (See Figure 5.1).

- Measurement procedure using "ABABA" method was applied here for the small differential pressure standard using the double pressure balances.
- In state "A", the two balances for the differential pressure standard were to be almost in equilibrium.
- In state "B", differential pressure was generated between the two balances by applying a small weight on either pressure balance.
- Measuring time interval M (1 minute): During this time interval, the software program continuously acquired the outputs from three transducers and one PRT.
- Settling time interval S: this time interval was determined for each pressure point by the participating institute (practically 2-5 minutes). Once it was determined, each participant used the same time interval throughout the comparison. Typically the measurement procedure at each target pressure took

less than 30 minutes to complete.

- In each state, a set of readings (pressure and temperature) of the participant's pressure standard and the reading of each pressure transducer was recorded. Also the reference pressure measured by the participant's external gauge was recorded.
- According to the measurement sequence in the protocol[8], the differential pressure was generated and applied to the transfer standard using the participant's standard. The relative difference between the actual pressure applied and the nominal value was to be below 2 %.
- The applied pressure P_{STD} with the associated standard uncertainty $u(P_{STD})$ [k=1] at the reference level of the transfer standard was calculated. Any influence quantity for the institute system was taken into account and was included in the appropriate uncertainty estimation. The correction by the differential height of the reference levels between the participating institute's standard and the transfer standard was considered.

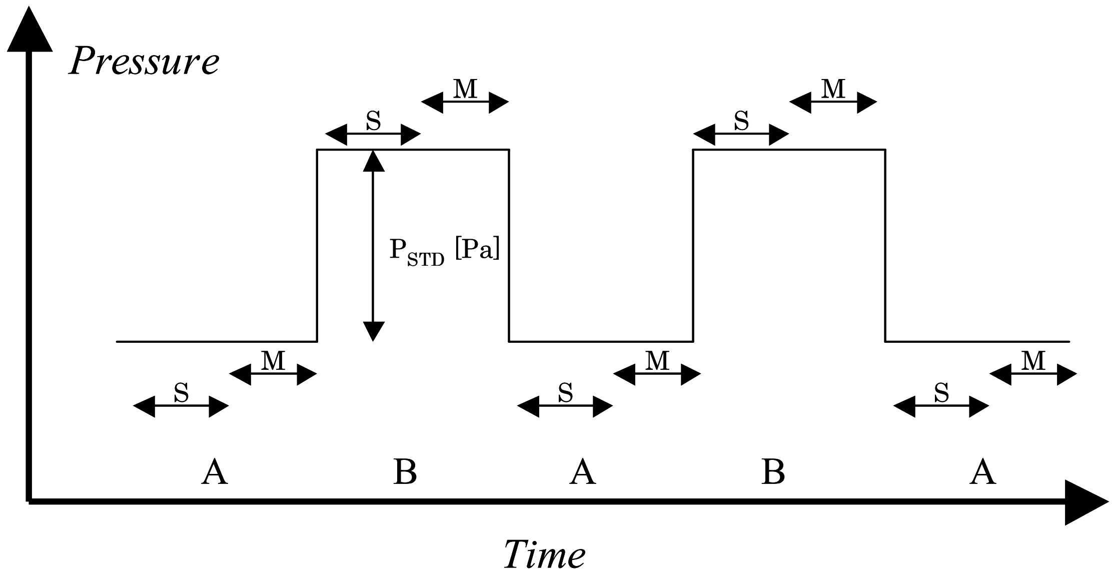


Figure 5.1: Measurement procedure at each pressure point

The environmental condition, such as atmospheric pressure, ambient temperature and relative humidity, during the calibration was measured using the participant's own devices. The institutes operated their pressure standards at their normal operating temperature. Head corrections were referenced to the top of the reference level bar from the surface of the base-plate of the PTP (73 mm).

The format for reporting calibration data followed the measurement sequence dictated by the data acquisition software developed for this comparison. The sequence for each set of associated readings of the transfer standard and the participant's primary standard was:

Set No. P_{CDG} P_{RSG1} P_{RSG2} T_{PRT} T_{STD} P_{REF} P_{STD} $u(P_{STD})$

where P_{REF} is the reference pressure as measured by an external gauge supplied by the participant, and P_{STD} and T_{STD} are the pressure and temperature readings of the participant's pressure standard. All calibration data were transmitted in the form of spreadsheet files provided by the pilot institute.

Upon completion of the measurement both the pilot institute NMIJ/AIST and MSL sent their data to the chair of the APMP TCM. The chair of the APMP TCM retained copies of the data confidentially for fair treatment and when he had received the two sets of data from NMIJ/AIST and the set of data from MSL, he then sent a copy of the data to NMIJ/AIST for analysis.

6. Analysis of reported data

Data obtained from one complete calibration run consists of the recordings of the pressure and temperature obtained from the transfer standard, the pressure applied by the pressure standard and the environmental parameters for each of the nine pressure points from 1 Pa to 5000 Pa in ascending sequence. 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 Re-scaling of the gauge readings,
6.4 Calculation of the predicted gauge readings,
6.5 Estimation of uncertainties,
6.6 Results of corrected mean gauge readings.

6.1 Correction for zero-pressure offsets

The first step in reducing the comparison data is to correct the readings of each gauge i for its zero-pressure offset. The index i refers to CDG (i = 0), RSG1 (i = 1) or RSG2 (i = 2). At a given target pressure during calibration run k, the corrected mean reading of gauge i is given by:

$$p_{ik} = \frac{1}{2} \cdot \left(R_{B1ik} + R_{B2ik}\right) - \frac{1}{4} \cdot \left(R_{A1ik} + 2 \cdot R_{A2ik} + R_{A3ik}\right) \tag{6.1}$$

where R_{B1}, R_{B2}, R_{A1}, R_{A2} and R_{A3} are the uncorrected readings obtained from the measurements using the method “ABABA” at realizing each target pressure.

6.2 Correction for difference between nominal pressure and actual pressure

As described in the protocol[8], the difference between actual pressure applied and the nominal target pressure was adjusted to be within two parts in 100 of the target pressure. The transfer standard gauges are nominally linear devices and so the ratio of transfer standard reading to primary standard reading will be essentially independent of pressure for a range of pressure about each target value. Once calculated these calibration ratios are used to correct the gauge readings for deviations of the primary standard from the target pressure and so they form the basis for the comparison of measurement standards from different NMIs.

At each target pressure during calibration run k the ratio of readings of transfer standard gauge i and primary standard j is given by

$$a_{ijk} = \frac{p_{ik}}{P_{jk}} \tag{6.2}$$

where p_{ik} and P_{jk} are the "simultaneous" readings of the gauge and primary standard, respectively. The mean of the a_{ijk} for 5 calibration runs defines a calibration ratio given by

$$a_{ij} = \frac{1}{5}\sum_{k=1}^{5} a_{ijk} \tag{6.3}$$

The calibration ratio, if expressed as

$$a_{ij} = \frac{p_i}{P_j}, \tag{6.4}$$

may be used to calculate a gauge reading p_i from the pressure being generated by primary standard j, P_j, or vice-versa.

Figure 6.1 shows the relative standard deviations of the three gauges, $\sigma(a_{ijk})/a_{ij}$, where $\sigma(a_{ijk})$ is the standard deviation of five values of a_{ijk} (about their mean). As shown in the figure, the superior stability of the RSG1 is clearly evident in the pressure range between 100 Pa and 1000 Pa. At 100 Pa, relative standard deviation of RSG1 is smaller than that of CDG. Similarly, at 1000 Pa, relative standard deviation of RSG1 is smaller than that of RSG2. In the pressure range below 100 Pa, the resolution of CDG is smaller than that of RSG1 though the relative standard deviations of CDG and RSG1 are comparable.

Figures 6.2, 6.3 and 6.4 present the calibration ratios for CDG, RSG1 and RSG2 in the transfer standard package as determined by two differential-mode calibrations of the package at NMIJ/AIST, respectively. The calibration ratios in the pressure range between 1 Pa to 100 Pa, 3 Pa to 1000 Pa, and 300 Pa to 5000 Pa are plotted in Figures 6.2, 6.3 and 6.4, respectively, although CDG, RSG1 and RSG2 were measured in the pressure range between 1 Pa to 100 Pa, 1 Pa to 1000 Pa and 1 Pa to 5000 Pa, respectively.

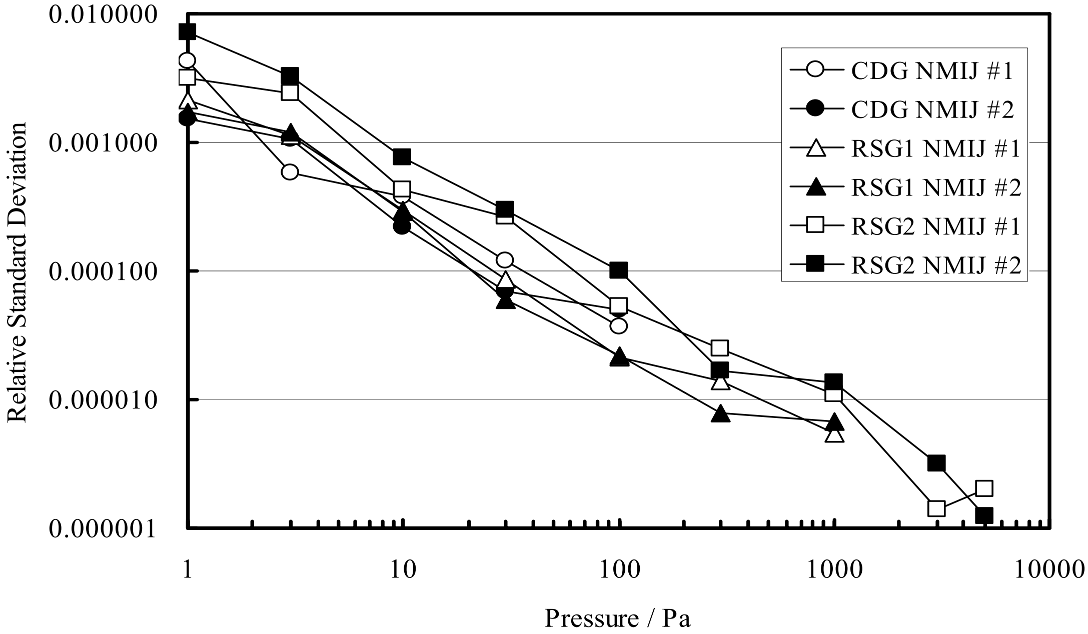


Figure 6.1: The relative standard deviations of the three gauges, $\sigma(a_{ijk})/a_{ij}$, where $\sigma(a_{ijk})$ is the standard deviation of five values of a_{ijk} about their mean.

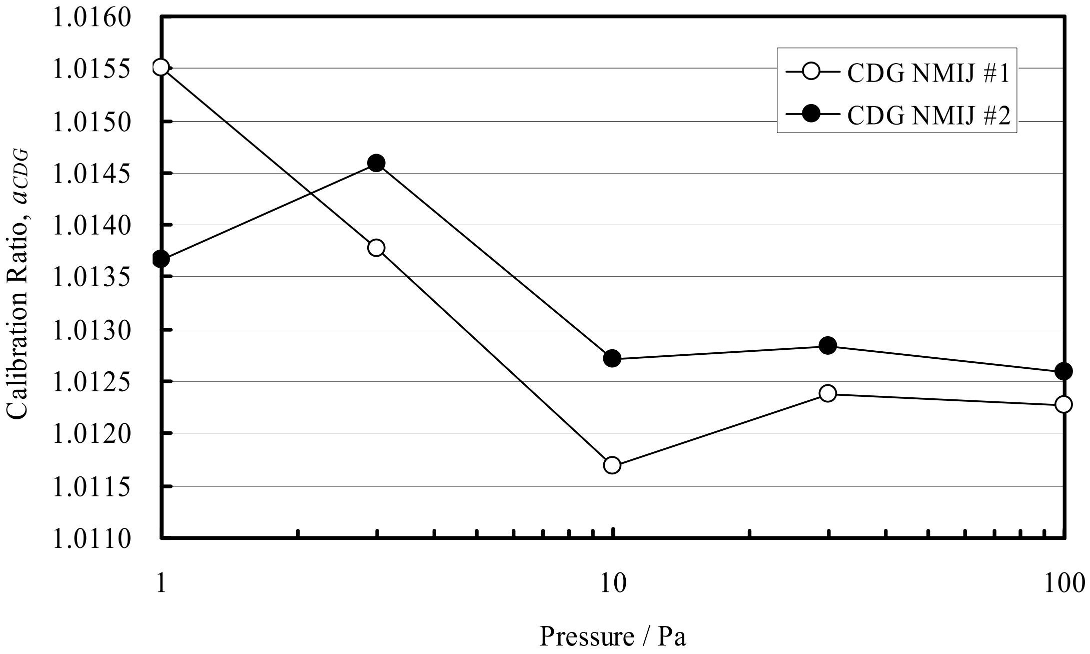


Figure 6.2: Calibration ratios for CDG as a function of pressure.

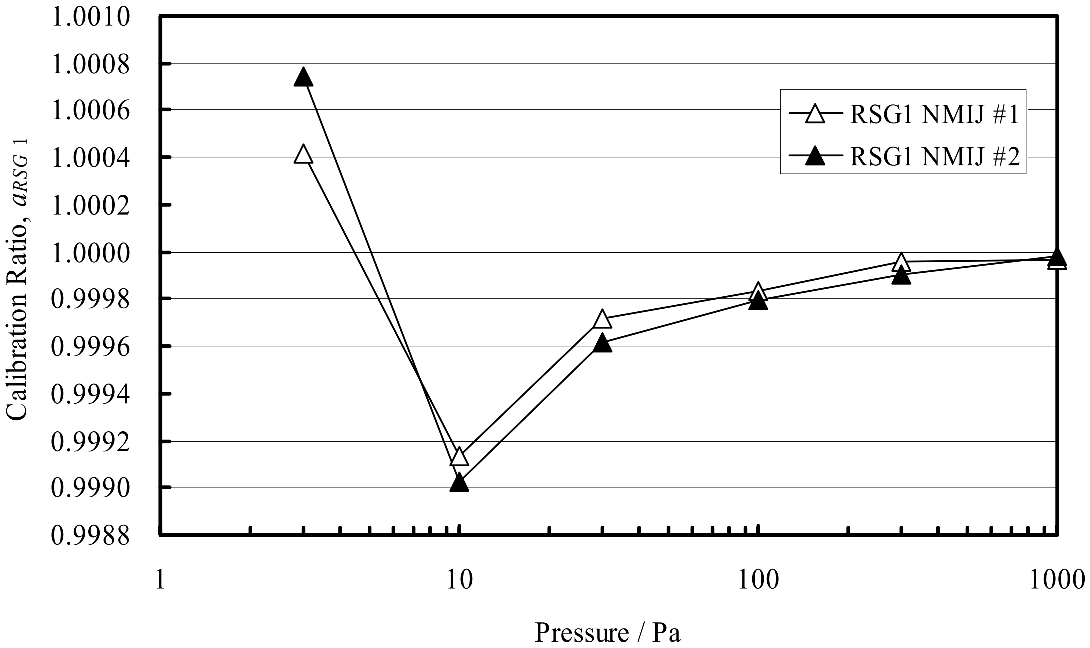


Figure 6.3: Calibration ratios for RSG1 as a function of pressure.

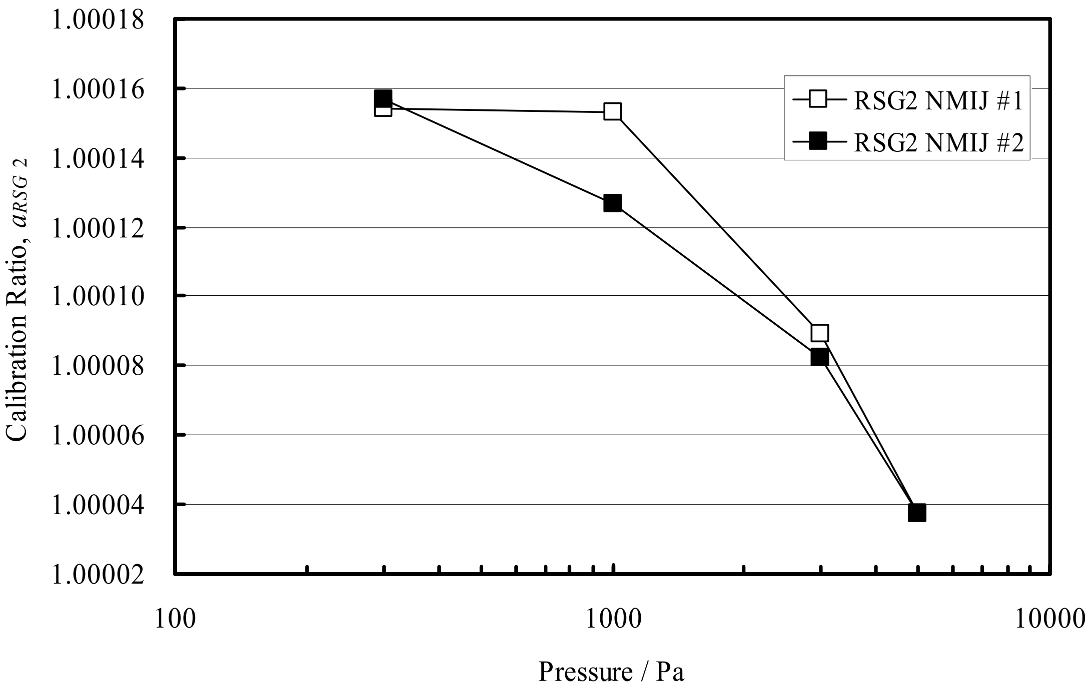


Figure 6.4: Calibration ratios for RSG2 as a function of pressure.

6.3 Re-scaling of the gauge readings

The relatively large calibration shifts of the CDG can be reduced significantly by re-scaling their readings so at 100 Pa they equal those of the RSG1 in the same way as CCM.P-K5[5]. The readings of the RSG1 and RSG2 gauges were not rescaled.

At target pressures $p_t < 100$ Pa, the re-scaled reading of capacitance diaphragm gauge may be expressed as

$$p_{CDG}(p_t) = p_{G1}(p_t) \cdot \left[\frac{p_{RSG1}(100)}{p_{G1}(100)} \right] \tag{6.5}$$

where $p_{G1}(p_t)$ is the CDG reading before re-scaling. This equation may be re-expressed in terms of calibration ratios by means of equation (6.4) as

$$a_{CDGj}(p_t) = a_{G1j}(p_t) \cdot \left[\frac{a_{RSG1j}(100)}{a_{G1j}(100)} \right] \tag{6.6}$$

where a_{G1j} and a_{CDGj} are the respective calibration ratios for capacitance diaphragm gauge before and after rescaling, and a_{RSG1j} is the calibration ratio for resonant silicon gauge 1. The observed shifts in the CDG ratios between successive calibrations at NMIJ/AIST are substantially reduced by re-scaling.

Table 6.1 lists the calibration ratios for the transfer standard package that were used in the comparison results. The calibration ratios for CDG were re-scaled to RSG1. The calibration ratios, A_j, as a function of pressure, are obtained as follows:

$$A_j(p_t) = \begin{cases} a_{CDGj}(p_t) & (p_t < 100) \\ a_{RSG1j}(p_t) & (100 \le p_t \le 1000) \\ a_{RSG2j}(p_t) & (p_t > 1000) \end{cases} \tag{6.7}$$

Figure 6.5 shows the calibration ratios for the transfer standard package, A_j. In summary, the present key comparison is based on the calculated calibration ratios for all the pressure points.

Table 6.1: Calibration ratios for the gauges, as a function of pressure. The calibration ratios for CDG were re-scaled to RSG1.

(Pa)	CDG #1	CDG #2	CDG MSL	RSG1 #1	RSG1 #2	RSG1 MSL	RSG2 #1	RSG2 #2	RSG2 MSL
1	1.003026	1.000851	1.001770						
3	1.001320	1.001767	1.000187						
10	0.999246	0.999918	0.999846						
30	0.999933	1.000028	1.000020						
100				0.999831	0.999792	0.999815			
300				0.999958	0.999905	0.999903			
1000				0.999970	0.999979	0.999991			
3000							1.000089	1.000082	1.000077
5000							1.000037	1.000038	1.000035

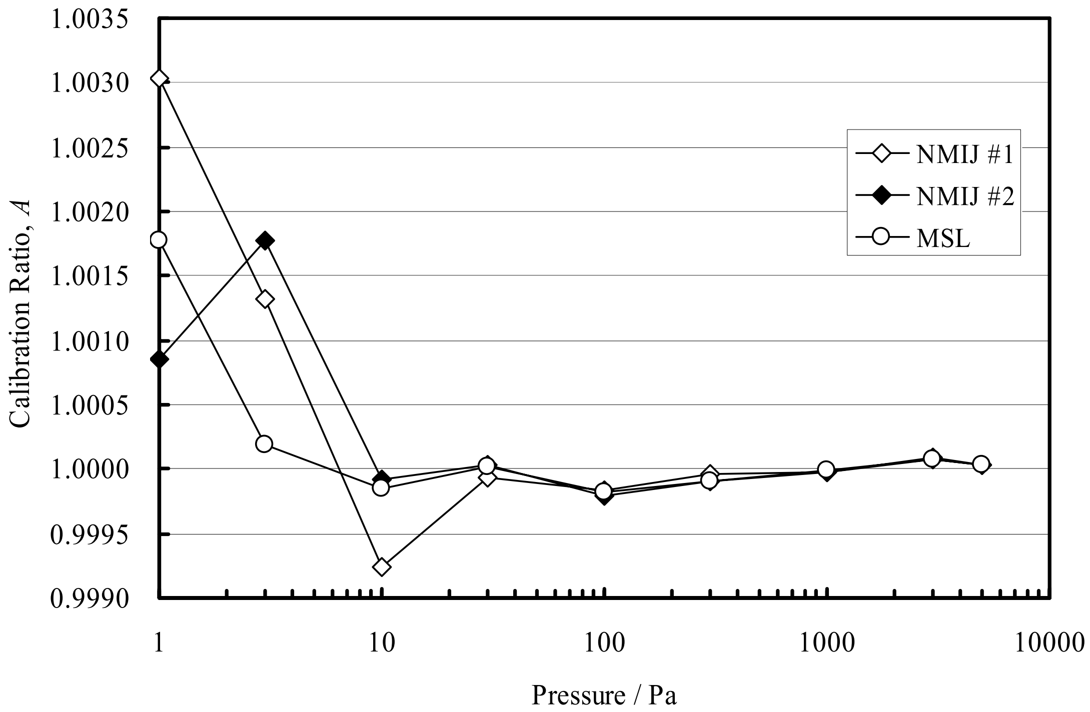


Figure 6.5: Calibration ratios for the transfer standard package after re-scaling as a function of pressure.

6.4 Calculation of the predicted gauge readings

Degrees of equivalence[1] of the primary standards for differential pressure can be expressed quantitatively by comparing pressure readings of the transfer standard gauges. The basic method adopted here is to use the calibration ratios to predict gauge readings that would be observed when different primary standards generate pressure exactly equal to the target value[5]. The difference in the predicted gauge readings is taken as a surrogate for the difference between "true" pressures actually realized by the different primary standards.

The reading for the transfer standard package for each pressure generated by primary standard j may be expressed as

$$p_{jU} = A_j p_t \tag{6.8}$$

where A_j is the calibration ratio for the transfer standard package, p_{jU} is the predicted transfer pressure reading that the institute would obtain had it exactly applied the target pressure p_t. For the pilot institute, a single value of p_{jU} was calculated as the arithmetic mean of two values of $p_{jU}{}^n$ obtained from two calibrations (n = 1, 2) of the transfer standard package at the pilot institute.

Following on from the analysis of CCM.P-K5 it is convenient to correct the p_{jU} gauge readings so that their ensemble average for all the institutes also equals the target pressure. Thus, the corrected mean gauge readings can be expressed as

$$p_j = f_c p_{jU} \tag{6.9}$$

where the correction factor f_c is given by

$$f_c = \frac{2p_t}{\sum_{n=1}^{2} p_{jU}} \tag{6.10}$$

where p_t is the target pressure. The resultant values for f_c are very nearly equal to one. The results for p_j from individual institutes are presented in Section 7. Implicit in the above analysis is the assumption that response functions of the transfer gauges do not change during the comparison[5].

6.5 Estimation of uncertainties

In this subsection, all the uncertainties are expressed as the standard ones.

The combined standard uncertainty in the normalized gauge readings calculated using equation (6.9) may be estimated from the root-sum-square of these component uncertainties[5,6],

$$u_c(p_j) = \sqrt{u_{std}^2(p_j) + u_{rdm}^2(p_j) + u_{lts}^2(p_j)} \tag{6.11}$$

where $u_{std}(p_j)$ is the uncertainty in p_j due to systematic effects in primary standard j, $u_{rdm}(p_j)$ is the uncertainty in p_j due to the combined effect of short-term random errors of transfer standard and primary standard j during calibration, and $u_{lts}(p_j)$ is the uncertainty arising from long-term shifts in the response function of transfer standard during the course of the comparison.

6.5.1 Uncertainty due to systematic effect in pressure standard

Table 6.2 and Figure 6.6 present the estimated relative uncertainties in pressure arising from systematic effects in the primary standards, as stated by the participants for target pressures used in the comparison. Such estimated usually involve both Type A and Type B evaluations.

Table 6.2: Relative standard uncertainties, as stated by the participants, due to systematic effects in their primary standards. Not all digits are significant but are retained for calculation of final results.

Target Pressure Pa	$100 \times u_{std}(p_t)/p_t$	
	NMIJ/AIST	MSL
1	0.5100	0.4400
3	0.1700	0.1467
10	0.0510	0.0440
30	0.0173	0.0147
100	0.0051	0.0045
300	0.0019	0.0019
1000	0.0009	0.0012
3000	0.0007	0.0011
5000	0.0007	0.0011

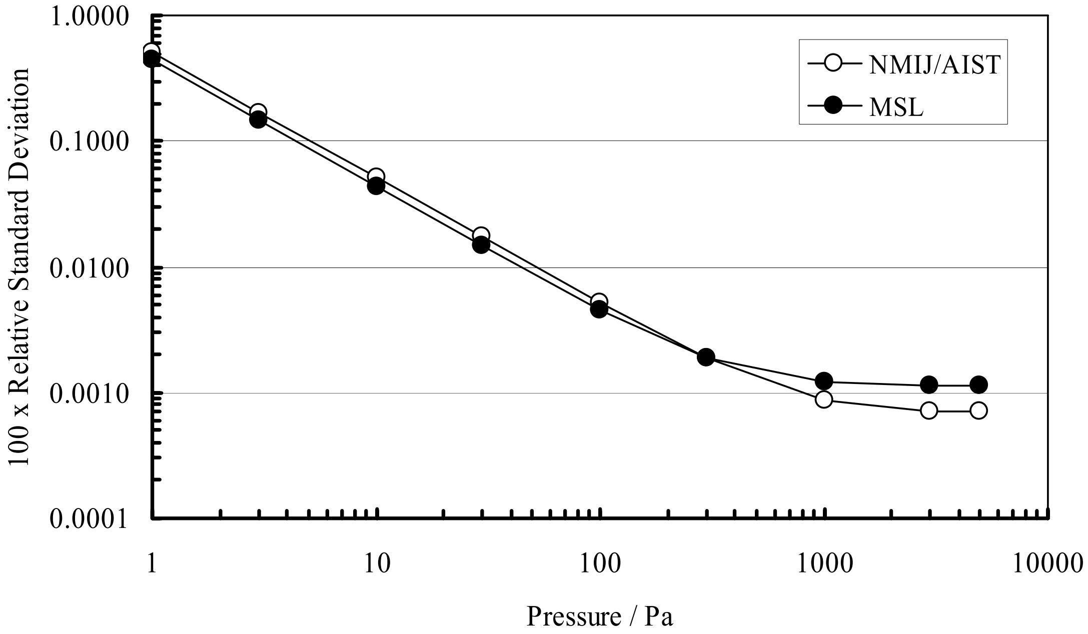


Figure 6.6: Relative uncertainty due to systematic effects in primary standards at the participating institutes as a function of pressure.

The relative uncertainty in p_j due to short-term random effects during calibration can be estimated from the corresponding uncertainties in the calibration ratios via equation (6.11):

$$\frac{u_{rdm}(p_j)}{p_j} = \frac{u_{rdm}(A_j)}{A_j} \tag{6.12}$$

Similarly the relative uncertainty in p_j due to long-term shifts in gauge response between calibrations is given by

$$\frac{u_{lts}(p_j)}{p_j} = \frac{u_{lts}(A_j)}{A_j}. \tag{6.13}$$

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

The short-term random uncertainty in a calibration ratio, A_j, as given by (6.3), may be estimated by a Type A evaluation[5].

$$u_{rdm}\left(A_j\right) = \frac{\sigma_{jk}}{\sqrt{5}} \tag{6.14}$$

where σ_{jk} is the standard deviation of five values of the means, A_{jk}, about their mean A_j. The short-term random uncertainties in the re-scaled calibration ratios obtained via equation (6.6) were estimated as the root-sum-square of component uncertainties arising from random effects in $a_{G1j}(p_t)$, $a_{G1j}(100)$, $a_{RSG1j}(100)$, each evaluated using equation (6.13). The uncertainty obtained using equation (6.13) is given in column eight of Table 6.3.

6.5.3 Uncertainty arising from the long-term shift

Long-term shifts in gauge response are often one of the largest component uncertainties, particularly for CDG[5]. The long term shift in the transducers was estimated by analysis of the two pilot institute calibrations at the start and end of the comparison and a type B evaluation was used to estimate the long term shift uncertainty $u_{lts}(a_{ij})$.

At a given target pressure, the variation due to long-tern shifts was modeled by a normal distribution such that the best estimated value is $((A_{PI})_{\max}-(A_{PI})_{\min})/2$ and there is a 2 out of 3 chance the calibration ratio lies in the interval between maximum and minimum values of A_{PI} obtained from two calibrations at the pilot institute. Then the standard uncertainty due to this source of error equals one-half the difference between the maximum and minimum values:

$$u_{lts}\left(A_j\right) = \left(\left(A_{PI}\right)_{\max} - \left(A_{PI}\right)_{\min}\right)/2\,. \tag{6.15}$$

This estimate is unaffected by any systematic bias in the pilot institute primary standard, which would be present in two calibrations at the pilot institute. The stability of the primary standard at the pilot institute had been checked by many calibrations using several different pressure transducers at the pilot institute in the period of this comparison and it was confirmed that there was no systematic shift in the primary pressure standard.

The relative uncertainties in calibration ratios due to long-term shifts in gauge response estimated using equation (6.14) are given in column nine of Table 6.3. The estimates for CDG1 are based on variability of their calibration ratios after re-scaling to the RSG1. As listed in the table, the long-term shifts of the transfer standard was enough small to compare the pressure standards established by the participating institutes.

6.5.4 Combined uncertainty in the transfer standard reading

Finally, the combined uncertainty in the transfer standard readings, p_j, at each target pressure, was estimated by combining the component uncertainties given in Table 6.3 using the "root-sum-squares" method and is presented in column twelve of Table 6.3.

Table 6.3: Summary of key comparison results for calibration ratios, A_j, uncertainty due to systematic effects in primary standards, $u_{std}(p_t)$, uncertainty due to short-term random effects, $u_{rdm}(A_j)$, uncertainty due to long-term shifts, $u_{lts}(A_j)$, relative combined uncertainty, $u_c(A_j)/A_j$, calculated values for normalized reading of transfer standard, p_j, when the pressure generated by primary standard *j* equals the target pressure, and their combined standard uncertainty, $u_c(p_j)$. Not all digits are significant but are retained for calculation of final results. All the uncertainties are expressed as the standard ones.

NMI	Target Press. Pa	Calibrations Ratios Before Re-scaling			A_j	100 × $u_{std}(p_t)/p_t$	100 × $u_{rdm}(A_j)/A_j$	100 × $u_{lts}(A_j)/A_j$	100 × $u_c(A_j)/A_j$	p_{jU} / Pa	$u(p_{jU})$ / Pa
		CDG	RSG1	RSG2							
NMIJ #1	1	1.015508	1.006239	0.989878	1.003026	0.510000	0.429784	0.108559	0.675722	1.0030	0.0068
	3	1.013780	1.000414	1.007975	1.001320	0.170000	0.058658	0.022319	0.181215	3.0040	0.0054
	10	1.011681	0.999135	0.998550	0.999246	0.051000	0.038828	0.033592	0.072367	9.9925	0.0072
	30	1.012376	0.999714	0.999747	0.999933	0.017333	0.012979	0.004766	0.022172	29.9980	0.0067
	100	1.012273	0.999831	1.000224	0.999831	0.005100	0.002161	0.001981	0.005882	99.9831	0.0059
	300		0.999958	1.000154	0.999958	0.001867	0.001414	0.002678	0.003558	299.9875	0.0107
	1000		0.999970	1.000153	0.999970	0.000860	0.000547	0.000474	0.001124	999.9699	0.0112
	3000			1.000089	1.000089	0.000717	0.000138	0.000330	0.000801	3000.267	0.024
	5000			1.000037	1.000037	0.000700	0.000204	0.000007	0.000729	5000.187	0.036
MSL	1	1.014305	0.997507	0.999864	1.001770	0.440000	0.099631	0.108559	0.464016	1.0018	0.0046
	3	1.012702	0.999002	1.001584	1.000187	0.146667	0.037194	0.022319	0.152946	3.0006	0.0046
	10	1.012357	1.000242	1.001625	0.999846	0.044000	0.008348	0.033592	0.055983	9.9985	0.0056
	30	1.012533	0.999388	1.000592	1.000020	0.014667	0.007025	0.004766	0.016946	30.0006	0.0051
	100	1.012325	0.999815	1.000317	0.999815	0.004500	0.003264	0.001981	0.005901	99.9815	0.0059
	300		0.999903	1.000183	0.999903	0.001867	0.001167	0.002678	0.003467	299.9708	0.0104
	1000		0.999991	1.000149	0.999991	0.001220	0.000331	0.000474	0.001350	999.9911	0.0135
	3000			1.000077	1.000077	0.001147	0.000491	0.000330	0.001290	3000.231	0.039
	5000			1.000035	1.000035	0.001140	0.000290	0.000007	0.001176	5000.175	0.059
NMIJ #2	1	1.013665	0.999982	1.020678	1.000851	0.510000	0.156912	0.108559	0.544524	1.0009	0.0054
	3	1.014593	1.000747	1.002569	1.001767	0.170000	0.109141	0.022319	0.203248	3.0053	0.0061
	10	1.012720	0.999027	1.001598	0.999918	0.051000	0.023075	0.033592	0.065283	9.9992	0.0065
	30	1.012832	0.999613	1.000251	1.000028	0.017333	0.008903	0.004766	0.020060	30.0008	0.0060
	100	1.012592	0.999792	1.000118	0.999792	0.005100	0.002231	0.001981	0.005908	99.9792	0.0059
	300		0.999905	1.000157	0.999905	0.001867	0.000775	0.002678	0.003356	299.9715	0.0101
	1000		0.999979	1.000127	0.999979	0.000860	0.000684	0.000474	0.001196	999.9794	0.0120
	3000			1.000082	1.000082	0.000717	0.000313	0.000330	0.000849	3000.247	0.025
	5000			1.000038	1.000038	0.000700	0.000125	0.000007	0.000711	5000.188	0.036

6.5.5 Uncertainty in the corrected mean gauge readings

The component uncertainties in $u_c(p_j)$ will also propagate to the combined uncertainty on the corrected mean gauge reading p_j calculated via equation (6.9). For the non-pilot institute, the combined uncertainty was estimated from

$$u_c^2(p_j) \cong u_c^2(p_{jU}) = u_{std}^2(p_j) + u_{rdm}^2(p_j) + u_{lts}^2(p_j). \qquad (6.16)$$

where $u_{std}(p_{jU}) = u_{std}(p_j)$, and the approximation $f_c \cong 1$ was used[5].

For the pilot institute, p_{jU} is the mean of two values of p_j^n at target pressures, where n is the calibration number. In this case the combined uncertainty in p_j was estimated from:

$$u_c^2(p_j) \cong u_c^2(p_{jU}) = u_{std}^2(p_j) + u_{lts}^2(p_j) + \sum_{n=1}^{2} c^2 u_{rdm}^2(p_j^n). \qquad (6.17)$$

where c=1/2. The multiple calibrations at the pilot institute tend to reduce the influence of the uncorrelated uncertainties arising from short-term variability of the gauges on the combined uncertainty in p_j for the pilot institute[5].

6.6 Results of corrected mean gauge readings

Table 6.3 presents a summary of the normalized gauge readings, p_j, obtained from calibrations at the participating institutes as a function of target pressures. Results are presented in chronological order of the calibrations.

Table 6.4 presents a summary of final results for the pilot (NMIJ/AIST) and MSL as a function of target pressures. The values for the corrected mean gauge readings p_j, which were calculated from equation (6.9) using data in Table 6.3, are given in column three. The combined standard (k=1) uncertainties $u_c(p_j)$, which were calculated using equation (6.16) or (6.17), are given in column four.

Table 6.4: Corrected mean gauge readings and their standard uncertainties. Not all digits are significant but are retained for calculation of final results.

NMI	Target Press. Pa	p_j / Pa	$u(p_j)$ / Pa
NMIJ	1	1.0001	0.0057
	3	3.0020	0.0055
	10	9.9987	0.0065
	30	29.9994	0.0059
	100	99.9998	0.0057
	300	300.0044	0.0101
	1000	999.9918	0.0108
	3000	3000.0131	0.0242
	5000	5000.0061	0.0355
MSL	1	0.9999	0.0046
	3	2.9980	0.0046
	10	10.0013	0.0056
	30	30.0006	0.0051
	100	100.0002	0.0059
	300	299.9956	0.0104
	1000	1000.0082	0.0135
	3000	2999.9869	0.0387
	5000	4999.9939	0.0588

7. Results for key comparison APMP.M.P-K5

The pressure range of APMP.M.P-K5 was wider than that of CCM.P-K5. Therefore, the results for APMP.M.P-K5 are analyzed in this section independently and are processed by the following procedure:

7.1 Calculation of APMP Key Comparison Reference Values (APMP 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[17,18]. The typical methods are (i) unweighted mean method, (ii) weighted mean method and (iii) median method. Each method has some advantages and disadvantages. For this APMP comparison, an unweighted mean method was selected as a reasonable procedure to obtain reference values for this key comparison[5]. The unweighted mean value of the normalized mean gauge readings obtained from all participating institutes is calculated at the nominal target pressure as the APMP KCRV for this key comparison, p_R, using similar ways as given in the key comparisons CCM.P-K5[5]. This means that the KCRV is numerically equal to the target pressure

$$p_R = p_t \tag{7.1}$$

where p_R is the key comparison reference value and using the approximation $f_c \cong 1$, the combined uncertainty in p_R can be estimated from[5]:

$$u_c^2(p_R) \cong \sum_{j=1}^{2} \frac{u_c^2(p_j)}{2^2}. \tag{7.2}$$

where $u_c(p_R)$ is standard uncertainty of p_R.

Table 7.1 presents the APMP KCRVs and their combined standard uncertainties calculated for the normalized mean gauge readings.

Table 7.1: APMP.M.P-K5 Key comparison reference values and their combined standard uncertainties calculated for the normalized mean gauge readings. All the uncertainties are expressed as the standard ones.

Target Press. Pa	p_R / Pa	$u(p_R)$ / Pa
1	1.0000	0.0037
3	3.0000	0.0036
10	10.0000	0.0043
30	30.0000	0.0039
100	100.0000	0.0041
300	300.0000	0.0072
1000	1000.0000	0.0086
3000	3000.0000	0.0228
5000	5000.0000	0.0344

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 normalized mean gauge readings quantitatively in two ways:

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

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

7.2.1 Deviation of institute’s value from APMP KCRV

By comparing the normalized mean gauge readings of j-th participating institute relative to a KCRV, the deviation from the reference value, D_j, is calculated by the following equation:

$$D_j = p_j - p_R \tag{7.3}$$

and the expanded uncertainty of D_j, U_j, is estimated from

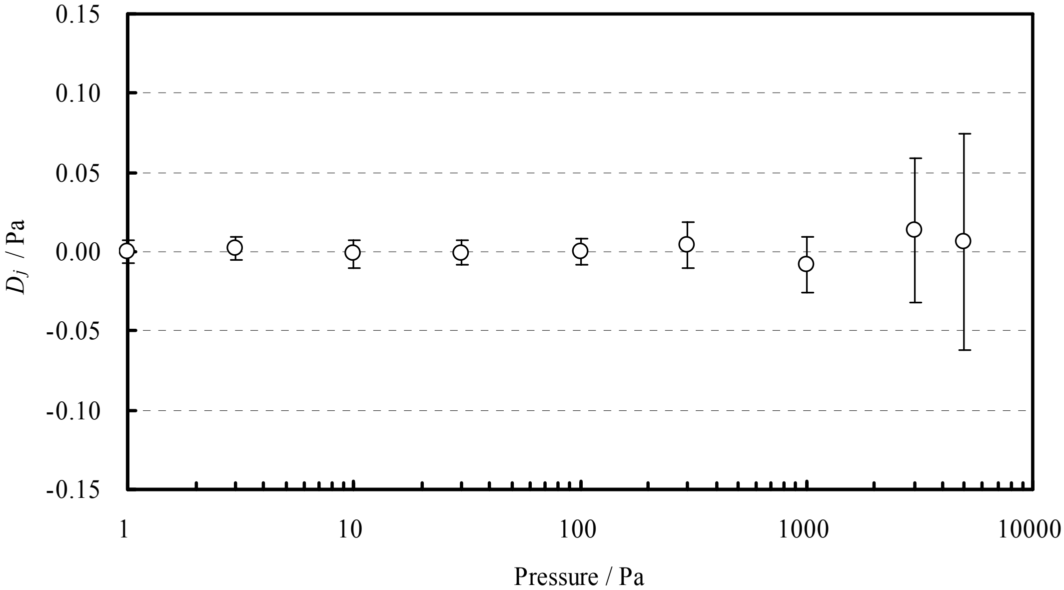
$$U_j = k \cdot u_c\left(D_j\right) = k \cdot \sum_{j=1}^{2} \frac{u_c^2\left(p_j\right)}{2^2} = k \cdot u_c\left(p_R\right) \tag{7.4}$$

where $u_c(D_j)$ is the combined standard uncertainty of the deviation, k is the coverage factor and k = 2 is adopted, and $u_c(p_R)$ is the combined uncertainty of the reference value.

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

Table 7.2: Deviations from the APMP.M.P-K5 KCRVs, D_j, the expanded (k = 2) uncertainties of the deviations, U_j and the degrees of equivalence as expressed by the ratios, D_j/U_j.

NMI	Target Press. Pa	D_j / Pa	U_j / Pa	D_j / U_j
NMIJ	1	0.0001	0.0073	0.01
	3	0.0020	0.0071	0.28
	10	-0.0013	0.0086	-0.15
	30	-0.0006	0.0078	-0.08
	100	-0.0002	0.0082	-0.02
	300	0.0044	0.0145	0.30
	1000	-0.0082	0.0173	-0.48
	3000	0.0131	0.0457	0.29
	5000	0.0061	0.0687	0.09
MSL	1	-0.0001	0.0073	-0.01
	3	-0.0020	0.0071	-0.28
	10	0.0013	0.0086	0.15
	30	0.0006	0.0078	0.08
	100	0.0002	0.0082	0.02
	300	-0.0044	0.0145	-0.30
	1000	0.0082	0.0173	0.48
	3000	-0.0131	0.0457	-0.29
	5000	-0.0061	0.0687	-0.09



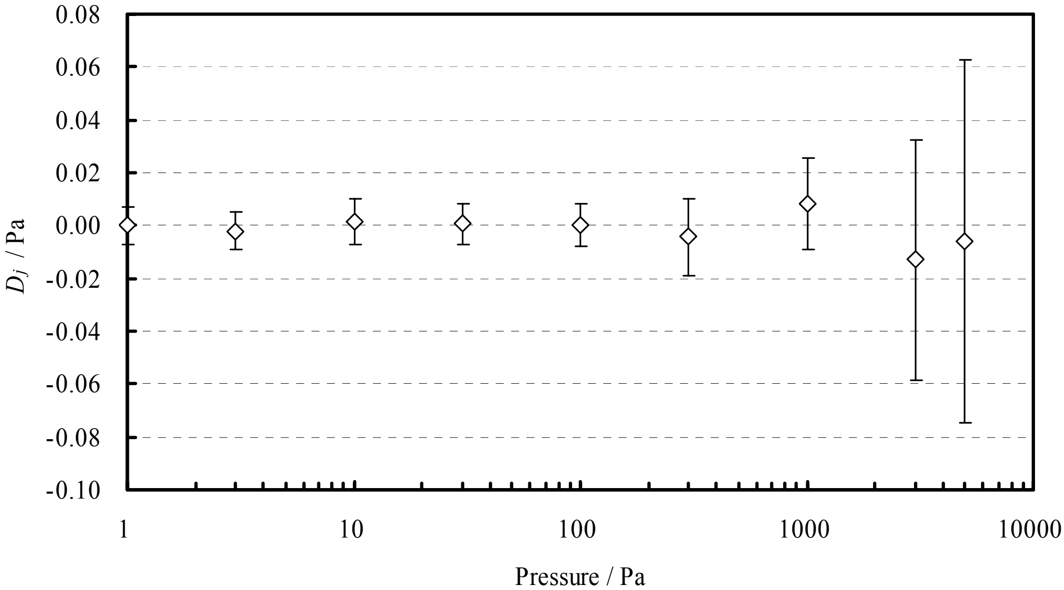


Figure 7.1: Deviations from the APMP KCRVs, D_j, and the expanded uncertainties of D_j, U_j. The symbols show deviations D_j and the error bars refer to expanded (k = 2) uncertainties U_j. [Upper] NMIJ/AIST, [Lower] MSL.

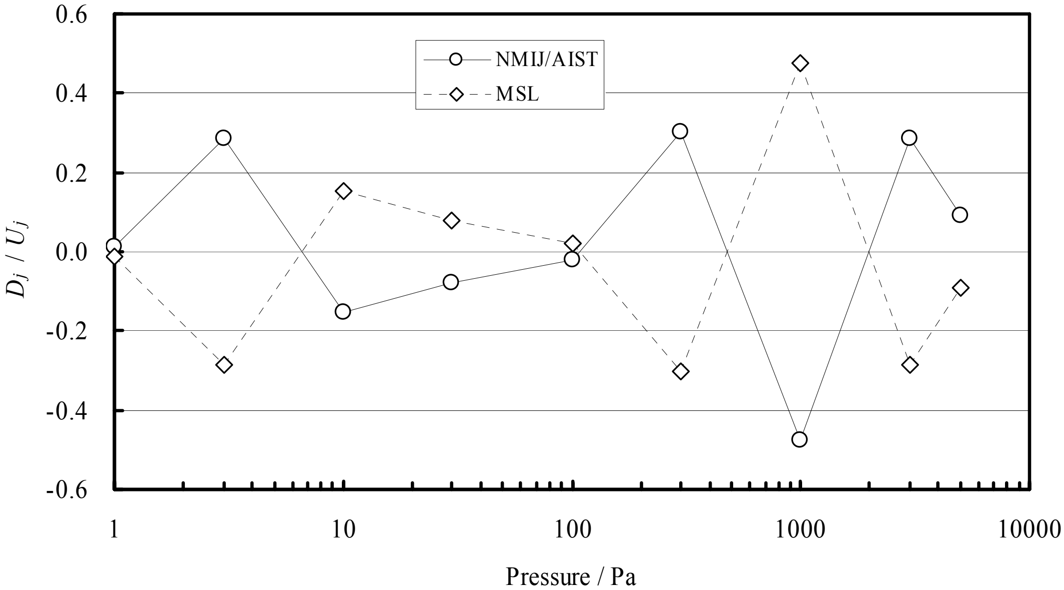


Figure 7.2: Degrees of equivalence of the participating institutes with respect to the APMP key comparison reference values. Ratios D_j /U_j for the participating institutes are plotted as a function of target pressure.

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:

$$D_{jj'} = D_j - D_{j'} = (p_j - p_R) - (p_{j'} - p_R) = p_j - p_{j'} \tag{7.5}$$

where $D_{jj'}$ is the difference of their deviations from the reference values, and the expanded uncertainty of the difference, $U_{jj'}$, is estimated from

$$U_{jj'} = k \cdot u_c(D_{jj'}) = k \cdot \sqrt{u_c^2(p_j) + u_c^2(p_{j'})} \tag{7.6}$$

where $u_c(D_{jj'})$ is the combined standard uncertainty of the difference, *k* is the coverage factor and $k = 2$ is adopted, $u_c(p_j)$ and $u_c(p_{j'})$ are the combined uncertainties in the normalized mean ratio of *j*-th and *j'*-th institutes, respectively.

Table 7.3 present a summary of results of the differences, $D_{jj'}$, the expanded ($k = 2$) uncertainties of the differences, $U_{jj'}$, and the degrees of equivalence expressed by the ratios, $D_{jj'}/U_{jj'}$, for the participating institutes. A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $|D_{jj'}/U_{jj'}| \le 1$. 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, $D_{jj'}$, expanded (k = 2) uncertainties of differences, $U_{jj'}$ and degrees of equivalence expressed by ratios, $D_{jj'}/U_{jj'}$.

j	NMI	j'	1			2		
		NMI	NMIJ			MSLNZ		
		Target Press. Pa	$D_{jj'}$ / Pa	$U_{jj'}$ / Pa	$D_{jj'}$ / $U_{jj'}$	$D_{jj'}$ / Pa	$U_{jj'}$ / Pa	$D_{jj'}$ / $U_{jj'}$
1	NMIJ	1				0.0002	0.0146	0.01
		3				0.0041	0.0142	0.29
		10				-0.0026	0.0165	-0.16
		30				-0.0012	0.0154	-0.08
		100				-0.0003	0.0162	-0.02
		300				0.0087	0.0267	0.33
		1000				-0.0164	0.0339	-0.49
		3000				0.0262	0.0902	0.29
		5000				0.0123	0.1374	0.09
2	MSLNZ	1	-0.0002	0.0146	-0.01			
		3	-0.0041	0.0142	-0.29			
		10	0.0026	0.0165	0.16			
		30	0.0012	0.0154	0.08			
		100	0.0003	0.0162	0.02			
		300	-0.0087	0.0267	-0.33			
		1000	0.0164	0.0339	0.49			
		3000	-0.0262	0.0902	-0.29			
		5000	-0.0123	0.1374	-0.09			

8. Linking key comparison APMP.M.P-K5 to key comparison CCM.P-K5

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[18,19].

This APMP key comparison, APMP.M.P-K5, is linked to the corresponding CCM key comparison, CCM.P-K5, which has an overlapping pressure range with APMP.M.P-K5 namely 1 to 1000 Pa. The final report of CCM.P-K5 has been approved[5] and the results are available in the BIPM KCDB. The pressure points at which both comparisons were carried out were the same within 2 % of the target nominal pressure.

8.1 Difference calculated from linking institute

The values for the linkage are calculated by using the differences, which are calculated using the results of the corresponding differences of the linking institute in the both comparisons CCM.P-K5 and APMP.M.P-K5. In the present case, the results obtained from one institute, MSL, which participated in both the CCM.P-K5 and APMP.M.P-K5 comparisons, were used to establish the linkage.

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-K5 and APMP.M.P-K5 were the corrected mean gauge readings. By considering the relationship of both quantities, the degrees of equivalence of participating institutes in APMP.M.P-K5 comparison can be transferred to CCM.P-K5 comparison using:

$$D_J = D_{CCM} - D_{APMP} + D_j \qquad (8.1)$$

where D_J is the deviation from the CCM.P-K5 reference value of the J-th institute (NMIJ) participating in APMP.M.P-K5 and D_j is the deviation of j-th participating institute (NMIJ) from the APMP.M.P-K5 reference value.

Table 8.1 shows the differences, $D_{CCM} - D_{APMP}$, calculated from the results of the linking institute, MSL, which participated into both the CCM.P-K5 and APMP.M.P-K5 comparisons, as a function of nominal target pressure.

Table 8.1: Differences, $D_{CCM} - D_{APMP}$.

NMI	Target Press. Pa	Results in APMP.M.P-K5			Results in CCM.P-K5				D_{CCM} - D_{APMP} / Pa
		D_j / Pa	U_j / Pa	D_j / U_j	D_J / Pa	U_J / Pa	D_J / U_J	$U_{CCM}(p_R)$ / Pa	
MSL	1	-0.0001	0.0073	-0.01	-0.0042	0.0081	-0.52	0.0080	-0.0041
	3	-0.0020	0.0071	-0.29	-0.0026	0.0098	-0.27	0.0092	-0.0006
	10	0.0013	0.0083	0.16	0.0340	0.0260	1.31	0.0072	0.0327
	30	0.0006	0.0077	0.08	-0.0032	0.0078	-0.41	0.0076	-0.0038
	100	0.0002	0.0081	0.02	-0.0040	0.0120	-0.33	0.0126	-0.0042
	300	-0.0044	0.0133	-0.33	0.0110	0.0180	0.61	0.0178	0.0154
	1000	0.0082	0.0169	0.49	0.0060	0.0280	0.21	0.0280	-0.0022
	3000	-0.0131	0.0451	-0.29					
	5000	-0.0061	0.0687	-0.09					

Normally, if the results of the linking institute in both comparisons are comparable, the expanded uncertainty for the institutes that participated only in the APMP comparison would be simply transferred from APMP results to the CCM results in similar way as given in the linkage between the key comparisons, CCM.P-K1.c and APMP.M.P-K1.c, CCM.P-K7 and APMP.M.P-K7[20,21]. In the present linkage, the uncertainties of the results of the linking institute (MSL) for the CCM comparison were larger than those for the APMP comparison and were comparable with those of the reference values for the CCM comparison, $U_{CCM}(p_R)$, except 10 Pa as shown in Table 8.1. Therefore, the expanded uncertainty of D_J for the institute that participated in APMP.M.P-K5 was estimated from

$$U_J = \sqrt{U_j^2 + U_{CCM}^2(p_R)} \qquad (8.2)$$

Table 8.2 presents respectively the deviations from the CCM KCRVs, D_J, the expanded (k = 2) uncertainties of the deviations, U_J, and the degrees of equivalence expressed by the ratios, D_J / U_J, for individual NMIs at the target pressures from 1 Pa to 1000 Pa. However, the results at 10 Pa are not included in the table since the CCM reference value at 10 Pa did not include the result from MSL. The deviations from the CCM.P-K5 reference value and the expanded uncertainties for the institutes participated into CCM.P-K5 are simply transferred from the result of CCM.P-K5[5]. A measure of the degree of equivalence is provided by the relative magnitude of the deviation as

$|D_J / U_J| \le 1$. For the present comparison, the condition was established for NMIJ/AIST, which participated only in APMP.M.P-K5, at all nominal target pressures.

Figures 8.1 presents D_J with U_J graphically for the participating institutes as a function of target pressure.

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:

$$D_{JJ'} = D_J - D_{J'} \tag{8.3}$$

where $D_{JJ'}$ is the difference of their deviations, and the expanded uncertainty of the difference, $U_{JJ'}$, is estimated from

$$U_{JJ'} = \sqrt{U_J^2 + U_{J'}^2} \tag{8.4}$$

where U_J and $U_{J'}$ are the expanded (k = 2) uncertainties of the deviation of J-th and J'-th institutes, respectively.

Tables 8.2 presents the results of the differences, $D_{JJ'}$, the expanded (k = 2) uncertainties of the differences, $U_{JJ'}$, and the degrees of equivalence expressed by the ratios, $D_{JJ'} / U_{JJ'}$, for the participating institutes in CCM.P-K5 and APMP.M.P-K5 from 1 Pa to 1000 Pa.

A measure of the degree of equivalence is provided by the relative magnitude of the deviation as $|D_{JJ'} / U_{JJ'}| \le 1$.

Table 8.2: Deviations from the CCM KCRVs, D_J, the expanded (k = 2) uncertainties of the deviations, U_J, the degrees of equivalence as expressed by the ratios, D_J / U_J, the results of the differences, $D_{JJ'}$, the expanded (k = 2) uncertainties of the differences, $U_{JJ'}$, and the degrees of equivalence expressed by the ratios, $D_{JJ'}$ /$U_{JJ'}$.

						NMIJ		
J	Target Press. Pa	D_J / Pa	U_J / Pa	D_J / U_J		$D_{JJ'}$ / Pa	$U_{JJ'}$ / Pa	$D_{JJ'}$ / $U_{JJ'}$
IMGC	1	0.0080	0.0150	0.53		0.0120	0.0185	0.65
	3	0.0050	0.0170	0.29		0.0035	0.0206	0.17
	30	0.0130	0.0220	0.59		0.0174	0.0245	0.71
	100	0.0300	0.0430	0.70		0.0343	0.0455	0.75
	300	0.0170	0.0470	0.36		-0.0027	0.0520	-0.05
	1000	0.0110	0.0600	0.18		0.0214	0.0683	0.31
MSL	1	-0.0042	0.0081	-0.52		-0.0002	0.0135	-0.01
	3	-0.0026	0.0098	-0.27		-0.0041	0.0152	-0.27
	30	-0.0032	0.0078	-0.41		0.0012	0.0133	0.09
	100	-0.0040	0.0120	-0.33		0.0003	0.0192	0.02
	300	0.0110	0.0180	0.61		-0.0087	0.0286	-0.31
	1000	0.0060	0.0280	0.21		0.0164	0.0431	0.38
NIST	1	0.0006	0.0082	0.07		0.0046	0.0136	0.34
	3	0.0010	0.0100	0.10		-0.0005	0.0153	-0.03
	30	-0.0028	0.0092	-0.30		0.0016	0.0142	0.11
	100	0.0040	0.0150	0.27		0.0083	0.0212	0.39
	300	-0.0050	0.0190	-0.26		-0.0247	0.0292	-0.85
	1000	-0.0030	0.0290	-0.10		0.0074	0.0437	0.17
NPL	1							
	3	0.0010	0.0100	0.10		-0.0005	0.0153	-0.03
	30	0.0000	0.0110	0.00		0.0044	0.0154	0.28
	100	-0.0230	0.0250	-0.92		-0.0187	0.0291	-0.64
	300	-0.0450	0.0360	-1.25		-0.0647	0.0423	-1.53
	1000	-0.0250	0.0880	-0.28		-0.0146	0.0939	-0.16
NMIJ	1	-0.0040	0.0108	-0.37				
	3	0.0015	0.0116	0.13				
	30	-0.0044	0.0108	-0.41				
	100	-0.0043	0.0150	-0.29				
	300	0.0197	0.0222	0.89				
	1000	-0.0104	0.0327	-0.32				

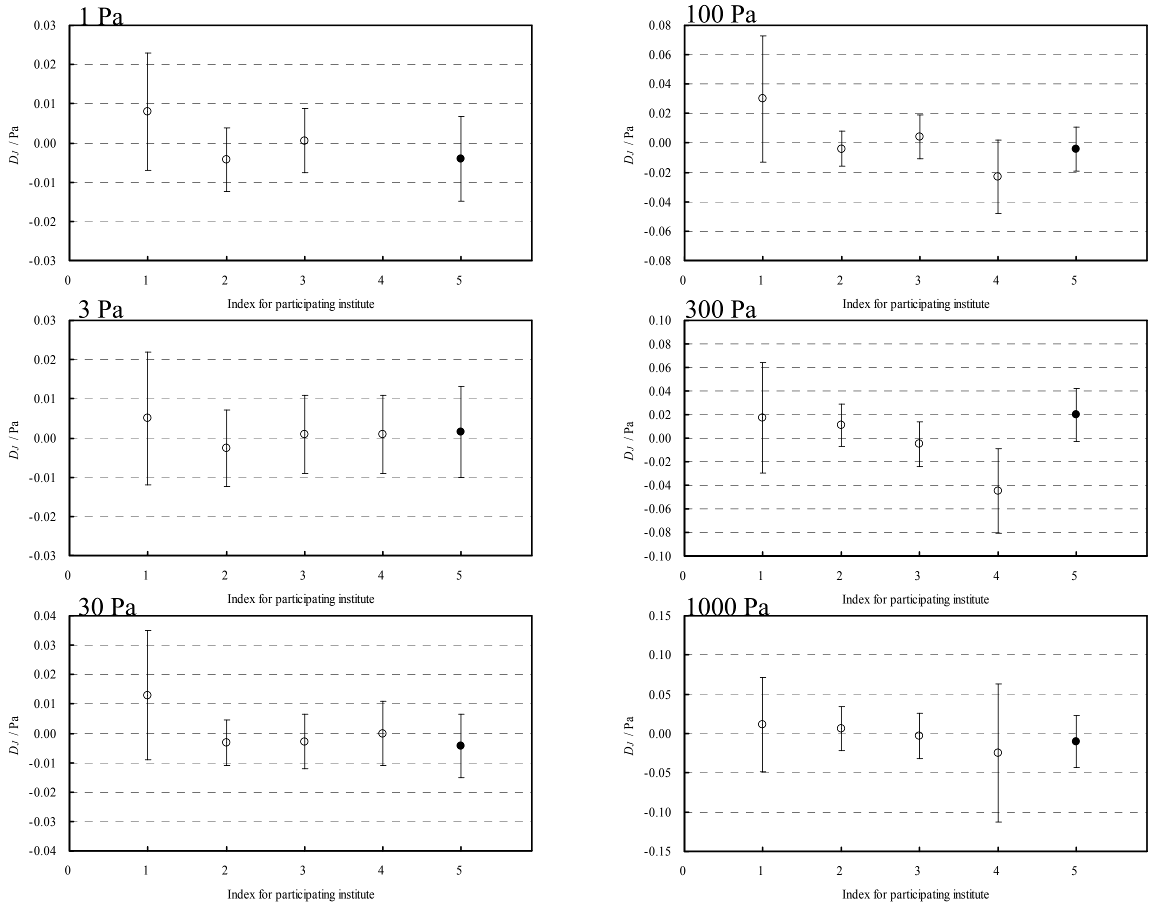


Figure 8.1: Deviations from the CCM KCRVs, D_J, and the expanded uncertainties of D_J, U_J. The symbols show deviations D_J and the error bars refer to expanded (k = 2) uncertainties U_J. [Index of participating institute: 1 IMGC, 2 MSL, 3 NIST, 4 NPL and 5 NMIJ/AIST].

9. Discussions

All the participants calibrated three pressure transducers on the transfer standard against the double pressure balances following the protocol[7,8]. The results presented in this report are based on data originally submitted to the pilot institute for preparation of the draft A report. From the calibration data of each participating institute, the corrected mean gauge readings for each participating institute were calculated with associated uncertainties.

In this report, the APMP.M.P-K5 reference values were calculated using the unweighted mean method and the degrees of equivalence with respect to the APMP.M.P-K5 reference values and the degrees of equivalence between pairs of participating institutes in APMP.M.P-K5 were presented as the main result.

The results of the participating institute, NMIJ/AIST, which participated only in APMP.M.P-K5 were linked to CCM.P-K5 and the degrees of equivalence with respect to the CCM.P-K5 reference values and the degrees of equivalence between pairs of participating institutes in APMP.M.P-K5 and CCM.P-K5 were presented.

10. Conclusions

Two National Metrology Institutes (NMIs) participated into this APMP key comparison of low gas differential pressure standards from 1 Pa to 5 kPa. High-precision electronic differential pressure transducers were circulated as the transfer standard for the whole comparison. In order to ensure the reliability of the transfer standard, three high-precision pressure transducers with the following ranges; 133 Pa, 2,000 Pa, 10,000 Pa were used on a transfer standard. The three transducers were selected for reasons of redundancy and resolution to cover the four decade pressure range.

The transfer standard was calibrated at the pilot institute (NMIJ/AIST) at the beginning and the end of this comparison. The stability of the transfer standard during the comparison period was evaluated from the pilot institute calibration results and it is shown that the transfer standard was sufficiently stable to meet the requirements of this key comparison.

The degrees of equivalence of the low differential pressure standards at the two participating NMIs were obtained. They were expressed quantitatively by two terms, deviations from the APMP key comparison reference values and pair-wise differences between deviations of participating institutes. The small differential pressure standards in the range 1 Pa to 5000 Pa of the two participating NMIs (NMIJ/AIST and MSL) were found to be equivalent compared with their claimed expanded uncertainties.

The degrees of equivalence in this comparison were also transferred to the corresponding CCM key comparison, CCM.P-K5, and it is shown that the NMIJ values were equivalent to the CCM KCRV within the claimed uncertainties.

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