ASIA-PACIFIC METROLOGY PROGRAMME

Comparison Identification Number: APMP.M.P.K1.c.1

Final Report on APMP.M.P-K1.c.1 Pneumatic Key Comparison from 0.4 MPa to 4.0 MPa in gauge mode

Chen-Chuan Hung[1], Wu Jian[2], Tawat Changpan[3],

[1] Center for Measurement Standards/ITRI, Hsinchu, Taiwan 300, R.O.C.

[2] National Metrology Centre SPRING Singapore, 1 Science Park Drive, Singapore 118221

[3] National Institute of Metrology, 75/7 Rama VI Road, Bangkok 10400, Thailand

Abstract

This report describes the key comparison APMP.M.P-K1.c.1 among the three National Metrology Institutes, Center for Measurement Standards-ITRI (CMS-ITRI, Chinese Taipei), SPRING Singapore and National Institute of Metrology (NIMT) in the pressure range from 0.4 MPa to 4.0 MPa in gas media and gauge mode executed during the period April 2003 to April 2004. This comparison was conducted by CMS-ITRI and was based on the calibration procedure of APMP Pneumatic Pressure Comparison APMP.M.P-K1.c. We intended to link to the key Comparison APMP.M.P-K1.c via the results of SPRING Singapore. All three participating institutes used pneumatic piston gauges as their pressure standards. Ruska 2465 gas-operated piston-cylinder assembly V-1215 used as transfer standard offered by CMS-ITRI was calibrated three times by the pilot institute during the comparison period and showed that it was very stable after evaluated. The comparison was conducted on the basis of cross-float experiments to determine the effective area of transfer standard from the national standards of three institutes. The mean value of the results obtained by all participating institutes measuring the same quantity from 0.4 MPa to 4.0 MPa in gas media and gauge mode lay within their expanded uncertainty with confidence level 95 %. Linking key comparison APMP.M.P-K1.c to key comparison APMP.M.P-K1.c.1 at two nominal pressures near 1 MPa and 4 MPa had been established.

Contents:

Figure and Table List:

1. Introduction

The regional pneumatic comparison program has been agreed with the Technical Committee for Mass and Related Quantities (TCM) of the Asia-Pacific Metrology Programme (APMP) for pneumatic pressure measurements from 0.4 MPa to 4.0 MPa in gauge mode. The key comparison was identified APMP.M.P-K1.c.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 comparison among Center for Measurement Standards-ITRI (CMS-ITRI, Chinese Taipei), SPRING Singapore and National Institute of Metrology (NIMT) was based on the calibration procedure of APMP Pneumatic Pressure Comparison APMP.M.P-K1.c. We extended the measuring pressure to 6.0 MPa although APMP.M.P-K1.c only measured the pressure up to 4.0 MPa. The transfer standard offered by the pilot institute, CMS-ITRI, was Ruska 2465 gas-operated piston-cylinder assembly (V-1215) and the effective area of the transfer standard can be determined by the cross-float technique against the participants' primary standards. The comparison activity was started on April 2003 and was completed on April 2004. In order to reach international consistence at same pressure range, this key comparison APMP.M.P-K1.c.1 will be linked to the key comparison APMP.M.P-K1.c via the results of SPRING Singapore.

The protocol prepared by CMS-ITRI was refereed to the calibration procedure of APMP.M.P-K1.c.1. The protocol was also an important part in the comparison. Therefore, all three participants agreed to follow the guidelines of the protocol. The protocol was applied to the pneumatic pressure comparison between CMS-ITRI and SPRING. At first, the transfer standards were transported to SPRING Singapore after the first time of the comparison in CMS-ITRI was carried out, and then the transfer standards were transported to CMS-ITRI after the comparison was performed by SPRING Singapore. Because NIMT Thailand joined the comparison activity at this moment, the protocol was amended and then the transfer standards were transported to NIMT Thailand after the second time of the comparison in CMS-ITRI was carried out. Finally, the transfer standards were transported to CMS-ITRI and the third time of the comparison in CMS-ITRI was performed after the comparison was carried out by NIMT.

This report include description of transfer standard, package and transportation, participants standards, calibration procedure, data calculation, the calibration results of the transfer standard performed at three participating laboratories, analysis of the results and the comparison results.

2. Transfer standard

2.1 Description of transfer standard

The transfer standard was a Ruska (Model 2465) piston pressure gauge base fully equipped with weight set, temperature probe and piston-cylinder assembly (V-1215) with nominal effective area 8.4 mm^2 used to measure the pressure range from 0.4 MPa to 6.0 MPa in the gauge mode using nitrogen gas as the pressure transmitting media. Both piston and cylinder are made of tungsten carbide. All masses were calibrated in mass laboratory with standard mass density of 8,000 kg/cm^3. The handing, mounting, cleaning etc. instructions of piston –cylinder assembly is described in the Ruska 2465 User's Manual[1]. Some points should be concerned about the height difference between reference level of the two compared standards and head correction.

(a) The reference level of piston gage is usually at a line marked on the piston gage base.
(b) To minimize uncertainties in pressure measurement, height difference between the reference levels of the laboratory standards and transfer standards will be kept as low as possible.
(c) The two compared standards placed by CMS-ITRI are in the same level so that the height correction is zero.
(d) The densities of air and nitrogen should be considered if any height correction is necessary.

2.2 Package and Transportation

To prevent the package of transfer standard from any damage, all effort should be made by each participant. The instruments must be handled with care. When the package arrives at participating institute, the package must be unpacked, and an inspection of the appearance and the function should be made immediately. The time schedule for the comparison and transportation of transfer standard is shown in Table 1.

Table 1: The time schedule for the comparison and the transportation of transfer standard

No.	Date of arrival	Date of departure	Name of the laboratories
1		9th October, 2003	CMS-ITRI (Taiwan)
2	13th October, 2003	20th November, 2003	SPRING (Singapore)
3	24th November, 2003	2nd February, 2004	CMS-ITRI (Taiwan)
4	9th February, 2004	22nd March, 2004	NIMT (Thailand)
5	29th March, 2004		CMS-ITRI (Taiwan)

2.3 Stability of the transfer standard

To concern about the stability of transfer standard in any international comparison is very important. It took over one year to carry out this comparison from the beginning to the end. The performance of the transfer standard will be affected if the transfer standard is not stable.

The values of the effective area $A'_{P'}$(23°C, p')(mm^2) versus p'(MPa) which were obtained by CMS/ITRI on April 2003, December 2003 and April 2004 are shown in Fig.1. The standard deviations were indicated through the error bars in order to establish the long-term stability of the transfer standard during one year. Table 2 provides the data of the effective area $A'_{P'}$(23°C, p')(mm^2) versus p'(MPa) of the transfer standard calibrated three times by CMS-ITRI during the comparison time period. Each standard deviation was calculated from ten pressure points of five measuring cycles including ascending and descending pressures of the three sets of data (totally 45 standard deviations in Table 2). The maximum difference of the average $A'_{P'}$ in three measurement sets is 5.8×10^{-5} mm^2 at 5.21 MPa. So, we propose the estimated instability contributed from maximum difference (5.8×10^{-5} mm^2) divide by nominal effective area (8.39 mm^2) is 7.0×10^{-6}.

Fig 1. The stability of transfer standard was indicated in standard deviation of effective area $A'_{P'}$ on April 2003, December 2003 and April 2004.

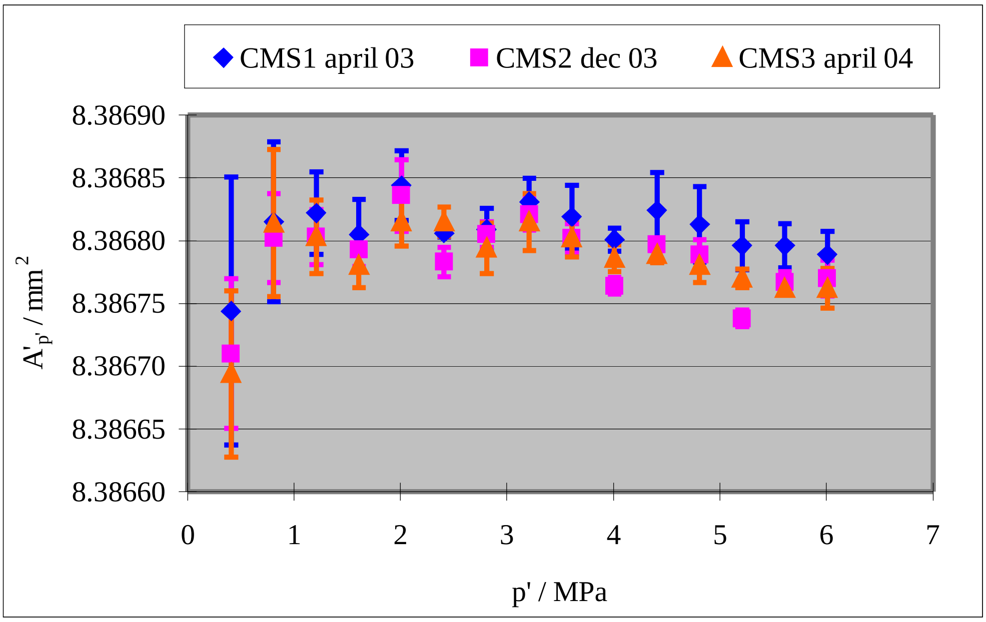


Table 2: The stability data showed the effective area of the transfer standard $A'_{P'}$ (mm^2) at 23 °C and *p'* as a function of pressure *p'*(MPa) on April 2003, December 2003 and April 2004.

Lab. Name	CMS					
Nominal Pressure	Date (Period) 18 April 2003 to 7 May 2003		Date (Period) 17 Dec. 2003 to 26 Dec. 2003		Date (Period) 21 April 2004 to 29 April 2004	
	Average of $A'_{P'}$	standard deviation of $A'_{P'}$	Average of $A'_{P'}$	standard deviation of $A'_{P'}$	Average of $A'_{P'}$	standard deviation of $A'_{P'}$
(MPa)	(mm^2)	(10^{-6})	(mm^2)	(10^{-6})	(mm^2)	(10^{-6})
0.41	8.386744	12.7	8.38671	7.1	8.386694	7.9
0.81	8.386815	7.6	8.386802	4.2	8.386814	7.0
1.21	8.386822	3.9	8.386803	2.6	8.386803	3.5
1.61	8.386805	3.3	8.386793	1.6	8.38678	2.1
2.01	8.386844	3.3	8.386836	3.4	8.386815	2.3
2.41	8.386806	0.4	8.386783	1.4	8.386815	1.4
2.81	8.386809	2.0	8.386805	1.2	8.386794	2.4
3.21	8.386831	2.2	8.386821	1.5	8.386815	2.7
3.61	8.386819	3.0	8.386802	1.4	8.386802	1.8
4.01	8.386801	1.1	8.386764	0.8	8.386786	1.3
4.41	8.386824	3.6	8.386797	0.6	8.386789	0.8
4.81	8.386813	3.6	8.386789	1.4	8.38678	1.6
5.21	8.386796	2.3	8.386738	0.8	8.38677	0.9
5.61	8.386796	2.1	8.386767	1.0	8.386762	0.6
6.01	8.386789	2.2	8.38677	1.7	8.386762	1.9

2.4 Participants standards

The characteristics of all participants standards used in this comparison are shown in the Table 3.

Table 3: The characteristics of all participants' standards.

Institute		CMS-ITRI	SPRING	NIMT
Country		(Taiwan R.O.C)	Singapore	Thailand
Pressure balance base	Manufacturer	Ruska		DHI
	Model	2465	2578	PG7601
Piston-cylinder	Type	Simple	Simple	Negative free deformation
	Material (Piston/Cylinder)	WC/WC	WC/WC	WC/WC
Effective area A_e	Value (mm^2)	8.395263	49.0267	49.0180
	Uncertainty (10^{-6}), k=2	40	29	27
Ref. temp	t_r(°C)	23	20	20
Distortion coefficient ? (MPa^{-1})	Value (MPa^{-1})	$-4.25\times10^{-6*}$	$-3.2\times10^{-6*}$	-2.35×10^{-6}
	Uncertainty (10^{-6}), k=2	?	0.3	5.3
Traceability		NIST	NPL	PTB

- : The values were calculated from curves fitting.

3. Calibration procedure and data calculation

3.1 Calibration procedure

The transfer standard was cross-floated against the measurement standard[2,3]. The standard pressures (P') are the pressure generated at the reference level of the transfer standard by the measurement standard. The effective area ($A'_{P'}$) of the transfer standard can be determined by the standard pressures and forces (F') exerted on the transfer standard.

The comparison was conducted on the basis of cross-float experiment to determine the effective area of transfer standard by carrying out five measuring cycles with clockwise rotation. The comparison was performed at the nominal pressures (in MPa) of: 0.41, 0.81, 1.21, 1.61, 2.01, 2.41, 2.81, 3.21, 3.61, 4.01, 4.41, 4.81, 5.21, 5.61, 6.01(ascending pressure), 6.01, 5.61, 5.21, 4.81, 4.41, 4.01, 3.61, 3.21, 2.81, 2.41, 2.01, 1.61, 1.21, 0.81, 0.41(descending pressure) in each measuring cycle. There were only 15 nominal pressures after we average the ascending pressure and descending pressure in this comparison results.

3.2 Data Calculation

The standard pressure measured at the reference level of laboratory standard is expressed as[2]

$$P = \frac{\sum_i M_i g \left(1 - \rho_a / \rho_{M_i}\right)}{A_0 \left[1 + \left(\alpha_p + \alpha_c\right)\left(T - T_0\right)\right]\left[1 + \lambda P\right]} \qquad (1)$$

Where

- A_0: The effective area of the laboratory standard
- M_i: The individual mass of each weight applied on the measurement standard
- g: The local acceleration due to gravity
- ρ_a: The air density at time of measurement
- ρ_{Mi}: The density of the individual mass of laboratory standard
- α_p: The thermal expansion coefficient of the laboratory standard piston
- α_c: The thermal expansion coefficient of the laboratory standard cylinder
- λ: The pressure distortion coefficient piston cylinder assembly
- T: The temperature of the laboratory standard during measurement
- T_0: The reference temperature

The pressure measured by the laboratory standard at the transfer standard reference level is

$$P' = P \pm \left(\rho_f - \rho_a\right) g h \qquad (2)$$

Where

- ρ_f: The density of pressure transmitted medium
- h: The height difference between reference level of the two standards

The force on transfer standard is expressed as:

$$F' = \sum_i M'_i \, g \left(1 - \rho_a / \rho'_{M_i}\right) \qquad (3)$$

In equilibrium condition between the two standards and by reversing the above formula and using the pressure *p'* measured by the laboratory standard at the reference level of the transfer standard, we obtain the effective area of the transfer standard

$$A'_{P'} = \frac{F'}{P'} = \frac{\sum_i M'_i \, g \left(1 - \rho_a / \rho'_{M_i}\right)}{P' \left[1 + \left(\alpha'_p + \alpha'_c\right)\left(T' - T'_0\right)\right]} \qquad (4)$$

Where

$A'_{P'}$: The effective area of the transfer standard

M'_i : The individual mass of each weight applied on the transfer standard

$\rho'_{M'i}$: The density of the individual mass of transfer standard

α_p' : The thermal expansion coefficient of the transfer standard piston

α_c' : The thermal expansion coefficient of the transfer standard cylinder

T' : The temperature of the transfer standard during measurement

T'_0 : The reference temperature of the transfer standard piston

The average value of the effective areas $A'_{P'}$ (mm^2) at 23°C of the transfer standard for each participating laboratory is calculated by averaging the experimental determinations at each nominal pressure point of five measurement cycles. The averages values of the effective area of the transfer standard $A'_{P'}$ (mm^2) at 23°C and *p'* versus *p'*(MPa) for all the participating laboratories are shown in Table 4.

The relative combined standard uncertainty, u_{rc} and the relative expanded uncertainty, U_{re} of $A'_{P'}$ (mm^2) at 23°C, *p'* and each nominal pressure point in the calibration procedure for each laboratory are estimated from the equation[3] as follows,

$$U_{re} = ku_{rc} = k\sqrt{\left(u_{rA'}{}^2 + u_{rT'}{}^2 + u_{rp'}{}^2\right)} \qquad (5)$$

Where

$u_{rA'}$: The relative standard uncertainty of effective area

$u_{rT'}$: The relative standard uncertainty of temperature

$u_{rp'}$: The relative standard uncertainty of standard pressure

k: Coverage factor (k = 2.)

The relative standard uncertainty of pressure ($u_{rp'}$) and the relative standard uncertainty of temperature ($u_{rT'}$) at each nominal pressure point were offered by the participating laboratories. Table 4 shows the relative expanded uncertainty U_{re} at k=2 of all the participating laboratories.

Table 4: Average values of the effective area and relative expanded uncertainty (U_{re}) at k=2 of the transfer standard $A'_{P'}$ (mm^2).

Lab. Name	CMS		SPRING		NIMT	
Nominal Pressure	Average of $A'_{P'}$	Relative Expanded Uncertainty (U_{re})	Average of $A'_{P'}$	Relative Expanded Uncertainty (U_{re})	Average of $A'_{P'}$	Relative Expanded Uncertainty (U_{re})
(MPa)	(mm^2)	(10^{-6})	(mm^2)	(10^{-6})	(mm^2)	(10^{-6})
0.41	8.386744	42.8	8.386820	30.4	8.38695	62.6
0.81	8.386815	42.2	8.386912	28.8	8.38698	39.6
1.21	8.386822	42.0	8.386923	28.8	8.38699	33.5
1.61	8.386805	42.0	8.387017	28.8	8.38700	31.1
2.01	8.386844	42.0	8.386989	28.6	8.38700	29.9
2.41	8.386806	42.0	8.387038	28.6	8.38702	29.3
2.81	8.386809	42.0	8.386986	28.6	8.38703	28.9
3.21	8.386831	42.0	8.386982	28.6	8.38704	28.6
3.61	8.386819	42.0	8.386996	28.6	8.38705	28.4
4.01	8.386801	42.0	8.386998	28.6	8.38705	28.3
4.41	8.386824	42.0	8.386918	28.6	8.38707	28.3
4.81	8.386813	42.0	8.386976	28.8	8.38709	28.2
5.21	8.386796	42.0	8.386991	28.6	8.38709	28.2
5.61	8.386796	42.0	8.386990	28.6	8.38710	28.2
6.01	8.386789	42.0	8.386975	28.6	8.38711	28.2

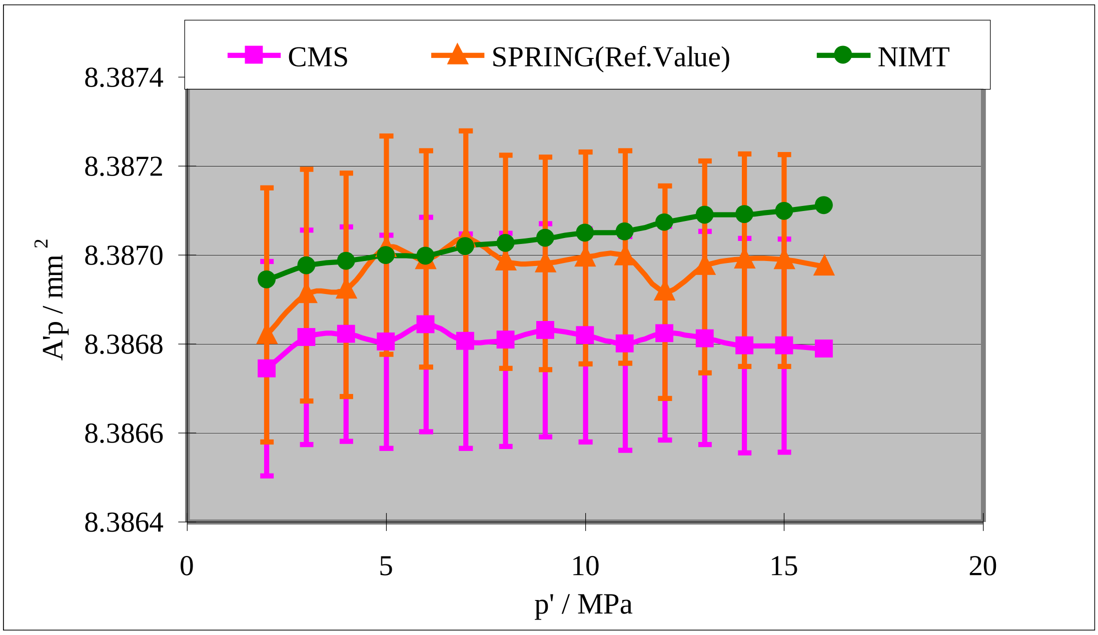
4. Analysis of the results

4.1 Reference value

The reference value[4,5] (x_R) for the transfer standard was estimated from the value reported by SPRING as they are the link laboratory to the APMP.M.P-K1.c. The standard uncertainty (u_R) of the reference value was taken as one standard deviation of the value reported by SPRING.

The reference values x_R (mm^2) at all of the nominal pressures are shown in Fig 2.

Fig 2. Average values and reference value of the effective area $A'_{P'}$(mm^2) versus p' (MPa) for all laboratories were shown. Where reference value was estimated from the value reported by SPRING. The expanded uncertainties(k=2) of the effective area $A'_{P'}$(mm^2) were indicated in error bars.



4.2 Estimation of the relative deviation from the reference value:

The relative deviation of the laboratory value from the reference value was calculated based on

$$D_i = (x_i - x_R)/ x_R \qquad (6)$$

Where x_i represents the effective area of the laboratory i at different nominal pressure and x_R represents the reference value.

The expanded uncertainty at k=2 for this reference value is given by:

$$U_i = 2(u_i{}^2 + u_R{}^2)^{0.5} / x_R \qquad (7)$$

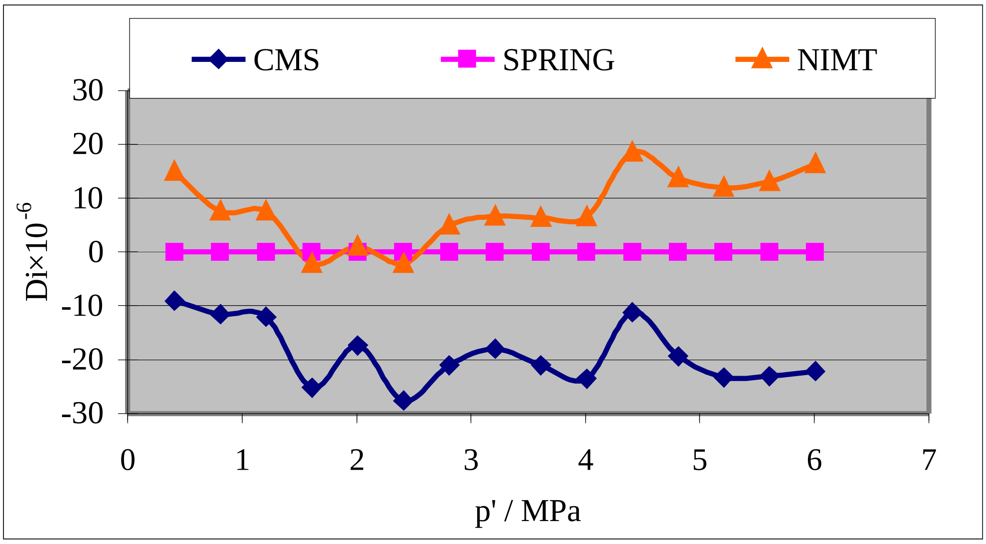
Where u_i represents the standard uncertainty of the laboratory i value and u_R represents the standard uncertainty of the reference value.

D_i and U_i are shown in Table 5 and Fig 3.

Table 5: The relative deviation from the reference value is given by $D_i = (x_i - x_R)/x_R$, and its relative expanded uncertainty $U_i = 2(u_i^2 + u_R^2)^{0.5}/x_R$ (k=2).

Nominal Pressure	CMS		SPRING		NIMT	
(MPa)	$Di\times10^{-6}$	$Ui\times10^{-6}$	$Di\times10^{-6}$	$Ui\times10^{-6}$	$Di\times10^{-6}$	$Ui\times10^{-6}$
0.41	-9.1	52	0.0	41	14.9	69
0.81	-11.6	51	0.0	40	7.6	49
1.21	-12.1	51	0.0	40	7.5	44
1.61	-25.2	51	0.0	40	-2.1	42
2.01	-17.3	51	0.0	40	1.0	41
2.41	-27.6	51	0.0	40	-2.1	41
2.81	-21.1	51	0.0	40	4.9	41
3.21	-18.0	51	0.0	40	6.7	40
3.61	-21.1	51	0.0	40	6.4	40
4.01	-23.5	51	0.0	40	6.5	40
4.41	-11.2	51	0.0	40	18.5	40
4.81	-19.4	51	0.0	40	13.7	40
5.21	-23.3	51	0.0	40	12.0	40
5.61	-23.1	51	0.0	40	13.1	40
6.01	-22.1	51	0.0	40	16.3	40

Fig 3. The relative deviation from the reference value $D_i = (x_i - x_R)/x_R$ versus p' (MPa) for all laboratories.



4.3 Degree of equivalence among the participating laboratories:

The degree of equivalence between any two laboratories were calculated by the equation as follows.

$D_{ij}= D_i - D_j= (x_i- x_j)/ x_R$ (8)

D_{ij} is the relative difference between participating institute's results, and

$U_{ij}=2(u_i^2+ u_j^2+u_{tr.std}^2)^{0.5}/ x_R$ (9)

U_{ij} is the relative expanded uncertainty (k=2).

$u_{tr.std}$ is the stability of transfer standard (7×10^{-6})

The degree of equivalence for two nominal pressures at 1.2 MPa and 4 MPa between any two laboratories for the transfer standard are shown in Table 6 and Table 7.

Table 6: The degree of equivalence between two laboratories at 1.2 MPa.

V-1215	p' = 1.2 MPa	Labj					
		CMS		SPRING		NIMT	
		D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
		10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Labi	CMS			-12.1	51.4	-19.6	54.2
	SPRING	12.1	51.4			-7.5	44.7
	NIMT	19.6	54.2	7.5	44.7		

Table 7: The degree of equivalence between two laboratories at 4 MPa.

V-1215	p' = 4 MPa	Labj					
		CMS		SPRING		NIMT	
		D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
		10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Labi	CMS			-23.5	51.3	-30.0	51.1
	SPRING	23.5	51.3			-6.5	40.8
	NIMT	30.0	51.1	6.5	40.8		

4.4 Linkage to APMP.M.P-K1.c key comparison

SPRING is one of the participating laboratories in the key comparison APMP.M.P-K1.c, so that the results of the present comparison APMP.M.P-K1.c.1 can easily be linked to the results[4] of the key comparison APMP.M.P-K1.c performed in the gauge mode up to 4 MPa. The uncertainty of the key comparison reference value is not involved in the computation of the linkage. In the key comparison APMP.M.P-K1.c, the relative deviation from the reference value x_R of the participating laboratory SPRING was defined as $D_{SPRING\_AMPM.M.P\text{-}K1c}$.

$D_{SPRING\_AMPM.M.P\text{-}K1c}$ = 16×10^{-6} and 19.8×10^{-6} respectively near 1.2 MPa and 4 MPa are refer to the Table 6 in the final report of APMP key comparison (APMP.M.P-K1c).

The degree of equivalence of CMS and NIMT obtained in the APMP.M.P-K1.c.1 comparison can be transferred to the APMP.M.P-K1.c comparison as follows by using the similar method[4] of APMP.M.P-K1.c.

$D_{ij} = D_{i\text{-}APMP\text{-}K1c1} + 16 \times 10^{-6} - D_{j\text{-}APMP\text{-}K1c}$ and the relative expanded uncertainty is $U_{ij}=(U_{i\text{-}APMP\text{-}K1c1}^2 + U_{j\text{-}APMP\text{-}K1c}^2)^{0.5}$ at pressure close to 1.2 MPa;

$D_{ij} = D_{i\text{-}APMP\text{-}K1c1} + 19.8 \times 10^{-6} - D_{j\text{-}APMP\text{-}K1c}$ and the relative expanded uncertainty is $U_{ij}=(U_{i\text{-}APMP\text{-}K1c1}^2 + U_{j\text{-}APMP\text{-}K1c}^2)^{0.5}$ at pressure close to 4 MPa

Where $D_i = D_{i\text{-}APMP\text{-}K1c1} + 16 \times 10^{-6}$ and $D_{i\text{-}APMP\text{-}K1c1}$ is the relative deviation of participants from the reference value of APMP.M.P-K1c.1 key comparison.

$D_{j\text{-}APMP\text{-}K1c}$ is the relative deviation of participants from the reference value of APMP.M.P-K1c key comparison.

$U_{i\text{-}APMP\text{-}K1c1}$ is the relative expanded uncertainty (k=2) of $D_{i\text{-}APMP\text{-}K1c1}$ including the stability of transfer standard (7×10^{-6}).

$U_{j\text{-}APMP\text{-}K1c}$ is the relative expanded uncertainty (k=2) of $D_{j\text{-}APMP\text{-}K1c}$.

The degree of equivalence of CMS and NIMT obtained in the APMP.M.P-K1.c.1 comparison can also be transferred to the CCM.P-K1.c comparison as follows[4,5]:

$D_{ij} = D_{i\text{-}APMP\text{-}K1c1} + 16 \times 10^{-6} - 3.8 \times 10^{-6} - D_{j\text{-}CCM\text{-}K1c}$ and the relative expanded uncertainty is $U_{ij}=(U_{i\text{-}APMP\text{-}K1c1}^2+U_{j\text{-}CCM\text{-}K1c}^2)^{0.5}$ at pressure close to 1 MPa,

$D_{ij} = D_{i\text{-}APMP\text{-}K1c1} + 19.8 \times 10^{-6} - 7.1 \times 10^{-6} - D_{j\text{-}CCM\text{-}K1c}$ and the relative expanded uncertainty is $U_{ij}=(U_{i\text{-}APMP\text{-}K1c1}^2+U_{j\text{-}CCM\text{-}K1c}^2)^{0.5}$ at pressure close to 4 MPa

Where $D_{j\text{-}CCM\text{-}K1c}$ is the relative deviation of participants from the reference value of CCM.P-K1.c key comparison.

$U_{j\text{-}CCM\text{-}K1c}$ is the relative expanded uncertainty (k=2) of $D_{j\text{-}CCM\text{-}K1c}$.

As Table 8 and Table 9 showed, linkage with APMP.M.P-K1.c at two nominal pressures near 1.2 MPa and 4 MPa has been established. We also can see the linkage with CCM.P-K1.c key comparison at two nominal pressures near 1 MPa and 4 MPa in Table 10 and Table 11 respectively.

Table 8: Linkage of APMP.M.P-K1.c.1 with APMP.M.P-K1.c at a nominal pressure 1.2 MPa. Lab.j are SPRING laboratory and the laboratories that have used a primary standard in the APMP.M.P-K1.c key comparison.

Lab j → APMP.M.P-K1c												
P = 1.21 MPa	SPRING		NPLI		KRISS		CSIRO-NML		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
SPRING			16.9	76	22.7	72	23.2	68	16.2	66	13.1	65
NPLI	-17	76			5.7	54	6.2	48	-0.7	45	-3.8	43
KRISS	-22.7	72	-5.7	54			0.5	42	-6.4	38	-9.5	36
CSIRO-NML	-23.2	68	-6.2	48	-0.5	42			-6.9	38	-10	26
NMLJ	-16.2	66	0.7	45	6.4	38	6.9	30			-3.1	21
PTB	-13.1	65	3.8	43	9.5	36	10	26	3.1	21		

Lab i ↓

CMS/ITRI	-12.1	78	4.8	61	10.5	56	11	50	4.1	47	1	45
NIMT	7.5	73	24.4	55	30.1	50	30.6	43	23.7	40	20.6	38

Table 9: Linkage of APMP.M.P-K1.c.1 with APMP.M.P-K1.c at a nominal pressure 4 MPa. Lab.j are SPRING laboratory and the laboratories that have used a primary standard in the APMP.M.P-K1.c key comparison.

Lab j → APMP.M.P-K1c												
P = 4 MPa	SPRING		NPLI		KRISS		CSIRO-NML		NMIJ		PTB	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
SPRING			16.6	76	16.9	72	30.1	68	15.7	66	11.2	65
NPLI	-16.6	76			0.3	54	13.5	48	-0.9	45	-5.4	43
KRISS	-16.9	72	-0.3	54			13.2	42	-1.2	38	-5.7	36
CSIRO-NML	-30.1	68	-13.5	48	-13.2	42			-14.4	38	-18.9	26
NMLJ	-15.7	66	0.9	45	1.2	38	14.4	30			-4.5	21
PTB	-11.2	65	5.4	43	5.7	36	18.9	26	4.5	21		

Lab i↓

CMS/ITRI	-23.5	78	-6.9	61	-6.6	56	6.6	50	-7.8	49	-12.3	47
NIMT	6.5	71	23.1	52	23.4	46	36.6	39	22.2	38	17.7	35

Table 10: Linkage of APMP.M.P-K1.c.1 with CCM.P-K1.c at a nominal pressure 1 MPa. Lab.i are the laboratories that had participated in the EUROMET.M.P-K2 key comparison and Lab.j are the laboratories that had participated in the CCM.P-K1.c key comparison.

Lab i ↓ / Lab j → CCM.P-K1c	INRIM		LNE		PTB		NMIJ		NIST	
P = 1 (MPa)	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
INRIM			-3	24	-6	25	2	27	-13	29
LNE	3	24			-3	13	5	17	-10	20
PTB	6	25	3	13			8	18	-7	21
NMIJ	-2	27	-5	17	-8	18			-15	24
NIST	13	29	10	20	-7	21	15	24		
BEV	25	51	22	47	19	47	27	49	12	50
MIKES	-7	41	-10	35	-13	35	-6	37	-20	38
CEM	7	50	4	45	1	45	9	47	-6	48
SP/FFA	3	41	0	35	-3	35	5	37	-10	38
NPLI	1	50	-2	46	-5	46	3	48	-12	49
KRISS	-4	44	-2	39	-10	40	-2	41	-17	42
CSIRO-NML	-5	37	-8	31	-11	31	-3	33	-18	35
MSL-IRL	-40	67	-43	63	-46	64	-38	65	-53	65
SPRING	18	70	15	67	12	67	20	68	5	69
NML-SIRIM	-2	53	-5	49	-8	49	0	51	-15	52
SCL	-25	47	-28	42	-31	42	-23	44	-38	45
CSIR-NML	41	49	38	45	35	45	43	47	28	48
NIS-Egypt	-18	69	-21	66	-24	66	-16	67	-31	68
CMS	6	52	-9	45	0	46	8	47	-7	48
NIMT	25	42	21	38	19	38	27	40	12	41

Table 11: Linkage of APMP.M.P-K1.c.1 with CCM.P-K1.c at a nominal pressure 4 MPa. Lab.i are the laboratories that had participated in the EUROMET.M.P-K2 key comparison and Lab.j are the laboratories that had participated in the CCM.P-K1.c key comparison.

Lab j → CCM.P-K1c										
P = 4 (MPa)	INRIM		LNE		PTB		NMIJ		NIST	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
INRIM			0.95	27.6	-8.3	30.6	6.9	31.0	-13.4	35.8
LNE	-0.95	27.6			-9.3	17.0	6.0	17.8	-14.3	23.6
PTB	8.3	30.6	9.3	17.0			15.3	22.4	-5.0	27.2
NMIJ	-6.9	31.0	-6.0	17.8	-15.3	22.4			-20.3	27.6
NIST	13.4	35.8	14.3	23.6	5.0	27.2	20.3	27.6		

Lab i ↓

BEV	25	52	26	46	17	48	32	48	12	50
MIKES	-11	40	-10	31	-19	34	-4	34	-24	38
CEM	-3	51	-2	44	-11	46	4	46	-16	49
SP/FFA	4	42	5	33	-4	36	11	36	-9	39

NPLI	-3	52	-2	46	-11	47	4	48	-16	50
KRISS	-3	47	-2	39	-11	41	4	42	-16	44
CSIRO-NML	-16	40	-15	31	-25	33	-9	34	-30	37
MSL-IRL	-47	68	-46	63	-55	65	-40	65	-60	67
SPRING	14	71	15	67	6	68	21	68	1	70
NML-SIRIM	-12	55	-11	49	-21	51	-5	51	-26	53
SCL	-27	49	-26	42	-35	44	-20	44	-40	47
CSIR-NML	26	47	27	39	18	42	33	42	13	45
NIS-Egypt	-12	57	-11	51	-21	52	-5	53	-26	55

CMS	-10	52	-9	45	-18	47	-3	48	-23	50
NIMT	21	42	21	33	12	36	27	36	7	39

5. Discussion

Although we revised the schedule because NIMT Thailand joined the activity in the middle of the comparison, the activity had been carried out smoothly. Each participating institute performed the comparison following the protocol of the comparison and offered the calibration data to the pilot institute for preparation of the draft report.

The transfer standard, Ruska 2465 gas-operated piston-cylinder assembly V-1215, was calibrated three times by the pilot institute during these four transits of the comparison period in order to confirm the performance of the transfer standard and showed that it was very stable after evaluated. It should be noted that the transfer standard stability (4×10^{-6}) had been taken into account through equation (10) in the degree of equivalence between two laboratories.

The reference value was calculated from the results of CMS/ITRI, SPRING and NIMT laboratories through equation (6). As we can see in Eq. (7) and Eq. (9), the same method was used as APMP.M.P-K1.c key comparison to calculate the relative deviation of the laboratory value from the reference value and the relative difference between participating institute's deviation.

The relative deviation from the reference value of SPRING was fluctuating in Figure 3. It was because the average values of the effective area $A'_{P'}$(mm^2) from SPRING was fluctuating as shown in Figure 2. But, the maximum difference of relative deviation D_i from SPRING was 2.3×10^{-5} between 0.41 MPa and 2.41 MPa in Table 5. It was much smaller than the relative expanded uncertainty U_i (about 3.8×10^{-5}) of SPRING. So, this fluctuating phenomenon can be reasonably accepted.

6. Conclusion

(a) The reference value of the results obtained by all participating institutes measuring the same quantity from 0.4 MPa to 6.0 MPa in gas media and gauge mode lay within their expanded uncertainty with confidence level 95 %.

(b) For all the laboratories, the relative differences (D_{ij}) between laboratory values and APMP.M.P-K1.c.1 reference values are within 2.0×10^{-5} and 3.0×10^{-5} respectively at 1.2 MPa and 4 MPa .

(c) Linking key comparison APMP.M.P-K1.c to APMP.M.P-K1.c.1 and CCM.P-K1.c at two nominal pressures near 1 MPa and 4 MPa has been established.

7. Acknowedgements

We would like to thank the help from SPRING Singapore in order let us to link to the key comparison APMP.M.P-K1.c via the results of SPRING Singapore. We are grateful to Dr. N. Bignell, the former chairman of the TCM of APMP for his advice and kind help to register in the BIPM key comparison database. And the present chairman of the TCM of APMP Dr. A.K.Bandyopadhyay who help to organize and review this report in the final stage. The completion of this key comparison thanks to the efforts of each participating institute, they are Mr. Wu Jian from NMC Spring Singapore, Mr. Tawat Changpan from NIM Thailand and Dr. Chi-Shen Chang and Mr. Feng Yu Huang from CMS/ITRI Taiwan R.O.C.

8. Reference

[1] Gas Lubricated Piston Gage, Model No.2465-752, User's Manual, RUSKA Instrument Corporation.

[2] Draft Report of the APMP.M.P-K1.c pneumatic pressure comparison [Phase A]: (1) 20 kPa to 105 kPa and (2) 0.4 MPa to 4.0 MPa (Gauge Mode), Calibration Procedure, A.K. Bandyoapdhyay, Pressure and Vacuum Standards, National Physical Laboratory, New Delhi-110012, India, 2000.

[3] Protocol of APMP.M.P-K1.c.1 pneumatic pressure comparison (1) 20 kPa to 105 kPa (2) 100 kPa to 400 kPa (3) 0.4 MPa to 6.0 MPa (Gauge Mode), Calibration Procedure, FengYu Huang, Chen-Chuan Hung, Center for Measurement Standards/ITRI, 2003.

[4] Final report of APMP Key Comparison (APMP.M.P-K1.c), A.K. Bandyopadhyay, Sam Yong Woo, Mark Fitzgerald, John Man, Akira Ooiwa, M.Jescheck, Wu Jian, Chen Soo Fatt, T.K. Chan, Ken Moore and Al aaeldin A.E.EI-Tawil, 2002.

[5] Final report of CCM key comparison 7 MPa, Phase B (CCM.P-K1.c), G. Molinar, J.C. Legras, J. Jaeger, A. Ooiwa and J. Schmidt, October 2000.