Final Report
on Key Comparison COOMET.M.P-K1
in the range 0.05 MPa to 0.5 MPa of pneumatic gauge pressure

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Abstract

This report describes a COOMET key comparison of pneumatic pressure standards of six National Metrology Institutes (NMIs) that was carried out in the period from September 2004 to June 2006 in order to determine their degrees of equivalence in the range 50 kPa to 500 kPa of the gauge pressure. The pilot laboratory was VNIIM. The pressure standards of the participating NMIs were pressure balances of different design. The transfer standard was a 5 cm^2 piston-cylinder assembly accompanied by a mounting post and a weight carrier supplied by VNIIM. The pressure-dependent effective areas of the transfer standard at specified pressures were reported by the participants. The reference values were calculated as weighted means of the results of VNIIM and PTB which were primary and independent laboratories in this comparison. The results of this comparison were linked to the 1 MPa comparison CCM.P-K1.b using the results of the PTB obtained in both comparisons. Results by all but one participants agree with the reference values and with each other within the expanded uncertainties calculated with a coverage factor 2, roughly a half of the reported results demonstrate agreement within their standard uncertainties. With the exception of one laboratory, the results of the comparison demonstrate equivalence of the laboratory standards and support their measurement capability statements. For laboratories whose CMCs are not presented in the KCDB yet, this comparison provides a basis for submissions for the range 50 kPa to 500 kPa of pneumatic gauge pressure.

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Contents

1. Introduction

This comparison was organized by Technical Committee (TC) 1.6 "Mass and Related Quantities" of COOMET and was approved by the TC meeting held in April 21 – 24, 2004, in Bratislava. This work is registered within COOMET as Project no. 234 entitled "Mutual comparison in the pressure range 0.05 to 0.5 MPa". It is identified in the BIPM database as the COOMET.M.P-K1 key comparison. VNIIM, Russia, was chosen as a pilot laboratory. This document gives the results of the comparison.

Six national metrology institutes (NMI) participated in the comparison between August 2004 and June 2006. The list of the laboratories, with the metrologists who took part in the work, is given below in the chronological order of the measurements:

Table 1. Schedule of the comparison

Country	Institute	Contact person	Measurement date
Russia	D.I. Mendeleyev Institute for Metrology (VNIIM)	Yury Kiselev	September 2004
Germany	Physikalisch – Technische Bundesanstalt (PTB)	Wladimir Sabuga	November 2004
Lithuania	Vilnius Metrology Center (VMC)	Ksaverija Dapkeviciene	April 2005
Slovakia	Slovak Institute of Metrology (SMU)	Peter Farar	August 2005
Byelorussia	Byelorussian State Institute of Metrology (BelGIM)	Konstantin Saczuk	December 2005
Romania	National Institute of Metrology (INM)	Ion Sandu	April 2006
Russia	D.I. Mendeleyev Institute for Metrology (VNIIM), final investigation	Yury Kiselev	June 2006

2. Transfer standard

2.1 Structure and identification of the transfer standard

The comparison was realized with the help of the transfer standard (TS) being a piston gauge with a simple piston. The TS was provided by VNIIM. At VNIIM it is identified by no. 7.

2.2 Main metrological characteristics of the TS

1. Measurement range: (0.05-0.5) MPa.
2. Nominal value of the piston area is 5 cm^2.
3. Typical relative standard deviation of the average effective area as observed in the preliminary investigation by the pilot laboratory is not higher than $4 \cdot 10^{-6}$.
4. Working position of the piston is 15 mm above its rest position in the cylinder.
5. Recommended angle of the piston axis deflection from verticality is not greater than 30”.
6. Time of the piston rotation at a pressure of 0.1 MPa and temperature of (20±0.5) °C is not less than 20 min.
7. The piston fall rate at the pressure of 0.5 MPa and temperature of (20±0.5) °C is not higher than 0.2 mm/min.
8. Relative uncertainty of mass values of weights used with the TS is recommended not to exceed 10^{-6}.

9. Recommended temperature range for the ambient air in the room is (20±2) °C. Temperature variation of the piston-cylinder unit during one measurement day should not be greater than ±0.5 °C. Difference of temperatures during a series of measurements should not exceed 0.2 °C.
10. Material of the piston-cylinder assembly is hard alloy (tungsten carbide) BK-6M with the following characteristics:
    - Young's modulus: E = 621 GPa
    - Poisson's coefficient: μ = 0.23
    - thermal coefficient of linear expansion: $\alpha = 4.5 \cdot 10^{-6}$ K^{-1}
    - pressure distortion coefficient: $\lambda = 1.2 \cdot 10^{-12}$ Pa^{-1}
    - density of the piston material: $14.95 \cdot 10^{3}$ kg/m^{3}
11. Working medium is a dry non-aggressive gas.
    The TS piston-cylinder assembly has a clearance of approximately 0.5 μm which provides a possibility of its operation also by using a filtered non-aggressive liquid with the dynamic viscosity of (1-1.4) mPa·s at 20 °C.
12. Piston-cylinder tungsten carbide alloy BK-6M contains cobalt (6%). At VNIIM, measurements of the magnetic flux of the piston and cylinder were carried out with the help of a flux-gate magnetometer MT 3 grade 0.1. These measurements were carried out at a distance of 20 mm from the end surfaces of component parts and showed 2 μT for the piston and 3 μT for the cylinder.

2.3 Transfer standard stability

The date of manufacturing the piston assembly of the TS is April, 2003. Variations of the piston effective aria values observed by the pilot laboratory in the course of one year did not exceed $2 \cdot 10^{-6}$.

3. Standards of the participants

National pressure standards (NPS) were pressure balances for all laboratories. Their properties and traceability of the effective area of their piston-cylinder units are given below.

3.1 Pressure standards of VNIIM

Characteristics of NPS	Identification no. of NPS		
	11	10	8
Measurement range (MPa)	0.05 – 0.5	0.3 - 3	0.3 – 3
Manufacturer	Russia	Russia	Russia
Piston material	Steel nitrided	WC+Co	WC+Co
Cylinder material	Steel nitrided	WC+Co	WC+Co
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	19.94844	4.984006	4.983761
Total relative standard uncertainty of A_0 (10^{-6})	9.3	6.6	6.3
Pressure distortion coefficient (10^{-12} Pa^{-1})	6.84	1.80	1.80
Pressure-transmitting medium	Kerosene		
Reference temperature (°C)	20		
Participation in previous comparisons	COOMET 115, EUROMET.M.P-K3		
References	[1, 2]		

The zero pressure effective areas were determined from dimensional measurements. The connection to the TS was realised with an liquid-gas interface.

3.2 Pressure standards of PTB

Characteristics of NPS	Identification no. of NPS	
	288	6222
Measurement range (MPa)	0.06 - 1	0.1 - 2
Manufacturer	DH-Budenberg	DH-Budenberg
Piston material	WC+Co	WC+Co
Cylinder material	WC+Co	WC+Co
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	9.804917	4.9026345
Total relative standard uncertainty of A_0 (10^{-6})	5.0	4.1
Pressure distortion coefficient (10^{-12} Pa^{-1})	4.0	1.47
Reference temperature (°C)	20	
Pressure-transmitting medium	Nitrogen	
Participation in previous comparisons	COOMET 115, EUROMET 305, CCM.P-K1, EUROMET M.P-K3, APMP.M.P-K1c	
References	[1, 3]	

The zero-pressure effective areas were determined from dimensional measurements and from measurements against a primary mercury manometer. The pressure distortion coefficients (λ) of these piston-cylinder assemblies were determined from their dimensions and the elastic constants of their materials using Lamé equations.

3.3 Pressure standards of VMC

Characteristics of NPS	Identification no. of NPS	
	525	487
Measurement range (MPa)	0.005 – 0.5	0.1 – 10
Manufacturer	DHI	DHI
Piston material	WC+Co	WC+Co
Cylinder material	WC+Co	WC+Co
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	9.80534	0.490144
Total relative standard uncertainty of A_0 (10^{-6})	19.4	20.4
Pressure distortion coefficient (10^{-12} Pa^{-1})	4.2	-1.55
Pressure-transmitting medium	Nitrogen	
Reference temperature (°C)	20	
Participation in previous comparisons	-	-
References	-	-

The pressure standards set was calibrated by PTB (Germany).

3.4 Pressure standards of SMU

Characteristics of NPS	Identification no. of NPS				
	A01	A03	D04	203	506
Measurement range (MPa)	0.07 – 7	0.07 – 7	0.05 – 0.5	0.1 – 3	0.05 – 0.5
Manufacturer	SMU	SMU	SMU	SMU	SMU
Piston material	WC+Co	WC+Co	WC+Co	SS	SS
Cylinder material	WC+Co	WC+Co	WC+Co	SS	SS
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	0.981125	0.980105	9.823155	1.999493	4.999842
Total relative standard uncertainty of A_0 (10^{-6})	20.0	20.0	20.0	10.2	11.0
Pressure distortion coefficient (10^{-12} Pa^{-1})	1.0	1.0	4.0	3.4	3.0
Pressure-transmitting medium	gas	gas	gas	gas/liquid	gas
Reference temperature (°C)	20				
Participation in previous comparisons	COOMET 115, EUROMET.M.P-K3				
References	[1, 2]				

The zero effective areas were determined from dimensional measurement and from the statistical evaluations of the SMU pistons mutual crossfloatings. The pressure distortion coefficients were derived from material constants using Lame´s equation.

3.5 Pressure standards of BelGIM

Characteristics of NPS	Identification no. of NPS
	11
Measurement range (MPa)	0.003 – 0.2
Manufacturer	Ukraine
Piston material	WC+Co
Cylinder material	WC+Co
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	4.998866
Total relative standard uncertainty of A_0 (10^{-6})	21.3
Pressure distortion coefficient (10^{-12} Pa^{-1})	3.88
Pressure-transmitting medium	gas
Reference temperature (°C)	20
Participation in previous comparisons	-
References	-

The pressure standards set was calibrated by UkrMetTestStandard (Ukraine).

3.6 Pressure standards of INM

Characteristics of NPS	Identification no. of NPS
	240
Measurement range (MPa)	0.01 – 0.7
Manufacturer	Budenberg
Piston material	Stainless steel
Cylinder material	Stainless steel
Effective area of the piston at the atmosphere pressure and reference temperature, A_0 (cm^2)	3.225818
Total relative standard uncertainty of A_0 (10^{-6})	25.0
Pressure distortion coefficient (10^{-12} Pa^{-1})	-
Pressure-transmitting medium	Nitrogen
Reference temperature (°C)	20
Participation in previous comparisons	No
References	NMi standards

INM standard has traceability of the effective area to the NMi (Netherlands) standards.

4. Methods for comparing the standards

The comparison of the national standards for the pressure unit was realized by the countries-participants by the cross-float method. The method for determining the effective area of the TS piston-cylinder assembly (Δp- or p-method) as well as the way for stating the equilibrium between the cross-floated pressure balances were independently chosen by each of the countries-participants in accordance with their specific working conditions. In the case that the NPS were oil-operated pressure balances, they were connected to the TS using an oil-gas interface.

5. Procedure of comparisons

In accordance with the Technical Protocol of the comparison, VNIIM supplied a piston-cylinder assembly in a mounting post to be used as a transfer standard whose parameters are close to the parameters of the national primary standards of Russia nos. 8 and 10.

Before the comparisons, each country-participant performed preparatory activities relating to mass measurement of dead weights used with the NPS and TS, to tightness check of the pressure-measuring systems as well as to fabrication of accessories required for connecting the TS to NPS.

After receiving the transfer standard by a country-participant, the determination of the piston fall rate and the time of the piston's free rotation was done as outlined e.g. in the International Recommendation OIML R110 "Pressure balances".

The effective area of the TS was determined with the methods implemented for evaluating metrological characteristics of the national pressure standards in the countries-participants. The piston-cylinder assembly of the TS installed in a pressure comparator was compared with one or several piston-assemblies of the NPS in the pressure points uniformly distributed within the measurement range at monotonously increasing and decreasing pressure.

The comparisons were carried out at nominal pressure values of (0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.4, 0.3, 0.2, 0.1, 0.05) MPa with the pressure point at 0.05 MPa being optional. The number of series (cycles) was not less than 5.

The effective area of the TS was determined by the *p*-method in PTB, VMC and INM and by the Δp-method in VNIIM, SMU and BelGIM.

6. Results and their evaluation

From the effective areas of the TS obtained by the participants with each of their NPS (A_p) and their standard uncertainties ($u(A_p)$), an average effective area for each pressure was calculated ($\langle A_p \rangle$), which was taken as a weighted mean of the effective areas obtained with all NPS of the participant:

$$\langle A_p \rangle = \frac{\sum_{k=1}^{m} \frac{A_{p,k}}{u^2(A_{p,k})}}{\sum_{k=1}^{m} \frac{1}{u^2(A_{p,k})}}, \tag{1}$$

where *m* is the number of the piston assemblies of the NPS. The uncertainties of type A and B of the average mean, $u_A(\langle A_p \rangle)$ and $u_B(\langle A_p \rangle)$, as well as the combined uncertainties, $u(\langle A_p \rangle)$, were calculated by corresponding formulae:

$$u_A(\langle A_p \rangle) = \left[\frac{m}{m-1} \cdot \sum_{k=1}^{m} \frac{(A_{p,k} - \langle A_p \rangle)^2}{u^2(A_{p,k})} \bigg/ \sum_{k=1}^{m} \frac{1}{u^2(A_{p,k})} \right]^{0.5}, \tag{2}$$

$$u_B(\langle A_p \rangle) = \sum_{k=1}^{m} \frac{1}{u(A_{p,k})} \bigg/ \sum_{k=1}^{m} \frac{1}{u^2(A_{p,k})}, \tag{3}$$

$$u(\langle A_p \rangle) = \left[u_A^2(\langle A_p \rangle) + u_B^2(\langle A_p \rangle) \right]^{0.5}. \tag{4}$$

The effective areas of the TS as obtained by the participants with each of their NPS (A_p), their relative standard uncertainties ($u(A_p)/A_p$), the average effective areas ($<A_p>$) and their relative standard uncertainties ($u(<A_p>)/<A_p>$) are presented in Tables 2.1 to 2.6.

Table 2.1 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by VNIIM pressure standards 11, 10 and 8 as well as average effective areas ($<A_p>$) and their relative standard uncertainties ($u(<A_p>)/<A_p>$) at selected pressures (p_e)

p_e / kPa	VNIIM NPS						$<A_p>$/cm^2	$u(<A_p>)/<A_p>$ $\times10^6$
	11		10		8			
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$		
50	4.999658	11					4.999658	11
100	4.999643	11					4.999643	11
200	4.999646	9.9					4.999646	9.9
300	4.999641	9.7	4.999659	7.3	4.999647	7.2	4.999650	8.0
400	4.999652	9.8	4.999651	6.9	4.999654	6.8	4.999652	7.5
500	4.999650	9.6	4.999657	6.8	4.999651	6.5	4.999654	7.2

Table 2.2 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by PTB pressure standards 288 and 6222 as well as average effective areas ($<A_p>$) and their relative standard uncertainties ($u(<A_p>)/<A_p>$) at selected pressures (p_e)

p_e / kPa	PTB NPS				$<A_p>$/cm^2	$u(<A_p>)/<A_p>$ $\times10^6$
	288		6222			
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$		
67	4.999728	6.3			4.999728	6.3
100	4.999724	5.9	4.999719	5.0	4.999721	5.5
200	4.999722	5.5	4.999712	4.6	4.999716	5.2
300	4.999720	5.4	4.999709	4.5	4.999714	5.1
400	4.999721	5.3	4.999708	4.4	4.999714	5.1
500	4.999721	5.3	4.999706	4.4	4.999712	5.1

Table 2.3 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by VMC pressure standards 525 and 487 as well as average effective areas ($<A_p>$) and their relative standard uncertainties ($u(<A_p>)/<A_p>$) at selected pressures (p_e)

p_e / kPa	VMC NPS				$<A_p>$/cm^2	$u(<A_p>)/<A_p>$ $\times10^6$
	525		487			
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$		
50	4.999685	25			4.999685	25
100	4.999685	23			4.999685	23
200	4.999693	22			4.999693	22
300			4.999752	21	4.999752	21
400			4.999757	21	4.999757	21
500			4.999752	21	4.999752	21

Table 2.4 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by SMU pressure standards A01, A03, D04, 203 and 506 as well as average effective areas ($<A_p>$) and their relative standard uncertainties ($u(<A_p>)/<A_p>$) at selected pressures (p_e)

p_e / kPa	SMU NPS										$<A_p>$/cm^2	$u(<A_p>)/<A_p>$ $\times10^6$
	A01		A03		D04		203		506			
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$		
50	4.999716	20	4.999718	20	4.999790	20	-		4.999783	14	4.999755	19
100	4.999725	20	4.999755	21	4.999781	20	4.999781	15	4.999773	14	4.999764	18
200	4.999738	20	4.999752	20	4.999773	20	4.999785	15	4.999783	14	4.999768	17
300	4.999740	20	4.999752	20	4.999767	20	4.999782	14	4.999791	13	4.999768	17
400	4.999737	20	4.999757	21	4.999765	20	4.999794	14	4.999791	13	4.999771	17
500	4.999736	20	4.999757	20	4.999766	20	4.999786	14	4.999798	13	4.999771	17

Table 2.5 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by BelGIM pressure standard 11 at selected pressures (p_e)

p_e / kPa	BelGIM NPS	
	11	
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$
50	4.999884	34
100	4.999840	32
200	4.999827	23

Table 2.6 Effective areas of TS (A_p) and their relative standard uncertainties ($u(A_p)/A_p$) obtained by INM pressure standard 240 at selected pressures (p_e)

p_e / kPa	INM NPS	
	240	
	A_p/cm^2	$u(A_p)/A_p$ $\times10^6$
50	5.000171	37
100	5.000061	31
200	4.999997	28
300	4.999976	27
400	4.999955	27
500	4.999941	26

The number of the NPS used by each participant varied from 1 to 5. Thus, in the case of the laboratories applying more than one standard with overlapping pressure ranges, the uncertainties of the mean effective areas reflect both the consistency and the uncertainties of the standards used.

In addition, each participant calculated the zero pressure effective area of the TS (A_0) using equation

$$A_0 = A_p / (1+\lambda p_e) \quad (5)$$

with λ of the TS taken as given in Section 2. The results obtained with each NPS are shown graphically in Figure 1, the mean effective areas are presented in Table 3.

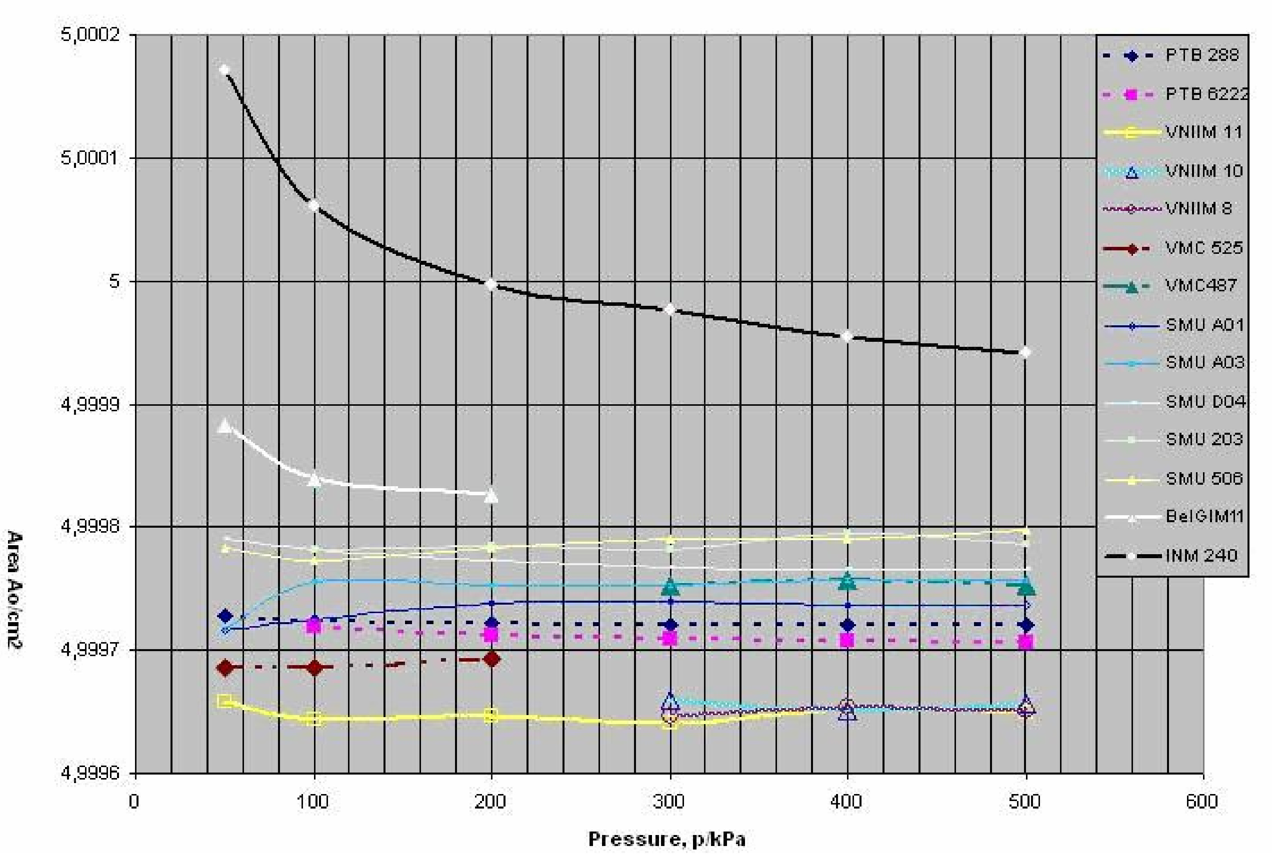

Figure 1 **Effective area of the TS determined from comparison with the NPS of VNIIM, PTB, VMC, SMU, BelGIM and INM.**

Table 3 **Zero-pressure effective areas of TS (A_0), their relative standard type A, B and combined uncertainties ($u_A(A_0)/A_0$, $u_B(A_0)/A_0$, $u(A_0)/A_0$) obtained with different NPS as well as average effective areas ($\langle A_0\rangle$) and their relative standard uncertainties ($u(\langle A_0\rangle)/\langle A_0\rangle$)**

Institute	NPS	A_0/cm^2	$u_A(A_0)/A_0$ $\times 10^6$	$u_B(A_0)/A_0$ $\times 10^6$	$u(A_0)/A_0$ $\times 10^6$	$\langle A_0\rangle$/cm^2	$u(\langle A_0\rangle)/\langle A_0\rangle$ $\times 10^6$
VNIIM	11	4.999648	2.9	9.9	10	4.999651	7.8
	10	4.999653	1.9	7.0	7.3		
	8	4.999650	2.5	6.8	7.2		
PTB	228	4.999721	1.1	5.4	5.5	4.999714	5.2
	6222	4.999709	1.2	4.4	4.6		
VMC	525	4.999688	4.4	23	24	4.999720	27
	487	4.999752	17	21	27		
SMU	A01	4.999731	3.7	20	20	4.999756	18
	A03	4.999748	4.9	20	20		
	D04	4.999774	2.5	20	20		
	203	4.999787	3.4	14	14		
	506	4.999787	3.0	13	14		
BelGIM	11	4.999829	7.8	27	28	4.999829	28
INM	240	4.999978	20	26	33	4.999978	33

7. Key comparison reference value calculation

As the Key Comparison Reference Value (KCRV), the weighted mean effective areas, $A_{p,\mathrm{ref}}$, measured by the independent laboratories, VNIIM, PTB and SMU, at nominal pressures of (50, 100, 200, 300, 400, 500) kPa were taken:

$$A_{p,\mathrm{ref}} = \frac{A_{p,\mathrm{VNIIM}} / u^2(A_{p,\mathrm{VNIIM}}) + A_{p,\mathrm{PTB}} / u^2(A_{p,\mathrm{PTB}}) + A_{p,\mathrm{SMU}} / u^2(A_{p,\mathrm{SMU}})}{1/u^2(A_{p,\mathrm{VNIIM}}) + 1/u^2(A_{p,\mathrm{PTB}}) + 1/u^2(A_{p,\mathrm{SMU}})}. \tag{6}$$

The uncertainty of the KCRV, $u(A_{p,\mathrm{ref}})$, was calculated by:

$$u(A_{p,\mathrm{ref}}) = \frac{1/u(A_{p,\mathrm{VNIIM}}) + 1/u(A_{p,\mathrm{PTB}}) + 1/u(A_{p,\mathrm{SMU}})}{1/u^2(A_{p,\mathrm{VNIIM}}) + 1/u^2(A_{p,\mathrm{PTB}}) + 1/u^2(A_{p,\mathrm{SMU}})}. \tag{7}$$

The KCRV and their uncertainties are presented in Table 4.

Table 4 Key Comparison Reference Values ($A_{p,\mathrm{ref}}$) and their relative standard uncertainties ($u(A_{p,\mathrm{ref}})/A_{p,\mathrm{ref}}$)

p_e / kPa	$A_{p,\mathrm{ref}}$/cm^2	$u(A_{p,\mathrm{ref}})/A_{p,\mathrm{ref}} \times 10^6$
50	4.999714	8.3
100	4.999709	7.4
200	4.999705	7.0
300	4.999700	6.6
400	4.999699	6.5
500	4.999697	6.4

8. Degrees of equivalence

The degree of equivalence of NMI i with respect to the reference value ($A_{p,\mathrm{ref}}$) at each pressure is given by a pair of terms, the relative deviation from the reference value:

$$D_i = (A_{p,i} - A_{p,\mathrm{ref}}) / A_{p,\mathrm{ref}}, \tag{8}$$

and its expanded uncertainty ($k = 2$):

$$U_i = 2[u^2(A_{p,i}) + u^2(A_{p,\mathrm{ref}})]^{0.5} / A_{p,\mathrm{ref}}. \tag{9}$$

The degree of equivalence between two laboratories i and j is given by a pair of terms, the relative difference between their results:

$$D_{ij} = D_i - D_j = (A_{p,i} - A_{p,j}) / A_{p,\mathrm{ref}}, \tag{10}$$

and its expanded uncertainty ($k = 2$):

$$U_{ij} = 2(u^2(A_{p,i})^2 + u^2(A_{p,j}))^{0.5} / A_{p,\mathrm{ref}}. \tag{11}$$

The degrees of equivalence with respect to the reference value calculated with (8) and (9) are presented in Table 5. The relative deviations of the participants' results from the KCRVs are shown graphically in Figs. 2.1 to 2.6. The error bars present the expanded (k=2) relative uncertainties of these deviations calculated by (9).

Table 5 Degrees of equivalence with respect to the reference values, relative deviations from the KCRV (D_i) and relative expanded uncertainties of these deviations (U_i)

p_e / kPa	VNIIM		PTB		VMC		SMU		BelGIM		INM	
	D_i ×10^6	U_i ×10^6	D_i ×10^6	U_i ×10^6	D_i ×10^6	U_i ×10^6	D_i ×10^6	U_i ×10^6	D_i ×10^6	U_i ×10^6	D_i ×10^6	U_i ×10^6
50	-11	27	2.8	21	-5.8	53	8.2	41	34	70	91	77
100	-13	26	2.4	18	-4.8	48	11	38	26	65	70	64
200	-12	24	2.1	17	-2.5	45	13	37	24	47	58	58
300	-10	21	2.8	17	10	44	14	36			55	56
400	-9.4	20	3.0	17	12	44	14	37			51	55
500	-8.6	19	3.0	16	11	44	15	37			49	54

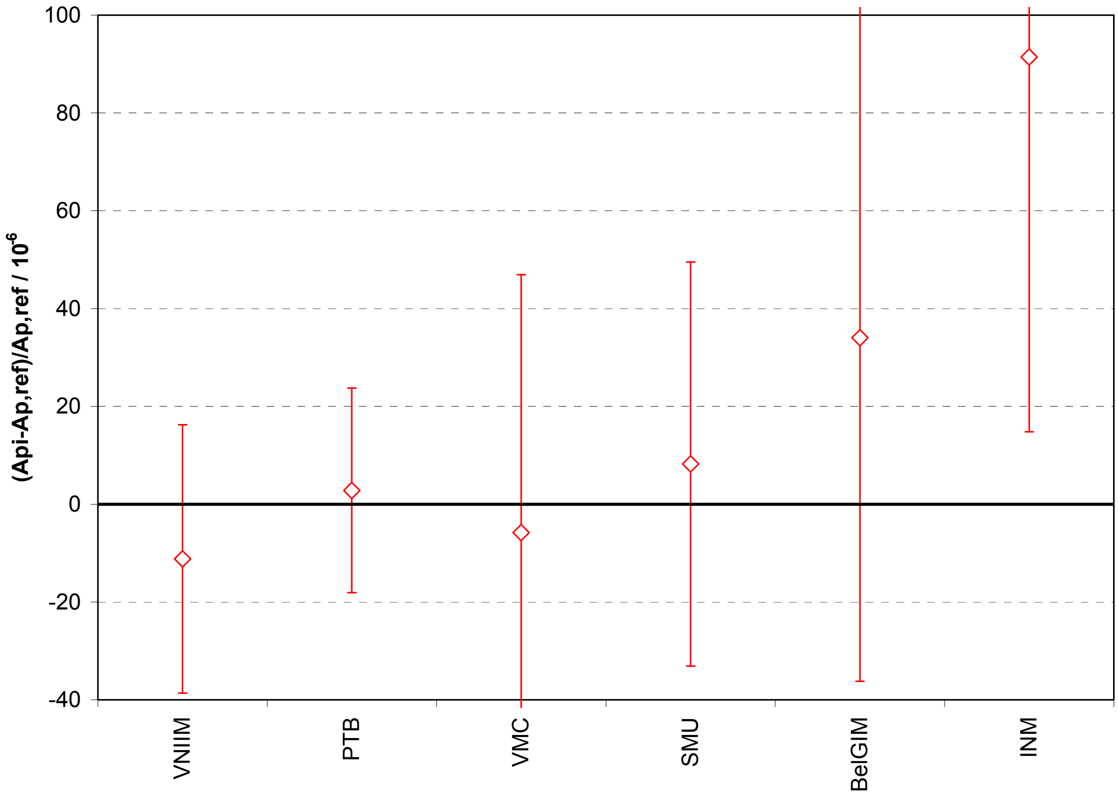

Figure 2.1 Relative deviations of the participants results' from the reference value and the expanded (k=2) uncertainties of these deviations at 50 kPa

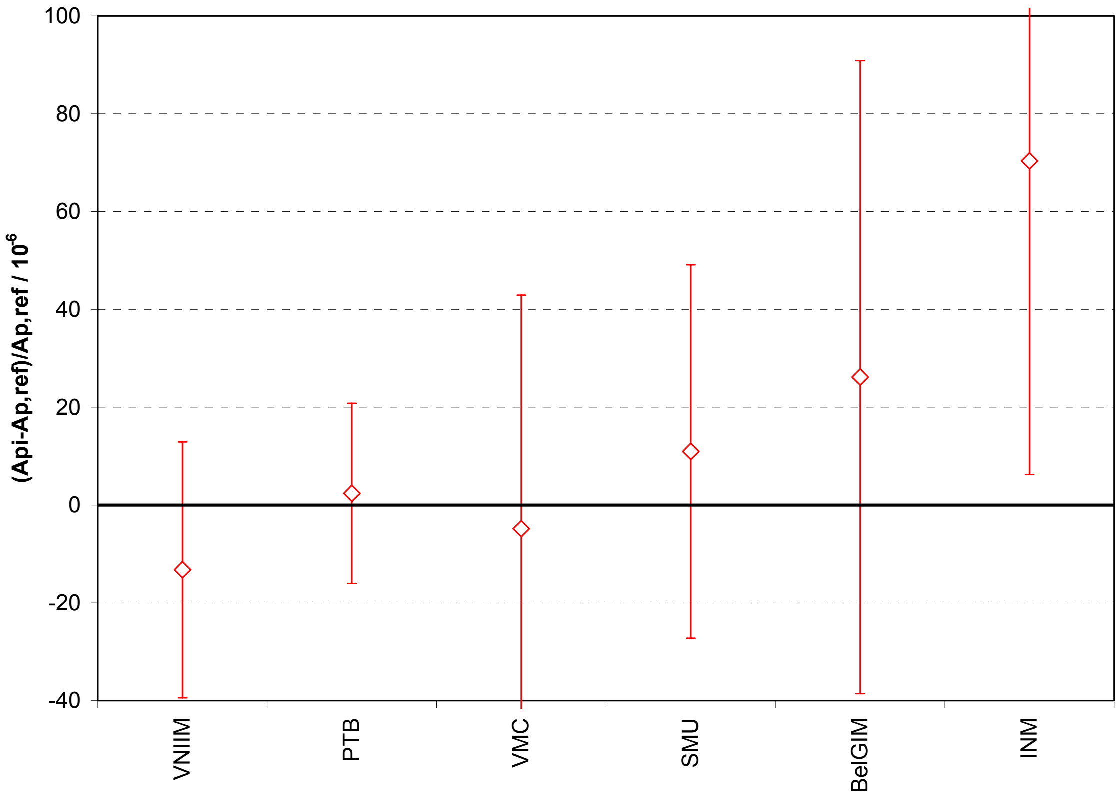

Figure 2.2 Relative deviations of the participants results' from the reference value and the expanded (*k*=2) uncertainties of these deviations at 100 kPa

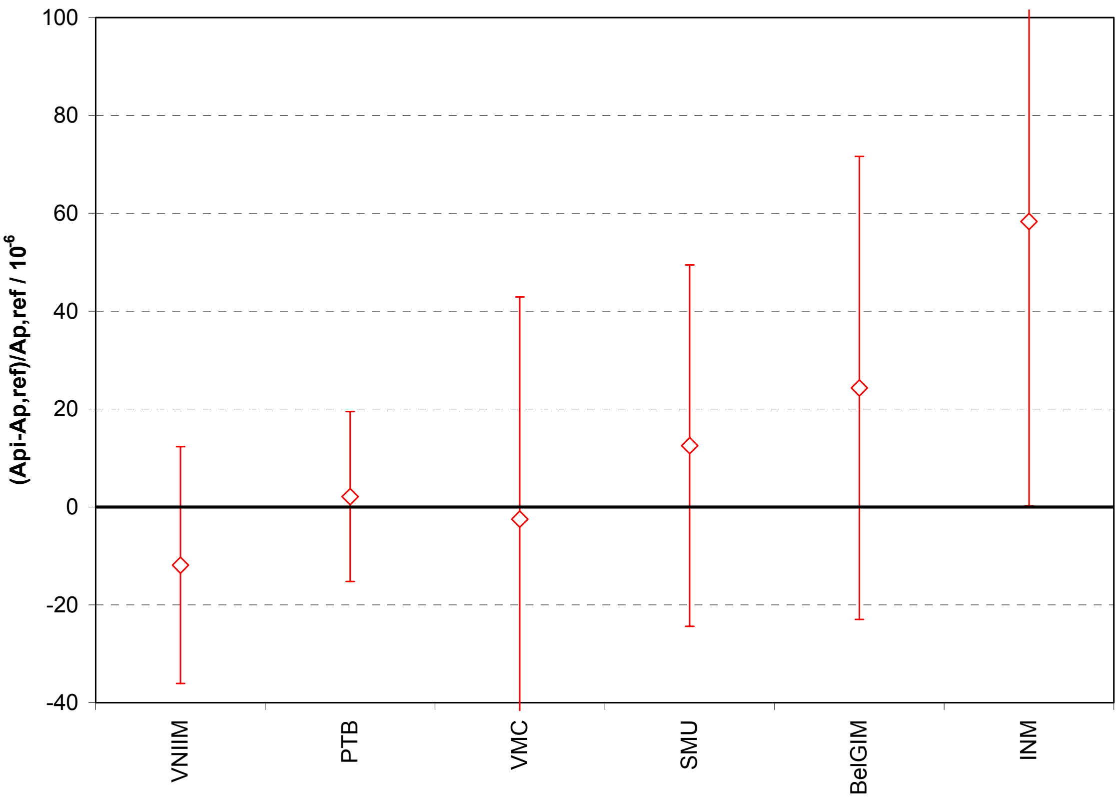

Figure 2.3 Relative deviations of the participants results' from the reference value and the expanded (*k*=2) uncertainties of these deviations at 200 kPa

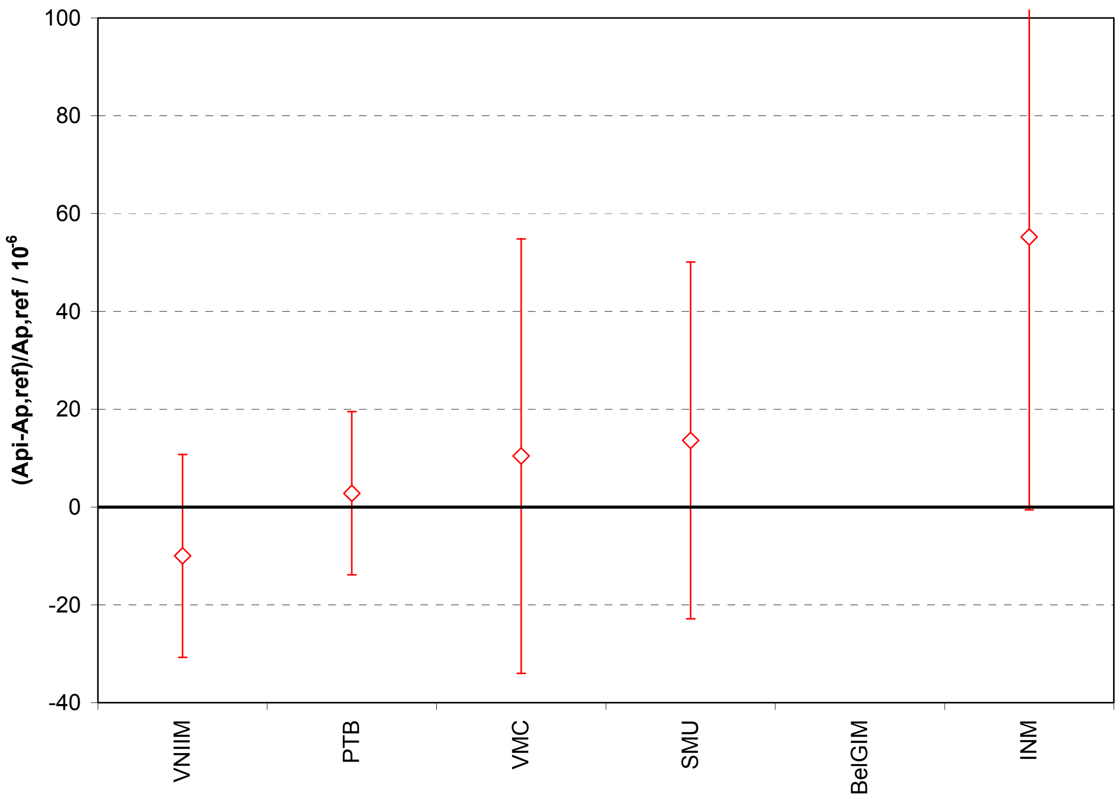

Figure 2.4 **Relative deviations of the participants results' from the reference value and the expanded (*k*=2) uncertainties of these deviations at 300 kPa**

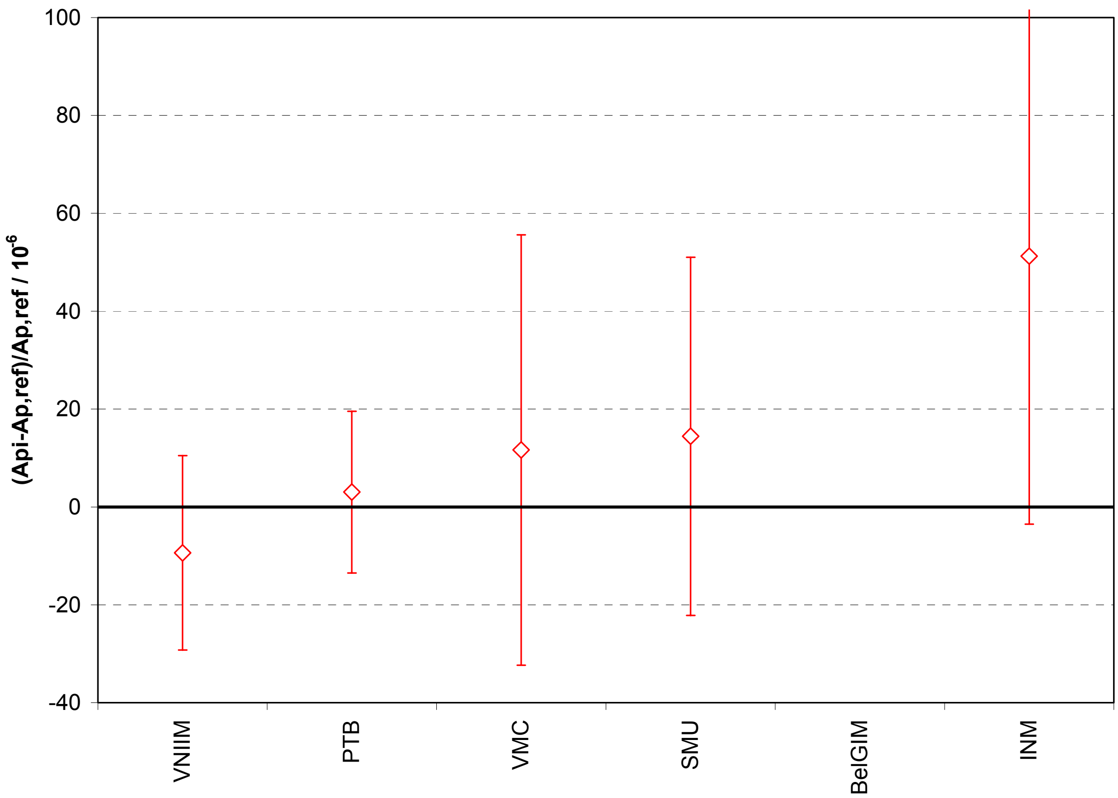

Figure 2.5 **Relative deviations of the participants results' from the reference value and the expanded (*k*=2) uncertainties of these deviations at 400 kPa**

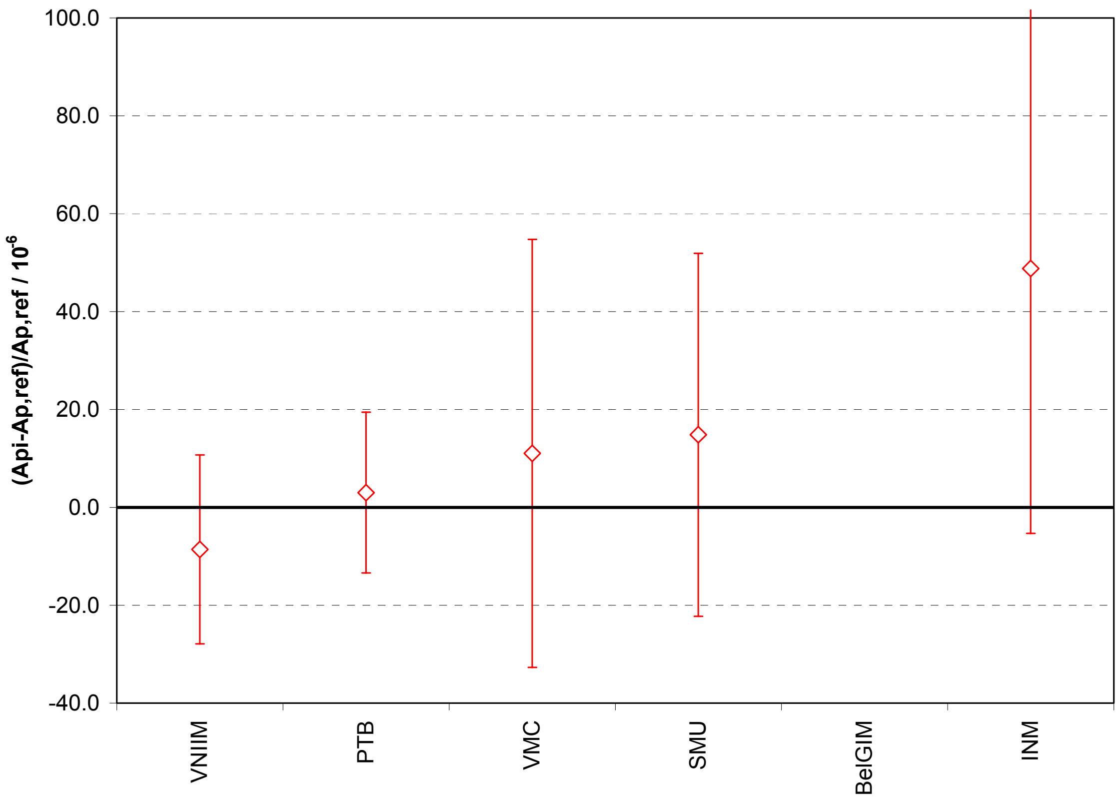

Figure 2.6 **Relative deviations of the participants results' from the reference value and the expanded (*k*=2) uncertainties of these deviations at 500 kPa**

All NMIs except INM are in agreement with the KCRVs at all pressures, the most of them even within standard uncertainties. INM disagrees with the reference values at pressures (50, 100, 200 and 300) kPa and agrees with them at (400 and 500) kPa.

The degrees of equivalence between two NMIs calculated with (10) and (11) are presented in Tables 6.1 – 6.6.

Table 6.1 **Degrees of equivalence between two laboratories *i* and *j* at pressure 50 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})**

	j	VNIIM		PTB		VMC		SMU		BelGIM	
		$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
i	PTB	14	25								
	VMC	5.4	55	-8.6	52						
	SMU	19	44	5.4	40	14	63				
	BelGIM	45	72	31	69	40	85	26	78		
	INM	103	78	89	76	97	90	83	84	57	101

Table 6.2 Degrees of equivalence between two laboratories *i* and *j* at pressure 100 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})

	j	VNIIM		PTB		VMC		SMU		BelGIM	
		$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
i	PTB	16	24								
	VMC	8.4	50	-7.2	47						
	SMU	24	41	8.6	37	16	57				
	BelGIM	39	67	24	64	31	78	15	72		
	INM	84	66	68	63	75	77	59	72	71	89

Table 6.3 Degrees of equivalence between two laboratories *i* and *j* at pressure 200 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})

	j	VNIIM		PTB		VMC		SMU		BelGIM	
		$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
i	PTB	14	22								
	VMC	9.4	48	-4.6	44						
	SMU	24	40	10	36	15	55				
	BelGIM	36	49	22	46	27	63	12	57		
	INM	70	60	56	57	61	71	46	66	59	72

Table 6.4 Degrees of equivalence between two laboratories *i* and *j* at pressure 300 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})

	j	VNIIM		PTB		VMC		SMU	
		$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
i	PTB	13	19						
	VMC	20	45	7.6	44				
	SMU	24	38	11	35	3.2	54		
	INM	65	57	52	55	45	69	42	64

Table 6.5 Degrees of equivalence between two laboratories *i* and *j* at pressure 400 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})

	j	VNIIM		PTB		VMC		SMU	
		$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
i	PTB	12	18						
	VMC	21	45	8.6	43				
	SMU	24	37	11	36	2.8	54	24	37
	INM	61	55	48	54	40	68	37	63

Table 6.6 Degrees of equivalence between two laboratories *i* and *j* at pressure 500 kPa, relative deviations (D_{ij}) and relative expanded uncertainties of these deviations (U_{ij})

i \ *j*	VNIIM		PTB		VMC		SMU	
	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
PTB	12	18						
VMC	20	44	8.0	43				
SMU	23	38	12	36	3.8	54		
INM	57	55	46	54	38	67	34	63

At all pressures, the results of INM deviate from the VNIIM results stronger than the expanded uncertainties of the differences. In addition, the INM results disagree with the PTB result at 100 kPa and with the PTB and VMC results at 50 kPa. All other pairs of the results show an agreement at all pressures.

Additionally, degrees of equivalence for the zero-pressure effective areas determined by the participants are shown in Table 7.

Table 7 Degrees of equivalence between the zero pressure effective areas determined by two laboratories *i* and *j*, $A_{0,i}$ and $A_{0,j}$: relative differences, $(A_{0,i} - A_{0,j}) / A_0$, and relative expanded uncertainties of these differences $2[u^2(A_{0,i}) + u^2(A_{0,j})]^{0.5}$

i \ *j*	VNIIM		PTB		VMC		SMU		BelGIM	
	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$	$D_{ij}\times10^6$	$U_{ij}\times10^6$
PTB	13	19								
VMC	14	56	1	55						
SMU	21	39	8	37	7	64				
BelGIM	36	58	23	57	22	78	15	66		
INM	65	67	53	66	52	85	44	74	30	86

Here, only a disagreement between the INM and VNIIMS results is observed. All other results considered in pairs appear equivalent.

9. Link to CCM.P-K1.b

With the PTB results in actual comparison COOMET.M.P-K1 ($A_{\text{PTB,COOMET}}$) and in CCM.P-K1.b comparison ($A_{\text{PTB,CCM}}$), a link of the COOMET KCRV ($A_{\text{ref,COOMET}}$) to the CCM KCRV ($A_{\text{ref,CCM}}$) is possible at pressures (50, 100, 200 and 400) kPa. The relative difference between the COOMET and the CCM KCRVs ($\Delta_{\text{COOMET,CCM}}$) is then:

$$\Delta_{\text{COOMET,CCM}} = \frac{A_{\text{ref,COOMET}} - A_{\text{PTB,COOMET}}}{A_{\text{ref,COOMET}}} + \frac{A_{\text{PTB,CCM}} - A_{\text{ref,CCM}}}{A_{\text{ref,CCM}}} \tag{12}$$

The deviation of NMI *i* from the COOMET KCRV, $D_{i,\text{COOMET}}$, as defined by (6), can be transformed into the deviation from the CCM KCRV ($D_{i,\text{CCM}}$) by:

$$D_{i,\text{CCM}} = D_{i,\text{COOMET}} + \Delta_{\text{COOMET,CCM}}, \tag{13}$$

with the expanded ($k = 2$) relative uncertainty of this deviation:

$$U(D_{i,\mathrm{CCM}}) = 2[(u(A_i)/A_{\mathrm{ref,COOMET}})^2 + (u(A_{\mathrm{ref,CCM}})/A_{\mathrm{ref,CCM}})^2 + s_{\mathrm{PTB}}{}^2]^{0.5}, \tag{14}$$

where s_{PTB} is stability of the PTB standards (in relative units) involved in the two comparisons.
In the same manner the degree of equivalence between any NMI-participant (i) linked to the current COOMET KC by $D_{i,\mathrm{COOMET}}$ and any other NMI (j) linked to the CCM KC by $D_{j,\mathrm{CCM}}$ can be found as

$$D_{ij} = D_{i,\mathrm{COOMET}} + D_{j,\mathrm{CCM}} + \Delta_{\mathrm{COOMET,CCM}}, \tag{15}$$

with the expanded ($k = 2$) relative uncertainty of this deviation

$$U(D_{ij}) = 2[(u(A_i)/A_{\mathrm{ref,COOMET}})^2 + (u(A_j)/A_{\mathrm{ref,CCM}})^2 + s_{\mathrm{PTB}}{}^2]^{1/2}. \tag{16}$$

As the key comparison CCM.P-K1.b was performed with two transfer standards, DH 6594 and DHI 107, for the simplicity of the link, the results obtained with both standards were averaged before performing the link. The PTB standards used in both comparisons were shown to be stable in the time between the two comparisons within $2{\cdot}10^{-6}$ relative. The standard deviation of the pressure measurements with them is typically lower than $1{\cdot}10^{-6}$. Thus, the uncertainty of the link can be taken as $s_{\mathrm{PTB}} = 3{\cdot}10^{-6}$.

The relative deviations of the results of the participants in both comparisons CCM.P-K1.b and COOMET.M.P-K1 from the KCRVs of CCM.P-K1.b are shown graphically in Figs. 3.1 to 3.4. The error bars in these figures present the expanded (k=2) relative uncertainties of these deviations, which were calculated by (14).

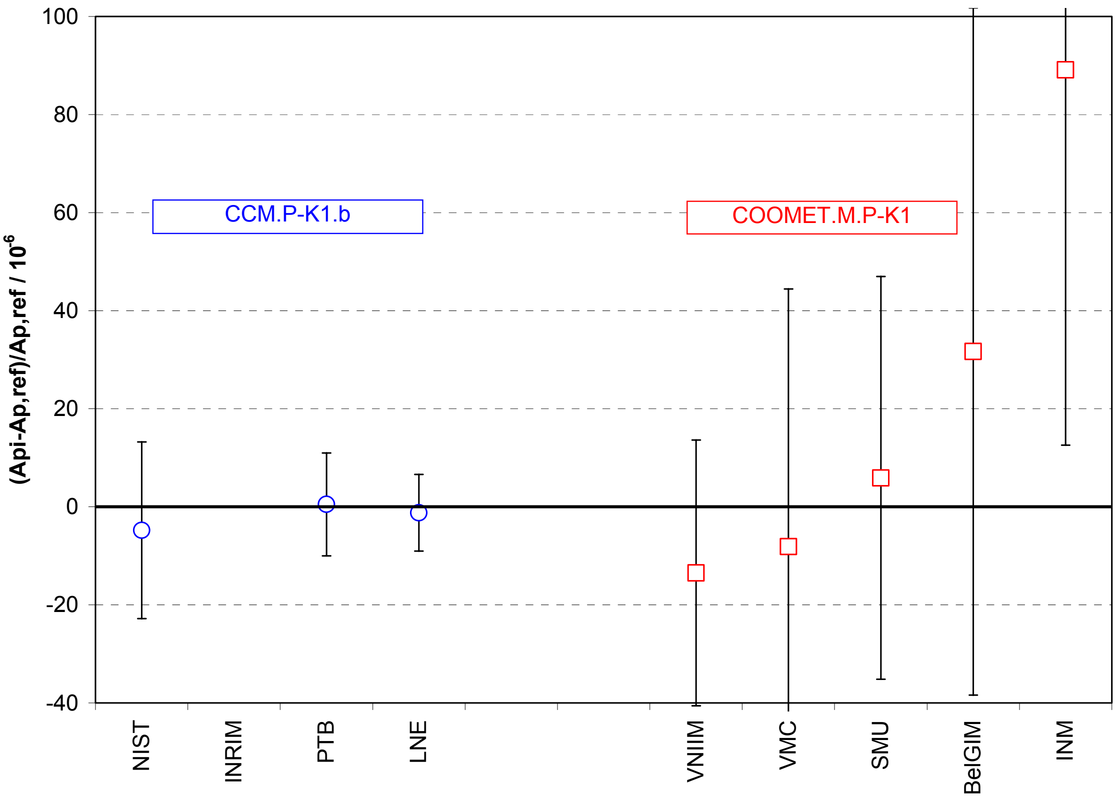

Figure 3.1 **Relative deviations of the participants results' from the reference value of comparison CCM.P-K1.b and the expanded (k=2) uncertainties of these deviations at 50 kPa**

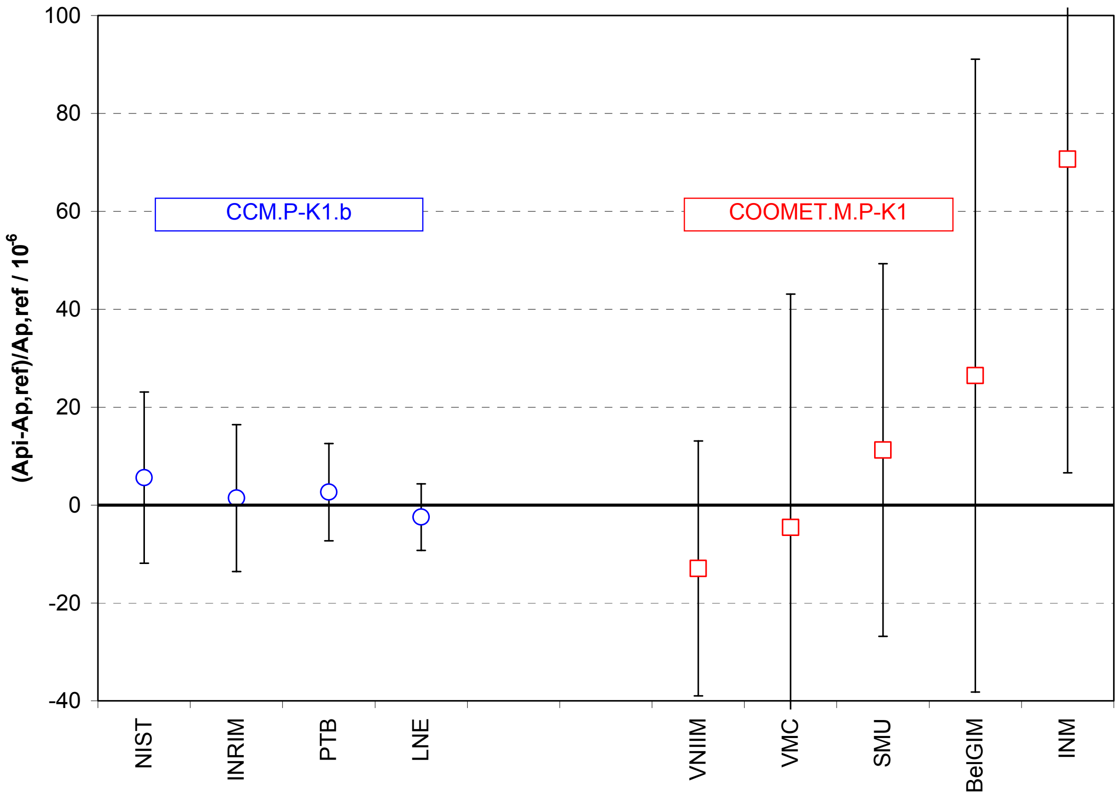

Figure 3.2 **Relative deviations of the participants results' from the reference value of comparison CCM.P-K1.b and the expanded (*k*=2) uncertainties of these deviations at 100 kPa**

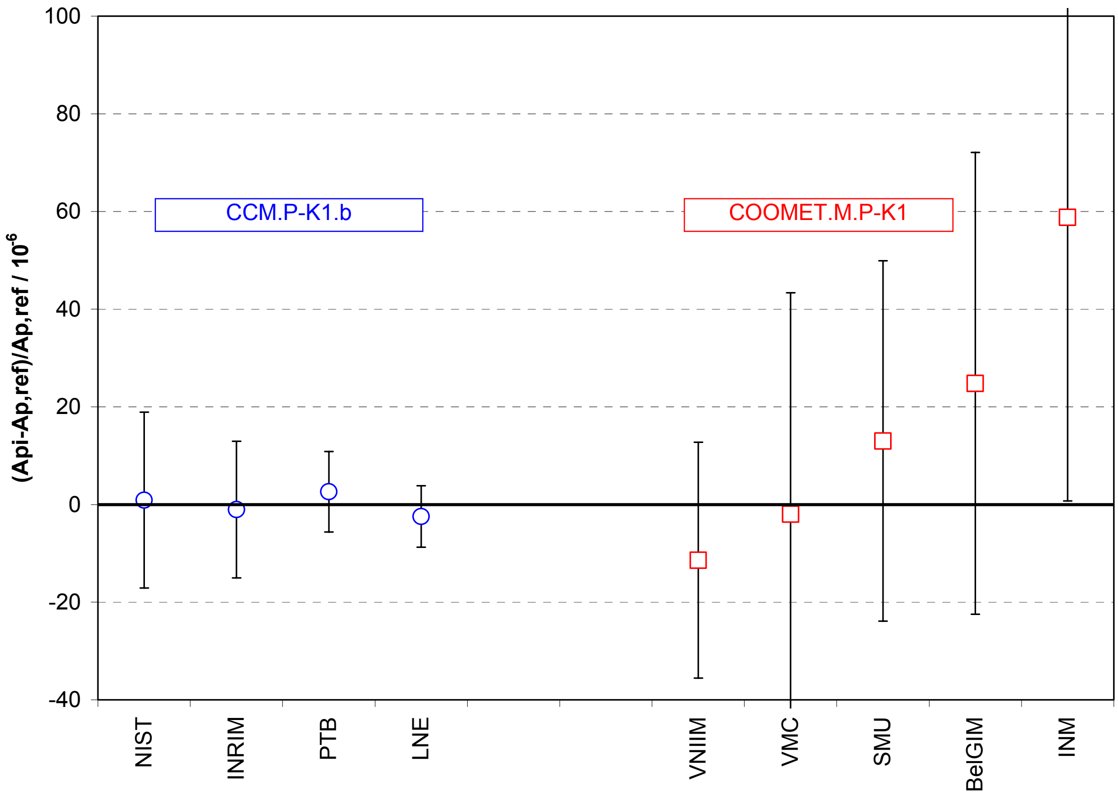

Figure 3.3 **Relative deviations of the participants results' from the reference value of comparison CCM.P-K1.b and the expanded (*k*=2) uncertainties of these deviations at 200 kPa**

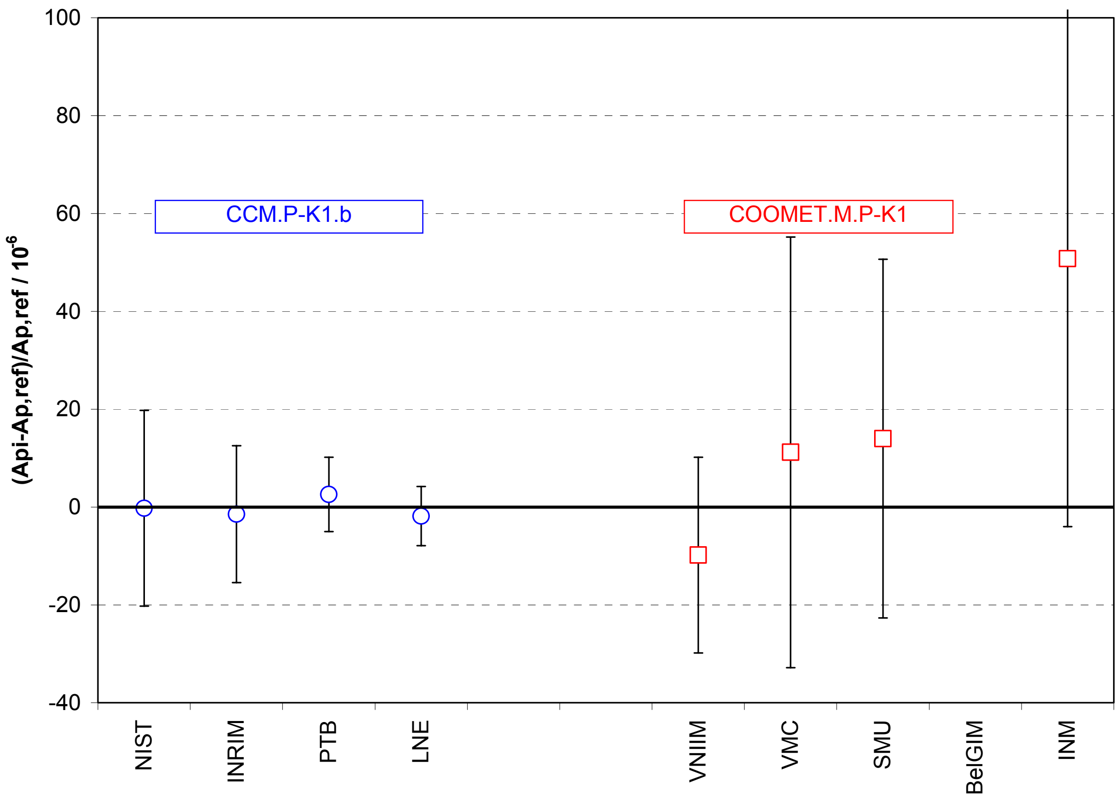

Figure 3.4 **Relative deviations of the participants results' from the reference value of comparison CCM.P-K1.b and the expanded (*k*=2) uncertainties of these deviations at 400 kPa**

All NMIs except INM are in agreement with the CCM.P-K1.b KCRVs at all pressures. INM disagrees with the CCM.P-K1.b KCRVs reference values at pressures (50, 100 and 200) kPa and agrees with them at 400 kPa.

The degrees of equivalence between two NMIs calculated with (15) and (16) are presented in Tables 8.1 – 8.4.

Table 8.1 **Degrees of equivalence between two laboratories participated in COOMET.M.P-K1 (*i*) and in CCM.P-K1.b (*j*) at pressure 50 kPa, relative deviations (D_{ij}), relative expanded uncertainties of these deviations (U_{ij}) and their ratios (D_{ij}/U_{ij})**

	j	NIST			PTB			LNE		
		D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}
i	VNIIM	-8.7	33	0.26	-14	30	0.47	-12	29	0.42
	VMC	-3.3	56	0.06	-8.6	54	0.16	-6.9	54	0.13
	SMU	11	45	0.24	5.4	43	0.13	7.1	42	0.17
	BelGIM	37	73	0.50	31	71	0.44	33	71	0.46
	INM	94	79	1.19	89	78	1.14	90	77	1.17

Table 8.2 Degrees of equivalence between two laboratories participated in COOMET.M.P-K1 (*i*) and in CCM.P-K1.b (*j*) at pressure 100 kPa, relative deviations (D_{ij}), relative expanded uncertainties of these deviations (U_{ij}) and their ratios (D_{ij}/U_{ij})

i \ *j*	NIST			INRIM			PTB			LNE		
	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}
VNIIM	-19	32	0.58	-14	31	0.47	-16	29	0.54	-11	28	0.38
VMC	-10	51	0.20	-6.0	50	0.12	-7.2	49	0.15	-2.1	49	0.04
SMU	5.7	42	0.13	9.8	41	0.24	8.6	40	0.22	14	39	0.35
BelGIM	21	67	0.31	25	67	0.37	24	66	0.36	29	65	0.44
INM	65	67	0.97	69	66	1.05	68	65	1.04	73	65	1.13

Table 8.3 Degrees of equivalence between two laboratories participated in COOMET.M.P-K1 (*i*) and in CCM.P-K1.b (*j*) at pressure 200 kPa, relative deviations (D_{ij}), relative expanded uncertainties of these deviations (U_{ij}) and their ratios (D_{ij}/U_{ij})

i \ *j*	NIST			INRIM			PTB			LNE		
	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}
VNIIM	-12	31	0.40	-10	29	0.36	-14	26	0.53	-9.0	26	0.35
VMC	-2.9	49	0.06	-1.0	48	0.02	-4.6	47	0.10	0.4	46	0.01
SMU	12	42	0.29	14	40	0.35	10	38	0.27	15	38	0.41
BelGIM	24	51	0.47	26	50	0.52	22	48	0.46	27	48	0.57
INM	58	61	0.95	60	60	1.00	56	59	0.95	61	59	1.04

Table 8.4 Degrees of equivalence between two laboratories participated in COOMET.M.P-K1 (*i*) and in CCM.P-K1.b (*j*) at pressure 400 kPa, relative deviations (D_{ij}), relative expanded uncertainties of these deviations (U_{ij}) and their ratios (D_{ij}/U_{ij})

i \ *j*	NIST			INRIM			PTB			LNE		
	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}	D_{ij} ×10^6	U_{ij} ×10^6	D_{ij} / U_{ij}
VNIIM	-10	29	0.33	-8.4	25	0.33	-12	22	0.56	-8.0	22	0.37
VMC	11	49	0.24	13	47	0.27	8.6	45	0.19	13	45	0.29
SMU	14	42	0.34	15	40	0.39	11	38	0.30	16	38	0.42
INM	51	59	0.87	52	57	0.92	48	56	0.87	53	55	0.95

Between the groups of the participants in the COOMET.M.P-K1 and CCM.P-K1.b comparisons, a disagreement is observed between INM on one side and NIST, PTB, LNE on the other side at 50 kPa; INM on one side and INRIM, PTB, LNE on the other side at 100 kPa; INM on one side and LNE on the other side at 200 kPa.

10. Conclusions

Five out of six laboratories which participated in this comparison could support the uncertainties claimed in their CMC tables. For the laboratories which has not submitted their CMC tables, the results obtained in this comparison provide a basis for a submission. The only results of INM show deviations from the KCRVs and from several results of other participants which disagree with the uncertainty statements made in the INM CMC table.

Out of the 84 pairs of the results, in 75 pairs agreement within the expanded uncertainties and in 43 pairs agreement within the standard uncertainties is observed.

With the exception of INM all participants have also demonstrated an agreement with the KCRVs of comparison CCM.P-K1.b and with the results of all participants in that comparison.

For VNIIM, PTB and SMU, which compared last time between 1995 and 1998 within COOMET project 115/RU/95 [1], the differences in the actual comparison are close to those in the last project. For others countries–participants in this project this comparison allowed demonstration of their pressure calibration capabilities for the first time.

When comparing this comparison with the similar comparison EUROMET.M.P-K3 (EUROMET project 439) [2], the differences in the results within the two projects may be explained not only by different methods for determination of the effective area but also different design of the piston–cylinder assemblies used in the pressure balances of the participants' national pressure standards.

Acknowledgements

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