Regional Key Comparison

COOMET.M.P-K2

In the Pressure Range 10 MPa to 100 MPa

Hydraulic gauge pressure

FINAL REPORT

The Results of Measurements

Performed in the Period from June 2005 to July 2008

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1. INTRODUCTION

The comparison was organized by Technical Committee (TC) 1.6 “Mass and Related Quantities” of COOMET and was approved in the April of 2004 at the TC meeting in Bratislava (SMU). The project is registered within COOMET as project Nr. 331/LT/05, entitled “International comparison of the National Pressure Standards in the Field of Gauge Pressure in the range 10 MPa to 100 MPa.

In the BIPM database, it is identified as COOMET.M.P-K2.

SE Vilnius Metrology Center (VMT/VMC) was chosen as a pilot laboratory.

The results of the comparison are given in this document.

A respective CIPM key comparison in the range from 10 MPa to 100 MPa was organized at the CCM High Pressure Working Group meeting held at BIPM on the 22 May of 2002. This comparison, which was identified as CCM.P-K7, final report on January 2005, included two laboratories, PTB and NPL, which also participated in the actual COOMET.M.P-K2 comparison. Thus, the results of COOMET.M.P-K2 comparison will be linked to the results of CCM.P-K7.

The actual comparison should give opportunity to the laboratories COOMET-members to support their uncertainty statements made in their Calibration and Measurement Capability (CMC) Tables.

The comparison was conducted in accordance with the Technical Protocol prepared by the VMC and approved by the participants.

Seven national metrology institutes (NMIs) participated in this comparison, which was carried out between June 2005 and July 2008.

2. LABORATORY STANDARDS OF THE PARTICIPANTS

All laboratory standards (LSs) were pressure balances equipped with piston-cylinder assemblies. The different methods had applied by the participants to compare their standards with the transfer standard (TS). The uncertainties of the LSs given below are standard uncertainties.

2.1. VMC/VMT pressure balance

VMC/VMT used the national pressure standard in the range 0.5 to 200 MPa whose properties are given below together with measurement conditions.

Standards:	Nr.482	Nr.531
Manufacturer	DHI	DHI
Model:	PG7302-M	PG7302-M
Measurement range with piston-cylinder unit in MPa	0,5 to 50	5 to 500
Material of piston and cylinder	tungsten carbide	tungsten carbide
Operation mode	free-deformation	free-deformation
Pressure-transmitting medium	DHS[1)]	DHS[1)]
Zero-pressure effective area (A_0) at reference temperature, in mm^2	19.61248	1.960680
Relative uncertainty of A_0 in 10^{-6}	10	16
Pressure distortion coefficient in MPa^{-1}	$1.2 \cdot 10^{-6}$	$1.01 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.11 \cdot 10^{-6}$	$0.11 \cdot 10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	5.0	5.0
Linear thermal expansion coefficient of assembly in °C^{-1}	$9 \cdot 10^{-6}$	$9 \cdot 10^{-6}$
Reference temperature, in °C	20.0	20.0
Local gravity, in m/s^2	9.8143792	9.8143792
Relative uncertainty of g in 10^{-6}	1.7	1.7
Height difference between LS and TS, in mm	- 63.0	- 63.0
Uncertainty of h in mm	1.0	1.0

1) DHS = di(2)-ethyl-hexyl-sebacate.

The zero-pressure effective area of LS piston-cylinder assemblies ($A_{0,LS}$) and their pressure distortion coefficients were determined during the calibration in PTB and thus are traceable to the German National Pressure Standard.

2.2. PTB pressure balance

The PTB used a home-made pressure balance with a piston-cylinder assembly identified as Ruska 703/1 whose properties are given below together with measurement conditions.

Standards:	main: 703/1	supplementary: 702/2
Manufacturer	Ruska	Ruska
Measurement range in MPa	10 to 100	2.8 to 50
Material of piston	tungsten carbide	tungsten carbide
Material of cylinder	tungsten carbide	tungsten carbide
Operation mode, free-deformation or controlled-clearance	free-deformation	free-deformation
Pressure-transmitting medium	DHS	DHS
Zero-pressure effective area (A_0) at reference temperature in mm^2	8.395432	30.41915
Relative uncertainty of A_0 in 10^{-6}	10	8.6
Pressure distortion coefficient (λ) in MPa^{-1}	$0.725 \cdot 10^{-6}$	$0.803 \cdot 10^{-6}$

Uncertainty of λ in MPa^{-1}	$0.1\cdot10^{-6}$	$0.1\cdot10^{-6}$
Relative uncertainty of mass pieces in 10^{-6}	1	1
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	$4.32\cdot10^{-6}$	$4.32\cdot10^{-6}$
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	$4.32\cdot10^{-6}$	$4.32\cdot10^{-6}$
Reference temperature (t_0) in °C	20.0	20.0
Local gravity (g) in m/s^2	9.812533	9.812533
Relative uncertainty of g in 10^{-6}	0.54	0.54
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0.02	-0.48
Uncertainty of h in mm	0.37	0.37
Participation in previous comparisons	CCM.P-K7	

During its stay at the PTB the transfer standard was investigated in the 100 MPa range using PTB 8.4 mm^2 piston-cylinder assembly 703/1 as a reference, the same as PTB had used in the CCM, EURAMET and APMP 100 MPa KCs. In addition, it was studies in the 50 MPa range using PTB 30 mm^2 piston-cylinder assembly 702/2, to which standard 703/1 is linked [2]. The results of the measurements with assembly 702/2 should be considered as supplementary. Both piston-cylinder assemblies were used in the 100 MPa pressure balance described in [3].

The zero pressure effective areas of both piston-cylinder units were derived from pressure comparison measurements with the standards for lower pressure as described in reference [2], but the primary standard at the starting point of the step-up procedure was a new instrument for the 10 MPa range equipped with 5 cm^2 piston-cylinder assemblies, the effective areas of which were calculated from dimensional data [4].

The pressure distortion coefficient (λ) of assembly 703/1 was calculated by three national metrology institutes using finite element and other advanced numerical methods within the scope of EURAMET project 256 [5] with the results lying in the interval

$$0.719\cdot10^{-6}\ \text{MPa}^{-1} < \lambda < 0.739\cdot10^{-6}\ \text{MPa}^{-1}.$$

From the well-known simple formula the following value was calculated [2]:

$$\lambda = 0.725\cdot10^{-6}\ \text{MPa}^{-1}.$$

For assembly 702/2, the distortion coefficient was determined by the simple formula:

$$\lambda = 0.803\cdot10^{-6}\ \text{MPa}^{-1}$$

The evaluation of the uncertainty contributions due to material's elastic constants and dimensions of the piston-cylinder gives a strong belief that the standard uncertainty of the distortion coefficient of each assembly is not larger than

$$u(\lambda) = 0.1\cdot10^{-6}\ \text{MPa}^{-1}.$$

The TS was directly connected with the LS, and the cross-floating was performed by controlling pistons' fall rates. The *p*-method was used.

2.3. NPL pressure balance

The NPL used the national pressure standard in the range from 1 to 100 MPa whose properties are given below together with measurement conditions.

Manufacturer	Desgranges et Huot (D&H)
Measurement range in the pressure balance used, in MPa	1 to 100 (1 MPa/kg PCU)
Material of piston and cylinder	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	free-deformation
Pressure-transmitting medium	DHS
Zero-pressure effective area (A_0) at reference temperature, in mm^2	9.804825
Relative uncertainty of A_0 in 10^{-6}	10.1
Pressure distortion coefficient, in MPa^{-1}	$1.07\ 10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.1 \cdot 10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	0.5
Linear thermal expansion coefficient of assembly, in °C^{-1}	$9.0 \cdot 10^{-6}$
Reference temperature, in °C	20
Local gravity, in m/s^2	9.811813
Relative uncertainty of g	$0.3 \cdot 10^{-6}$
Height difference between LS and TS, in mm	+ 0.16
Uncertainty of h, in mm	0.1
Participation in previous comparisons	CCM.P-K7

The effective area and distortion coefficient of this standard are traceable via a series of cross-float comparisons to a 25 mm diameter piston-cylinder assembly calibrated by dimensional metrology at the NPL.

2.4. SMU pressure balance

The SMU used a custom-made pressure balance MPZ 01 Nr.01 with a piston-cylinder assembly identified as, serial Nr. C01 whose properties are given below together with measurement conditions.

Manufacturer	SMU
Measurement range in the pressure balance used, in MPa	10 to 100
Material of piston and cylinder	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	Free-deformation
Pressure-transmitting medium	DHS
Zero-pressure effective area (A_0) at reference temperature, in mm^2	9.81960
Relative uncertainty of A_0 in 10^{-6}	20.0
Pressure distortion coefficient, in MPa^{-1}	$1.4 \cdot 10^{-6}$

Uncertainty of λ in MPa^{-1}	$0.14{\cdot}10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	1.0
Linear thermal expansion coefficient of assembly, in °C^{-1}	$9.0{\cdot}10^{-6}$
Reference temperature, in °C	20.0
Local gravity, in m/s^2	9.808732
Relative uncertainty of g	$2.0{\cdot}10^{-6}$
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS)	80 mm in cycle 1 63 mm in cycles 2, 3 3.7 mm in cycles 4, 5
Uncertainty of h, in mm	0.25

The zero pressure effective of the standard is determined by series of cross floating measurements traceable to the national pressure standard the effective area of which was determined from dimensional measurements. The distortion coefficient was devaluated from dimensional measurements and material constants.

2.5. VNIIM pressure balance

The national pressure standard (NPS) used in this comparison is pressure balance.

It is equipped with piston-cylinder units identified by number 2 and 5 whose pressure effective areas were determined from measurements against a primary manometer. Piston-cylinder unit number 2 was used in the comparison. The metrological properties of this standard are:

Manufacturer	Russia
The pressure balance used with piston-cylinder unit	NPS N2
Measurement range in the pressure balance used, in MPa	1.25 to 60
Material of piston and cylinder	Steel CrVG
Material of cylinder	Steel CrVG
Operation mode	Free-deformation
Pressure-transmitting medium	Castor oil
Zero-pressure effective area (A_0) at reference temperature, in mm^2	19.9907
Relative uncertainty of A_0 in 10^{-6}	12.0
Pressure distortion coefficient, in MPa^{-1}	$2.9{\cdot}10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.5{\cdot}10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	2.0
Linear thermal expansion coefficient of piston, in °C^{-1}	$11.5{\cdot}10^{-6}$
Linear thermal expansion coefficient of cylinder, in °C^{-1}	$11.5{\cdot}10^{-6}$
Reference temperature, in °C	20.0
Local gravity, in m/s^2	9.819308
Relative uncertainty of g	$0.1{\cdot}10^{-6}$
Height difference between LS and TS, in mm	48.0
Uncertainty of h, in mm	1.0

The pressure distortion coefficient (λ) of the piston-cylinder assembly was determined from its dimensions and the elastic constants of its material using Lame′ equations.

The note: comparison of the standards NPS and TS were performed on the castor oil in the all measurement system.

2.6. BelGIM pressure balance

The BelGIM used the pressure standard whose properties are given below together with measurement conditions.

Manufacturer	DH-Budenberg SA
Measurement range in the pressure balance used, in MPa	10 to 100
Material of piston and cylinder	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	Free-deformation
Pressure-transmitting medium	DHS
Zero-pressure effective area (A_0) at reference temperature, in mm^2	9.805279
Relative uncertainty of A_0 in 10^{-6}	44.0
Pressure distortion coefficient, in MPa^{-1}	$0.93 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.05 \cdot 10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	5.0
Linear thermal expansion coefficient of assembly, in °C^{-1}	$9.0 \cdot 10^{-6}$
Reference temperature, in °C	20.0
Local gravity, in m/s^2	9.8136734
Relative uncertainty of g	$1.8 \cdot 10^{-6}$
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	1
Uncertainty of h, in mm	0,3

The zero-pressure effective area of LS piston-cylinder assembly ($A_{0,LS}$) and the pressure distortion coefficient were determined during the calibration in DH-Budenberg laboratory (COFRAC), FRANCE, accreditation №2-1033.

2.7. INM pressure balance

The INM used the standard pressure balance Ruska, type 2400, serial Nr. 21601, whose properties are given below together with measurement conditions.

Manufacturer	Ruska
Measurement range in the pressure balance used, in MPa	5 to 85
Material of piston and cylinder	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	Re-entrant cylinder
Pressure-transmitting medium	DHS
Zero-pressure effective area (A_0) at reference temperature, in mm^2	16.8003
Relative uncertainty of A_0 in 10^{-6}	21.0
Pressure distortion coefficient, in MPa^{-1}	$-2.7 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.37 \cdot 10^{-6}$
Relative uncertainty of mass pieces, in 10^{-6}	0.5
Linear thermal expansion coefficient of piston, in °C^{-1}	$4.55 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder, in °C^{-1}	$4.55 \cdot 10^{-6}$

Reference temperature, in °C Local gravity, in m/s^2 Relative uncertainty of g Height difference between LS and TS, in mm Uncertainty of h, in mm	20 9.8053953 $0.5 \cdot 10^{-6}$ -106.1 0,2

The zero-pressure effective area of LS piston-cylinder assembly ($A_{0,LS}$) and the pressure distortion coefficient were determined during the calibration in PTB, and thus are traceable to the German National Pressure Standard.

3. TRANSFER STANDARD

3.1. Purpose and structure of the transfer standard

The comparison was realized with the help of a transfer standard (TS) which was a simple pressure balance equipped with a set of weights.

The TS had been manufactured by and is property of SMU.

3.2. Main metrological characteristics of the TS

Item	Identification	Notes
Pressure balance platform	Serial number MPZ 01 Nr.02	
Piston-cylinder assembly	Serial number C04	
Measurement range	(10 ÷ 100) MPa	
Nominal effective area of the assembly	$A_{0,nom}$ = 9.81 mm^2	
Nominal sensitivity	1 MPa/kg	
Nominal initial mass (including the weight carrier)	≈ 895 g	
Piston-cylinder material		
Material of the piston	Tungsten carbide	Manufacturer's information
Material of the piston cap	Stainless steel	
Mean density of piston and cap combination	9204 kg/m^3	
Linear thermal expansion coefficient of the piston-cylinder unit	$\alpha_p+\alpha_c$ =(9.0 ± 0.45)$\cdot 10^{-6}$ K^{-1}	
Pressure distortion coefficient [kPa^{-1}]	To be determined by the participating laboratories	
Pressure reference level: the bottom of the piston	Working position of the piston is 4.6 mm above its rest position in the cylinder.	
Piston fall rate at pressure 100 MPa	0.36 mm/min.	

Piston rotation time at pressure 20 MPa	Not less than 20 min	Initial speed (2±0.15) s^{-1}
<u>Weight carrier</u>		
Material of the weight carrier	stainless steel	
Density of material	7800 kg/m^3	
<u>Pressure transmitting medium</u>		
Liquid di(2)-ethyl-hexyl-sebacate (DHS)		
Density of liquid	913 kg/m^3	
Surface tension (σ)	31.2 x (1 ± 0.05) mN/m	

4. ORGANIZATION, CHRONOLOGY AND PROBLEMS DURING THE COMPARISON

The list of the laboratories and contact persons responsible for the works are given below in the chronological order:

NMI	Contact person	Measurement date
VMT/VMC	Ksaverija Dapkeviciene	June 2005
PTB	Wladimir Sabuga	August 2005
NPL	Bernard Waller	October 2005
SMU	Peter Farar	January 2006
VNIIM	Yury Kiselev	October 2006
BelGIM	Konstantin Saczuk	September 2007
INM	Ion Sandu	December 2007
VMT/VMC	Ksaverija Dapkeviciene	May 2008
PTB, (TS stability investigation)	Wladimir Sabuga	July 2008

There were different problems during the comparison. Its finish was delayed by the twenty-one month because of technical problems and due to customs problems. When sending the TS from VMC to PTB the piston of TS was broken from its upper end near the piston cap. The specialists in PTB could repair the piston with a new cap, this led to a shortening of the total piston length. Because the first stability check measurement had been done at VMC/VMT before the piston broke, it was decided that the stability of the TS after its repair should be controlled by two measurements at PTB, the first immediately after the repair and the second at the end of the comparison. The two measurements at VMC/VMT scheduled for the beginning and the end of the comparison had to be also performed now with the aim to see the change in the properties of the TS due to its repair.

When sending TS from Slovakia to Byelorussia an ATA carnet could not be issued because Byelorussia is not a carnet member. For this reason some participants had difficulties with the temporary import of TS.

The completeness and state of TS were controlled and documented with the departure and arrival protocols.

5. 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-methods) 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 the specific working conditions. The laboratories used the Δp-method were: VNIIM and BelGIM.

6. MEASUREMENT PROCEDURES

The measurements included five cycles each with nominal pressures created in the following order (10, 20, 30, 40, 50, 60 70, 80, 90, 100, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10) MPa. At each pressure the participants had to determine the effective area (A_{p}) of the TS by cross-floating it against their pressure standards. A_{p} was calculated at the reference temperature of 20°C using the equation, p-method:

$$A_p = \frac{\sum_i m_i g\left(1 - \frac{\rho_{0\mathrm{a}}}{\rho_0} + \frac{\rho_{0\mathrm{a}} - \rho_{\mathrm{a}}}{\rho_i}\right) + 2\sigma\sqrt{\pi A_{0,\mathrm{nom}}}}{p\left[1 + \left(\alpha_{\mathrm{p}} + \alpha_{\mathrm{c}}\right)\left(t - t_0\right)\right]}, \tag{1}$$

where:

m_i	conventional masses of the piston, the weight carrier and the mass pieces placed on the weight carrier of TS;
ρ_i	densities of the parts with masses m_i;
ρ_{a}	air density;
$\rho_{0\mathrm{a}}$	conventional value of the air density, $\rho_{0\mathrm{a}}$ = 1.2 kg/m^3;
ρ_0	conventional value of the mass density, ρ_0 = 8000 kg/m^3;
g	local gravity acceleration;
σ	surface tension of the TS oil;
$A_{0,\mathrm{nom}}$	nominal effective area of TS;

p	pressure generated by the laboratory standard at the TS reference level;
α_p and α_c	thermal expansion coefficients of the piston and cylinder materials, respectively;
t	temperature of TS;
t_0	reference temperature, t_0 = 20 °C.

and Δp-method:

$$A_p = A_{\text{NPS}} \frac{\left[m_{2i} + M_{20} \cdot 2\alpha_2 (t_{20} - t_{2i})\right] \cdot \left[1 + 2\alpha_1 (t_{1i} - 20) + \lambda_1 \cdot p\right]}{\left[m_{1i} + M_{10} \cdot 2\alpha_1 (t_{10} - t_{1i})\right] \cdot \left[1 + 2\alpha_2 (t_{2i} - 20)\right]} \quad (1a)$$

where:

A_{NPS}	zero-pressure effective area of NPS;
m_{1i}, m_{2i}	masses imposed on weight carrier device NPS and TS at that «i»-comparisons after an equilibration of both piston systems;
M_{10} M_{20}	masses of a mobile part and weights NPS and TS at a preliminary equilibration;
p_{Ni}	nominal value of measurements pressure;
α_1 α_2	thermal expansion coefficients of the piston-cylinder assemblies of NPS and TS, respectively;
λ_1	coefficient of deformation of the NPS piston-cylinder assembly;
t_{10}, t_{20}	temperatures of piston-cylinder assemblies of NPS and TS at the preliminary equilibration;
t_{1i}, t_{2i}	temperatures of piston-cylinder assemblies of NPS and TS at i^{th} equilibration.

The participants calculated values of p and ρ_a, measured t, and applied the local value of g. The pilot laboratory provided all other parameters.

For each measurement point the participants reported the ambient conditions (air temperature and pressure), temperatures of LS and TS, generated pressure and A_p.

For each nominal pressure they reported summary results including the sensitivity of the cross float, uncertainties of t and p, average A_p, its standard deviation and combined standard uncertainty. For pressures 10 MPa and 100 MPa, a list of the main uncertainty sources and their contributions to A_p were presented.

Additionally, each participant included the zero-pressure effective area of the TS (A_0) and its pressure distortion coefficient (λ) which satisfy equation

$$A_p = A_0 \cdot (1 + \lambda \cdot p) \quad (2)$$

and are based on the results of all 100 measurements. The combined standard uncertainties of A_0 and λ as well as a description of how they were calculated were included.

7. RESULTS

7.1. Transfer standard stability

The stability of the transfer standard during the comparison time was checked by PTB, which measured first after the TS repair and repeated measurements at the end of the comparison. The change of the TS due to its repair can be estimated from the VMC/VMT measurements at the beginning and the end of the comparison. Results of all these measurement are shown in Table 1.

The PTB results of 2005 and 2008 are in a good agreement within their standard uncertainties – the zero pressure effective areas differ relatively by only $2.8 \cdot 10^{-6}$ and the pressure distortion coefficients by only $0.01 \cdot 10^{-6}$ MPa^{-1}:

<u>2005</u> $\boldsymbol{A_0 = 9.817527 \times (1 \pm 1.1 \cdot 10^{-5})}$ **mm²** **and** $\boldsymbol{\lambda = (1.16 \pm 0.11) \cdot 10^{-6}}$ **MPa^{-1}**.

<u>2008</u> $\boldsymbol{A_0 = 9.817555 \times (1 \pm 1.1 \cdot 10^{-5})}$ **mm²** **and** $\boldsymbol{\lambda = (1.17 \pm 0.11) \cdot 10^{-6}}$ **MPa^{-1}**.

From these results it can be concluded that TS remained stable in the time from 2005 to 2008.

The VMC/VMT measurements before and after the TS repair resulted in:

<u>2005 (before repair)</u> $\boldsymbol{A_0 = 9.817519 \times (1 \pm 2.7 \cdot 10^{-5})}$ **mm²** **and** $\boldsymbol{\lambda = (1.22 \pm 0.11) \cdot 10^{-6}}$ **MPa^{-1}**.

<u>2008 (after repair)</u> $\boldsymbol{A_0 = 9.817558 \times (1 \pm 2.3 \cdot 10^{-5})}$ **mm²** **and** $\boldsymbol{\lambda = (1.34 \pm 0.13) \cdot 10^{-6}}$ **MPa^{-1}**.

The A_0 and λ values differ by only $3.9 \cdot 10^{-6}$ and $0.12 \cdot 10^{-6}$ MPa^{-1} and demonstrate that the TS has not significantly changed due to its repair.

7.2. Results of the participants

The participants' pressure-dependent effective areas averaged for each nominal pressure (Ap), their standard deviations and combined standard uncertainties are given in Table 1. For PTB, the results obtained in 2005 were used as a PTB contribution because the control measurements in 2008 were performed in a lower extent than the Technical protocol prescribed. For VMC/VMT, the results obtained in 2008 had to be taken for the comparison purpose because the measurements in 2005 were done on the TS before its brake and repair.

VNIIM, in their first report, instead of A_p values presented the effective area A_0 values which were calculated using a value of pressure distortion coefficient for TS based on supposed elastic constants of the transfer standard's piston and cylinder (in the Technical Protocol, the values of the elastic constants were not given). After circulating the Draft A report, VNIIM corrected their results to effective area A_p values calculated using the formula (1a). VNIIM 1-st and VNIIM corrected result both are presented in Figure 1. For further evaluation of comparison results, the VNIIM corrected results are used.

The results for the effective area A_p of the transfer standard obtained by the laboratories are shown graphically in Figure 1. All standard deviations in Table 1 are the experimental standard deviations characterizing the distribution of the observed values (not the standard deviations of means!), which were calculated by the following formulae.

Standard deviation of the pressure-dependent effective area:

$$s\left(A_{p_i}\right)=\left[\frac{n\sum_j A_{p_i,j}^2-\left(\sum_j A_{p_i,j}\right)^2}{n(n-1)}\right]^{0.5}, \tag{3}$$

Zero-pressure effective area and distortion coefficient:

$$A_0=\frac{1}{mn}\left[\sum_{i,j}A_{p_i,j}-bn\sum_i p_i\right], \qquad \lambda=\frac{b}{A_0}, \tag{4}$$

and their standard deviations:

$$s\left(A_0\right)=\left[\frac{m\sum_i p_i^2}{mn-2}\times\frac{\sum_{i,j}\left(A_{p_i,j}-A_0-bp_i\right)^2}{m\sum_i p_i^2-\left(\sum_i p_i\right)^2}\right]^{0.5}, \quad s(\lambda)=\frac{1}{A_0}\left[\frac{m^2}{mn-2}\times\frac{\sum_{i,j}\left(A_{p_i,j}-A_0-bp_i\right)^2}{m\sum_i p_i^2-\left(\sum_i p_i\right)^2}\right]^{0.5}, \tag{5}$$

where b is slope of dependence $A_p(p)$:

$$b=\frac{\sum_i p_i\sum_{i,j}A_{p_i,j}-m\sum_{i,j}p_iA_{p_i,j}}{n\left(\sum_i p_i\right)^2-mn\sum_i p_i^2}, \tag{6}$$

and $A_{p_i,j}$ are A_p-values at $p = p_i$; n is number of points at p_i, n = 10; m is number of different pressures, m = 10; i = 1,…,m; j = 1,…,n.

Zero-pressure effective area (A_0) of TS, with relative standard type A and B uncertainties (u_A) and (u_B), respectively, as determined in the participating laboratories are presented in Table 3.

Pressure distortion coefficient of TS (λ) and it's standard uncertainty $u(\lambda)$ was determined by participating laboratory with results:

VMC-2005	$\lambda = (1.22 \pm 0.11)\cdot 10^{-6}$ MPa^{-1}.
PTB	$\lambda = (1.16 \pm 0.11)\cdot 10^{-6}$ MPa^{-1}.
NPL	$\lambda = (1.4 \pm 0.2)\cdot 10^{-6}$ MPa^{-1}.
SMU	$\lambda = (1.4 \pm 0.1)\ 10^{-6}$ MPa^{-1}.
VNIIM	$\lambda = (0.81 \pm 0.2)\cdot 10^{-6}$ MPa^{-1}.
BelGIM	$\lambda = (0.88 \pm 0.05)\cdot 10^{-6}$ MPa^{-1}
INM	$\lambda = (0.89 \pm 0.22)\cdot 10^{-6}$ MPa^{-1}
VMC-2008	$\lambda = (1.34 \pm 0.13)\cdot 10^{-6}$ MPa^{-1}.

Table 1. Effective areas (A_p), their relative standard deviations ($s(A_p)/A_p$) and combined relative standard uncertainties ($u(A_p)/A_p$)

p / MPa	VMC			PTB			NPL			SMU			VNIIM			BelGIM			INM			VMC			PTB-2008 *)		
	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$	A_p / mm^2	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$
10	9.817621	6.8	33	9.817653	1	11	9.817515	3.0	22	9.8177541	2.0	20.5	9.81752	7.5	23.6	9.81767	0.15	48.4	9.8180223	0.829	21.33	9.817697	5.4	17.9	9.817661	5.2	12
20	9.817749	6.7	32	9.817743	0.5	11	9.817639	1.4	23	9.8178693	1.2	20.6	9.81763	3.2	21.8	9.81775	0.15	48.4	9.8180533	1.158	21.63	9.817755	1.3	17.5	9.817777	3.1	11
30	9.817874	4.2	31	9.81786	0.5	11	9.817781	1.9	23	9.8179713	1.2	20.8	9.81770	5.0	21.6	9.81784	0.26	52.9	9.8179466	0.953	22.08	9.817872	1.9	17.4	9.817903	2.5	11
40	9.818021	2.8	31	9.817981	0.6	11	9.817926	2.0	23	9.8180643	2.1	21.3	9.81790	6.5	21.1	9.81793	0.49	67.2	9.8180831	0.656	22.69	9.818164	3.5	29	9.81802	2.0	11
50	9.818129	4.7	31	9.818099	0.4	11	9.818069	1.5	23	9.8181641	2.4	21.7	9.81807	4.6	19.8	9.81801	0.26	52.9	9.8181924	0.409	23.46	9.818288	2.5	28.9	9.818138	1.1	11
60	9.818242	4.4	31	9.818214	0.7	12	9.818215	1.3	23	9.8182875	3.1	22.4	9.81821	4.2	18.8	9.8181	0.24	51.9	9.8183496	0.331	24.39	9.818385	3.9	28.8	9.818252	1.1	12
70	9.818354	4.4	30	9.81833	0.9	12	9.818351	1.8	23	9.8183773	2.5	22.9				9.81817	0.32	56.1	9.8184658	0.554	25.43	9.818478	3.3	28.7	9.818364	0.4	12
80	9.818469	4.0	30	9.818439	0.7	13	9.818489	2.2	24	9.8184988	3.2	23.6				9.81827	0.47	65.8	9.8185889	0.446	26.58	9.818600	3.3	28.7	9.818474	1.4	13
90	9.818588	4.0	30	9.818551	0.7	14	9.81863	2.0	24	9.8186134	2.7	24.2				9.81836	0.54	70.9				9.818702	3.3	28.7	9.818613	0.6	14
100	9.81871	3.8	30	9.818664	1.0	14	9.818769	2.7	25	9.8187384	2.7	25.0				9.81844	0.56	72.5				9.818848	4.2	28.6	9.818699	0.4	14

*) Stability check measurement

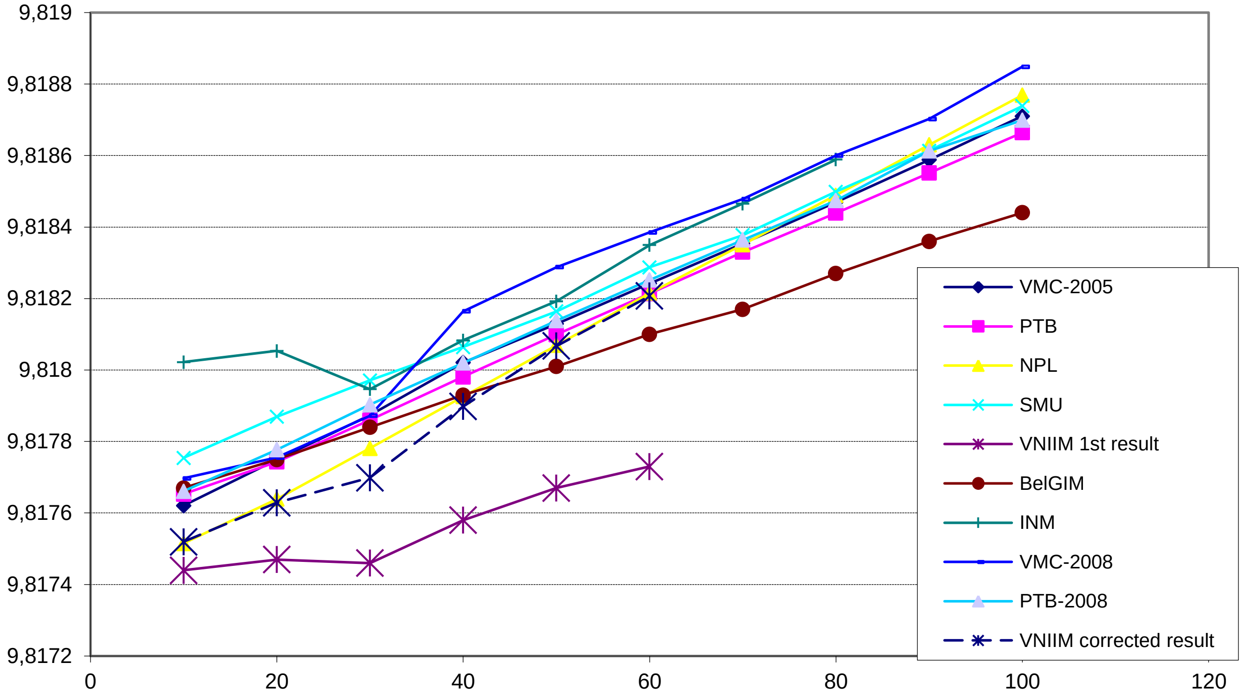


Figure 1. Effective areas (A_p) of the transfer standard obtained by measurements at VMC, PTB, NPL, SMU, VNIIM, BelGIM and INM.

Table 2. Zero-pressure effective areas of the transfer standard (A_0), with relative standard type A and B uncertainties $u_A(A_0)/A_0$ and $u_B(A_0)/A_0$, respectively, as determined by the participants.

NMI	A_0 [mm^2]	$u_A(A_0)/A_0 \times 10^6$	$u_B(A_0)/A_0 \times 10^6$
VMC/VMT	9.817558	3.0	23
PTB	9.817527	2.1	11
NPL	9.81736	2.0	23
SMU	9.817478	2.3	22
VNIIM	9.817558	5.2	20
BelGIM	9.817582	0.34	59
INM	9.817811	0.67	23

7.3. Reference value calculation

The results of comparisons may be regarded as independent for Germany, United Kingdom, Slovakia and Russia, which have primary pressure standards in the range from 10 MPa to 100 MPa. For the calculation of the effective area of TS the results of four laboratories were used: PTB, NPL, SMU and VNIIM.

The measurement results held in VMC laboratory in the year 2008 were used for final calculations, while the results from the year 2005 were not taken into account.
The weighted reference value was calculated at each pressure as:

$$A_{p,\mathrm{ref}} = \sum_{i=1}^{n} \frac{A_{p,i}}{u^2(A_{p,i})} \bigg/ \sum_{i=1}^{n} \frac{1}{u^2(A_{p,i})} \tag{7}$$

For the weighted means the standard uncertainties were calculated according to:

$$u(A_{p,\mathrm{ref}}) = \sum_{i=1}^{n} \frac{1}{u(A_{p,i})} \bigg/ \sum_{i=1}^{n} \frac{1}{u^2(A_{p,i})} \tag{8}$$

where:

n	the number of participant results', used for calculation (n = 4)
$A_{\mathrm{p,i}}$	the reference values of their results
$A_{\mathrm{p,ref}}$	the weighted reference value
$u(A_{\mathrm{p,i}})$	the standard uncertainties of participants

Table 3: Reference value and associated relative uncertainty (k = 1) calculated from PTB, NPL, SMU and VNIIM results and their uncertainties at each nominal pressure

p [MPa]	$A_{p,\mathrm{ref}}$ [mm^2]	$u(A_{p,\mathrm{ref}})/A_{p,\mathrm{ref}}$ x10^6
10	9.817633	8.3
20	9.817734	8.3
30	9.817844	8.3
40	9.817974	8.3
50	9.818100	8.2
60	9.818224	8.6
70	9.818342	9.6
80	9.818460	10.3
90	9.818580	10.8
100	9.818699	11.0

7.4. Degree of equivalence

The relative deviations of the participants' results from the reference values with the expanded (k=2) relative uncertainties of these deviations were calculated by:

$$d_{i,\mathrm{ref}} = \left(A_{p,i} - A_{p,\mathrm{ref}}\right) / A_{p,\mathrm{ref}} \ . \tag{9}$$

$$U\left(\Delta A_{p,i} / A_{p,\mathrm{ref}}\right) = 2 \cdot \left[u^2\left(A_{p,i}\right) - u^2\left(A_{p,\mathrm{ref}}\right)\right]^{1/2} / A_{p,\mathrm{ref}} \tag{10}$$

Numerical data for the deviations and the uncertainties at all pressures are given in Table 4.

The degrees of equivalence between the laboratories are presented in Tables 5 to 14 by the relative differences between the participants results ($d_{i,j}$) and their expanded uncertainties ($U(d_{i,j})$) which were calculated as:

$$d_{ij} = \left(A_{p,i} - A_{p,j}\right) / A_{p,\mathrm{ref,med}} \ , \tag{11}$$

$$U\left(d_{ij}\right) = 2 \cdot \left[u^2\left(A_{p,i}\right) + u^2\left(A_{p,j}\right)\right]^{1/2} / A_{p,\mathrm{ref,med}} \ . \tag{12}$$

The results of the present comparison can be linked to the results of the key comparison CCM.P-K7, performed in the gauge mode up to 100 MPa, using the results of PTB and NPL participated in both comparisons. The values for the link at each pressure is obtained using the weighted mean deviations of the PTB and NPL results in COOMET.M.P-K2 and CCM.P-K7 from the reference values of these comparisons and are presented in Table 15.

$$D_{\mathrm{PTB\_NPL,COOMET}} = (D_{\mathrm{PTB,COOMET}}/u^2_{\mathrm{PTB,COOMET}} + D_{\mathrm{NPL,COOMET}}/u^2_{\mathrm{NPL,COOMET}}) / (1/u^2_{\mathrm{PTB,COOMET}} + 1/u^2_{\mathrm{NPL,COOMET}}) \tag{13}$$

$$D_{\mathrm{PTB\_NPL,CCM}} = (D_{\mathrm{PTB,CCM}}/u^2_{\mathrm{PTB,CCM}} + D_{\mathrm{NPL,CCM}}/u^2_{\mathrm{NPL,CCM}}) / (1/u^2_{\mathrm{PTB,CCM}} + 1/u^2_{\mathrm{NPL,CCM}}) \tag{14}$$

The relative difference between the COOMET and the CCM KCRVs ($D_{\mathrm{COOMET,CCM}}$) is taken as

$$D_{\mathrm{COOMET,CCM}} = D_{\mathrm{PTB\_NPL,CCM}} - D_{\mathrm{PTB\_NPL,COOMET}} \ . \tag{15}$$

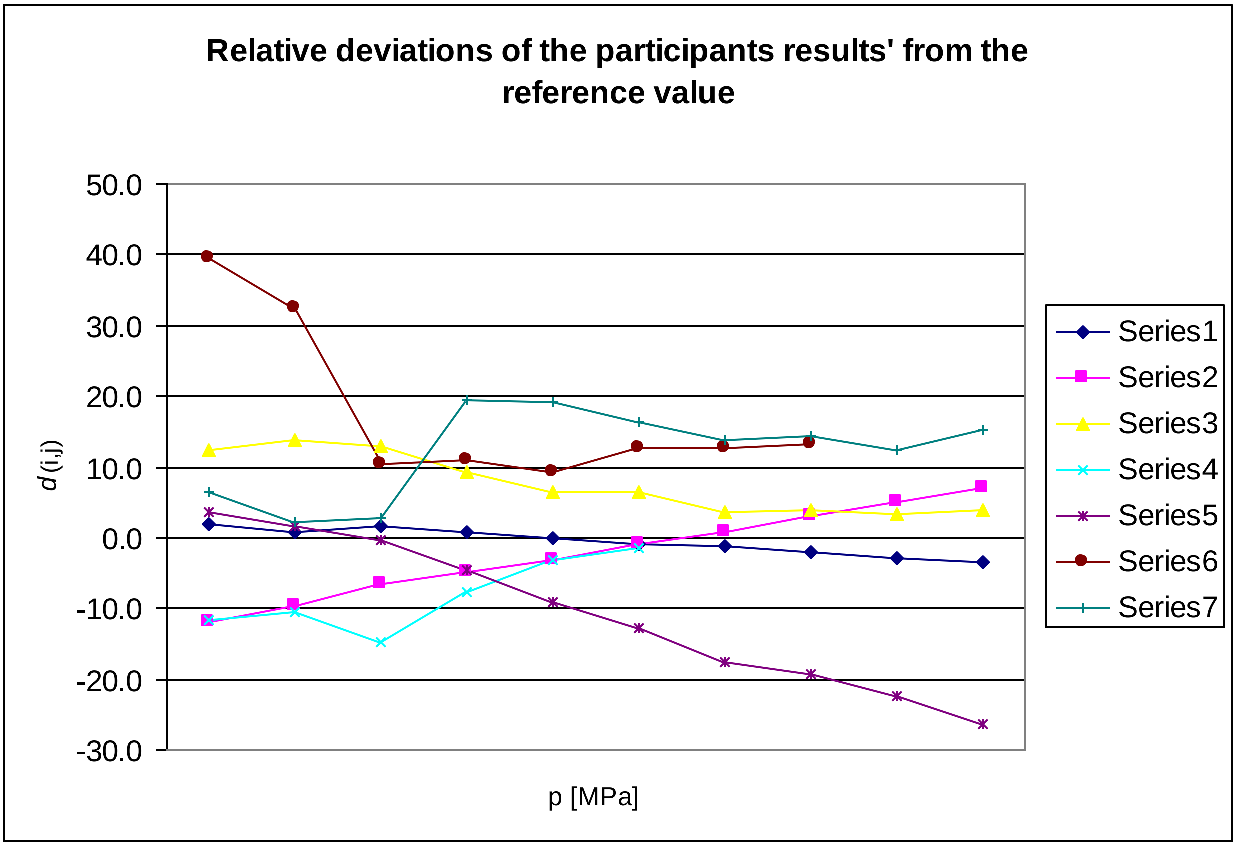


Figure 2. Relative deviations of the participants' results from the reference value

Explication:

1	2	3	4	5	6	7
PTB	**NPL**	**SMU**	**VNIIM**	**BelGIM**	**INM**	**VMC**

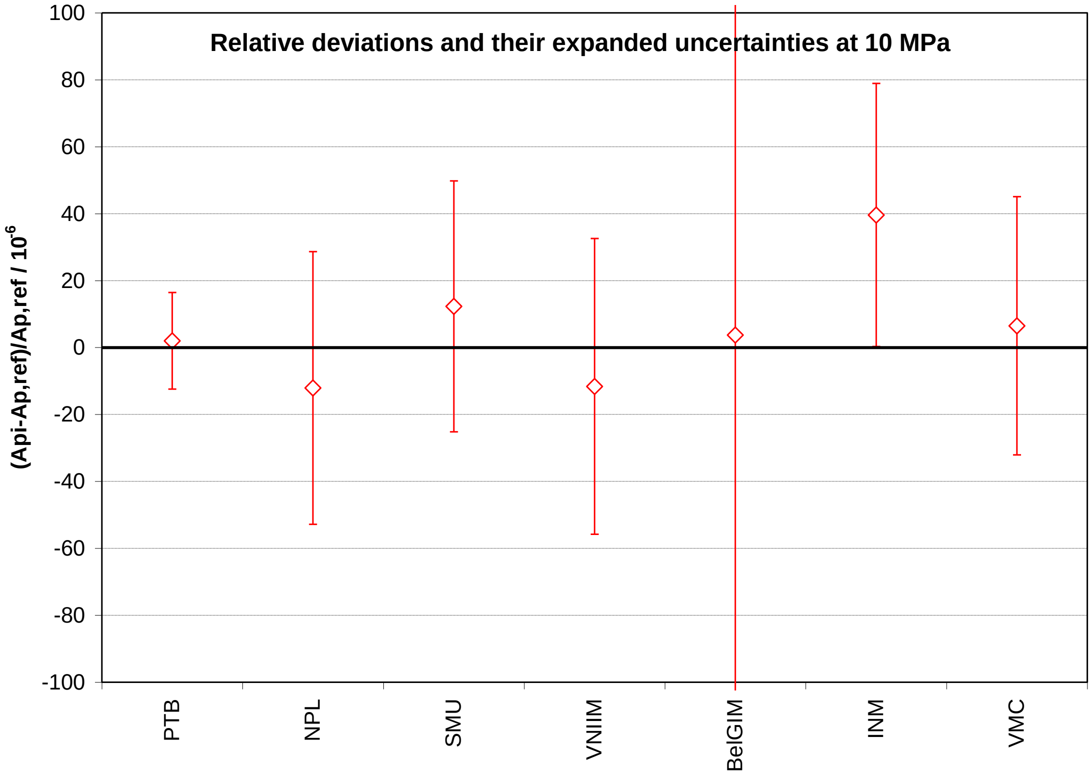


Figure 3 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 10 MPa**

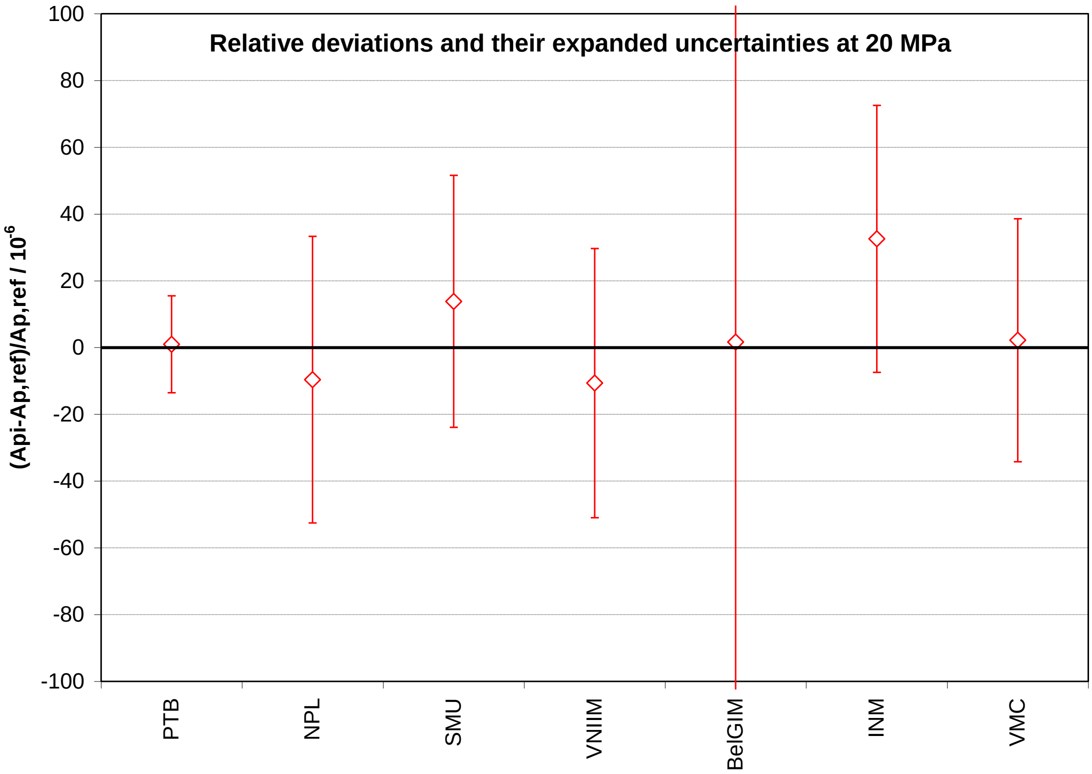


Figure 4 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 20 MPa**

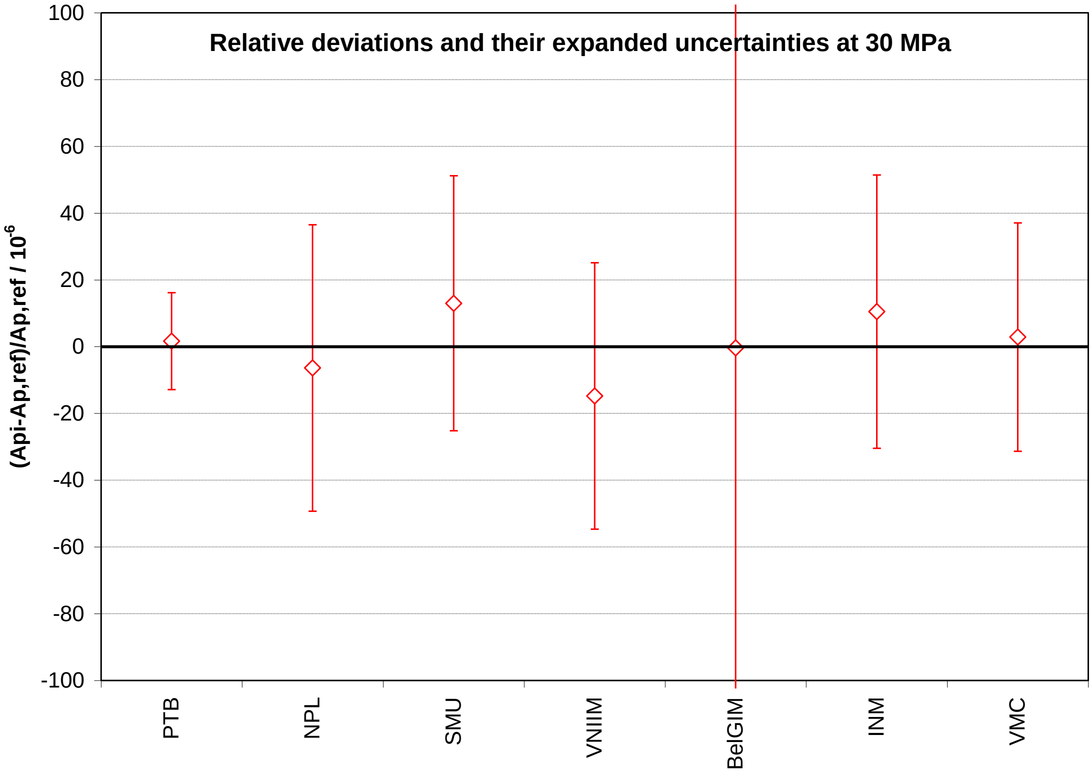


Figure 5 **Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 30 MPa**

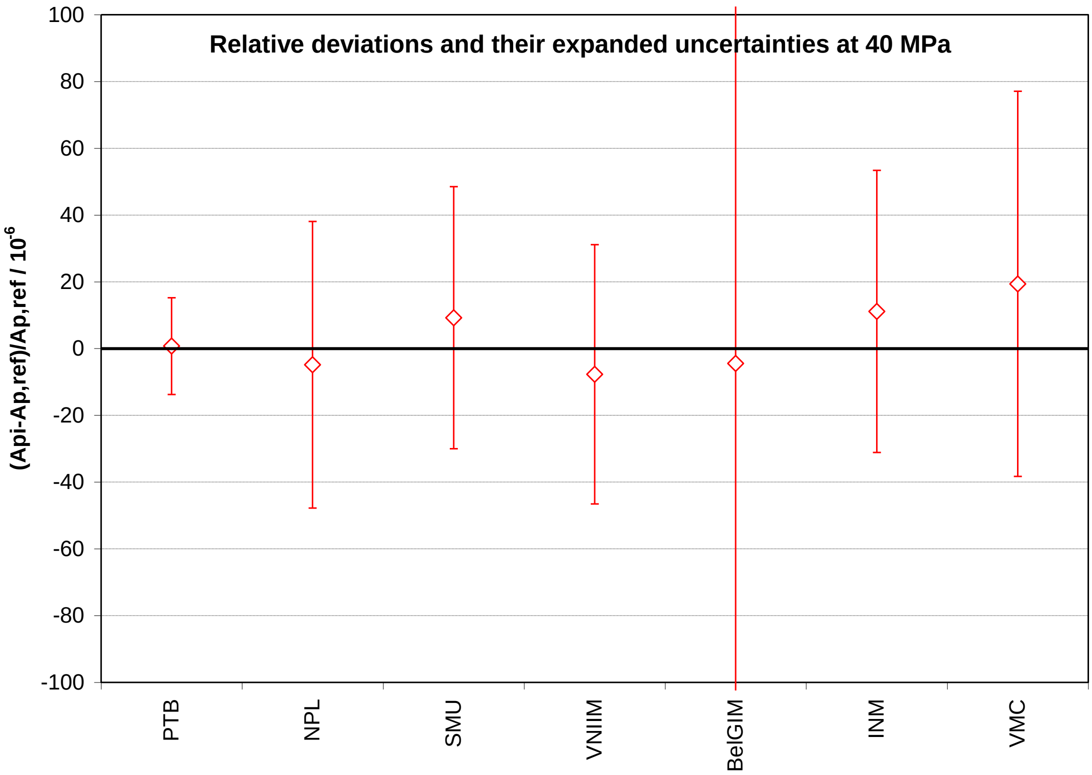


Figure 6 **Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 40 MPa**

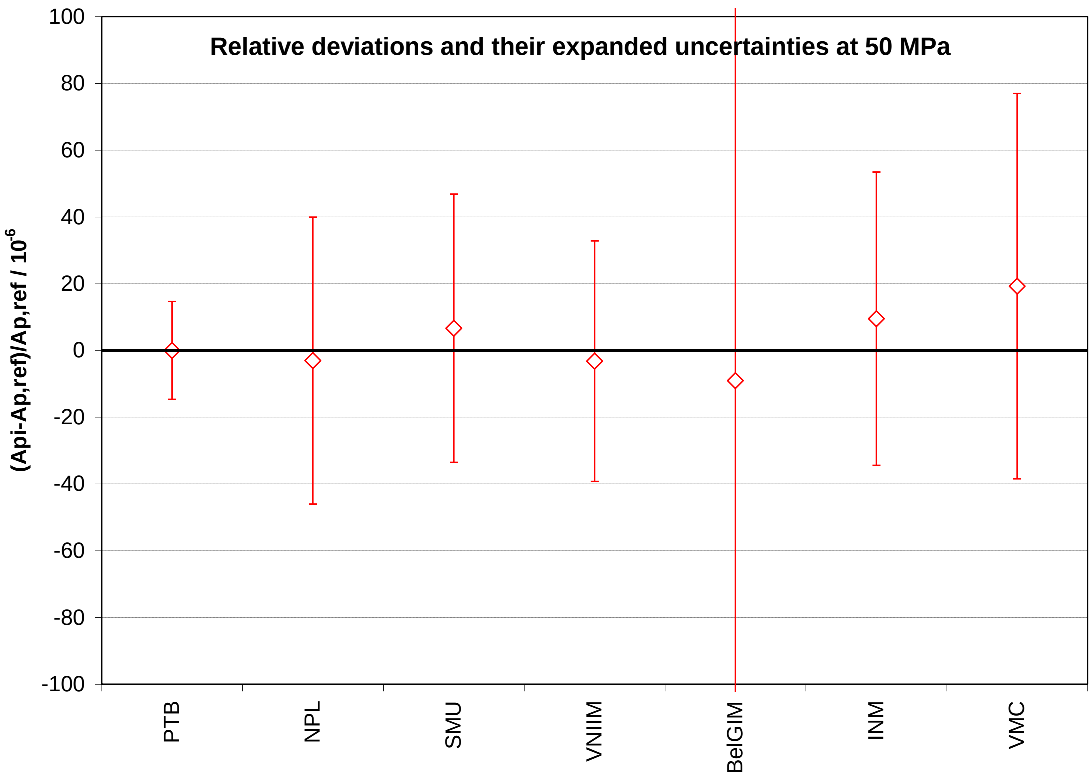


Figure 7 **Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 50 MPa**

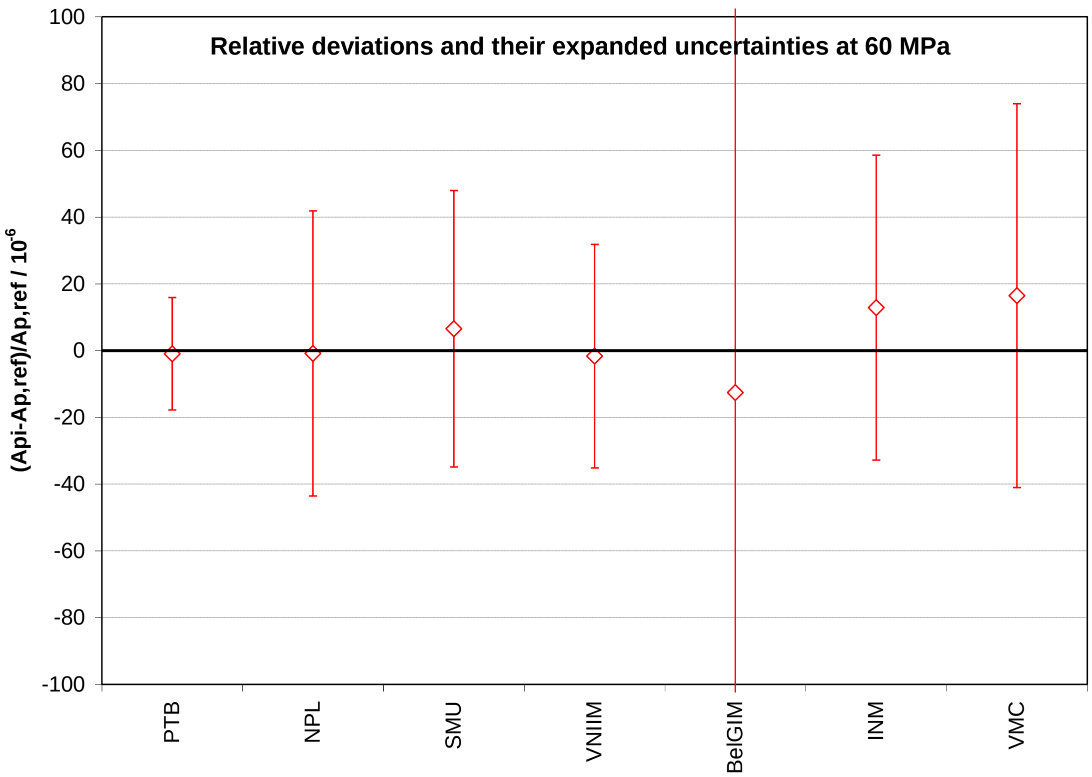


Figure 8 **Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 60 MPa**

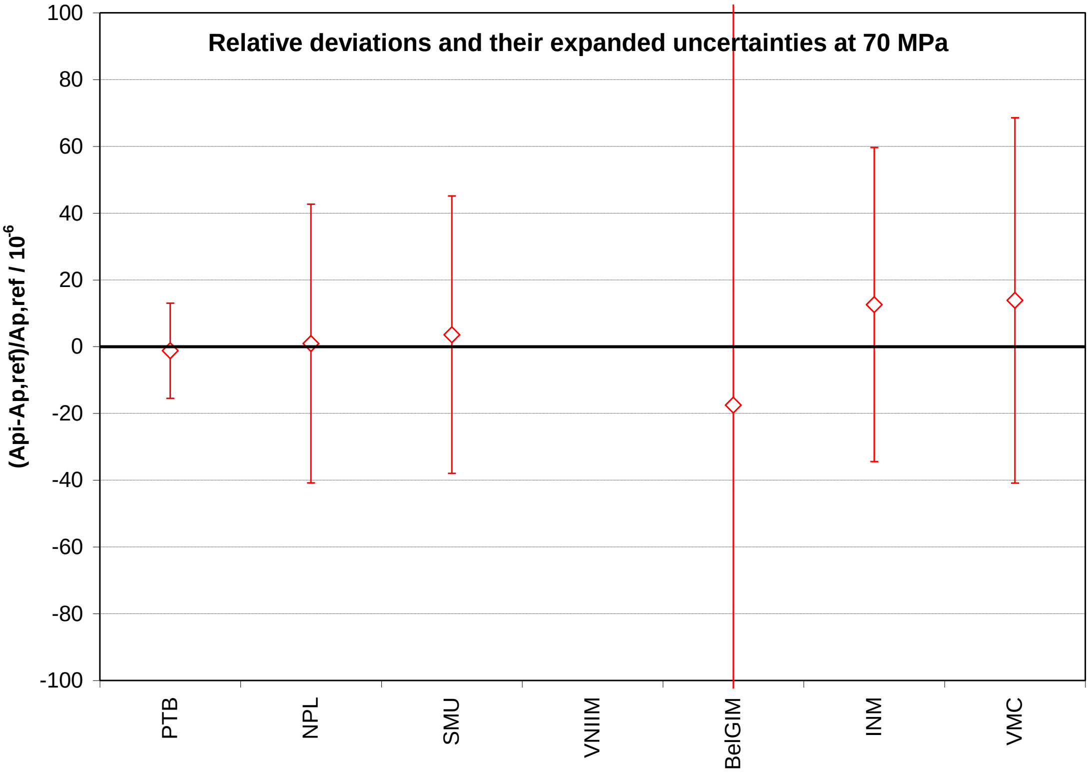


Figure 9 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 70 MPa**

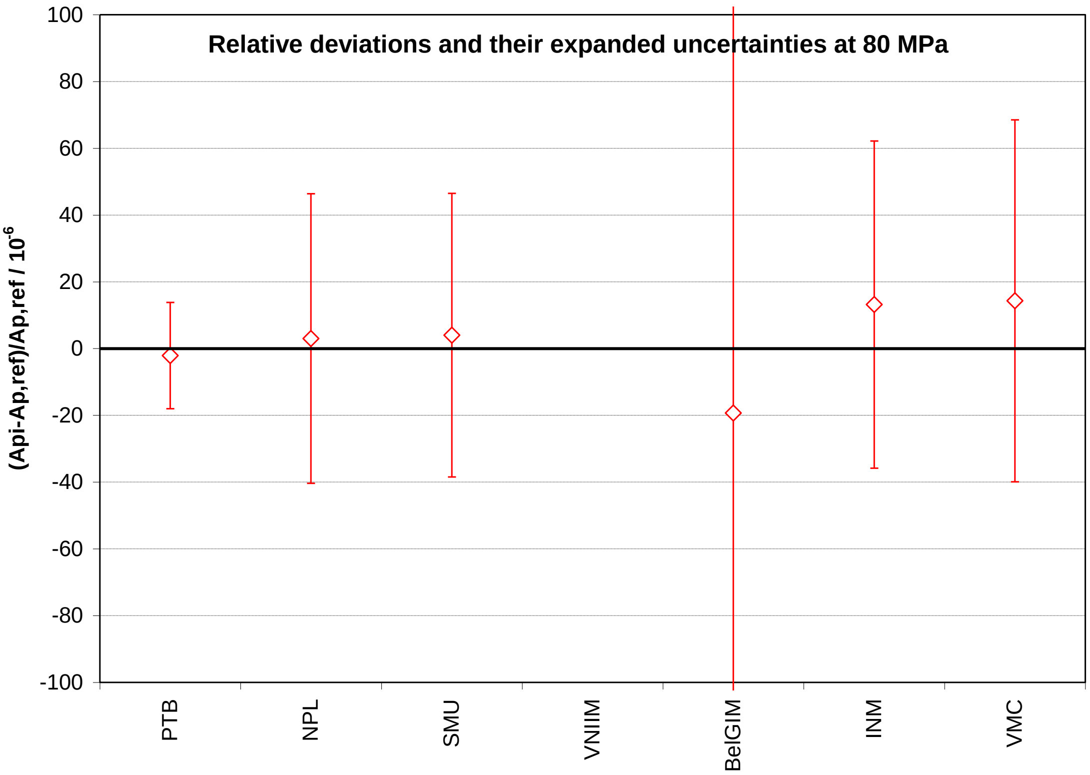


Figure 10 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 80 MPa**

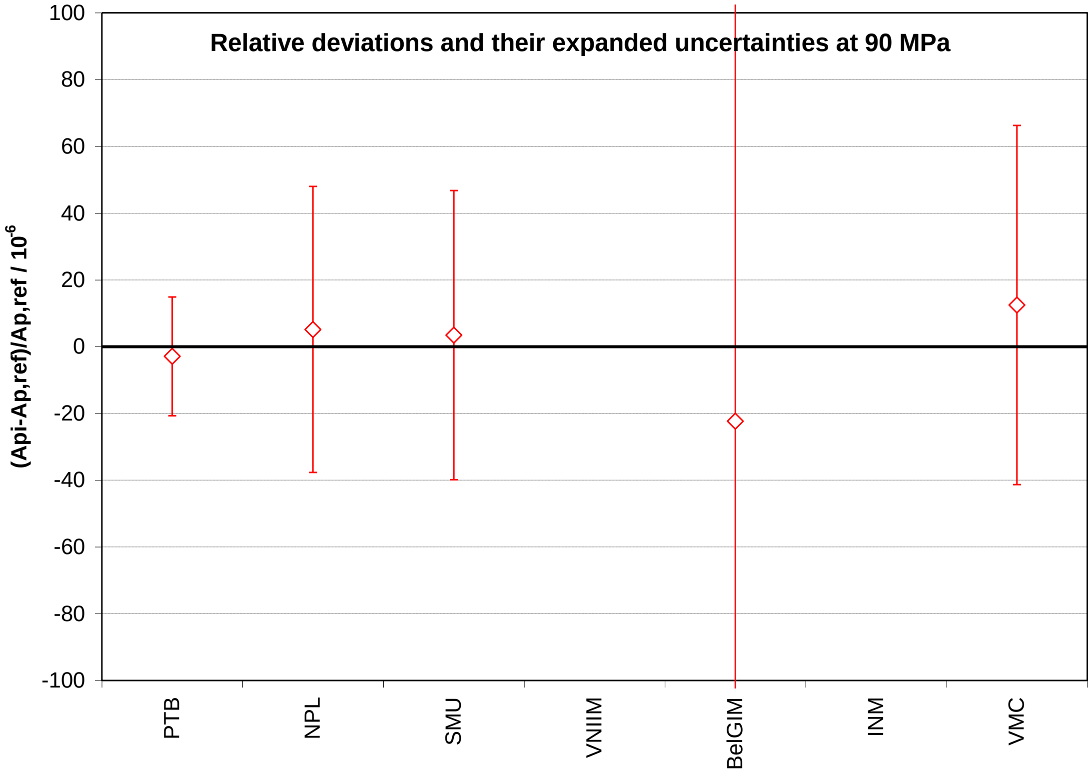


Figure 11 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 90 MPa**

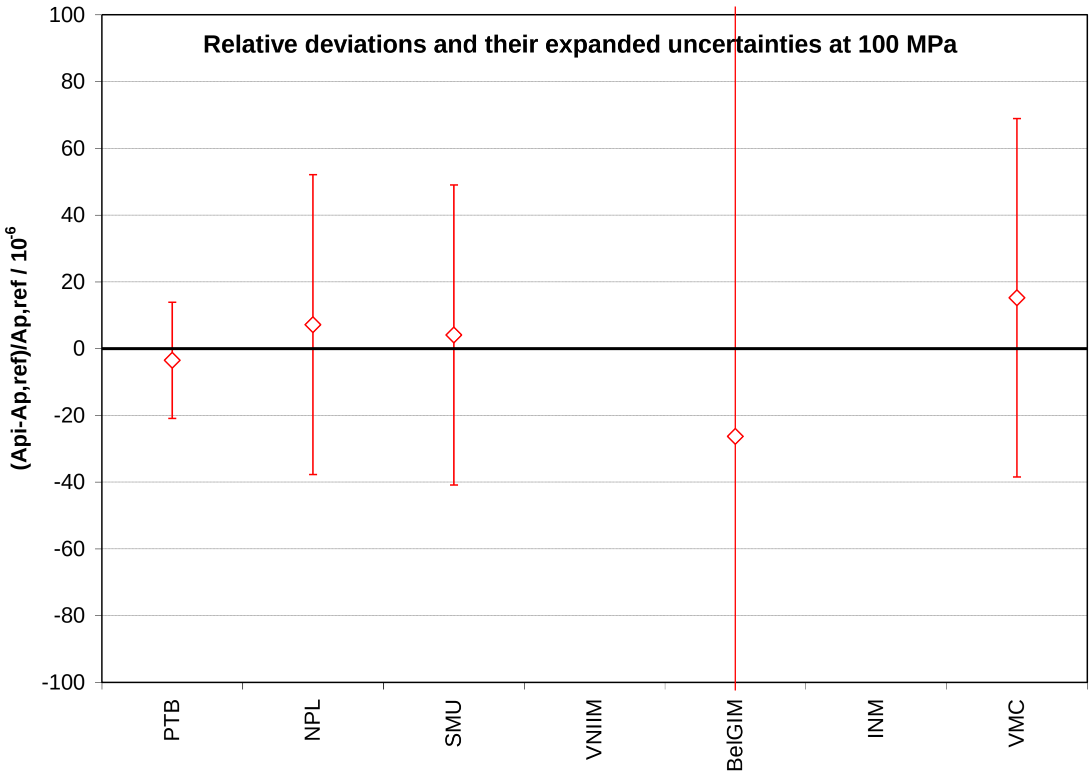


Figure 12 **Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 100 MPa**

Table 4. Relative deviations of the participants' results from the references values (dA_p/A_p) and their standard uncertainties ($U(dA_p/A_p)$)

p in MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}	*d*Ap/Apx 10^{-6}	*U*(*d*Ap/Ap) x10^{-6}
10	2	14	-12	41	12	37	-12	44	4	306	40	39	6	39
20	1	15	-10	43	14	38	-11	40	2	356	33	40	2	36
30	2	14	-6	43	13	38	-15	40	0	408	10	41	3	34
40	1	14	-5	43	9	39	-8	39	-4	458	11	42	19	58
50	0	15	-3	43	7	40	-3	36	-9	510	9	44	19	58
60	-1	17	-1	43	6	41	-1	33	-13	560	13	46	16	58
70	-1	14	1	42	4	42			-18	610	13	47	14	55
80	-2	16	3	43	4	42			-19	662	13	49	14	54
90	-3	18	5	43	3	43			-22	712			12	54
100	-4	17	7	45	4	45			-26	764			15	54

Table 5. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=10 MPa

Lab *j* →

Lab *i* ↓

p' = 10 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			14	49	-10	47	14	52	-2	307	-38	48	-4	47
NPL	-14	49			-24	60	-1	65	-16	309	-52	61	-19	61
SMU	10	47	24	60			24	63	9	309	-27	59	6	59
VNIIM	-14	52	1	65	-24	63			-15	310	-51	64	-18	63
BelGIM	2	307	16	309	-9	309	15	310			-36	309	-3	309
INM	38	48	52	61	27	59	51	64	36	309			26	60
VMC	4	47	19	61	-6	59	18	63	3	309	-26	60		

Table 6. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=20 MPa

Lab *j* →

Lab *i* ↓

p' = 20 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			11	51	-13	47	12	49	-1	357	-32	49	-1	46
NPL	-11	51			-23	62	1	63	-11	359	-42	63	-12	61
SMU	13	47	23	62			24	60	12	358	-19	60	12	57
VNIIM	-12	49	-1	63	-24	60			-12	359	-43	61	-13	59
BelGIM	1	357	11	359	-12	358	12	359			-29	359	2	358
INM	32	49	42	63	19	60	43	61	29	359			30	59
VMC	1	46	12	61	-12	57	13	59	-2	358	-30	59		

Table 7. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=30 MPa

Lab j ⟹

Lab i ⇓

p' = 30 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			8	51	-11	47	16	48	2	409	-9	49	-1	44
NPL	-8	51			-19	62	8	63	-6	411	-17	64	-9	60
SMU	11	47	19	62			28	60	13	410	3	61	10	56
VNIIM	-16	48	-8	63	-28	60			-14	410	-25	62	-18	58
BelGIM	-2	409	6	411	-13	410	14	410			-7	410	1	410
INM	9	49	17	64	-3	61	25	62	7	410			30	58
VMC	1	44	9	60	-10	56	18	58	-1	410	-30	58		

Table 8. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=40 MPa

Lab j ⟹

Lab i ⇓

p' = 40 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			6	51	-8	48	8	48	5	459	-10	50	-19	64
NPL	-6	51			-14	63	3	62	0	460	-16	65	-24	76
SMU	8	48	14	63			17	60	14	460	-2	62	-10	74
VNIIM	-8	48	-3	62	-17	60			-3	460	-19	62	-27	73
BelGIM	-5	459	0	460	-14	460	3	460			-7	460	-16	462
INM	10	50	16	65	2	62	19	62	7	460			13	75
VMC	19	64	24	76	10	74	27	73	16	462	-13	75		

Table 9. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=50 MPa

Lab *j* ⇒

Lab *i* ⇓

p' = 50 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			3	51	-7	49	3	45	9	510	-10	52	-19	64
NPL	-3	51			-10	63	0	61	6	512	-13	66	-22	76
SMU	7	49	10	63			10	59	16	512	-3	64	-13	74
VNIIM	-3	45	0	61	-10	59			6	512	-12	61	-22	72
BelGIM	-9	510	-6	512	-16	512	-6	512			-6	512	-15	514
INM	10	52	13	66	3	64	12	61	6	512			13	76
VMC	19	64	22	76	13	74	22	72	15	514	-13	76		

Table 10. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=60 MPa

Lab *j* ⇒

Lab *i* ⇓

p' = 60 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			0	52	-7	51	0	45	12	561	-14	54	-17	65
NPL	0	52			-7	64	1	59	12	562	-14	67	-17	76
SMU	7	51	7	64			8	58	19	562	-6	66	-10	75
VNIIM	0	45	-1	59	-8	58			11	561	-14	62	-18	71
BelGIM	-12	561	-12	562	-19	562	-11	561			-9	562	-13	563
INM	14	54	14	67	6	66	14	62	9	562			16	77
VMC	17	65	17	76	10	75	18	71	13	563	-16	77		

Table 11. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=70 MPa

Lab *j*

Lab *i*

p' = 70 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}
PTB			-2	52	-5	52			16	610	-14	56	-15	63
NPL	2	52			-3	65			18	612	-12	69	-13	74
SMU	5	52	3	65					21	612	-9	68	-10	74
VNIIM														
BelGIM	-16	610	-18	612	-21	612					-9	612	-10	613
INM	14	56	12	69	9	68			9	612			19	77
VMC	15	63	13	74	10	74			10	613	-19	77		

Table 12. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=80 MPa

Lab *j*

Lab *i*

p' = 80 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}	D_{ij}x10^{6}	U_{ij}x10^{6}
PTB			-5	55	-6	54			17	663	-15	59	-16	64
NPL	5	55			-1	67			22	664	-10	72	-11	75
SMU	6	54	1	67					23	664	-9	71	-10	75
VNIIM														
BelGIM	-17	663	-22	664	-23	664					-9	664	-11	665
INM	15	59	10	72	9	71			9	664			18	79
VMC	16	64	11	75	10	75			11	665	-18	79		

Table 13. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=90 MPa

Lab *j* ⇒

Lab *i* ⇓

p' = 90 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			-8	56	-6	56			19	713			-15	64
NPL	8	56			2	68			27	714			-7	75
SMU	6	56	-2	68					26	714			-9	76
VNIIM														
BelGIM	-19	713	-27	714	-26	714							-9	714
INM														
VMC	15	64	7	75	9	76			9	714				

Table 14. Relative differences between the participants' results ($d_{i,j}$) and their expanded uncertainties $U(d_{i,j})$ at p=100 MPa

Lab *j* ⇒

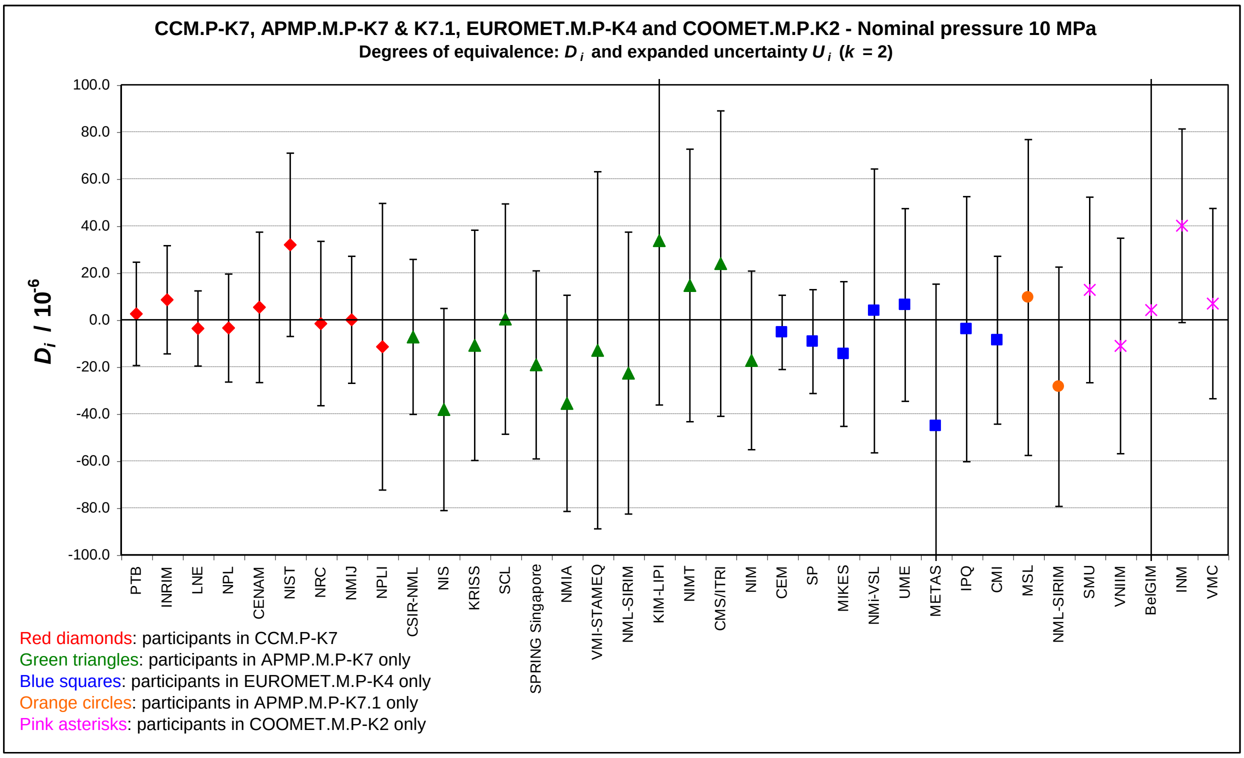
Lab *i* ⇓

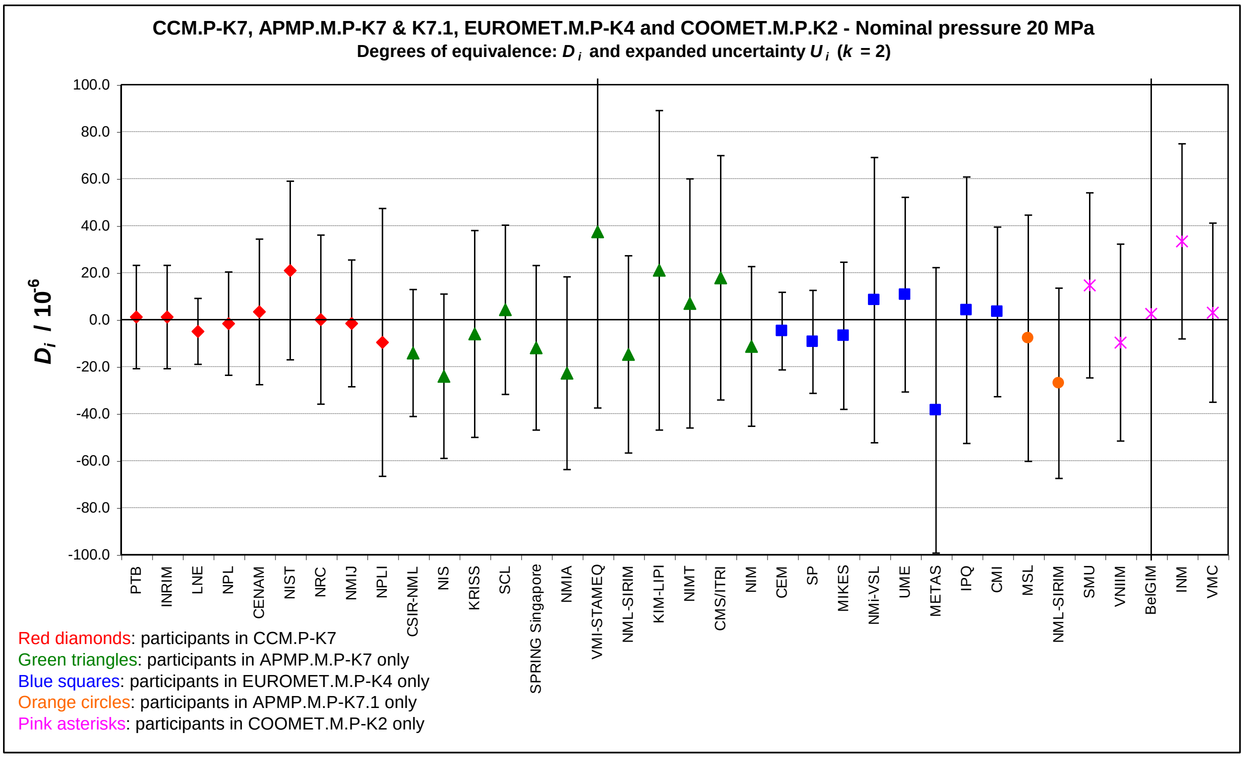
p' = 100 MPa	PTB		NPL		SMU		VNIIM		BelGIM		INM		VMC	
	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6	D_{ij}x10^6	U_{ij}x10^6
PTB			-11	57	-8	57			23	765			-19	64
NPL	11	57			3	71			34	766			-8	77
SMU	8	57	-3	71					30	766			-11	77
VNIIM														
BelGIM	-23	765	-34	766	-30	766							-11	766
INM														
VMC	19	64	8	77	11	77			11	766				

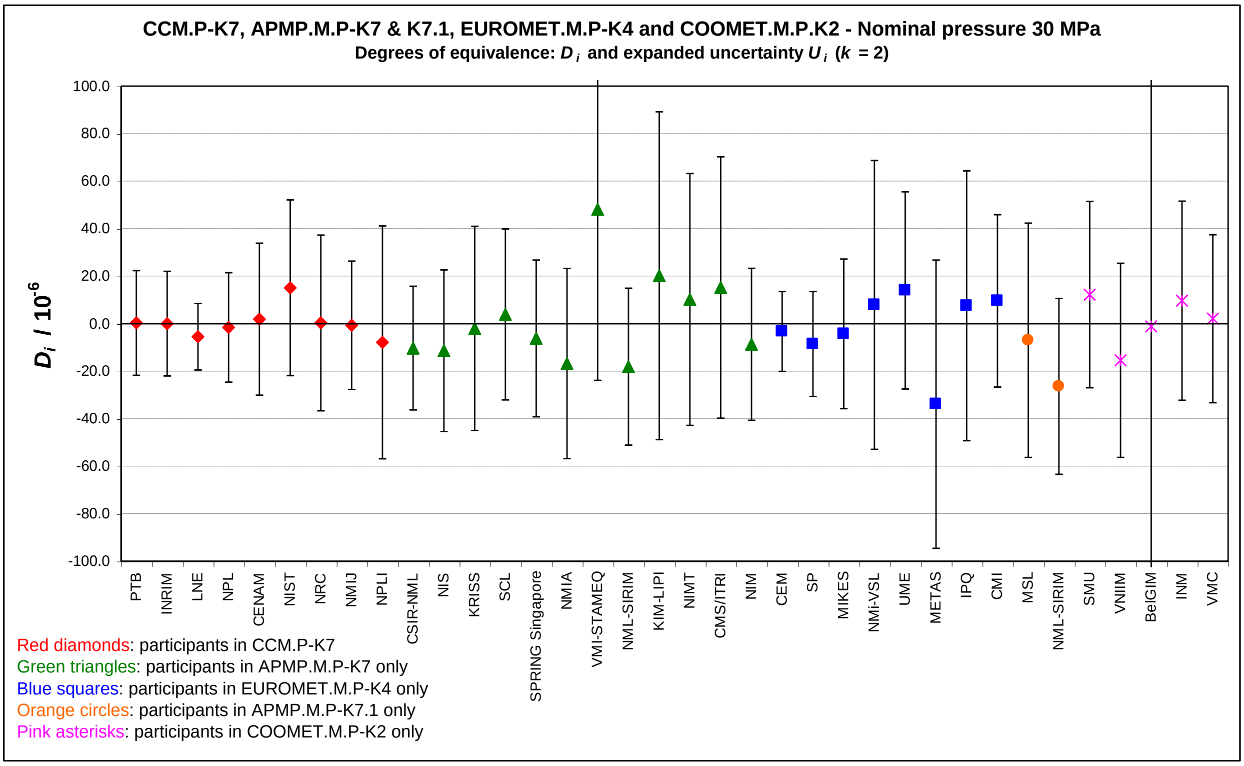
Table 15. Relation of the participants in COOMET.M.P-K2 to the KCRF of CCM.P-K7

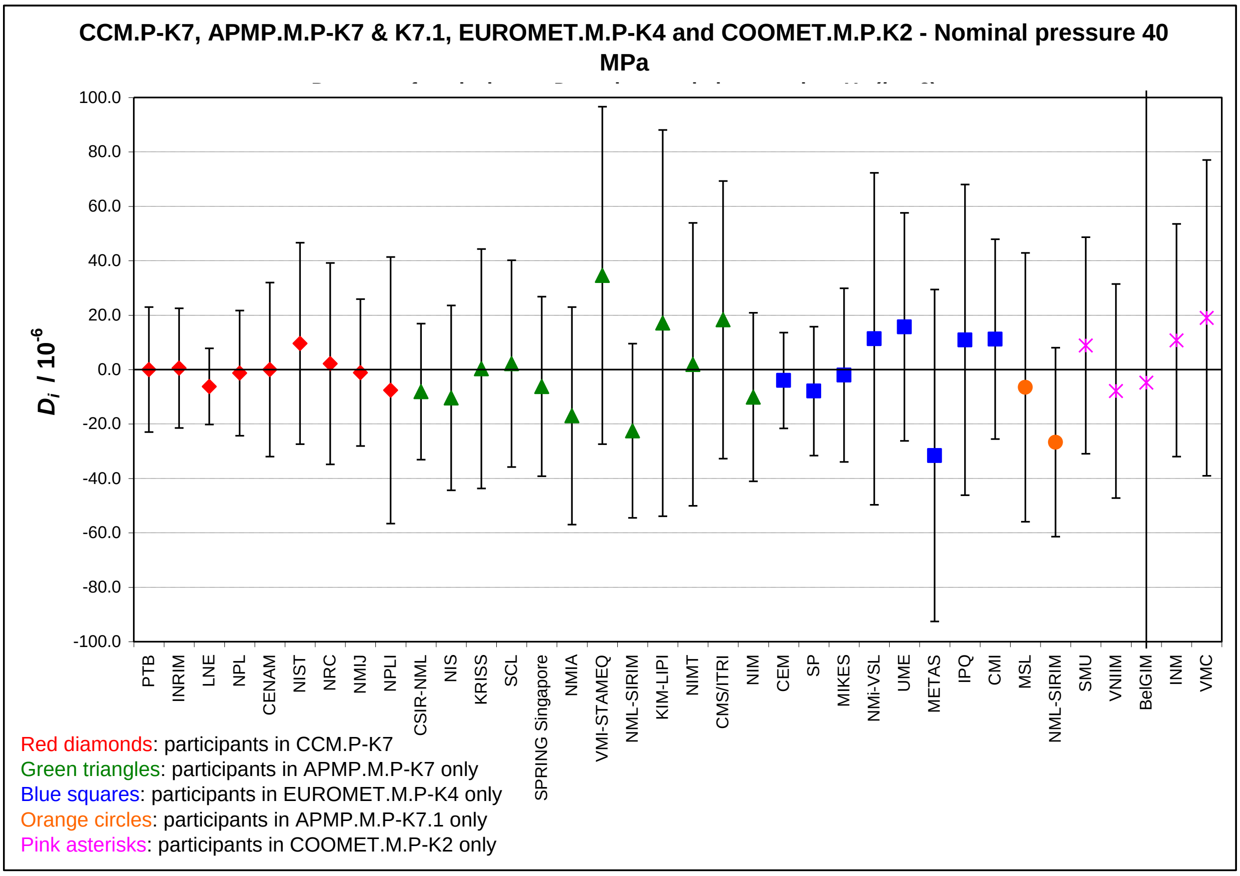
p' nom / MPa	10		20		30		40		50		60		70		80		90		100	
	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$	$D_i \cdot 10^6$	$U_i \cdot 10^6$
$D_{SMU,CCM}$	12.7	39	14.6	39	12.2	39	8.9	40	7.5	40	7.7	42	5.9	42	7.7	43	8.5	44	10.6	46
$D_{VNIIM,CCM}$	-11.1	46	-9.8	42	-15.4	41	-7.9	39	-2.1	36	-0.2	34								
$D_{BelGIM,CCM}$	4.1	306	2.4	356	-1.2	408	-4.8	458	-8.2	510	-11.4	560	-15.2	610	-15.6	662	-17.3	712	-19.8	764
$D_{INM,CCM}$	40.0	41	33.3	42	9.7	42	10.8	43	10.4	44	14.0	46	14.9	47	16.9	49				
$D_{VMC,CCM}$	6.9	41	3.0	38	2.1	35	19.0	58	20.1	58	17.6	58	16.2	55	18.1	55	17.5	54	21.7	54

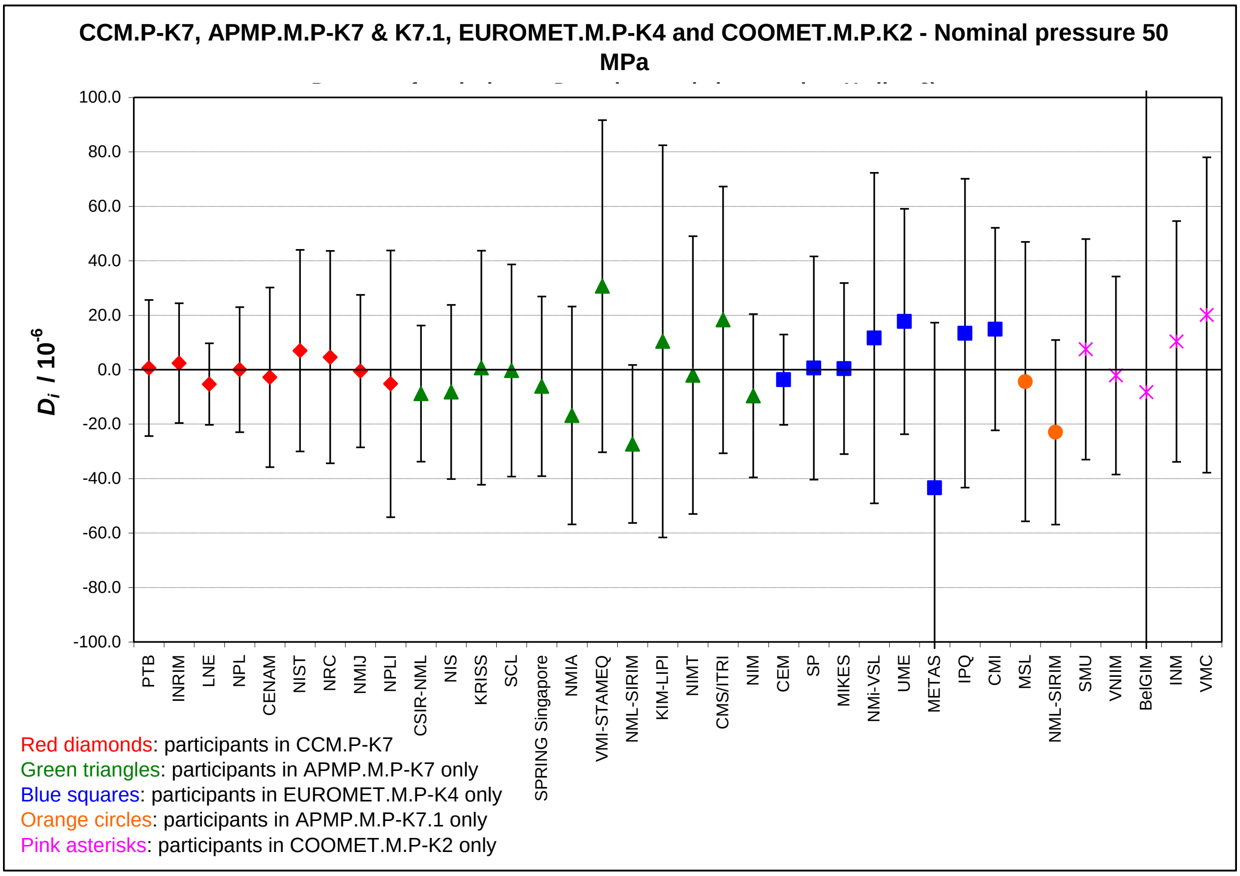
Figures 13 to 22. Degrees of equivalences and the expanded (k=2) uncertainties between the COOMET and the CCM KCRVs at pressure points from 10 MPa to 100 MPa






CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 30 MPa
Degrees of equivalence: D_i and expanded uncertainty U_i (k = 2)
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only


CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 40 MPa
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only


CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 50 MPa
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
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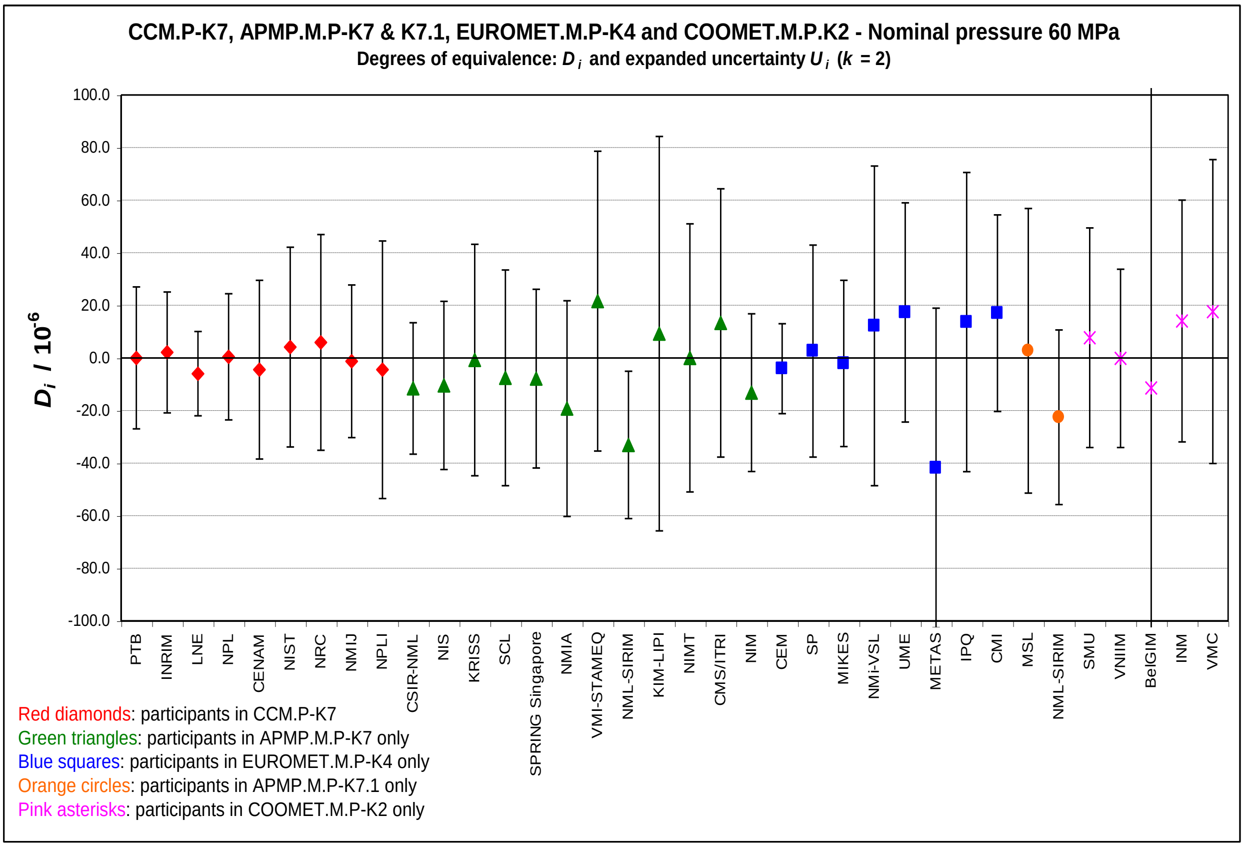
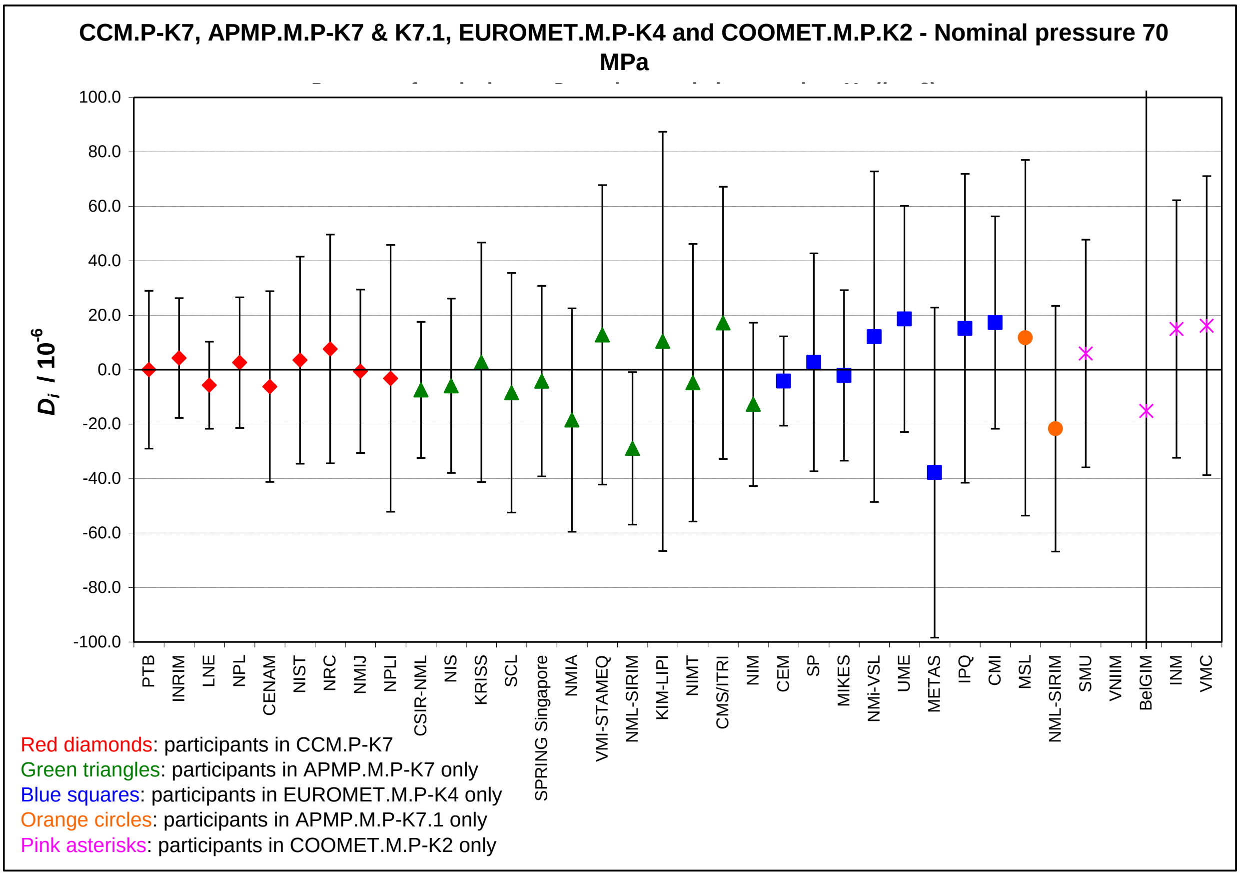
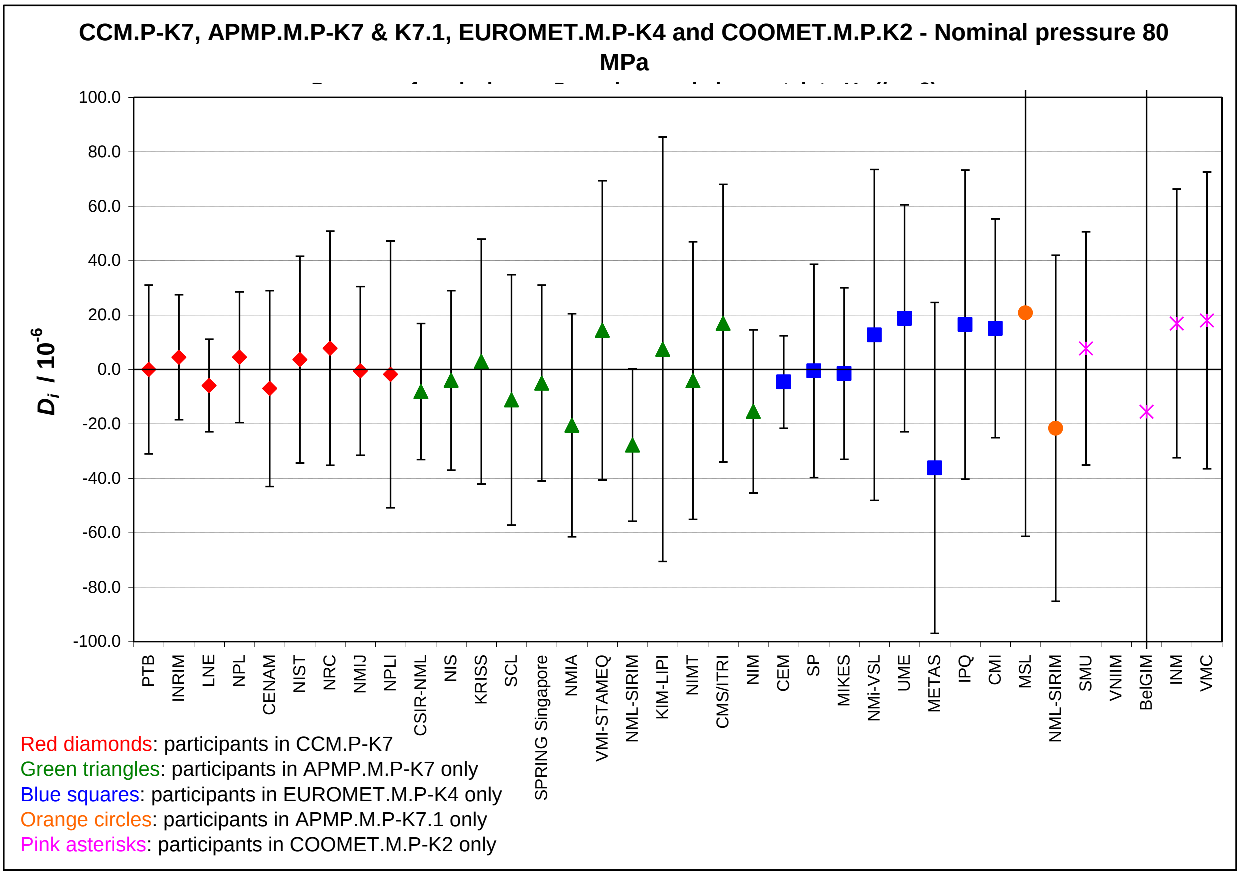
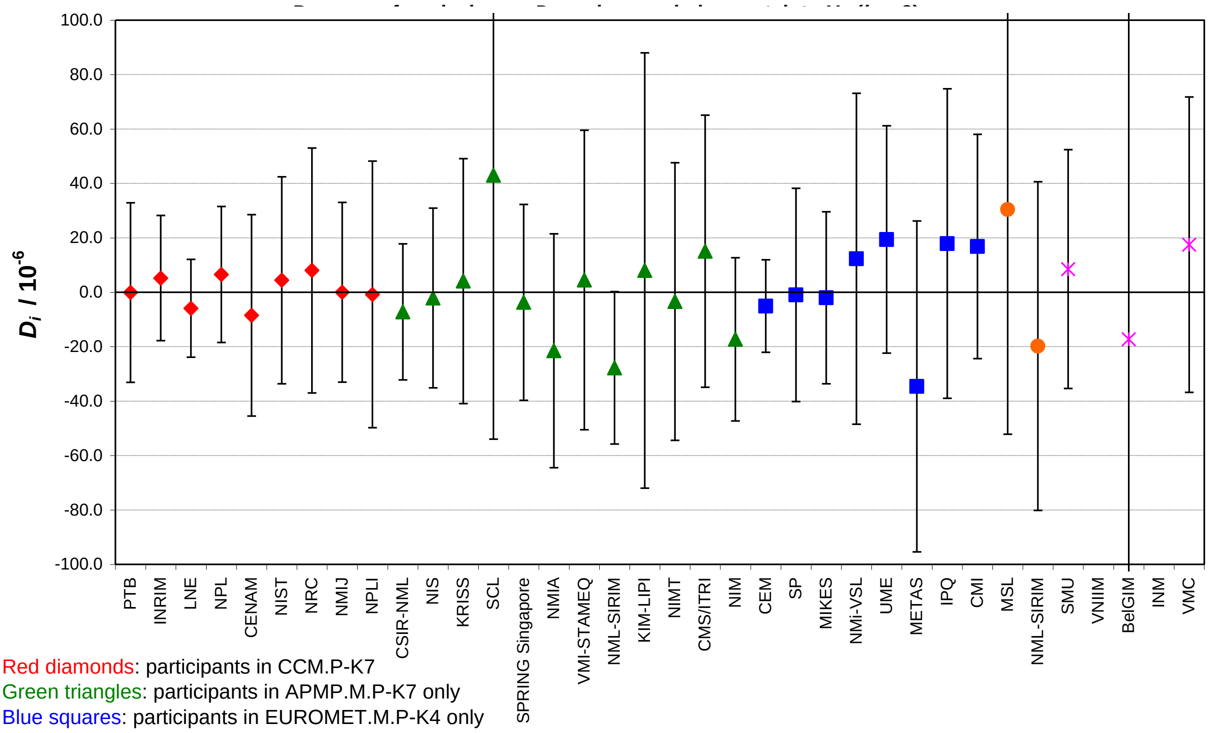
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only


CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 60 MPa
Degrees of equivalence: D_i and expanded uncertainty U_i (k = 2)
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only


CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 70 MPa
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only

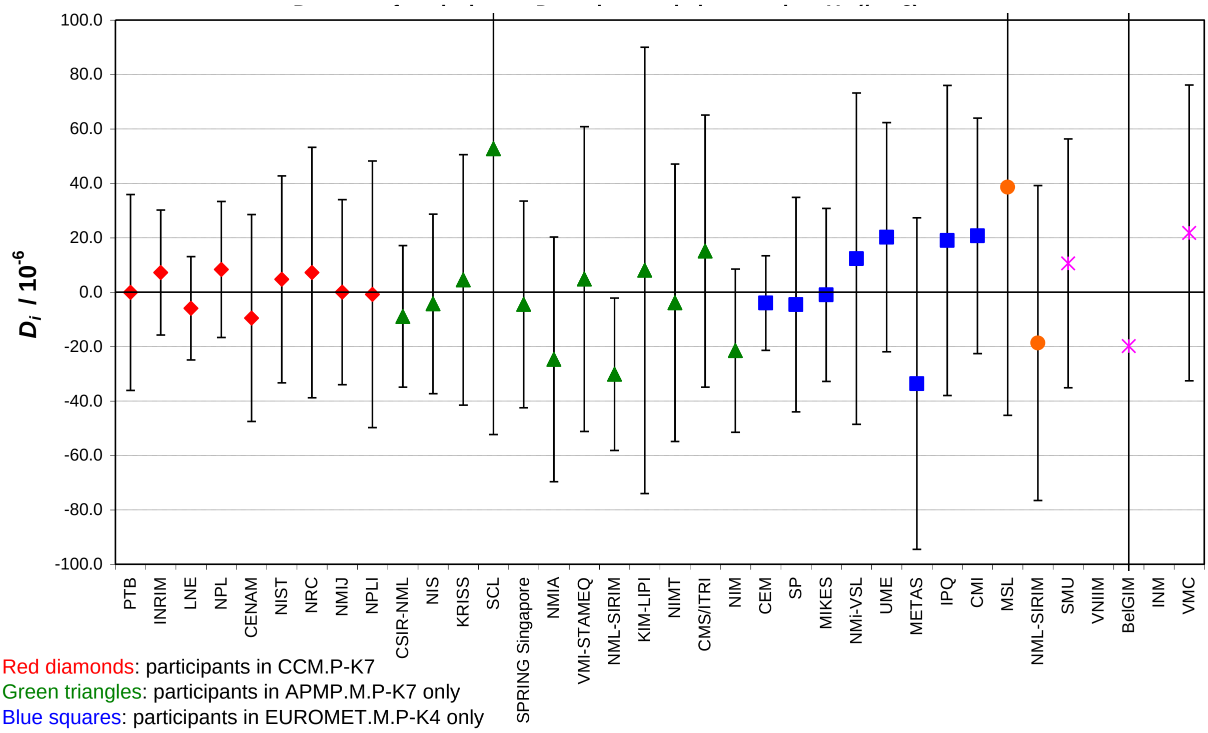

CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 80 MPa
D_i / 10^{-6}
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
PTB
INRIM
LNE
NPL
CENAM
NIST
NRC
NMIJ
NPLI
CSIR-NML
NIS
KRISS
SCL
SPRING Singapore
NMIA
VMI-STAMEQ
NML-SIRIM
KIM-LIPI
NIMT
CMS/ITRI
NIM
CEM
SP
MIKES
NMi-VSL
UME
METAS
IPQ
CMI
MSL
NML-SIRIM
SMU
VNIIM
BelGIM
INM
VMC
Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only

CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 90 MPa



Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only

CCM.P-K7, APMP.M.P-K7 & K7.1, EUROMET.M.P-K4 and COOMET.M.P.K2 - Nominal pressure 100 MPa



Red diamonds: participants in CCM.P-K7
Green triangles: participants in APMP.M.P-K7 only
Blue squares: participants in EUROMET.M.P-K4 only
Orange circles: participants in APMP.M.P-K7.1 only
Pink asterisks: participants in COOMET.M.P-K2 only

8. CONCLUSIONS

The results of comparisons may be regarded as equivalent for Germany, United Kingdom, Slovakia and Russia, which have participated the key comparison CCM.P-K7, organized by BIPM in 2002 and carried out up to2005 year, or have the primary pressure standards in the range from 10 MPa to 100 MPa.

This comparison COOMET.M.P-K2 is aimed to renew the equivalence statements derived from comparison CCM.P-K7.

The comparison objective of others countries – participants of this project has been obtained in the form of demonstration of standard base calibration potentialities for the first time.

From Table 1, good performance of the TS can be concluded. The typical relative standard deviations of A_p range from $0.2\cdot10^{-6}$ to $7.5\cdot10^{-6}$ with the most values being around value $2\cdot10^{-6}$. The changes of typical $s(A_p)/A_p$ values from laboratory to laboratory demonstrate different performance of pressure measurements.

The measurement results held in VMC laboratory in the year 2008 is used for final calculations, while the results from the year 2005 aren’t taken in account.

Relative deviations of the participants’ results from the references value and their standard uncertainties are in agreement with the KCRVs at all pressures.

A comparison of pairs demonstrates that all A_p values of the participants agree with each other within their expanded uncertainties (k=2). At the level of standard uncertainties there is a full agreement between 10 MPa and 100 MPa.

The results of the comparison show that cross-float measurements with pressure balances working with different liquids still remain problematic and can lead to increase uncertainties.

The transfer standard was stable within only a few 10^{-6} in the period of the comparison.

Degrees of equivalences and the expanded (k=2) uncertainties between the COOMET and laboratories participated in other KC: CCM.P-K7, APMP.P-K7, EURAMET.M.P-K4 and APMP.M.P-K7.1, at pressure points from 10 MPa to 100 MPa are presented in figures from 13 to 22.

9. REFERENCES

1. W. Sabuga , M. Bergoglio , T. Rabault , B. Waller , J.C. Torres , D.A. Olson , A. Agarwal , T. Kobata , A.K. Bandyopadhyay. Final Report on Key Comparison CCM.P-K7 in the Range 10 MPa to 100 MPa of Hydraulic Gauge Pressure. January, 2005

2. K. Dapkeviciene. COOMET.M.P-K2 (Nr. 331/LT/05). Technical Protocol o Key comparison of the National Pressure Standards in the Field of Gauge Pressure in the range 10 MPa to 100 MPa. SE Vilnius metrology center (VMT/VMC), Lithuania, 2005.

3. Cox M.G., The evaluation of key comparison data, *Metrologia*, 2002, **39**, 589-595.

4. Molinar G., Sabuga W., Robinson G., Legras J.C., Comparison of methods for calculating distortion in pressure balances up to 400 MPa - EUROMET Project #256. In: *Metrologia*, 1998, **35**, 739-759.