COOMET.M.P-S1

Supplementary comparison of COOMET

Supplementary comparison of national measurement standards of gauge pressure in the range from 1 MPa to 10 MPa

Final Report

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1 INTRODUCTION

The comparison was organized by Technical Committee (TC) 1.6 "Mass and Related Quantities" of COOMET. The project is registered within COOMET as project Nr. 589/UA/12, entitled "Supplementary comparison of national measurement standards of gauge pressure in the range from 1 MPa to 10 MPa".

In the BIPM database, it is identified as COOMET.M.P-S1.

National Scientific Centre "Institute of Metrology" (NSC IM) was chosen as a pilot laboratory.

The results of the comparison are given in this document.

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

2 PARTICIPANTS, CHRONOLOGY AND PROBLEMS DURING THE COMPARISON

Four national metrology institutes finally participated in this comparison including the pilot institute. KazlnMetr (Kazakhstan) completed their measurements and submitted a report, but decided to withdraw from the comparison during the preparation of the draft A report. INM-MD (Moldova) asked for repeated measurements in 2019 due to the loss of primary data based on the results of its measurements in 2016. Their report was sent to the pilot institute after completing the repeated measurements, but INM-MD also decided to withdraw from the comparison. Therefore, these two institutes are not included in the list.

The list of the laboratories with their responsible persons and measurement dates is given below.

NMI	Contact person	Measurement date
NSC IM (initial investigation)	Aleksey Zuyev	September 2015
BelGIM	Aleksandr Bardonov	December 2015
VNIIM	Maksim Leontyev	May 2016
VMT/VMC	Ksaveria Dapkeviciene	February 2018
NSC IM (final investigation)	Aleksey Zuyev	December 2019

The long duration of comparisons was primarily due to differences in the customs legislation of the countries participating in the comparisons. Many countries experienced certain difficulties with the temporary import of the TS into their territory and sending the TS to the next participant of the comparisons. In addition, long duration is associated with repeated measurements of INM-MD.

3 LABORATORY STANDARDS OF THE PARTICIPANTS

All laboratory standards (LSs) were pressure balances equipped with piston-cylinder assemblies. Different methods were applied by the participants to compare their standards with the transfer standard

(TS). The uncertainties of the LSs given below are standard uncertainties.

3.1 NSC IM pressure balance

Manufacturer	Etalon, Ukraine
Measurement range in MPa	0.05 to 10
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Pressure-transmitting medium	kerosene
Zero-pressure effective area (A_0) at reference temperature in cm^2	1.000521
Relative uncertainty of A_0 in 10^{-6}	6
Pressure distortion coefficient (λ) in MPa^{-1}	$9.3 \cdot 10^{-7}$
Uncertainty of λ in MPa^{-1}	$2.4 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	2
Linear thermal expansion coefficient of piston (α) in °C^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (β) in °C^{-1}	$4.5 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8099573
Relative uncertainty of g in 10^{-6}	0.1
Height difference between NMI standard and TS (h, positive if NMI standard is higher than TS) in mm	–
Uncertainty of h in mm	–
Traceability	NSC IM, Ukraine

The zero-pressure effective area of LS piston-cylinder assemblies (A_0) was determined from dimensional measurements. The distortion coefficient was evaluated from dimensional measurements and material constants.

3.2 BelGIM pressure balance

Manufacturer	Etalon, Ukraine
Measurement range in MPa	0.1 to 6
Material of piston	hard alloy
Material of cylinder	hard alloy

Pressure-transmitting medium	kerosene
Zero-pressure effective area (A_0) at reference temperature in cm^2	1.000465
Relative uncertainty of A_0 in 10^{-6}	10.8
Pressure distortion coefficient (λ) in MPa^{-1}	$7.59 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$3 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	0.22
Linear thermal expansion coefficient of piston (α) in °C^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (β) in °C^{-1}	$4.5 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.81367097
Relative uncertainty of g in 10^{-6}	0.045
Height difference between NMI standard and TS (h, positive if NMI standard is higher than TS) in mm	–
Uncertainty of h in mm	–
Traceability	VNIIM, Russia

The zero-pressure effective area of LS piston-cylinder assemblies (A_0) and the pressure distortion coefficient were determined during the calibration in VNIIM.

BelGIM performed measurements using the Δp method with a pre-equilibration done at 1 MPa.

3.3 VNIIM pressure balance

Manufacturer	Russia
Measurement range in MPa	1 to 10
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Pressure-transmitting medium	kerosene
Zero-pressure effective area (A_0) at reference temperature in cm^2	1.496331
Relative uncertainty of A_0 in 10^{-6}	9
Pressure distortion coefficient (λ) in MPa^{-1}	$1.57 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$2.86 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	0.98

Linear thermal expansion coefficient of piston (α) in °C^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (β) in °C^{-1}	$4.5 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.819308
Relative uncertainty of g in 10^{-6}	0.1
Height difference between NMI standard and TS (h, positive if NMI standard is higher than TS) in mm	–
Uncertainty of h in mm	–
Traceability	VNIIM, Russia

The zero-pressure effective area of LS piston-cylinder assemblies (A_0) was determined from dimensional measurements. The distortion coefficient was evaluated from dimensional measurements and material constants.

3.4 VMC/VMT pressure balance

Manufacturer	DH Instruments, USA
Measurement range in MPa	0.5 to 50
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Pressure-transmitting medium	DHS[1)]
Zero-pressure effective area (A_0) at reference temperature in cm^2	0.1961258
Relative uncertainty of A_0 in 10^{-6}	15
Pressure distortion coefficient (λ) in MPa^{-1}	$1.06 \cdot 10^{-6}$
Uncertainty of λ in MPa^{-1}	$0.25 \cdot 10^{-6}$
Relative uncertainty of mass pieces in 10^{-6}	5
Linear thermal expansion coefficient of piston (α) in °C^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (β) in °C^{-1}	$4.5 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.81438
Relative uncertainty of g in 10^{-6}	1.67
Height difference between NMI standard and TS (h, positive if NMI standard is higher than TS) in mm	- 48

Uncertainty of *h* in mm	2
Traceability	PTB, Germany

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

The zero-pressure effective area of LS piston-cylinder assemblies (A_0) and the pressure distortion coefficient were determined during the calibration in PTB.

4 TRANSFER STANDARD (TS)

4.1 Purpose and structure of the transfer standard

As a TS, a piston-cylinder assembly (PCA) with a simple piston proposed NSC IM was applied. PCA consists of:

– body of PCA;

– cylinder;

– bush;

– piston with a head and weight carrier;

– screw-nut clamping cylinder in the body;

– screw-limiter stroke of piston.

4.2 Main technical characteristics of the TS

Item	Identification
Piston-cylinder assembly	Serial number 12
Measurement range in MPa	1 to 10
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Material of the piston weight carrier	Stainless steel
Nominal effective area of the assembly in cm^2	1
Nominal initial mass (including the weight carrier) in kg	~ 1.619
Pressure reference level	the bottom of the piston
Working position of piston	8 mm above its rest position
Linear thermal expansion coefficient of piston (α) in $°C^{-1}$	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (β) in $°C^{-1}$	$4.5 \cdot 10^{-6}$
Piston fall rate in kerosene at pressure 10 MPa	0.11 mm/min

Piston rotation time in kerosene at pressure 1 MPa	Not less than 10 min (initial speed of rotation of 60 rpm)
Pressure transmitting medium	kerosene or other liquids non-aggressive to the material of the PCA with viscosity not higher than 30 mPa·s

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 laboratory used the p-method was: VMT/VMC. The laboratories used the Δp-method were: NSC IM, VNIIM and BelGIM.

6 MEASUREMENT PROCEDURES

The measurements included five cycles each with nominal pressures created in the following order (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1) MPa. Thus, a total of 100 measurements (10 measurements at each pressure). For each measurement 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:

$$A_\mathrm{p} = \frac{\sum_i m_i g\left(1 - \frac{\rho_{0\mathrm{a}}}{\rho_0} + \frac{\rho_{0\mathrm{a}} - \rho_\mathrm{a}}{\rho_i}\right) + 2\sigma\sqrt{\pi A_{0\mathrm{n}}}}{p[1 + (\alpha + \beta)\cdot(t - t_0)]},$$

where:

m_i are conventional masses of the piston, the weight carrier and the mass pieces placed on the weight carrier of TS;

g is local gravity acceleration;

ρ_i is density of the part with mass m_i;

ρ_a is air density;

$\rho_{0\mathrm{a}}$ is conventional value of the air density;

ρ_0 is conventional value of the mass density;

σ is surface tension of the TS working liquid;

$A_{0\mathrm{n}}$ is nominal effective area of TS;

p is pressure generated by the laboratory standard at the TS reference level (lower face of TS piston);

α, β are thermal expansion coefficients of the piston and cylinder materials of TS;

t is temperature of TS;

t_0 is reference temperature (20˚C).

The equation for A_p calculation in the Δp-method is the following:

$$A_p = A_{nps}\frac{\left[m_2 + M_2(\alpha_2+\beta_2)\cdot(t_{2,0}-t_2)\right]\cdot\left[1+(\alpha_1+\beta_1)\cdot(t_1-t_0)\right]\cdot(1+\lambda_1 p_n)}{\left[m_1 + M_1(\alpha_1+\beta_1)\cdot(t_{1,0}-t_1)\right]\cdot\left[1+(\alpha_2+\beta_2)\cdot(t_2-t_0)\right]},$$

where:

A_{nps} is zero-pressure effective area of NMI standard;

m_1, m_2 are masses imposed on weight carrier device of NMI standard and TS at a pressure measurement after the preliminary equilibration;

M_1, M_2 are masses of mobile parts and weights of NMI standard and TS at the preliminary equilibration;

α_1, β_1 are thermal expansion coefficients of the piston and cylinder materials of the NMI standard;

α_2, β_2 are thermal expansion coefficients of the piston and cylinder materials of TS;

$t_{1,0}$, $t_{2,0}$ are temperatures of NMI standard and TS at the preliminary equilibration;

t_1, t_2 are temperatures of participant standard and TS at pressure measurement;

t_0 is reference temperature (20 °C);

λ_1 is pressure distortion coefficient of the participant standard piston-cylinder assembly;

p_n is nominal value of pressure at pressure measurement.

For each nominal pressure the participants reported summary results including the sensitivity of the cross float, average A_p, its standard uncertainties (type A and B) and combined standard uncertainty. The standard uncertainty (type A) was defined as standard deviation of A_p. For pressures 1 MPa and 10 MPa, a list of the main uncertainty sources (type B) 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:

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

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 NSC IM, which took measurements at the beginning and the end of the comparison.

The NSC IM results of 2015 and 2019 are in a good agreement within their uncertainties - the zero pressure effective areas differ relatively by only $2\cdot10^{-6}$:

2015 A_0 = (1.000493 ± 0.000016) cm^2.

2019 A_0 = (1.000495 ± 0.000016) cm^2.

From these results it can be concluded that TS remained stable in the time from 2015 to 2019.

7.2 Results of the participants

The participants' pressure-dependent effective areas averaged for each nominal pressure (A_p), their standard deviations and combined standard uncertainties are given in Table 1. For NSC IM, the measurement results of 2019 were used.

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	NSC IM			BelGIM			VNIIM			VMT/VMC		
	A_p / cm^2	$s(A_p)/A_p$ ×10^6	$u(A_p)/A_p$ ×10^6	A_p / cm^2	$s(A_p)/A_p$ ×10^6	$u(A_p)/A_p$ ×10^6	A_p / cm^2	$s(A_p)/A_p$ ×10^6	$u(A_p)/A_p$ ×10^6	A_p / cm^2	$s(A_p)/A_p$ ×10^6	$u(A_p)/A_p$ ×10^6
1	1.000497	1.9	8.0				1.000473	0.8	9.1	1.000502	8.1	28.2
2	1.000496	1.4	7.5	1.000469	0.7	17.9	1.000476	0.3	9.1	1.000507	7.0	24.5
3	1.000497	0.9	7.3	1.000469	0.9	13.1	1.000477	0.3	9.1	1.000519	4.0	22.9
4	1.000499	1.1	7.2	1.000470	0.7	12.0	1.000479	0.2	9.1	1.000511	8.0	23.4
5	1.000498	0.8	7.2	1.000469	0.6	11.6	1.000481	0.3	9.1	1.000509	5.5	22.5
6	1.000500	0.9	7.2	1.000469	0.6	11.6	1.000482	0.1	9.1	1.000510	6.6	22.6
7	1.000501	1.0	7.2				1.000484	0.2	9.1	1.000506	4.4	21.9
8	1.000501	0.7	7.2				1.000485	0.1	9.1	1.000508	6.6	22.4
9	1.000503	0.7	7.2				1.000488	0.2	9.1	1.000507	5.4	22.0
10	1.000504	0.9	7.2				1.000488	0.1	9.1	1.000509	8.8	23.0

Zero-pressure effective area (A_0) of TS with combined relative standard uncertainty ($u(A_0)/A_0$), as determined in the participating laboratories are presented in Table 2.

Table 2. Zero-pressure effective areas of the transfer standard (A_0) with combined relative standard uncertainties ($u(A_0)/A_0$), as determined by the participants.

NMI	A_0 / cm^2	$u(A_0)$ / A_0 ×10^6
NSC IM	1.000495	8.0
BelGIM	1.000469	30.4
VNIIM	1.000474	9.1
VMT/VMC	1.000509	15.0

Pressure distortion coefficient of TS (λ) and it's combined relative standard uncertainty ($u(\lambda)$) are presented in Table 3.

Table 3. Pressure distortion coefficient of the transfer standard (λ) with combined standard uncertainties ($u(\lambda)$), as determined by the participants.

NMI	λ / MPa^{-1}	$u(\lambda)$ / MPa^{-1}
NSC IM	$9.3 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$
BelGIM	$9.98 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$
VNIIM	$1.26 \cdot 10^{-6}$	$1.5 \cdot 10^{-7}$
VMT/VMC	$1.0 \cdot 10^{-6}$	$0.6 \cdot 10^{-6}$

7.3 Reference value calculation

Among the participants, 3 laboratories are independent of each other, NSC IM and VNIIM having primary standards and VMT/VMC being traceable to PTB. Therefore, the results of these 3 laboratories were considered as independent and used for calculation of the comparison reference values, calculated as weighted means.

The weighted reference value was calculated at each pressure as:

$$A_{\mathrm{p,ref}} = \frac{\sum_{j=1}^{n} \frac{A_{\mathrm{p},j}}{u^2(A_{\mathrm{p},j})}}{\sum_{j=1}^{n} \frac{1}{u^2(A_{\mathrm{p},j})}}.$$

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

$$u(A_{\mathrm{p,ref}}) = \sqrt{\frac{1}{\sum_{j=1}^{n} \frac{1}{u^2(A_{\mathrm{p},j})}}},$$

where:

n is number of participant results used for calculation (n = 3);

$A_{\mathrm{p},j}$ is effective area reported by laboratory j;

$u(A_{\mathrm{p},j})$ is standard uncertainty of $A_{\mathrm{p},j}$.

Table 4: Reference value and associated relative uncertainty (k = 1) calculated from NSC IM, VNIIM and VMT/VMC results at each nominal pressure

p / MPa	$A_{\mathrm{p,ref}}$ / cm^2	$u(A_{\mathrm{p,ref}})$ / $A_{\mathrm{p,ref}}$ $\times 10^6$
1	1.000487	5.9
2	1.000489	5.6

3	1.000491	5.5
4	1.000492	5.5
5	1.000492	5.5
6	1.000494	5.5
7	1.000495	5.5
8	1.000496	5.5
9	1.000498	5.5
10	1.000498	5.5

7.4 Deviations from the reference value

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

$$d_i = A_{\mathrm{p},i} - A_{\mathrm{p,ref}},$$

$$U(d_i) = 2\cdot\sqrt{u^2(A_{\mathrm{p},i}) + u^2(A_{\mathrm{p,ref}})} \quad \text{(for BelGIM)},$$

$$U(d_i) = 2\cdot\sqrt{u^2(A_{\mathrm{p},i}) - u^2(A_{\mathrm{p,ref}})} \quad \text{(for NSC IM, VNIIM and VMT/VMC)}.$$

Numerical data for the deviations and the uncertainties at all pressures are given in Table 5 and shown graphically in Figs. 1 to 10.

Table 5. Relative deviations of the participants' results from the references values ($d/A_{\mathrm{p,ref}}$) and their relative expanded uncertainties ($U(d)/A_{\mathrm{p,ref}}$)

p / MPa	NSC IM		BelGIM		VNIIM		VMT/VMC	
	$d/A_{\mathrm{p,ref}}$ ×10^6	$U(d)/A_{\mathrm{p,ref}}$ ×10^6	$d/A_{\mathrm{p,ref}}$ ×10^6	$U(d)/A_{\mathrm{p,ref}}$ ×10^6	$d/A_{\mathrm{p,ref}}$ ×10^6	$U(d)/A_{\mathrm{p,ref}}$ ×10^6	$d/A_{\mathrm{p,ref}}$ ×10^6	$U(d)/A_{\mathrm{p,ref}}$ ×10^6
1	9.8	11			-14	14	15	55
2	7.1	9.9	-20	38	-13	14	18	48
3	6.1	9.5	-22	28	-14	14	28	44
4	6.6	9.3	-22	26	-13	15	19	45
5	5.5	9.3	-23	26	-11	15	16	44
6	5.9	9.3	-25	26	-12	15	16	44
7	5.8	9.4			-11	15	11	42
8	5.4	9.4			-11	15	12	43
9	5.2	9.4			-10	15	9.2	43
10	5.5	9.3			-10	15	11	45

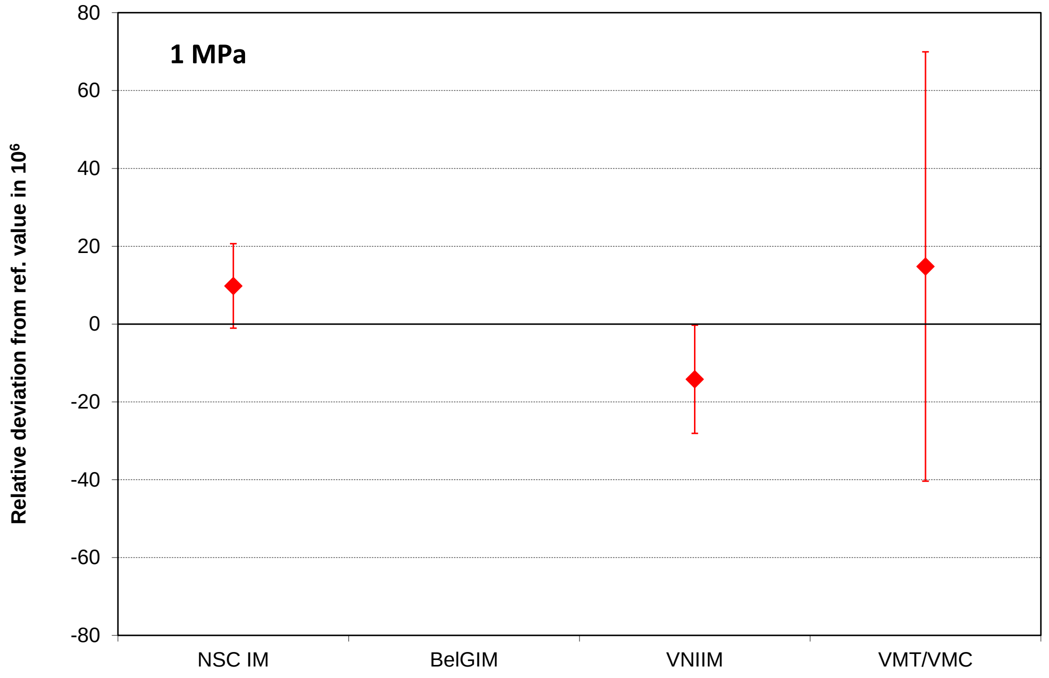

Figure 1. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 1 MPa

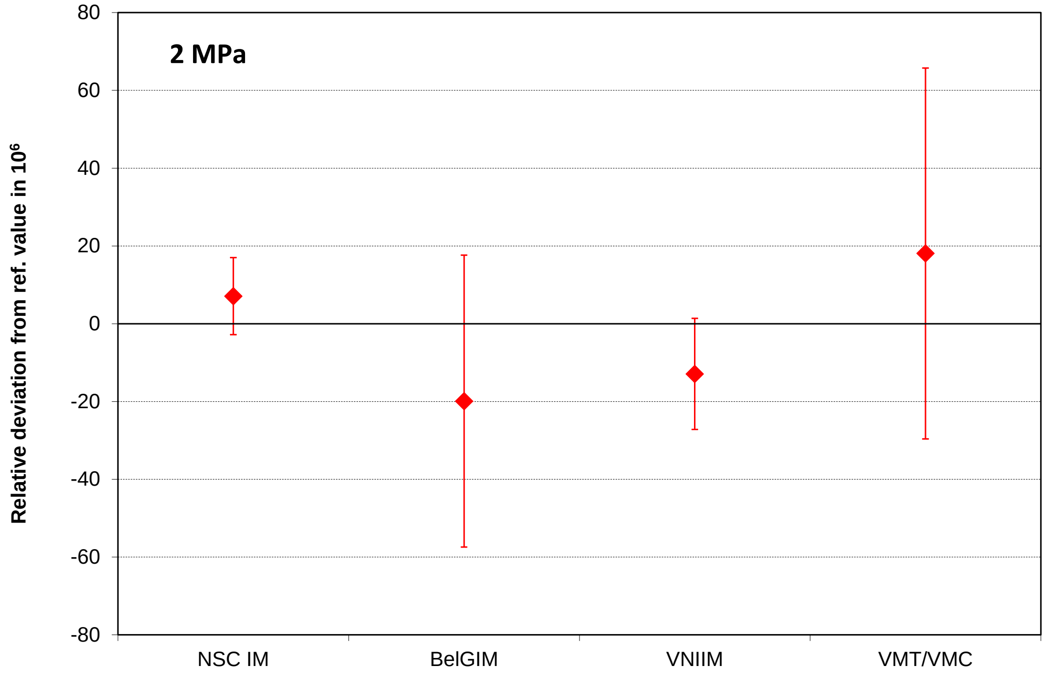

Figure 2. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 2 MPa

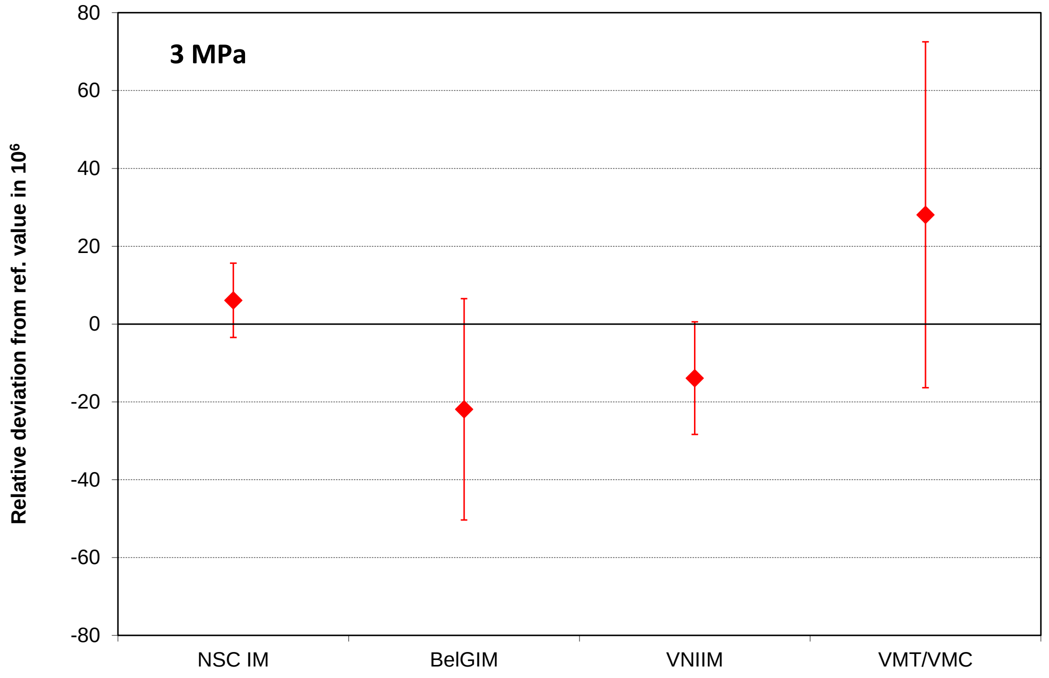

Figure 3. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 3 MPa

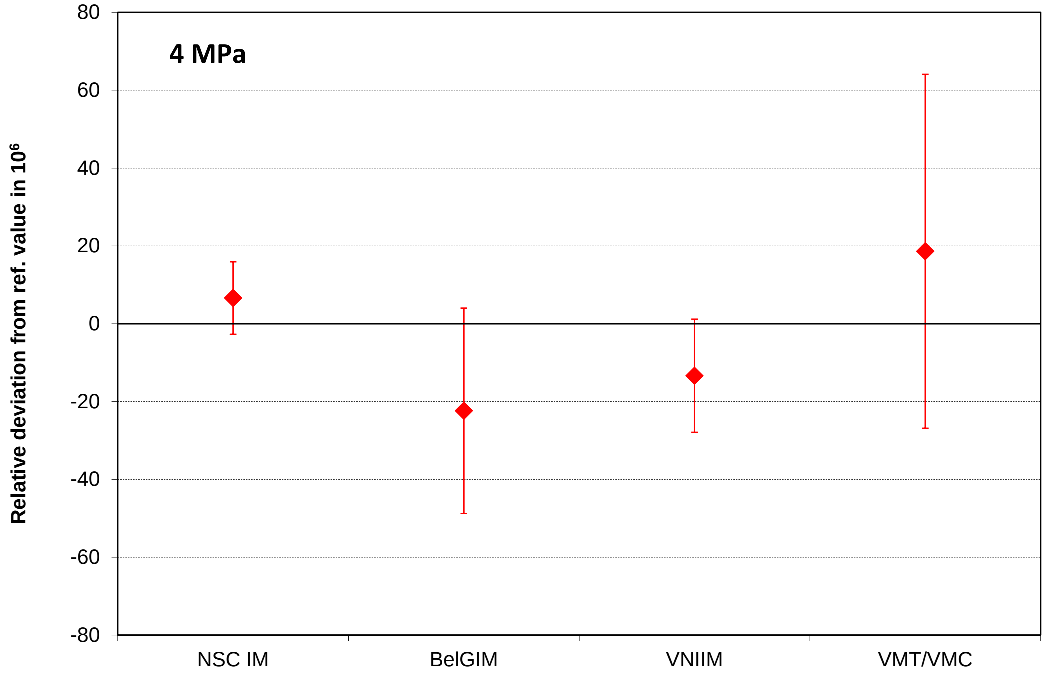

Figure 4. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 4 MPa

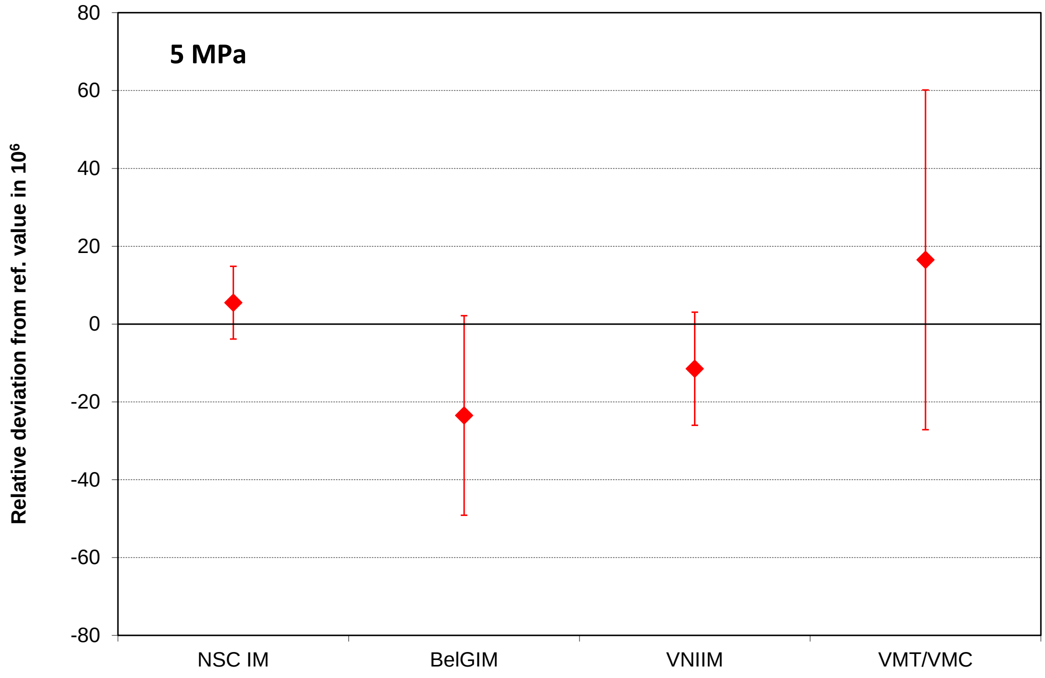

Figure 5. Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 5 MPa

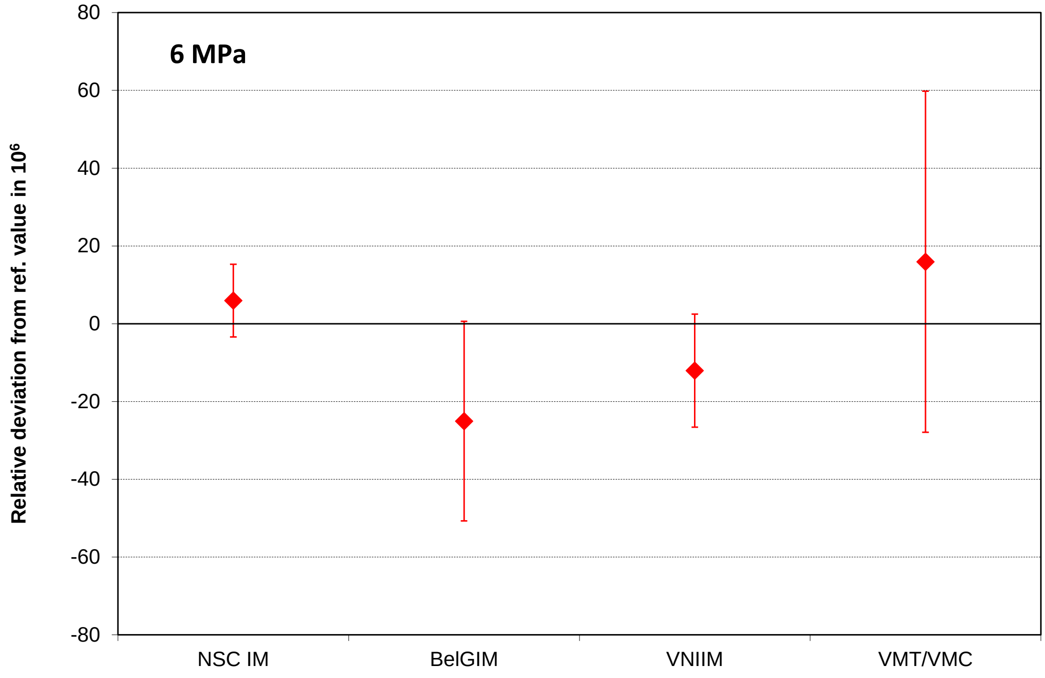

Figure 6. Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 6 MPa

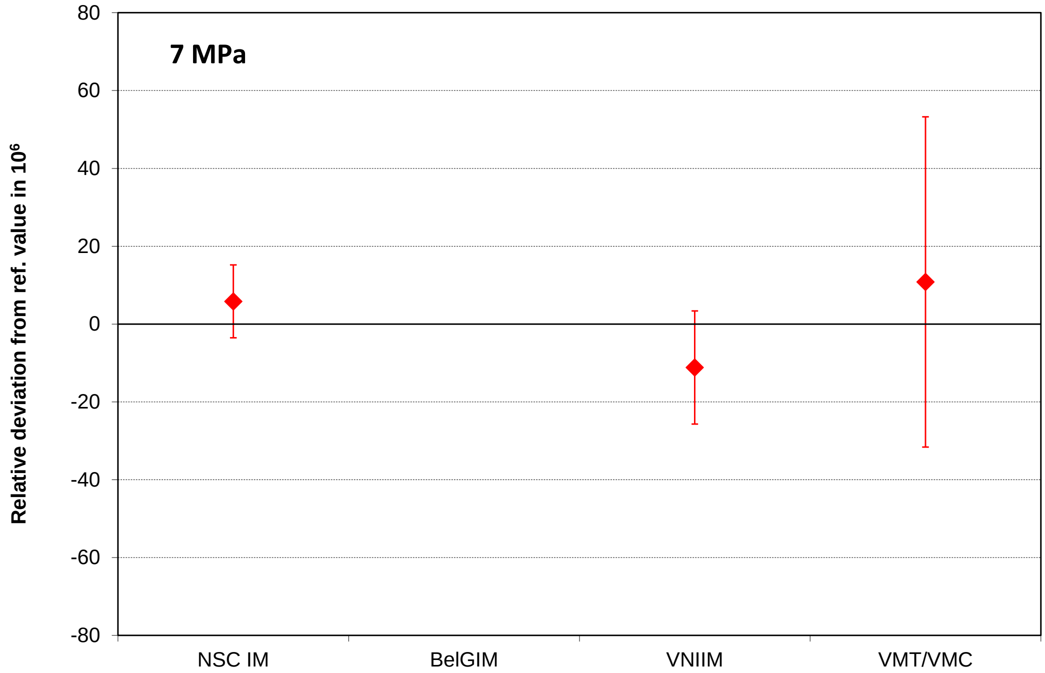

Figure 7. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 7 MPa

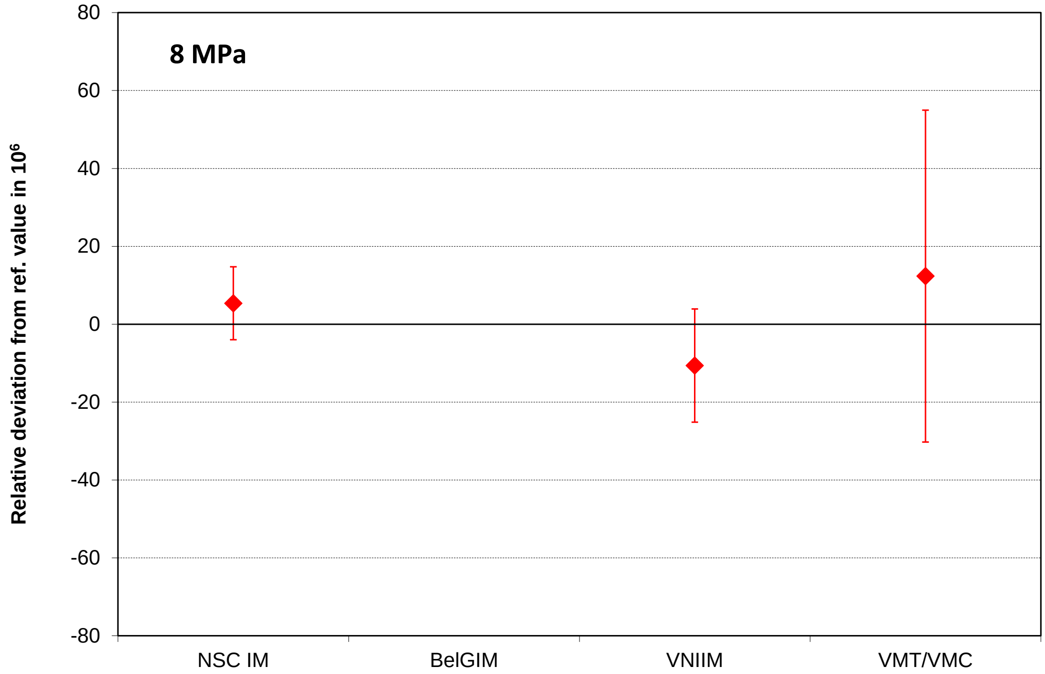

Figure 8. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 8 MPa

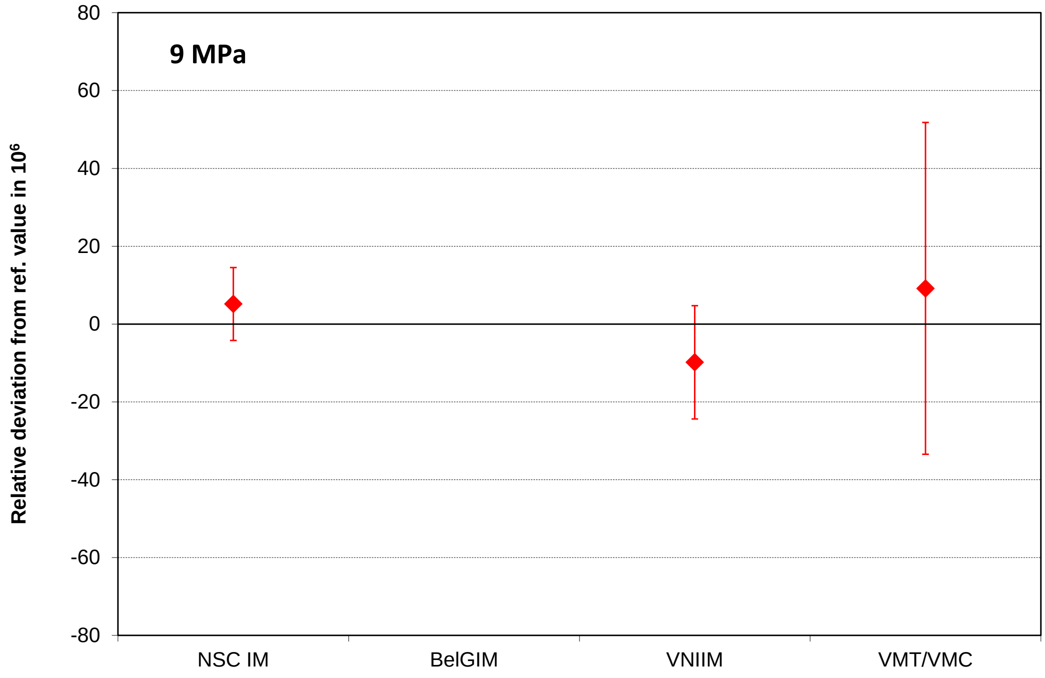

Figure 9. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 9 MPa

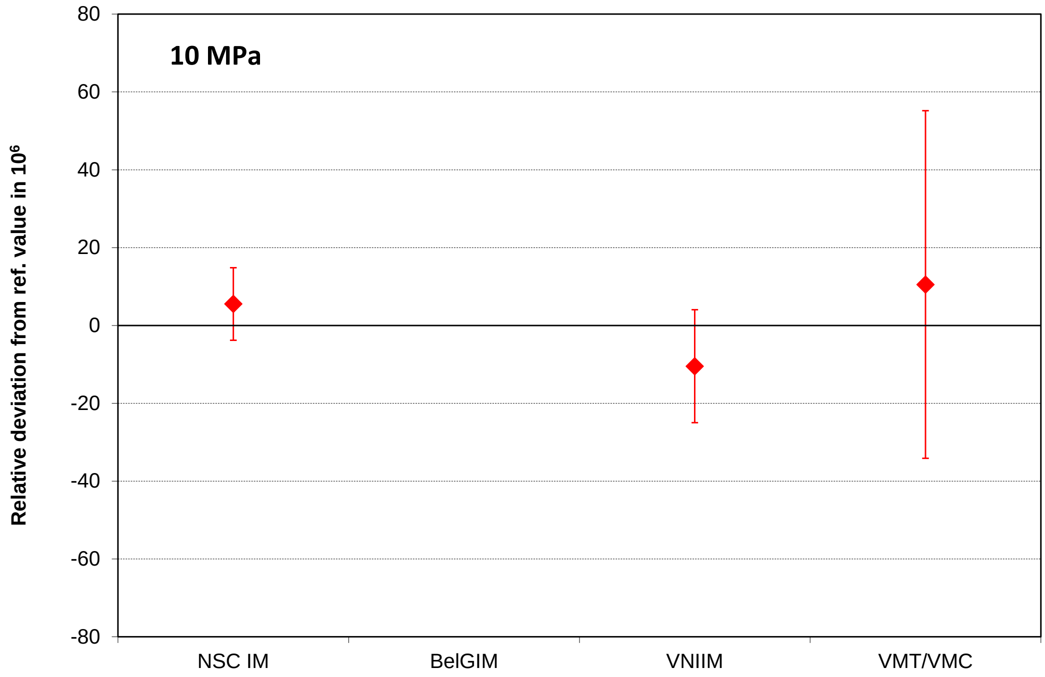

Figure 10. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 10 MPa

7.5 Performance evaluation

In order to evaluate agreement of the result of participant *i* with the reference, a normalized error ($E_{n,i}$) criteria was used,

$$E_{n,i} = d_i / U(d_i).$$

The performance is determined by the normalized error according to:

$|E_{n,i}| \leq 1$ - satisfactory result

$|E_{n,i}| > 1$ - unsatisfactory result.

Table 6 gives the normalized error values at each pressure for the participating laboratories with respect to the reference values.

Table 6. Normalized errors of laboratories' results with respect to the reference values

p / MPa	$E_{n,i}$ values			
	NSC IM	BelGIM	VNIIM	VMT/VMC
1	0.90		-1.0	0.27
2	0.71	-0.53	-0.90	0.38
3	0.64	-0.77	-0.96	0.63
4	0.71	-0.85	-0.92	0.41
5	0.59	-0.92	-0.79	0.38
6	0.63	-0.98	-0.83	0.36
7	0.62		-0.77	0.26
8	0.57		-0.73	0.28
9	0.55		-0.68	0.22
10	0.59		-0.72	0.24

A pairwise agreement between laboratories *i* and *j* was analyzed in terms of normalized errors of their results ($E_{n,ij}$) calculated as

$$E_{n,ij} = \left(A_{p,i} - A_{p,j}\right) / \left[u^2\left(A_{p,i}\right) + u^2\left(A_{p,j}\right)\right]^{0.5} / 2.$$

Results for normalized errors of the laboratories with respect to each other are presented in Table 7.

Table 7. Normalized errors of laboratories' results with respect to each other

p / MPa	$E_{n,ij}$ values					
	NSC IM – BelGIM	NSC IM – VNIIM	NSC IM – VMT/VMC	BelGIM – VNIIM	BelGIM – VMT/VMC	VNIIM – VMT/VMC
1		0.99	-0.09			-0.49
2	0.70	0.85	-0.21	-0.17	-0.63	-0.59
3	0.93	0.86	-0.46	-0.25	-0.95	-0.85
4	1.0	0.86	-0.24	-0.30	-0.78	-0.64
5	1.1	0.73	-0.23	-0.41	-0.79	-0.58
6	1.1	0.78	-0.21	-0.44	-0.81	-0.57
7		0.73	-0.11			-0.46
8		0.69	-0.15			-0.48
9		0.65	-0.09			-0.40
10		0.69	-0.10			-0.42

8 CONCLUSIONS

Four laboratories participated in this comparison. Three laboratories (NSC IM, VNIIM, VMT/VMC) reported results for all pressure points in the range from 1 MPa to 10 MPa, BelGIM reported results for pressure points 2, 3, 4, 5 and 6 MPa.

The transfer standard was practically stable in the period of the comparison.

The reference values at each pressure were calculated as weighted means of the results of the independent laboratories, which are NSC IM, VNIIM, VMT/VMC.

All values agree with the reference values within the expanded uncertainties taken with coverage factor $k = 2$. Compared in pairs, all laboratories except NSC IM and BelGIM agree with each other at all pressures. For NSC IM and BelGIM, their results at 5 and 6 MPa slightly disagree showing normalized errors of 1.1. Except these two pressure points, the results demonstrate equivalence between the participating laboratories in the calibration of pressure balances.

9 REFERENCES

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