Final Report on Key Comparison EURAMET.M.P-K13 in the Range 50 MPa to 500 MPa of Hydraulic Gauge Pressure

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Abstract

The regional key comparison EURAMET.M.P-K13 for pressure measurements in liquid media from 50 MPa to 500 MPa was piloted by the TÜBİTAK UME Pressure Group Laboratories, Turkey. The transfer standard was a DH-Budenberg pressure balance with a free deformation piston-cylinder unit of 2 mm^2 nominal effective area. Six laboratories from the EURAMET region, namely PTB, INRIM, SMU, IMT, NPL and UME, and two laboratories from the AFRIMETS region, NIS and NMISA participated in this comparison. Participant laboratories and countries are given in the bottom of the page.

PTB participated in this comparison to provide a link to corresponding 500 MPa CCM key comparison CCM.P-K13.

The results of all participants excepting NMISA and NPL were found to be consistent with the reference value of the actual comparison and of CCM.P-K13 within their claimed uncertainties (k = 2), at all pressures. Compared in pairs all laboratories with exception of NPL and NMISA demonstrate their agreement with each other within the expanded uncertainties (k = 2) at all pressures. The results are therefore considered to be satisfactory.

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1. Introduction

At the EURAMET TC-M Contact Persons Meeting in Bucharest in 2008, it was decided to carry out a new key comparison (KC) in the range of 500 MPa of hydraulic gauge pressure. The objective of the comparison is more precisely “to determine degrees of equivalence to the KCRV in pressure and to link to CCM.P-K13”. A piston-cylinder unit (PCU) of a pressure balance used as a transfer standard (TS) with the effective area (A_p) at specified pressures. This comparison was registered in the BIPM KCDB as EURAMET key comparison EURAMET.M.P-K13. UME was the pilot laboratory, and PTB took a part in this comparison to provide a link between this comparison and 500 MPa CCM key comparison CCM.P-K13.

2. Laboratory standards and measurement methods of the participants

All laboratory standards (LS) used were pressure balances equipped with PCUs. All participants applied the cross-float method to compare their standards with the TS.

2.1. UME pressure balance and measurement method

The properties of the UME pressure standard and measurement conditions are presented in Table 1. All uncertainties listed are standard uncertainties.

Table 1. UME laboratory standard and measurement conditions

Manufacturer	Desgranges et Huot, serial no. 9630
Measurement range	50 – 500
Material of piston	steel
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.961861
Relative uncertainty of A_0 in 10^{-6}	17
Pressure distortion coefficient (ª) in MPa^{-1}	$8.0 \cdot 10^{-7}$
Uncertainty of ª in MPa^{-1}	$1.0 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	1.5
Linear thermal expansion coefficient of piston ($\sim_p$) in °C^{-1}	$1.05 \cdot 10^{-5}$
Linear thermal expansion coefficient of cylinder ($\sim_c$) in °C^{-1}	$0.45 \cdot 10^{-5}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.802310
Relative uncertainty of g in 10^{-6}	2
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0.0
Uncertainty of h in mm	1

A_0 and ª were determined by cross-floating method in LNE in 2009.

The UME measurements were done in December 2009 and the control measurements were done in January 2011. The results obtained in January 2011 are used as UME result in this

KC. Prior to pressure measurements, demagnetisation of piston, cylinder and mass set has been done.

For the cleaning operations, pure ethyl alcohol was used as a solvent-cleaner. Soft paper was used to dry the pieces and pure nitrogen gas to blow the pieces after their cleaning.

Di(2)-ethyl-hexyl-sebacate (DHS) by DH-Budenberg was used as the working liquid.

During all measurements both the reference and the transfer standard were operated with their piston-cylinder assemblies rotating counter clockwise (CCW) and at almost constant rotation rate by means of their motor-drivers.

Reference and TS temperatures were measured by platinum resistance thermometers (PRTs). They were calibrated by UME Temperature Laboratory.

Position and fall rates of UME reference and transfer standard pistons were measured by means of laser sensors placed over the mass carrying bells. Fall rates data acquisition was done with a specific UME software program. Each fall rate measurement has been made before starting the calibration cycles, at temperature around 20 °C. The results obtained confirmed the piston fall rates measured by the pilot laboratory and reported in the protocol.

Atmospheric pressure was measured using DPM1 with the resolution 1 Pa and standard uncertainty of 2 Pa.

The two systems were intentionally arranged to be at the same height in order to minimise the correction due to different pressure reference levels of the pressure balances.

2.2. PTB pressure balance and measurement method

The PTB laboratory standard (LS) used in this KC was the 1 GPa pressure balance [1] equipped with a 1 GPa piston-cylinder assembly identified by no. 7594 (Table 2). All uncertainties in the table and anywhere in this section are standard ones.

Table 2. PTB laboratory standard and measurement conditions

Manufacturer	DH-Budenberg, ser. no. 7594
Measurement range in MPa	50 – 1000
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide with a sleeve of steel
Operation mode, free-deformation (FD) or controlled-clearance (CC)	both FD and CC are possible, CC was used
Zero-pressure effective area (A_0) at reference temperature in mm^2	4.902256
Relative uncertainty of A_0 in 10^{-6}	13
Pressure distortion coefficient (ª) in MPa^{-1}	4.37·10^{-7}
Uncertainty of ª in MPa^{-1}	5·10^{-8}
Relative uncertainty of mass pieces in 10^{-6}	0.6
Linear thermal expansion coefficient of piston ($\sim_p$) in °C^{-1}	4.5·10^{-6}
Linear thermal expansion coefficient of cylinder ($\sim_c$) in °C^{-1}	4.5·10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.812533
Relative uncertainty of g in 10^{-6}	0.53
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0.13
Uncertainty of h in mm	0.37

The zero-pressure effective area (A_0) of this assembly is traceable through a calibration chain to three primary 5 cm^2 10 MPa piston-cylinder units [2]. The value of the distortion coefficient (ª) with associated uncertainty was determined by FEA [3-4] and an experimental method [5]. This pressure standard was also used within the following comparisons: EURAMET.M.P-K7 (2005-2007), APMP.M.P-S8 (2007-2008) and EURAMET.M.P-S5 (2007-2010), CCM.P-K13 (2008-2010).

Prior to pressure measurements, magnetisation of TS was measured and found to be 8·10^{-6} Tesla at piston and 3·10^{-5} Tesla at cylinder.

The piston fall rates (v_f) were measured as:

p / MPa	v_f / (mm/min)
50	1.4
250	2.3
500	2.82

All measurements were performed by a direct cross-float of TS against LS using DHS as a pressure transmitting medium in both standards. The following density ($°_l$) in dependence on pressure (p) and temperature (t) as well as the surface tension (±) of DHS were used in the calculations:

$$°_l = [912.7 + 0.752(p/\text{MPa}) - 1.65\cdot10^{-3}(p/\text{MPa})^2 + 1.5\cdot10^{-6}\,(p/\text{MPa})^3] \times \times [1 - 7.8\cdot10^{-4}\,(t/°\text{C} - 20)] \times (1 \pm 0.01)\ \text{kg/m}^3 \quad (1)$$

$$\pm = 31.2 \times (1 \pm 0.05)\ \text{mN/m} \quad (2)$$

At each pressure, LS and TS were cross-floated using the fall rates of both pistons as an equilibrium criterion. To reach the equilibrium, trim masses were applied only to LS, whereas TS was operated only with the standard 5 kg weights set.

Temperatures of LS and TS (t_{LS} and t_{TS}) as well as ambient conditions, ambient temperature (t_{amb}) and pressure (p_{amb}), are summarised in Table 3.

Table 3. Experimental and ambient conditions

t_{LS} / °C	t_{TS} / °C	t_{amb} / °C	p_{amb} / hPa
19.74 – 20.58	19.91 – 21.20	19.82 – 20.75	1006.11 – 1017.60

The pressure measured in the reference level of TS (p) and the pressure dependent effective area of TS (A_p) were calculated from the well-known formulae:

$$p = \frac{g \cdot \sum m_{i,\text{LS}} \cdot \left(1 - °_{\text{a}} / °_{i,\text{LS}}\right) + 2 \cdot ® \cdot r_{\text{LS}} \cdot \pm}{A_{0,\text{LS}} \cdot \left[1 + \left(\sim_{\text{p,LS}} + \sim_{\text{c,LS}}\right) \cdot \left(t_{\text{LS}} - t_0\right)\right] \cdot \left(1 + ª_{\text{LS}} \cdot p\right)} + g \cdot \left(°_l - °_{\text{a}}\right) \cdot h \quad (3)$$

$$A_p = \frac{g \cdot \sum m_i \cdot \left(1 - °_{\text{a}} / °_i\right) + 2 \cdot ® \cdot r \cdot \pm}{p \cdot \left[1 + \left(\alpha_{\text{p}} + \alpha_{\text{c}}\right) \cdot \left(t - t_0\right)\right]}, \quad \text{where} \quad (4)$$

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

$°_i$ are densities of the parts with masses m_i,

$°_{\text{a}}$ is air density,

r is piston radius,

$\sim_{\text{p}}$ and $\sim_{\text{c}}$ are thermal expansion coefficients of the piston and cylinder materials, respectively,

t_0 is reference temperature, t_0 = 20 °C,

and other symbols as previously defined. Quantities with subscript "LS" refer to properties of LS, all other quantities are properties of TS or parameters which are common for both LS and TS.

The air density was calculated from the temperature, pressure and humidity, the latter taken as 60% ± 40%, of the ambient air using the equation given in [7].

2.3. INRIM pressure balance and measurement method

In Table 4, the main metrological characteristics of the INRIM primary standard used for the comparison are given. The uncertainties here are expressed as standard ones.

Table 4. INRIM laboratory standard and measurement conditions

Manufacturer	DH-Budenberg
Measurement range	50 – 500
Material of piston	non-magnetic stainless steel
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.961167
Relative uncertainty of A_0 in 10^{-6}	23
Pressure distortion coefficient (ª) in MPa^{-1}	$8.3 \cdot 10^{-7}$
Uncertainty of ª in MPa^{-1}	$4.5 \cdot 10^{-8}$
Relative uncertainty of mass pieces in 10^{-6}	2
Linear thermal expansion coefficient of piston ($\sim_p$) in $°C^{-1}$	$1.05 \cdot 10^{-5}$
Linear thermal expansion coefficient of cylinder ($\sim_c$) in $°C^{-1}$	$0.45 \cdot 10^{-5}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.805328
Relative uncertainty of g in 10^{-6}	1
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0.0
Uncertainty of h in mm	1

A_0 was determined by dimensional and cross-floating measurements made at INRIM. ª was determined by FEM elastic distortion calculation.

Pure ethyl alcohol was used to clean the PCU. Soft optical paper was used to dry the pieces and pure nitrogen gas to blow the pieces after their cleaning.

Surface magnetization of different parts of the transfer standards were measured by means of a Hall-effect sensor. The obtained results are the following: the maximal surface magnetization of the piston < $2x10^{-4}$ T, of the cylinder < $2x10^{-4}$ T, of the carrying bell < $2x10^{-4}$ T, and showed no need of demagnetisation. Working liquid was DHS by Fluke with purity better than 97 %.

During all tests both the INRIM-500DH standard and the TS were operated with their pistons rotating CCW at almost constant rotation rates by means of their motor-drivers.

Temperature of LS piston-cylinder INRIM-500DH was measured using a platinum resistance thermometer (PRT) traced to the international temperature scale (ITS-90) at INRIM Thermodynamic Department and inserted into the thermometer port on the base unit. Its standard measurement uncertainty was 0.01 °C. Temperature of the TS was measured using the PRT supplied with the pressure balance.

Position and fall rates of INRIM and TS pistons were measured by means of capacitance sensors placed over the top of the mass carrying bells. Fall rates data acquisition was done with a specific LabView program. Each fall rate measurement has been made before starting the calibration cycles, at temperature around 20 °C. The results confirmed the piston fall rates measured by the pilot laboratory and reported in the KC Technical protocol.

Air density (°_a) was calculated using the formulae given by R. Davis in (R.S. Davis, Equation for the determination of the density of moist air (1981/91), *Metrologia*, 1992, **29**, 67-70) at each pressure cross floating point, by measurements of atmospheric pressure, laboratory temperature, air relative humidity and assuming a mole fraction of carbon dioxide of 0.0004. The following instruments were used for such measurements:

- Atmospheric pressure: sensor Ruska 7220, resolution 0.1 Pa, standard uncertainty of 2 Pa

- Laboratory temperature: sensor Deltaohm DO 9406, resolution 0.1 °C, standard uncertainty of 0.7 °C - Relative air humidity: sensor Deltaohm DO 9406, resolution 0.1%, standard uncertainty of 0.3% The standard uncertainty of air density *a* ρ was calculated considering the different contributions of temperature, atmospheric pressure, air relative humidity, mole fraction of carbon dioxide and uncertainty in the formula given by R. Davis in the previous mentioned paper ($1·10^{-4}$ kg m^{-3}). A combined uncertainty $u(\text{°}_a) = 3·10^{-3}$ kg m^{-3} was obtained.

The LS and TS were intentionally arranged to be at the same height in order to minimise the correction due to different heights between the pressure balances. All length measurements were made using micrometers and cathetometers having resolutions of 0.01 mm. The measured difference was less than 0.8 mm. In all calculations, it was assumed $\Delta h = 0$ with an estimated standard uncertainty $u(\Delta h)$ =1 mm. When the estimated standard uncertainty of the height difference is 1 mm, this is equivalent, at 50 MPa, to 9 Pa only.

The formula used for the calculation of the pressure p measured by the INRIM standard at the TS reference level is:

$$p = \frac{g \cdot \sum M_{i,\mathrm{LS}} \cdot \Phi_{i,\mathrm{LS}} \cdot \left(1 - \text{°}_{\mathrm{a}}/8000\right) + 2 \cdot \text{®} \cdot r_{\mathrm{LS}} \cdot \text{±}}{A_{0,\mathrm{LS}} \cdot \left[1 + \left(\text{~}_{\mathrm{p,LS}} + \text{~}_{\mathrm{c,LS}}\right) \cdot \left(t_{\mathrm{LS}} - t_0\right)\right] \cdot \left(1 + \text{ª}_{\mathrm{LS}} \cdot p_{\mathrm{n}}\right)} + g \cdot \text{°}_{\mathrm{l}} \cdot h \text{, with} \quad (5)$$

$$\Phi_{i,\mathrm{LS}} = 1 - \left(\text{°}_{\mathrm{a}} - 1.2\right) \cdot \left(\frac{1}{\text{°}_i} - \frac{1}{8000}\right) \quad (6)$$

Where;

M_i is the conventional mass of the floating elements of the INRIM standard;

p_n is the nominal pressure;

and all other symbols as defined above.

The formula used for the calculation of the effective area of the transfer standard is

$$A_p = \frac{g \cdot \sum M_i \cdot \Phi_i \cdot \left(1 - °_{\mathrm{a}}/8000\right) + 2 \cdot \pm \cdot \left(® \cdot A_{0,\mathrm{nom}}\right)^{0.5}}{p \cdot \left[1 + \left(\sim_{\mathrm{p}} + \sim_{\mathrm{c}}\right) \cdot \left(t_{\mathrm{LS}} - t_0\right)\right]}, \quad (7)$$

where

$A_{0,\mathrm{nom}}$ is the nominal effective area of the TS

and other symbols as previously defined. Quantities with subscript "LS" refer to properties of LS, all other quantities are properties of TS or parameters which are common for both LS and TS.

2.4. NIS pressure balance and measurement method

Laboratory standard’s data and measurement conditions at NIS are given in Table 5. The uncertainties here are expressed as the standard ones.

Table 5. NIS laboratory standard and measurement conditions

Manufacturer	Desgranges et Huot
Measurement range in MPa	5 – 500
Material of piston	stainless steel
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.96122
Relative uncertainty of A_0 in 10^{-6}	17
Pressure distortion coefficient (ª) in MPa^{-1}	$8.5\cdot10^{-7}$ MPa^{-1}
Uncertainty of ª in MPa^{-1}	$8.5\cdot10^{-8}$ MPa^{-1}
Relative uncertainty of mass pieces in 10^{-6}	0.55
Linear thermal expansion coefficient of piston ($\sim_{\mathrm{p}}$) in °C^{-1}	$1.05\cdot10^{-5}$
Linear thermal expansion coefficient of cylinder ($\sim_{\mathrm{c}}$) in °C^{-1}	$4.5\cdot10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.79299376
Relative uncertainty of g in 10^{-6}	0.3
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0
Uncertainty of h in mm	1

2.5. NMISA pressure balance and measurement method

The laboratory standard is a Ruska 2485 PCU, serial number, J251, Table 6.

Table 6. NMISA laboratory standard and measurement conditions

Manufacturer	Ruska
Measurement range in MPa	0 – 500
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.9615874
Relative uncertainty of A_0 in 10^{-6}	97
Pressure distortion coefficient (ª) in MPa^{-1}	$7.25 \cdot 10^{-7}$
Uncertainty of ª in MPa^{-1}	$1 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	1
Linear thermal expansion coefficient of piston (~$_p$) in $°C^{-1}$	$4.55 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (~$_c$) in $°C^{-1}$	$4.55 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.7860994
Relative uncertainty of g in 10^{-6}	1.0
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	173.1
Uncertainty of h in mm	0.2

The calibrated weight set is the Ruska 2485 Mass set, serial number, PS-E-93 as well as a Class S2 100g weight set. The laboratory standard is traceable through an uninterrupted chain to the DHI, 359, characterised dimensionally by the dimensional laboratory of NMISA, which is the National Pressure Standard of South Africa. The mass calibration is traceable to the Mass laboratory of NMISA. Recent calibration for verification was done by the Manufacturer, Ruska, of the laboratory standard used in the comparison. The distortion coefficient was determined by a “simple” formula from the manufacturer’s dimensional properties and elastic constants supplied by the manufacturer.

Various equipment pieces were employed to complete the inter-comparison, such as seen in the Appendix attached.

Cross-Float Method used for calibration. The measurement procedure stipulated in the protocol was followed. The operations manual referenced[2] was used to operate the laboratory standard as well as the appendix attached.

Table 7. Experimental and ambient conditions

t_{LS} / °C	t_{TS} / °C	t_{amb} / °C	p_{amb} / hPa
19.9	19.33	19	867.07

2.6. SMU pressure balance and measurement method

Laboratory standard’s details and measurement conditions are given in Table 8. The uncertainties here are expressed as the standard ones.

Table 8. SMU laboratory standard and measurement conditions

Manufacturer	SMU
Measurement range in MPa	20 – 500
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.961600
Relative uncertainty of A_0 in 10^{-6}	20
Pressure distortion coefficient (ª) in MPa^{-1}	$7{\cdot}10^{-7}$
Uncertainty of ª in MPa^{-1}	$7{\cdot}10^{-8}$
Relative uncertainty of mass pieces in 10^{-6}	2
Linear thermal expansion coefficient of piston ($\sim_p$) in °C^{-1}	$4.5{\cdot}10^{-6}$
Linear thermal expansion coefficient of cylinder ($\sim_c$) in °C^{-1}	$4.5{\cdot}10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8087132
Relative uncertainty of g in 10^{-6}	0.1
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	140
Uncertainty of h in mm	0.5

A_0 uncertainty was determined from comparison measurement with the SMU low pressure standard the uncertainty of which was derived from dimensional measurement. ª uncertainty was determined from material constants.

2.7. IMT pressure balance and measurement method

Laboratory standard’s details and measurement conditions are given in Table 9. The uncertainties here are expressed as the standard ones.

Table 9. IMT laboratory standard and measurement conditions

Manufacturer	DH Instruments, USA
Measurement range in MPa	500
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.960953
Relative uncertainty of A_0 in 10^{-6}	11
Pressure distortion coefficient (ª) in MPa^{-1}	$7.7 \cdot 10^{-7}$
Uncertainty of ª in MPa^{-1}	$0.55 \cdot 10^{-7}$
Relative uncertainty of mass pieces in 10^{-6}	1.5
Linear thermal expansion coefficient of piston ($\sim_p$) in $°C^{-1}$	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder ($\sim_c$) in $°C^{-1}$	$4.5 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.806128
Relative uncertainty of g in 10^{-6}	0.5
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	-46
Uncertainty of h in mm	2

Laboratory standard of IMT is traceable to PTB.

2.8. NPL pressure balance and measurement method

Laboratory standard's details and measurement conditions are given in Table 10.

Table 10. NPL laboratory standards and measurement conditions

Manufacturer	Desgranges & Huot
Measurement range in MPa	5 - 500
Material of piston	steel
Material of cylinder	tungsten carbide
Operation mode, free-deformation (FD) or controlled-clearance (CC)	FD
Zero-pressure effective area (A_0) at reference temperature in mm^2	1.9614694
Relative uncertainty of A_0 in 10^{-6}	12.3
Pressure distortion coefficient (ª) in MPa^{-1}	$0.96 \cdot 10^{-6}$
Uncertainty of ª in MPa^{-1}	$0.12 \cdot 10^{-6}$
Relative uncertainty of mass pieces in 10^{-6}	0.5
Combined linear thermal expansion coefficient of piston ($\sim_p$) and cylinder ($\sim_c$) in $°C^{-1}$	$15 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8118165
Relative uncertainty of g in 10^{-6}	0.1
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	8.07
Uncertainty of h in mm	0.01

The D&H base supplied was not used. Instead, the TS was installed in a D&H post belonging to NPL and the TS was treated as would a 500 MPa PCU submitted for calibration – i.e. NPL normal procedures were followed. The post was attached to a ridged, steel tripod via an NPL manufactured kinematic base. A constant volume valve (CVV) was attached to the post via a short length of pipe and an elbow. The LS was mounted alongside in the same way and connected to the TS with the minimum length of pipework. The protocol was followed as closely as possible.

The TS was checked for magnetism prior to installation in the mounting post. It was found to be significant – the max residual magnetism found was 2.0 Gauss (on the piston). It was de-gaussed to less than 0.1 Gauss.

The pressure transmitting fluid used for both the LS & TS was DHS. The NPL pressure intensifier required a quantity of fluid greater than was supplied and therefore it was decided not to waste time draining the intensifier and to just use the fluid belonging to NPL. The equation supplied for calculating fluid density was not used and the following was used instead:

Oil density = $(\rho + T \times TC) + (CF_1 \times p) + (CF_2 \times p^2) + (CF_3 \times p^3) + (CF_4 \times p^4)$

Where:

ρ = 930.54 kg/m^3
T = Temperature of the oil in °C
TC = Temperature Coefficient = -0.7940 kg/m^3 ºC^{-1}
CF_1 = Compressibility Factor 1 = 0.5745546347 kg/m^3 MPa^{-1}
CF_2 = Compressibility Factor 2 = -0.0012784958 kg/m^3 MPa^{-2}
CF_3 = Compressibility Factor 3 = 0.0000022268 kg/m^3 MPa^{-3}
CF_4 = Compressibility Factor 4 = -0.0000000015 kg/m^3 MPa^{-4}

There was no need to use the 100 kg weight set supplied by the pilot laboratory as NPL had its own set.

The piston fall rates (v_f) were measured as:

p / MPa	v_f / (mm/min)
50	0.36
250	1.62
500	2.95

The PRT provided was not used. To save time, an Edale thermistor thermometer belonging to NPL was used to measure the temperature of both the LS & TS.

Equilibration was established by the 'traditional' method – i.e. by trimming either the LS or the TS with small masses until balance is achieved. Both the TS and LS were spun by hand.

The equation used to calculate p and A_p were identical with (5) and (7).

3. Transfer standard

The transfer standard was a piston-cylinder assembly of 2 mm^2 nominal effective area with serial number 6494. It was built in a pressure balance equipped with a mass carrier, all parts having been manufactured by DH-Budenberg, France. Some of participants operated the TS pressure balance with their own 100 kg mass sets. Laboratories which did not have masses suitable for operation of the TS pressure balance were provided with a mass set from UME. The piston-cylinder assembly of TS was manufactured in 2000.

The TS stability was checked by the pilot laboratory comparing the results of former calibrations with those obtained at the beginning of the comparison, at the intermediate test and at the final investigation. Stability check measurements were performed at UME in May 2009, November 2009 and at the end of comparison in January 2011. Average drift of effective area A_p was found as 0.000016 mm^2/ year. During the initial investigation, TS was compared with a nominally identical piston cylinder unit (no. 9630), which was then stored for the whole period of the comparison as a backup unit for the case of a TS lost or damage. The list of TS components is given below:

1. Piston-cylinder assembly serial no. 6494 in carrying case with a special mounting key
2. Carrying bell, serial no. 3387
3. Pressure balance model 5306, serial no. 9161
4. 4 foot rests for the pressure balance
5. 3 piston travel limit pins
6. Cylinder retaining nut
7. 2 quick connectors no. 41102
8. Plug for quick-connecting head
9. 1 glass bottle with sebacate
10. Oil run-off cup
11. Temperature probe serial no. 2651 (built in pressure balance and serial number is attached on temperature probe's cable)
12. Temperature probe output cable
13. Power supply SCL25-7612, AC input (100-240) V, (50-60) Hz
14. Power supply cord
15. User's Manual Reference Pressure Balance, 5300 Series, Model 5306
16. Handle of variable volume screw press
17. Plug for mounting post

18. Torque spanner TORQUELEADER model ads 8 serial no. 0AA000763 with an adapter.
19. Terminal 5000, serial no. 9163

The transfer standard was sent in one box. It was made of wood, had the size 64x84x81 cm^3 and the weight (with contents) of about 70 kg. It contained the dead weight base, the carrying bell, temperature probe's display, the piston-cylinder assembly in a wooden case as well as all other parts of TS. The mass set was sent in a separate box. It was made of wood, had the size 76x96x58 cm^3 and the weight (with contents) of about 177 kg. It contained the 100 kg mass set in 5 wooden cases. The transfer standard and all accompanying parts are the property of the UME. The total cost of TS including the pressure balance and the piston-cylinder unit is 37000 €. Mass set is 20000 € and temperature display is 4500 € .

The details of the initial TS evaluation by the pilot laboratory and all relevant technical data of TS are given in below: All uncertainties in this Annex are standard ones.

Piston-cylinder assembly

The serial number, 6494, is engraved on the upper cylinder face and the upper piston cap face. The nominal effective area of the assembly is

$A'_{0,nom}$ = 1.96 mm^2.

Piston-cylinder material properties

The cylinder of the assembly is made of tungsten carbide, and the piston is made of steel with the following linear thermal expansion coefficient (~), Young's modulus (*E*) and Poisson's coefficient (μ):

	Material	~ / $°C^{-1}$	*E* / GPa	μ
Piston	Non magnetic stainless steel (AISI 304L)	$(1.05 \pm 0.10)\cdot 10^{-5}$	200	0.3

	Material	β / $°C^{-1}$	E / GPa	μ
Cylinder	Tungsten carbide	$(0.45 \pm 0.05)\cdot 10^{-5}$	620	0.218

The thermal expansion coefficient of the piston-cylinder unit can be taken as

~ + β = $(1.50 \pm 0.15)\cdot 10^{-5}$ $°C^{-1}$ (see calibration certificate from DH-Budenberg with the number of 12855 and date of 16.06.2000)

The cylinder cap is of stainless steel.

Piston mass and density

	True mass / g	Density / (g/cm^3)
Piston	200.0069 ± 0.003	7.920 ± 0.02

Reference level and piston working position

The piston working position is 5 mm above its rest position.

The reference level of the TS coincides with the piston lower face; the total piston length (distance from the piston lower face to the upper piston cup edge) is 84.39 mm.

The pilot laboratory measurements in which the piston was located within [-1; +1] mm around its normal working position have not shown any systematic change in the effective area.

Typical cross-float sensitivity and reproducibility

The change in the TS piston load by 20 mg at 50 MPa, 50 mg at 150 MPa and 100 mg at 350 MPa led to a reproducible reverse of the TS piston motion when it was compared with the UME reference standard. This corresponds to the relative sensitivity in pressure of $2·10^{-6}$, $1.7·10^{-6}$ and $1.4·10^{-6}$ at pressures (50, 150 and 350) MPa, respectively.

The relative experimental standard deviations of single values of the effective areas measured at the pressures specified for the comparison lied typically between (3 and 7)$·10^{-6}$.

Piston-cylinder temperature drift

When the driving motor was continuously working, the temperature of the piston-cylinder assembly increased with a typical rate between (0.79, 0.49, 0.20 and 0.09) K/h during first 4 h.

Piston fall rates

Piston fall rates (v_f) measured by the pilot laboratory at temperatures around 20 °C were

p / MPa	v_f / (mm/min)
50	0.04
100	0.08
150	0.10
200	0.12
250	0.14
300	0.17
350	0.19
400	0.20
450	0.25
500	0.24

It had to be waited minimum 10 minutes after generating the pressure in the TS measurement system prior to starting the piston fall rate measurements in order to stabilise the TS temperature. When measuring v_f, both the low and the high pressure shut off valves had to be closed to avoid the effect of possible oil leak from the variable volume screw press.

Carrying bell

The carrying bell, serial number 3387, is made of stainless steel. Its true mass is m_b = (800.047 ± 0.001) g. Its density is °$_b$ = 7914·(1 ± 3·10^{-3}) kg/m^3.

Mass set

The mass set consists of 26 mass pieces listed in the table below. The material density of the mass pieces is °$_m$ = (7920 ± 25) kg/m^3. The conventional mass of the mass pieces is given in the table below.

Nominal value	Marking	Conventional mass in kg
5 kg	5 kg 1 3387	5000.000
5 kg	5 kg 2 3387	4999.987
5 kg	5 kg 3 3387	4999.977
5 kg	5 kg 4 3387	4999.975
5 kg	5 kg 5 3387	4999.983
5 kg	5 kg 6 3387	4999.971
5 kg	5 kg 7 3387	4999.973
5 kg	5 kg 8 3387	4999.971
5 kg	5 kg 9 3387	4999.962
5 kg	5 kg 10 3387	4999.971
5 kg	5 kg 11 3387	4999.969
5 kg	5 kg 12 3387	4999.966
5 kg	5 kg 13 3387	4999.971
5 kg	5 kg 14 3387	4999.98
5 kg	5 kg 15 3387	4999.982
5 kg	5 kg 16 3387	4999.995
5 kg	5 kg 17 3387	4999.974
5 kg	5 kg 18 3387	4999.988
4 kg	5 kg 19 3387	3999.995
2 kg	4 kg 3387	2000.007
2 kg	2 kg 3387	1999.997
1 kg	2 kg 3387	999.999
0.5 kg	0.5 kg 3387	499.999
0.2 kg	0.2 kg 3387	199.998
0.2 kg	0.2 kg 3387	199.999
0.1 kg	0.1 kg 3387	99.999

The uncertainty of the conventional mass values is 4.0 mg (k = 2) .

Temperature probe

The platinum resistance thermometer was calibrated with its display. The temperature value of piston-cylinder unit had to be read from the temperature display.

Reference temperature value in °C	Digital thermometer's temperature value in °C	Correction in °C	Uncertainty (k=2) in °C
19.01	19.01	0.00	0.03
20.02	20.01	0.01	
21.01	21.01	0.00	
22.02	22.02	0.00	
23.02	23.02	0.00	
24.02	24.02	0.00	
25.02	25.03	-0.01	

Pressure transmitting medium

The working liquid is di(2-ethylhexyl) sebacate (DHS). According to the literature data its density ($°_l$) in dependence on pressure (p) and temperature (t) is

$°_l = [912.7 + 0.752(p/\text{MPa}) - 1.65{\cdot}10^{-3}(p/\text{MPa})^2 + 1.5{\cdot}10^{-6}\,(p/\text{MPa})^3] \times [1 - 7.8{\cdot}10^{-4}\,(t/°\text{C} - 20)] \times (1 \pm 0.01)\ \text{kg/m}^3$.

The surface tension (±) of DHS as given by the PTB laboratory is: ± = 31.2 × (1 ± 0.05) mN/m.

4. Organization, chronology and problems during the comparison

The measurements with the transfer standard were performed in accordance with the schedule given below.

Table 11. Measurement Schedule

Measurement time	Institute	Equipment used
16 - 22 May 2009	UME (Turkey), initial investigation of TS	PCU, base and mass set
15 - 19 June 2009	PTB (Germany)	PCU and base
7-13 July 2009	INRIM (Italy)	PCU, base and mass set
28 August – 2 September 2009	NIS (Egypt)	PCU and base
17 November – 1 December 2009	UME (Turkey), intermediate check of TS	PCU, base and mass set
14 December 2009	NMISA (South Africa)	PCU, base and mass set
9 March – 13 April 2010	SMU (Slovakia)	PCU and base
5 – 9 Temmuz 2010	IMT (Slovenia)	PCU, base and mass set
3 – 17 November 2010	NPL (United Kingdom)	PCU
29 December 2010 – 04 January 2011	UME (Turkey), final investigation of TS	PCU, base and mass set

5. Measurement procedures

The transfer standard was handled and the piston-cylinder assembly mounted in accordance with the instructions given in the User's Manual Reference Pressure Balance, 5300 Series, Model 5306.

The results of a metrological characterisation of TS by the pilot laboratory were as presented above. They had to help participants to verify that the TS operates normally. In the case of any anomaly or significant deviation from the results of the pilot laboratory it had to be contacted.

Gloves had to be worn when handling the piston, the carrying bell and the masses of TS.

At the beginning, the magnetisation of the piston and cylinder had to be checked. The magnetic flow density at their surfaces had not to exceed $2{\cdot}10^{-4}$ Tesla. If it was higher, the parts had to be demagnetised and the magnetisation had to be checked again.

Before mounting the assembly the piston and cylinder had to be cleaned according to the usual practice in the laboratory.

The cylinder had to be installed in the mounting post and clamped with a torque of 5.5 Nm measured with a torque spanner sent with TS.

The TS pressure balance was operated with DHS as a pressure transmitting medium whose properties are reported in Annex 1. No other liquid had to be used in the TS pressure balance. If a participating laboratory used another liquid in its own standard, it had to take special measures to separate DHS from that liquid to avoid contamination of TS by it. These measures had to be reflected in the laboratory report. Nevertheless each laboratory receiving TS had to check that TS is filled with a clean DHS, and, if it was contaminated, had to report this in the Arrival check protocol.

To check the tightness of TS, the piston fall rate had to be measured preferably at pressures of (500, 250 and 50) MPa. Waiting a minimum of 10 minutes after generating the pressure in the TS measurement system prior to starting the piston fall rate measurements in order to stabilise the TS temperature was required. During these measurements both the low and the high pressure shut off valves had to be closed because even a minimal leak in the variable volume screw press can significantly disturb the results. The target fall rates were as given above. The measured fall rates had to be reported to the pilot laboratory in the laboratory report.

The temperature of TS was measured with a platinum resistance thermometer calibrated by the pilot laboratory (see Section 3). Each laboratory had to use the temperature display.

The reference temperature of the comparison was 20 °C. If measurements were performed at a temperature deviating from 20 °C, the effective area of TS had to be referred to 20 °C using the piston-cylinder thermal expansion coefficient given above.

TS was recommended to be located close to the laboratory's reference standard to keep the pressure line between the two instruments as short as possible.

It was also recommended to adjust the height position of TS to minimise the height difference between the reference level of TS defined in Section 3 and the reference level of the laboratory standard.

Piston displacement indicator could be used to control the piston position.

In the equilibrium state, the piston of TS had not to deviate from its working position by more than 0.5 mm.

During a cross-float equilibrium between the reference standard and TS, both the low and the high pressure shut off valves had to be closed to avoid the effect of possible oil leak in the variable volume screw press.

The pressure balance model 5306 had no electronics to be warmed up.

The direction and the rotation speed of the piston were predefined by the motor of the pressure balance model 5306. The rotation was CCW with the speed 21 rpm. It was assumed that the motor is switched on during the cross-float equilibrium measurement.

As the motor is the main source of heat (s. Section 3), the piston rotation had to be switched on at least 30 minutes before starting the measurement to get a quasi-stationary distribution of temperatures in the pressure balance. In the time between taking measurement points, the motor was recommended to stay switched on. Only if the time till the next measurement exceeded approximately 2 hours, the motor could be switched off. However, in such a case, it had to be switched on at least 30 minutes prior to the next measurement.

The time between a pressure level change and the acquisition of the data corresponding to the equilibrium of the laboratory standard and TS had to be not shorter than 5 minutes.

The measurements included five cycles each with nominal pressures generated in the following order (50, 100, 150, 200, 250, 300 350, 400, 450, 500, 500, 450, 400, 350, 300, 250, 200, 150, 100, 50) MPa. The generated pressures had to not deviate from these nominal values by more than 0.1 MPa. Thus, 100 measurements were performed in total. It had to be waited for at least 15 minutes between two consequent measurements at 500 MPa and between two measurement cycles.

The masses of the piston and the carrying bell are given in Section 3.

6. Results

6.1. Stability of the transfer standard

Stability check measurements performed at UME in May 2009, November 2009 and at the end of comparison in January 2011 are shown in Figures 1. They show an increase in the effective area with time.

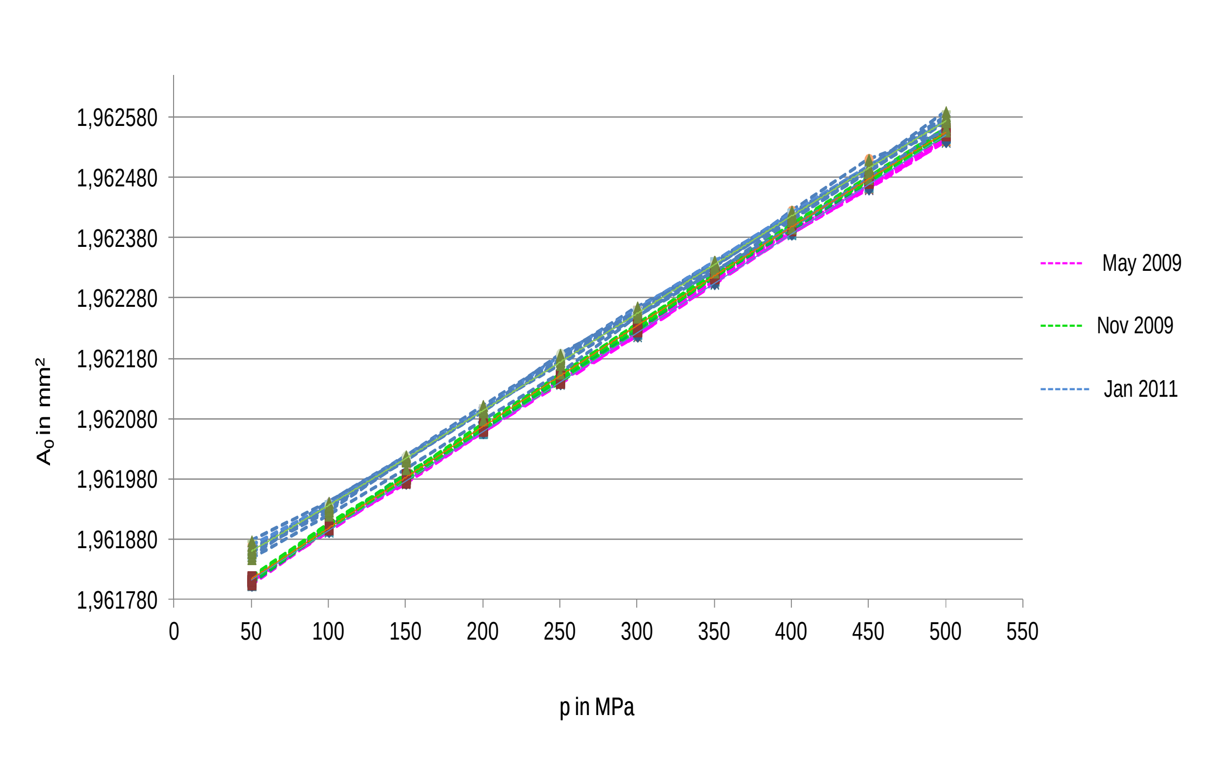

Figure 1. Stability of transfer standard. Single values of effective area by UME in May 2009, Nov 2009, Jan 2011

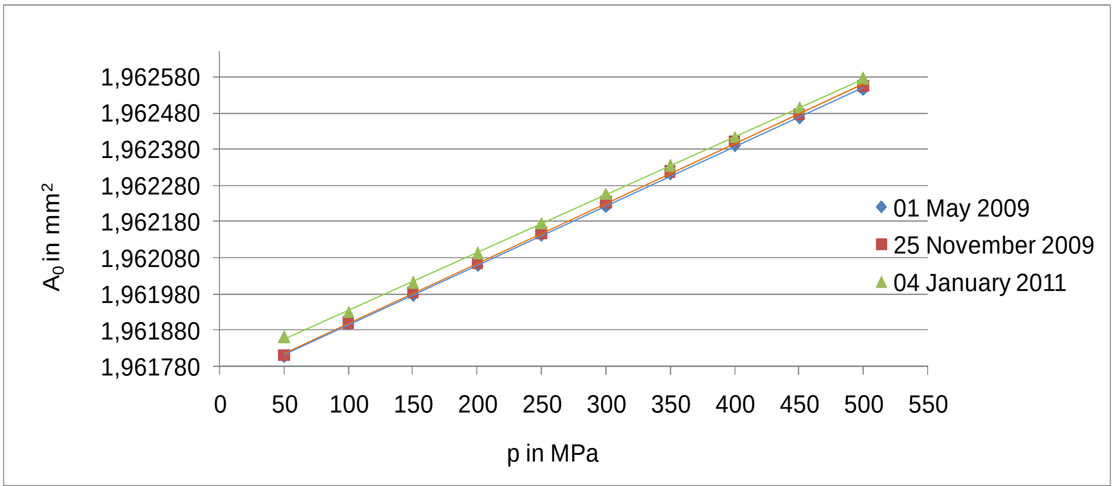

Figure 2. Stability of transfer standard. Mean effective areas measured by UME in May 2009, Nov 2009 and Jan 2011

The drift rate of A_p with time (T), $dA_p/dT/A_p$, was determined for each nominal pressure as the slope of a linear fit of the mean A_p values obtained by UME at this pressure in May 2009, November 2009 and January 2011. Choosing the end of the comparison January 2011 as a reference time point (T_0), any effective area measured at time T ($A_{p,T}$) can be corrected to this reference time according to

$$A_{p,T\text{o}} = A_{p,T} \times [1 + dA_p/dT/A_p \times (T_0 - T)]. \quad (8)$$

The uncertainty ($u(\Delta A_{p,T})$) of the drift correction $\Delta A_{p,T} = A_{p,T} \times dA_p/dT/A_p \times (T_0 - T)$, was determined as the sum of the uncertainty of the linear fit and standard deviation of the UME values from May 2009, November 2009 and January 2011 after having corrected them for the drift:

$$u(\Delta A_{p,T}) = \text{sqrt}((\text{StDev}\{A_{p,T\text{o},\text{UME-May2009}}; A_{p,T\text{o},\text{UME-Nov2009}}; A_{p,T\text{o},\text{UME-Jan2011}}\})^2 + u^2_{\text{linear fit}}) \quad (9)$$

UME results from the three measurements in May 2009, Nov. 2009 and Jan. 2011 used for drift correction calculation, the drift rate and the uncertainty for drift correction are shown in Table 12.

Table 12. Effective areas measured by UME in May 2009, Nov. 2009 and Jan.2011 ($A_{p,\text{UME}}$), mean drift rate ($dA_p/dT/A_p$) and relative standard uncertainty of the drift correction ($u(\text{a}A_{p,T})/A_p$)

p / MPa	$A_{p,\text{UME}}$ / mm^2			$dA_p/dT/A_p$ / day	$u(\Delta A_{p,T})/A_p \times 10^6$
	01 May 2009	25 Nov 2009	04 Jan 2011		
50	1.961807	1.961812	1.961862	4.94E-08	4.8
100	1.961897	1.961901	1.961933	3.16E-08	3.8
150	1.961976	1.961983	1.962012	3.16E-08	3.4
200	1.962058	1.962065	1.962093	3.11E-08	3.3
250	1.962142	1.962148	1.962175	2.96E-08	3.4
300	1.962221	1.962233	1.962257	3.06E-08	3.1
350	1.962311	1.962318	1.962333	1.94E-08	3.1
400	1.962389	1.962399	1.962414	2.09E-08	3.2
450	1.962465	1.962475	1.962494	2.45E-08	3.2
500	1.962543	1.962554	1.962575	2.65E-08	3.1

Maximum drift corrections and corrections to be applied to particular NMIs are presented in Figure 3 and Table 13, respectively.

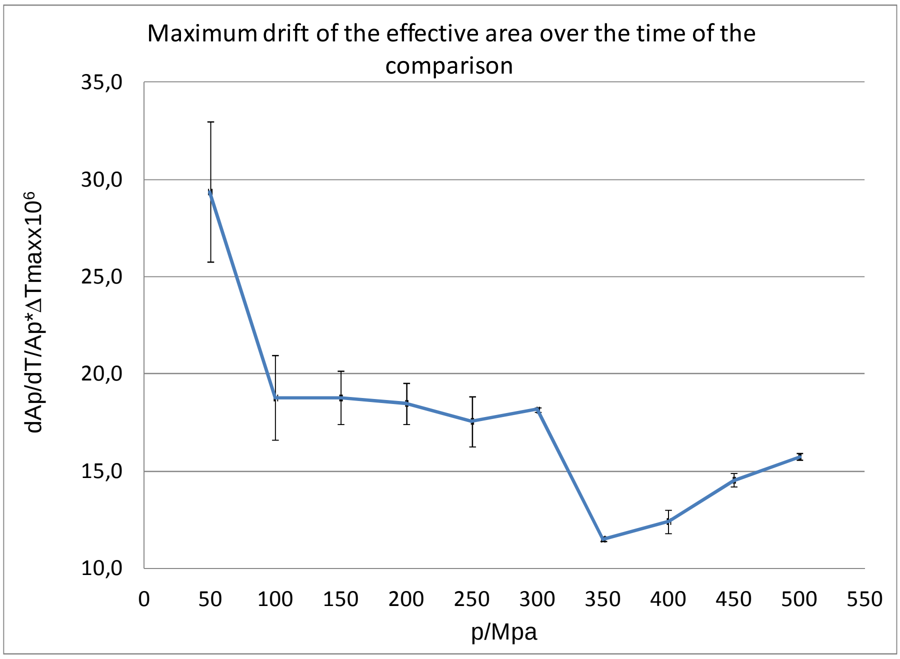

Figure 3. Maximum drift of the effective area over the time of the comparison with the vertical bars indicating the standard uncertainty of the drift correction

Table 13. Relative drift corrections (a$A_{p,T}/A_p$) to be applied to effective areas $A_{p,T}$ measured at pressure (p) and time (T) to transform them to reference time (T_0)

NMI	UME1	PTB	INRIM	NIS	UME2	NMISA	SMU	IMT	NPL	UME3
start date	16.5.09	15.6.09	7.7.09	28.8.09	17.11.09	14.12.09	9.3.10	5.7.10	3.11.10	29.11.10
end date	20.5.09	19.6.09	13.7.09	2.9.09	1.12.09	14.12.09	13.4.10	9.7.10	17.11.10	4.1.11
(T-T_0) / day	594	564	540	489	399	386	266	179	48	0
p / MPa	$\Delta A_{p,T}/A_p \times 10^6$									
50	29.4	27.9	26.7	24.2	19.7	19.1	13.2	8.9	2.4	0
100	18.8	17.8	17.1	15.5	12.6	12.2	8.4	5.7	1.5	0
150	18.8	17.8	17.1	15.5	12.6	12.2	8.4	5.7	1.5	0
200	18.5	17.5	16.8	15.2	12.4	12.0	8.3	5.6	1.5	0
250	17.6	16.7	16.0	14.5	11.8	11.4	7.9	5.3	1.4	0
300	18.2	17.2	16.5	15.0	12.2	11.8	8.1	5.5	1.5	0
350	11.5	10.9	10.5	9.5	7.7	7.5	5.2	3.5	0.9	0
400	12.4	11.8	11.3	10.2	8.3	8.1	5.6	3.7	1.0	0
450	14.5	13.8	13.2	12.0	9.8	9.4	6.5	4.4	1.2	0
500	15.7	14.9	14.3	13.0	10.6	10.2	7.0	4.7	1.3	0

6.2. Results of the participants

Mean effective areas, standard deviations of the effective areas at each pressure and the combined relative standard uncertainties of the effective areas declared by the participants are given in Table 14.

The participants’ mean effective areas corrected for drift are given in Table 15.

Table 16 presents the uncertainties of A_0 and ª for the laboratories standards, values for A_0 of the TS with their associated standard deviations, standard uncertainties and deviations from the mean zero-pressure effective area, $<A_0>$, and ª of the TS with its associated standard deviation, standard uncertainty, and deviation from the mean pressure distortion coefficient.

Table 14. Mean effective areas (A_p), their relative standard deviations ($s(A_p)/A_p$) and combined uncertainties ($u(A_p)/A_p$) as reported by participants without drift correction

p / MPa	PTB			INRIM			NIS			NMISA			SMU			IMT			NPL			UME		
	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	$s(A_p)/A_p \times 10^6$	$u(A_p)/A_p \times 10^6$
50	1.961879	0.7	14	1.961899	3.7	24	1.961853	1.5	18	1.961919	13.5	26	1.961915	7.1	16	1.961881	2.8	13	1.961853	2.2	24	1.961807	4.5	15
100	1.961959	1.3	14	1.961927	3.4	24	1.961936	2.5	19	1.961957	15.2	29	1.961989	6.6	19	1.961963	1.3	13	1.961972	2.9	26	1.961897	3.4	14
150	1.962045	1.5	15	1.961974	3.7	25	1.962024	2.9	21	1.962020	8.8	17	1.962062	6.7	22	1.962044	1.3	15	1.962085	2.8	28	1.961976	3.2	15
200	1.962125	1.6	17	1.962040	3.1	26	1.962115	2.1	24	1.962070	9.1	17	1.962140	7.3	22	1.962123	1.5	16	1.962198	2.1	31	1.962058	3.1	16
250	1.962207	1.2	18	1.962115	2.9	26	1.962204	1.3	27	1.962097	18.1	38	1.962217	10.4	26	1.962198	2.1	18	1.962308	1.7	34	1.962142	4.5	19
300	1.962286	1.0	20	1.962187	2.2	28	1.962294	0.9	31	1.962160	17.2	36	1.962295	16.6	31	1.962270	1.9	21	1.962410	1.6	38	1.962221	2.7	19
350	1.962366	1.8	22	1.962263	3.1	29	1.962384	0.5	34	1.962244	12.2	25	1.962374	17.6	36	1.962341	1.9	23	1.962513	1.7	42	1.962311	3.1	22
400	1.962445	2.4	24	1.962343	2.0	31	1.962472	0.4	38	1.962319	12.9	26	1.962454	16.6	41	1.962411	2.5	25	1.962614	1.2	46	1.962389	4.1	24
450	1.962527	2.6	26	1.962425	2.2	32	1.962557	0.3	42	1.962412	8.0	15	1.962533	15.8	50	1.962480	3.3	28	1.962714	1.1	51	1.962465	4.2	27
500	1.962607	3.0	28	1.962497	2.0	34	1.962649	0.3	46	1.962466	7.3	15	1.962614	12.1	55	1.962550	7.0	31	1.962812	1.4	55	1.962543	3.8	28

Table 15. Mean effective areas (A_p) corrected for transfer standard drift

p / MPa	PTB	INRIM	NIS	NMISA	SMU	IMT	NPL	UME
	A_p / mm^2	A_p / mm^2	A_p / mm^2	A_p / mm^2	A_p / mm^2	A_p / mm^2	A_p / mm^2	A_p / mm^2
50	1.961933	1.961951	1.961900	1.961956	1.961941	1.961898	1.961857	1.961865
100	1.961994	1.961960	1.961966	1.961981	1.962005	1.961974	1.961975	1.961955
150	1.962080	1.962007	1.962054	1.962044	1.962078	1.962055	1.962088	1.962034
200	1.962160	1.962073	1.962144	1.962094	1.962156	1.962134	1.962201	1.962115
250	1.962240	1.962146	1.962233	1.962119	1.962233	1.962208	1.962311	1.962200
300	1.962320	1.962219	1.962324	1.962183	1.962311	1.962281	1.962413	1.962279
350	1.962387	1.962284	1.962403	1.962259	1.962385	1.962348	1.962515	1.962368
400	1.962469	1.962365	1.962492	1.962335	1.962465	1.962418	1.962616	1.962447
450	1.962554	1.962451	1.962580	1.962431	1.962546	1.962489	1.962716	1.962523
500	1.962636	1.962525	1.962674	1.962486	1.962628	1.962559	1.962815	1.962601

Table 16. Relative standard uncertainties of zero-pressure effective areas ($u(A_{0,LS})/A_{0,LS}$) and standard uncertainties of distortion coefficients ($u(a_{LS})$) of the laboratory standards; zero-pressure effective areas of TS (A_0), their relative standard deviations ($s(A_0)/A_0$), standard uncertainties ($u(A_0)/A_0$) and relative deviations from the average zero-pressure effective area ((A_0-<A_0>)/<A_0>); pressure distortion coefficient of TS (a), its standard deviation ($s(a)$), standard uncertainty ($u(a)$) and deviation from the average pressure distortion coefficient (a-<a>).

Property	PTB	INRIM	NIS	NMISA	SMU	IMT	NPL	UME
$u(A_{0,LS}) / A_{0,LS} \times 10^6$	13	23	34	97	20	11	24	17
$u(a_{LS}) \times (10^6$ MPa)	0.05	0.05	0.17	10	0.07	0.06	0.25	0.05
A_0 / mm^2	1.961800	1.961785	1.961760	1.961881	1.961830	1.961819	1.961764	1.961731
A_0 / mm^2 *)	1.961845	1.961828	1.961800	1.961912	1.961852	1.961834	1.961768	1.961731
$s(A_0)/A_0 \times 10^6$	4.4	23.2	10.6	31.1	13.2	10.2	11.5	5.2
$s(A_0)/A_0 \times 10^6$ *)	7.3	27.7	12.3	32.5	14.1	9.5	11.2	5.2
$u(A_0)/A_0 \times 10^6$	13.7	32.6	35.6	101.9	24.0	15.0	26.6	17.5
$u(A_0)/A_0 \times 10^6$ *)	14.9	36.0	36.2	102.3	24.5	14.5	26.5	17.5
(A_0-<A_0>)/<A_0> $\times 10^6$ *)	12.4	3.6	-10.9	46.3	15.6	6.3	-27.2	-46.0
$a \times (10^6$ MPa) *)	0.80	0.69	0.88	0.58	0.78	0.75	1.08	0.83
$s(a) \times (10^6$ MPa)	0.01	0.07	0.03	0.10	0.04	0.03	0.04	0.02
$s(a) \times (10^6$ MPa) *)	0.02	0.09	0.04	0.10	0.05	0.03	0.04	0.02
$u(a) \times (10^6$ MPa)	0.1	0.1	0.2	10.0	0.1	0.1	0.3	0.1
(a-<a>) $\times (10^6$ MPa) *)	0.00	-0.11	0.09	-0.22	-0.02	-0.05	0.28	0.03

*) These values have been calculated by the pilot laboratory after applying the drift correction to the participants' results obtained in individual cycles

Relative deviations of the participants' results corrected for the TS drift from the linear fit are shown in Figure 4.

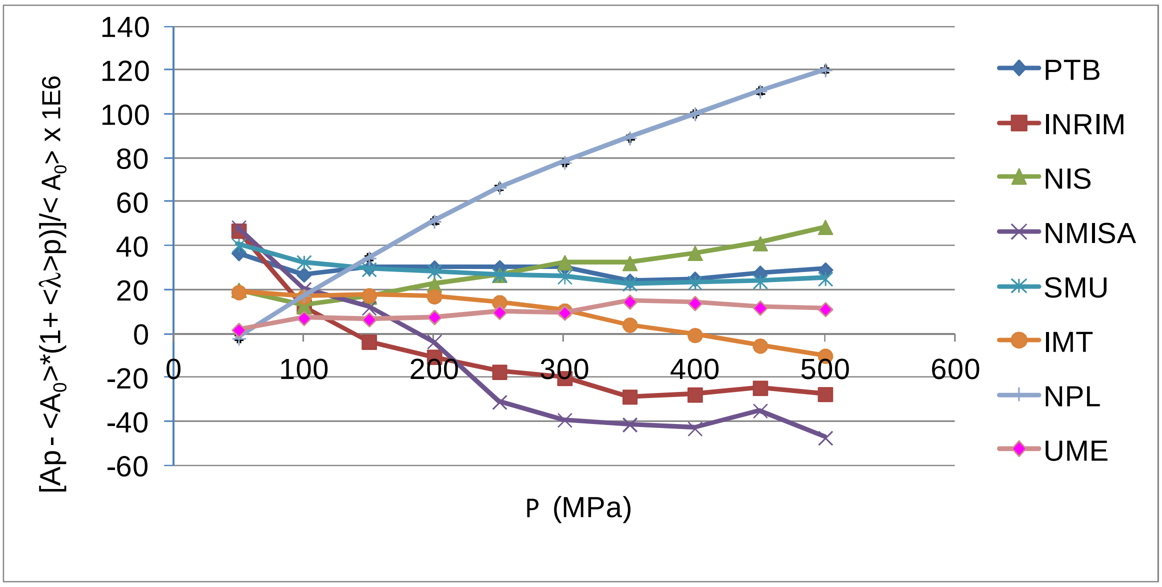

Figure 4. Relative deviations of participants' results from the linear fit

6.3. Reference value calculation

The weighted mean, non-weighted mean and median are 3 common methods which were considered for the calculation of the KC reference value (KCRV), $A_{p,\mathrm{ref}}$. Finally, it was decided to use the median for the KCRV calculation as the most robust method:

$$A_{p,\mathrm{ref}} = \mathrm{median}(A_{p,i}), \tag{10}$$

where $A_{p,i}$ are the participants' effective areas corrected for drift, i = 1,...,n, n = 8 being the number of the participants. The uncertainties of reference values were calculated according to:

$$u(A_{p,\mathrm{ref}}) = \left[\frac{1.858^2}{n-1} \mathrm{median}^2 \left| A_{p,i} - A_{p,\mathrm{ref}} \right| + u^2(A_{p,\mathrm{drift}}) \right]^{0.5}, \tag{11}$$

Among the participants, PTB, INRIM, NMISA, SMU and NPL used primary pressure standards. The NIS and UME pressure standards are traceable to LNE, and the standard of IMT is traceable to PTB. Due to this fact, a more sophisticated method of KCRV calculation could be required. However, as in the last step of the analysis the results of this KC are linked to the KCRV of CCM.P-K13, the choice of the method at this stage is not of great importance.

The KCRV deviations from the linear fit are presented in Figure 5, where the deviations of the non-weighted means are shown too. The KCRVs and their uncertainties are given in Table 17.

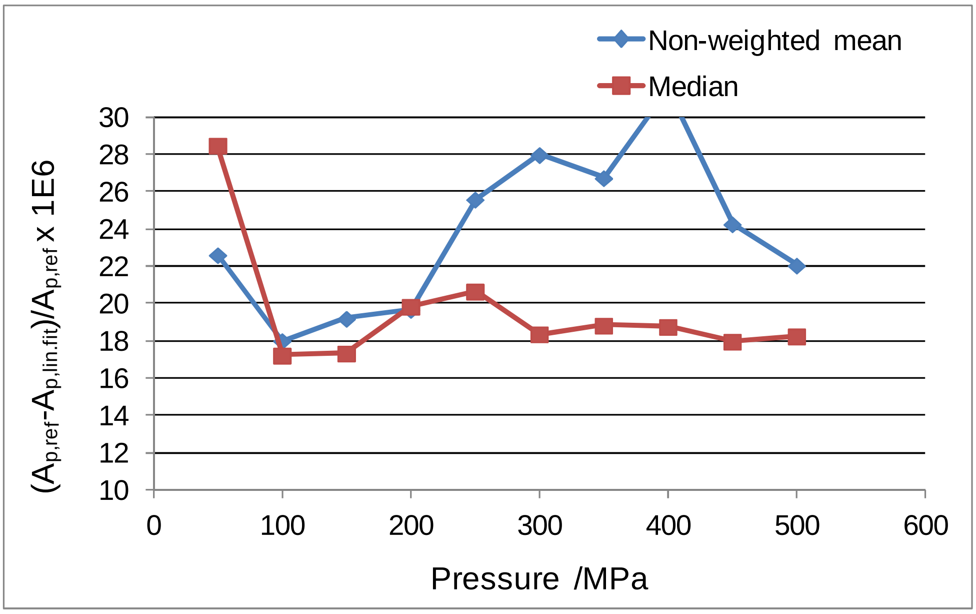

Figure 5. Relative deviations of the reference values calculated as the non-weighted mean and the median from the linear fit

Table 17. Key comparison reference values ($A_{p,\mathrm{ref}}$) and their relative standard uncertainties $u(A_{p,\mathrm{ref}})$ / $A_{p,\mathrm{ref}}$

p / MPa	$A_{p,\mathrm{ref}}$ / mm^2	$u(A_{p,\mathrm{ref}})$ / $A_{p,\mathrm{ref}} \times 10^6$
50	1.961917	11.0
100	1.961975	4.6
150	1.962055	8.1
200	1.962139	8.0
250	1.962221	7.3
300	1.962296	9.3
350	1.962376	9.9
400	1.962456	13.1
450	1.962534	16.4
500	1.962615	20.6

6.4. Degrees of equivalence

The degrees of equivalence of the laboratories are expressed by the relative differences of the laboratories' results from the KCRVs ($\Delta A_{p,i}/A_{p,ref}$) and the expanded (k = 2) relative uncertainties of these differences ($U(\Delta A_{p,i}/A_{p,\mathrm{ref}})$) were calculated by:

$$\Delta A_{p,i} / A_{p,\mathrm{ref}} = \left(A_{p,i} + \Delta A_{p,T,i} - A_{p,\mathrm{ref}}\right) / A_{p,\mathrm{ref}} \tag{12}$$

$$U\left(\frac{\Delta A_{p,i}}{A_{p,\mathrm{ref}}}\right) = 2 \times \frac{\left[u^2\left(A_{p,i}\right) + u^2(\Delta A_{p,T}) + u^2\left(A_{p,\mathrm{ref}}\right)\right]^{0.5}}{A_{p,\mathrm{ref}}} \tag{13}$$

where $\Delta A_{p,T,i}$ and $u(\Delta A_{p,T})$ are the drift corrections and their uncertainties as given in Tables 13 and 12, respectively.

The relative deviations of participants' results from the reference values, $\Delta A_{p,i}/A_{p,\mathrm{ref}}$, are shown graphically in Figure 6.

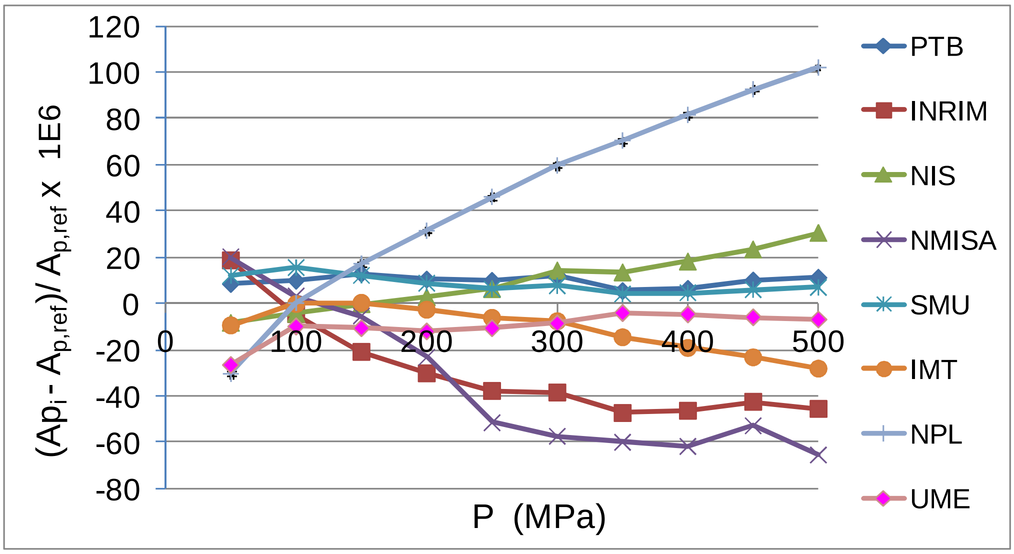

Figure 6. Relative deviations of the participants' results from the reference values

The relative differences between laboratories *i* and *j* were calculated as:

$$d_{ij} = \frac{A_{p,i} - A_{p,j}}{A_{p,\mathrm{ref}}}. \qquad (14)$$

Their expanded (k = 2) uncertainties of these differences were taken as:

$$U(d_{ij}) = 2 \times \frac{\left[u^2(A_{p,i}) + u^2(A_{p,j}) + u^2(A_{p,\mathrm{drift}})\right]^{0.5}}{A_{p,\mathrm{ref}}} \qquad (15)$$

Numerical data for the deviations and the uncertainties at all pressures are given in Table 18 and shown in Figures 7 - 16.

The relative differences between the participants' results with their uncertainties are presented in Tables 19 – 28.

Table 18. Relative deviations of participants' results from the reference values EaA_p/A_p) and their expanded uncertainties UEaA_p/A_p)

p / MPa	PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$	$\Delta A_p/A_p \times 10^6$	$U(\Delta A_p/A_p) \times 10^6$
50	8.4	36	17.6	53	-8.4	42	20.1	57	12.0	39	-9.5	35	-30.4	53	-26.6	37
100	9.8	30	-7.2	49	-4.4	40	3.2	58	15.5	39	-0.2	29	0.2	52	-9.9	29
150	12.9	34	-24.0	52	-0.3	46	-5.4	37	12.2	47	0.3	34	17.2	58	-10.7	34
200	10.4	38	-33.8	54	2.7	51	-23.3	38	8.8	47	-2.7	37	31.4	64	-12.1	35
250	9.8	39	-37.8	55	6.2	56	-51.6	77	6.2	54	-6.2	39	46.1	70	-10.7	40
300	12.2	44	-38.9	58	14.3	64	-57.4	75	7.7	65	-7.7	45	59.7	79	-8.6	42
350	5.4	48	-47.4	61	13.4	71	-60.0	54	4.1	75	-14.6	49	70.4	87	-4.1	48
400	6.3	55	-46.3	67	18.1	80	-61.8	58	4.6	86	-19.2	57	81.5	96	-4.6	55
450	9.9	61	-42.5	72	23.3	90	-52.9	45	6.0	105	-23.3	64	92.6	107	-6.0	63
500	11.1	70	-45.6	80	30.5	100	-65.5	51	7.0	117	-28.2	74	101.9	118	-7.0	70

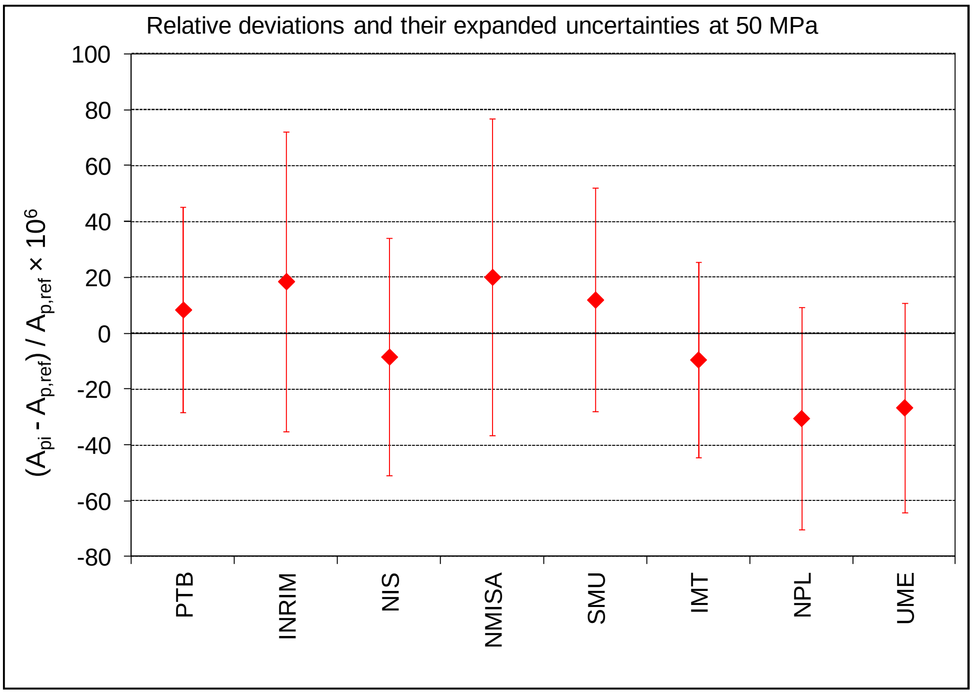

Figure 7. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 50 MPa

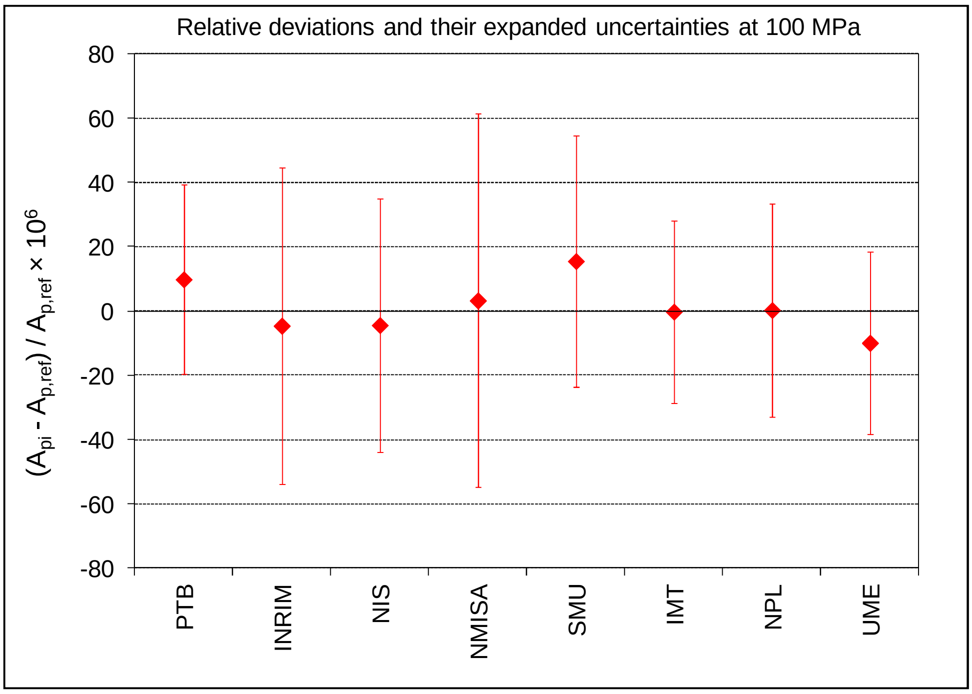

Figure 8. Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at 100 MPa

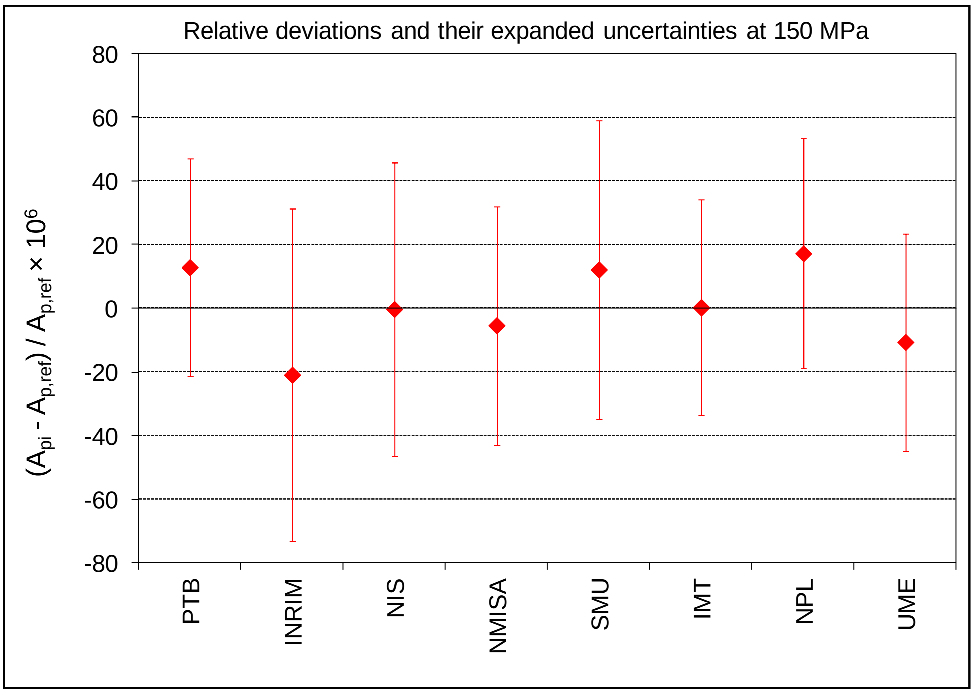

Figure 9. Relative deviations of the participants' results from the reference value and the expanded (*k* = 2) uncertainties of these deviations at150 MPa

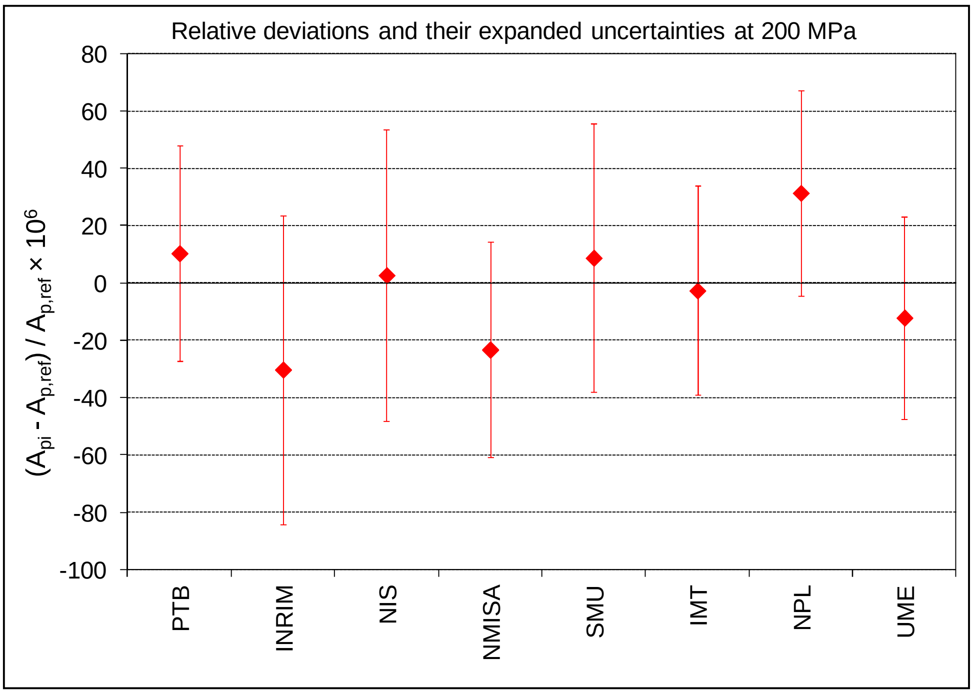

Figure 10. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 200 MPa

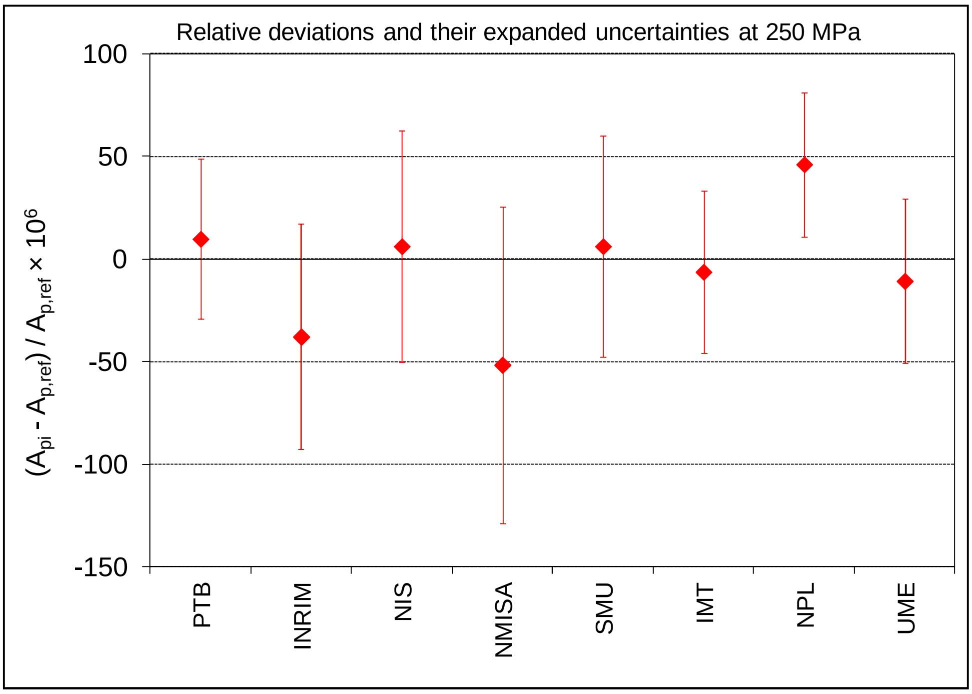

Figure 11. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 250 MPa

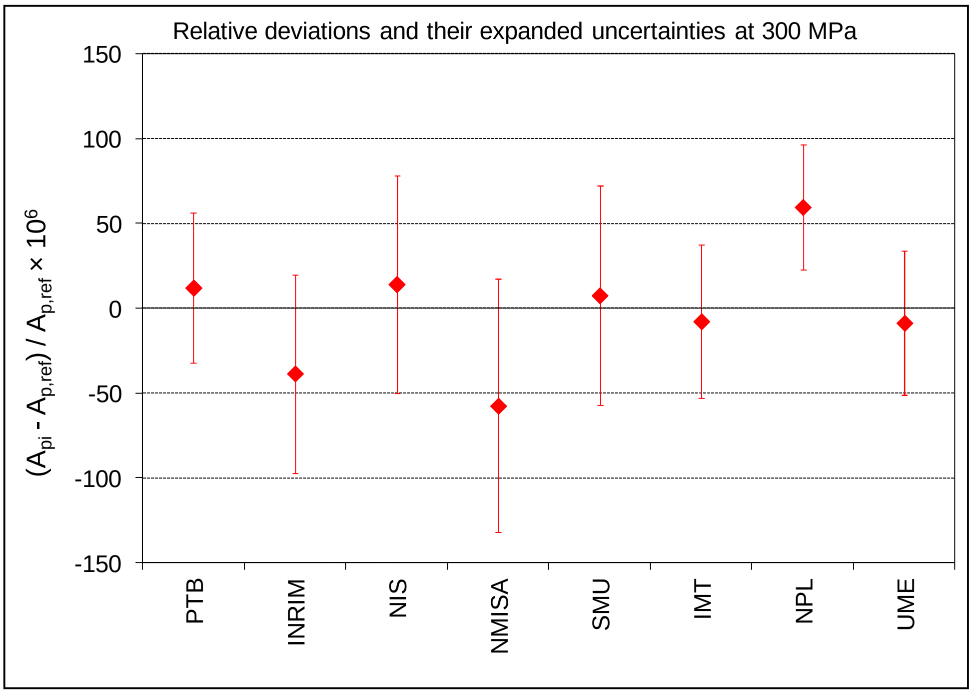

Figure 12. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 300 MPa

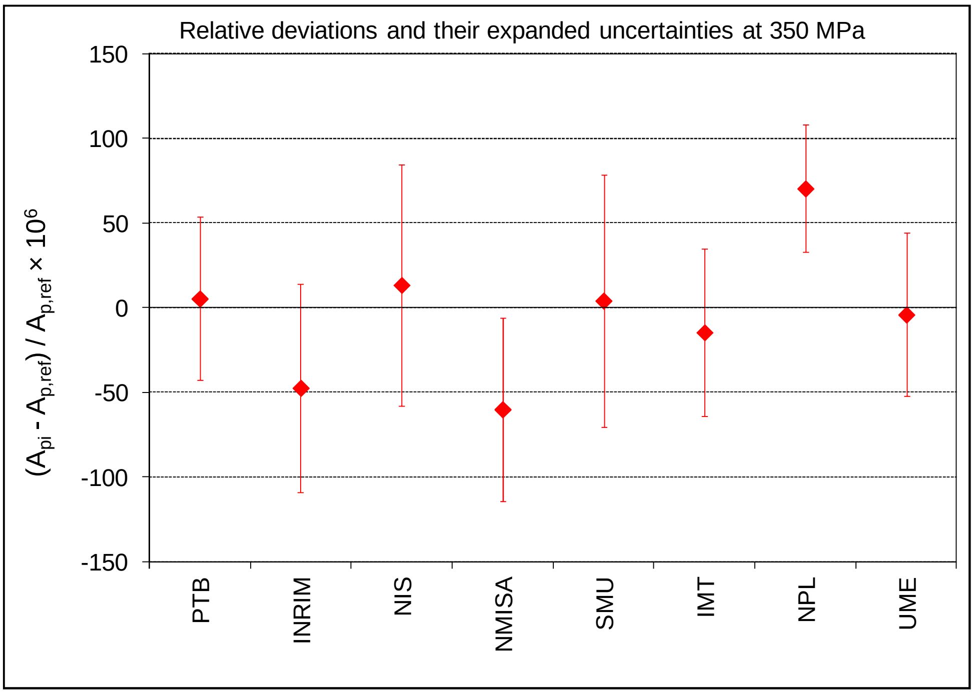

Figure 13. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 350 MPa

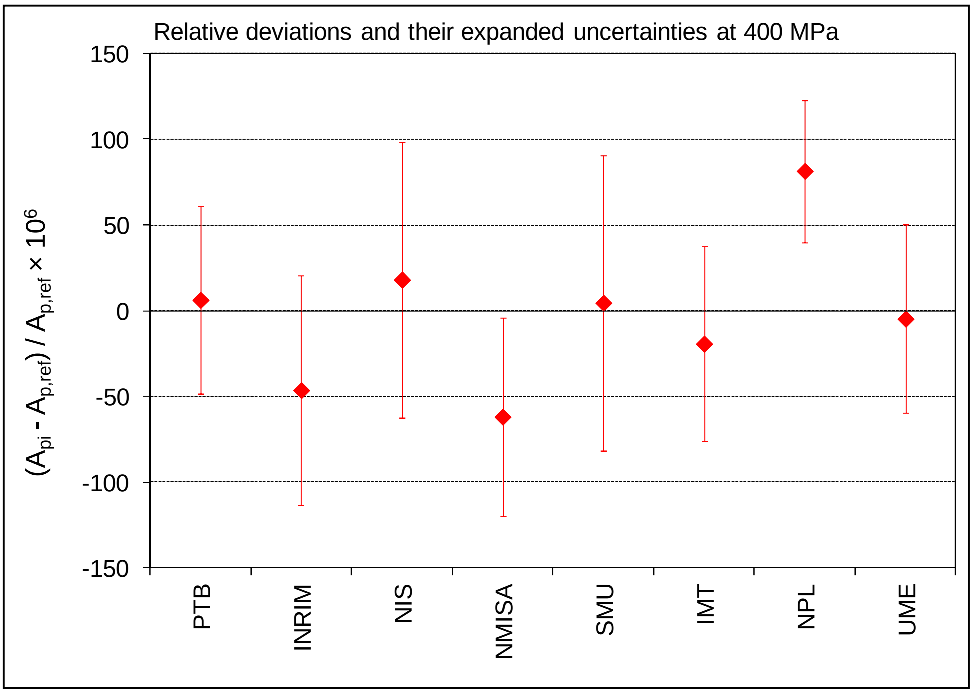

Figure 14. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 400 MPa

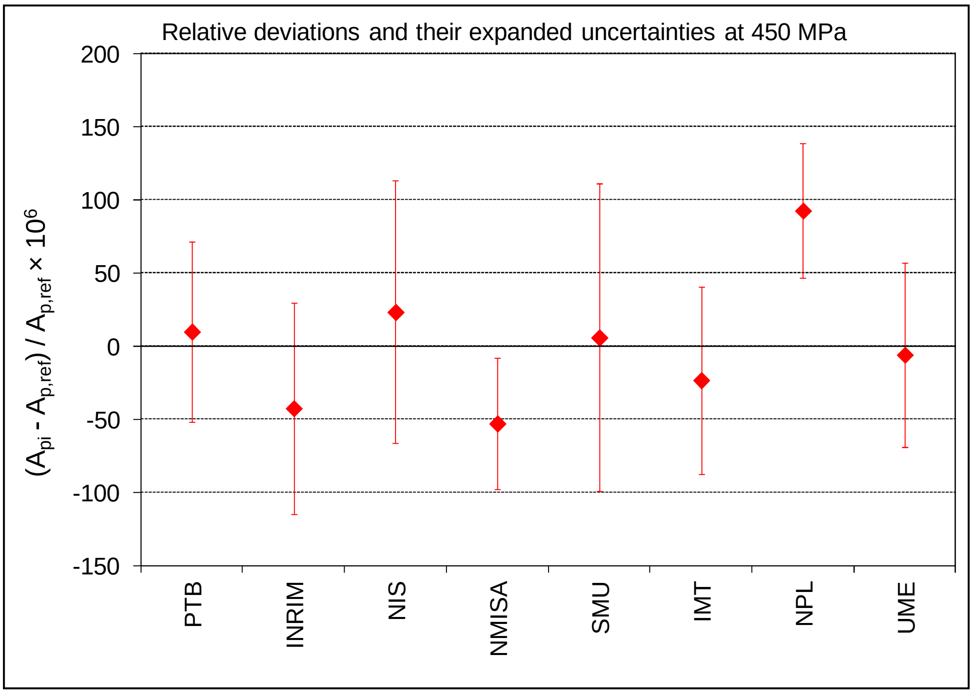

Figure 15. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 450 MPa

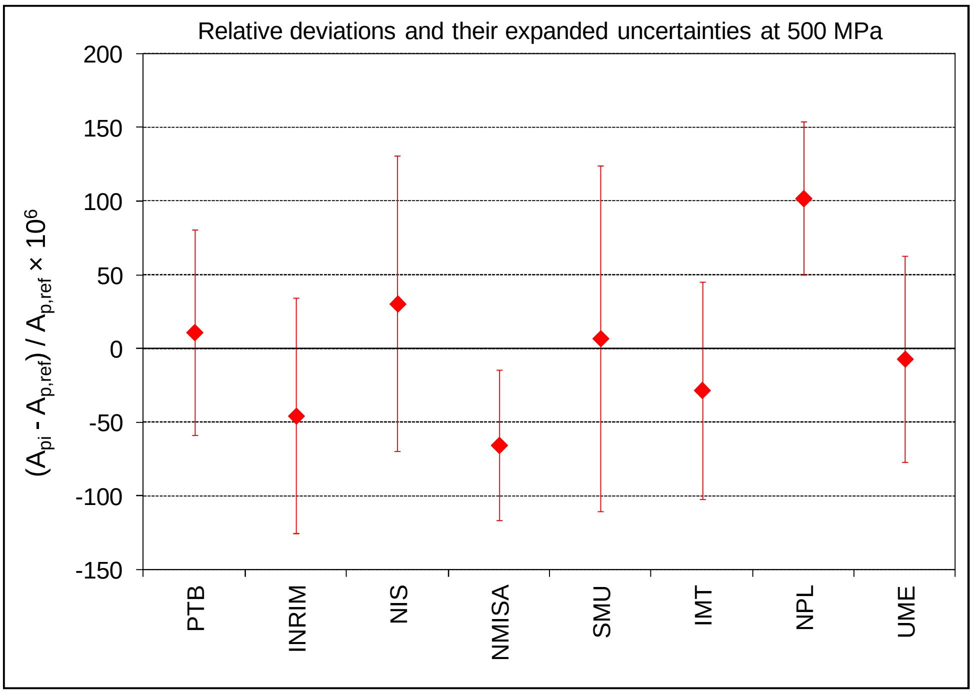

Figure 16. Relative deviations of the participants' results from the reference value and the expanded (k = 2) uncertainties of these deviations at 500 MPa

Table 19. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 50 MPa

		Lab. j															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	50 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. i	PTB			-9	56	17	46	-12	59	-4	43	18	39	39	56	35	41
	INRIM	9	56			26	60	-3	71	6	58	27	55	48	68	44	57
	NIS	-17	46	-26	60			-29	63	-20	48	1	44	22	60	18	46
	NMISA	12	59	3	71	29	63			8	61	30	58	51	71	47	60
	SMU	4	43	-6	58	20	48	-8	61			21	42	42	58	39	44
	IMT	-18	39	-27	55	-1	44	-30	58	-21	42			21	55	17	39
	NPL	-39	56	-48	68	-22	60	-51	71	-42	58	-21	55			-4	57
	UME	-35	41	-44	57	-18	46	-47	60	-39	44	-17	39	4	57		

Table 20. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 100 MPa

Lab. *j*																	
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	100 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. *i*	PTB			17	56	14	48	7	64	-6	47	10	39	10	59	20	39
	INRIM	-17	56			-3	62	-10	75	-23	62	-7	56	-7	71	3	56
	NIS	-14	48	3	62			-8	69	-20	54	-4	47	-5	64	6	47
	NMISA	-7	64	10	75	8	69			-12	69	3	64	3	77	13	64
	SMU	6	47	23	62	20	54	12	69			16	47	15	64	25	47
	IMT	-10	39	7	56	4	47	-3	64	-16	47			0	58	10	38
	NPL	-10	59	7	71	5	64	-3	77	-15	64	0	58			10	58
	UME	-20	39	-3	56	-6	47	-13	64	-25	47	-10	38	-10	58		

Table 21. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 150 MPa

Lab. *j*																	
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	150 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. *i*	PTB			37	58	13	53	18	45	1	53	13	42	-4	63	24	43
	INRIM	-37	58			-24	66	-19	60	-36	67	-24	58	-41	75	-13	58
	NIS	-13	53	24	66			5	55	-12	62	-1	52	-18	70	10	52
	NMISA	-18	45	19	60	-5	55			-18	55	-6	45	-23	65	5	45
	SMU	-1	53	36	67	12	62	18	55			12	53	-5	71	23	53
	IMT	-13	42	24	58	1	52	6	45	-12	53			-17	63	11	42
	NPL	4	63	41	75	18	70	23	65	5	71	17	63			28	63
	UME	-24	43	13	58	-10	52	-5	45	-23	53	-11	42	-28	63		

Table 22. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 200 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	200 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
	PTB			44	62	8	59	34	48	2	56	13	47	-21	71	22	46
	INRIM	-44	62			-36	71	-11	62	-43	68	-31	61	-65	80	-22	60
	NIS	-8	59	36	71			26	59	-6	65	5	58	-29	78	15	58
Lab. *i*	NMISA	-34	48	11	62	-26	59			-32	56	-21	47	-55	71	-11	46
	SMU	-2	56	43	68	6	65	32	56			11	55	-23	76	21	54
	IMT	-13	47	31	61	-5	58	21	47	-11	55			-34	70	9	45
	NPL	21	71	65	80	29	78	55	71	23	76	34	70			44	69
	UME	-22	46	22	60	-15	58	11	46	-21	54	-9	45	-44	69		

Table 23. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 250 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	250 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
	PTB			48	64	4	65	61	84	4	63	16	51	-36	78	20	52
	INRIM	-48	64			-44	76	14	92	-44	74	-32	64	-84	87	-27	65
	NIS	-4	65	44	76			58	93	0	75	12	66	-40	88	17	66
Lab. *i*	NMISA	-61	84	-14	92	-58	93			-58	92	-45	84	-98	102	-41	84
	SMU	-4	63	44	74	0	75	58	92			12	64	-40	86	17	64
	IMT	-16	51	32	64	-12	66	45	84	-12	64			-52	78	4	52
	NPL	36	78	84	87	40	88	98	102	40	86	52	78			57	78
	UME	-20	52	27	65	-17	66	41	84	-17	64	-4	52	-57	78		

Table 24. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 300 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	300 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. *i*	PTB			51	68	-2	73	70	83	5	74	20	57	-48	86	21	55
Lab. *i*	INRIM	-51	68			-53	83	18	91	-47	83	-31	69	-99	94	-30	67
Lab. *i*	NIS	2	73	53	83			72	95	7	87	22	74	-45	98	23	72
Lab. *i*	NMISA	-70	83	-18	91	-72	95			-65	95	-50	83	-117	105	-49	82
Lab. *i*	SMU	-5	74	47	83	-7	87	65	95			15	74	-52	98	16	73
Lab. *i*	IMT	-20	57	31	69	-22	74	50	83	-15	74			-67	87	1	56
Lab. *i*	NPL	48	86	99	94	45	98	117	105	52	98	67	87			68	85
Lab. *i*	UME	-21	55	30	67	-23	72	49	82	-16	73	-1	56	-68	85		

Table 25. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 350 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	350 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. *i*	PTB			53	73	-8	81	65	67	1	84	20	63	-65	95	9	62
Lab. *i*	INRIM	-53	73			-61	90	13	77	-51	93	-33	74	-118	103	-43	73
Lab. *i*	NIS	8	81	61	90			73	85	9	99	28	82	-57	109	18	81
Lab. *i*	NMISA	-65	67	-13	77	-73	85			-64	88	-45	68	-130	98	-56	67
Lab. *i*	SMU	-1	84	51	93	-9	99	64	88			19	85	-66	111	8	84
Lab. *i*	IMT	-20	63	33	74	-28	82	45	68	-19	85			-85	96	-11	63
Lab. *i*	NPL	65	95	118	103	57	109	130	98	66	111	85	96			75	95
Lab. *i*	UME	-9	62	43	73	-18	81	56	67	-8	84	11	63	-75	95		

Table 26. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 400 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	400 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
	PTB			53	78	-12	90	68	70	2	95	26	69	-75	105	11	68
	INRIM	-53	78			-64	98	15	80	-51	102	-27	79	-128	111	-42	78
	NIS	12	90	64	98			80	92	13	112	37	91	-63	120	23	90
Lab. *i*	NMISA	-68	70	-15	80	-80	92			-66	97	-43	72	-143	106	-57	70
	SMU	-2	95	51	102	-13	112	66	97			24	96	-77	124	9	95
	IMT	-26	69	27	79	-37	91	43	72	-24	96			-101	106	-15	69
	NPL	75	105	128	111	63	120	143	106	77	124	101	106			86	105
	UME	-11	68	42	78	-23	90	57	70	-9	95	15	69	-86	105		

Table 27. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 450 MPa

		Lab. *j*															
		PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	450 MPa	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
	PTB			52	83	-13	99	63	60	4	113	33	76	-83	114	16	75
	INRIM	-52	83			-66	106	10	72	-48	119	-19	85	-135	120	-37	84
	NIS	13	99	66	106			76	89	17	130	47	100	-69	132	29	100
Lab. *i*	NMISA	-63	60	-10	72	-76	89			-59	105	-30	63	-145	106	-47	62
	SMU	-4	113	48	119	-17	130	59	105			29	114	-87	143	12	114
	IMT	-33	76	19	85	-47	100	30	63	-29	114			-116	116	-17	77
	NPL	83	114	135	120	69	132	145	106	87	143	116	116			99	115
	UME	-16	75	37	84	-29	100	47	62	-12	114	17	77	-99	115		

Table 28. Relative differences between participants' results (d_{ij}) and their expanded (k = 2) uncertainties ($U(d_{ij})$) at p = 500 MPa

		Lab. *j*															
	500 MPa	PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
		$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$	$d_{ij} \times 10^6$	$U(d_{ij}) \times 10^6$
Lab. *i*	PTB			57	88	-19	107	77	63	4	123	39	83	-91	124	18	80
	INRIM	-57	88			-76	114	20	74	-53	129	-17	92	-148	130	-39	89
	NIS	19	107	76	114			96	96	24	143	59	110	-71	144	37	107
	NMISA	-77	63	-20	74	-96	96			-72	114	-37	68	-167	114	-59	64
	SMU	-4	123	53	129	-24	143	72	114			35	126	-95	156	14	124
	IMT	-39	83	17	92	-59	110	37	68	-35	126			-130	126	-21	83
	NPL	91	124	148	130	71	144	167	114	95	156	130	126			109	124
	UME	-18	80	39	89	-37	107	59	64	-14	124	21	83	-109	124		

7. Relation between key comparisons EURAMET.M.P-K13 and CCM.P-K13

The results of the present key comparison can be easily linked to the results of key comparison CCM.P-K13 [11] performed in the gauge pressure range up to 500 MPa using the results of PTB obtained in both comparisons. With the relative deviations of the PTB results from the KCRV of EURAMET.M.P-K13 ($D_{\text{PTB,EURAMET}}$) and from the KCRV of CCM.P-K13 ($D_{\text{PTB,CCM}}$), the link of the EURAMET.M.P-K13 KCRV to the CCM.P-K13 KCRV ($D_{\text{EURAMET,CCM}}$) at each pressure is given by:

$$D_{\text{EURAMET,CCM}} = D_{\text{PTB,CCM}} - D_{\text{PTB,EURAMET}}. \qquad (16)$$

Herewith, the result of laboratory i which participated in EURAMET.M.P-K13 and had deviation from the EURAMET.M.P-K13 KCRV denoted as $D_{i,\text{EURAMET}}$, would have a deviation from the CCM.P-K13 KCRV ($D_{i,\text{CCM}}$) equal to:

$$D_{i,\text{CCM}} = D_{i,\text{EURAMET}} + D_{\text{EURAMET,CCM}} \qquad (17)$$

The standard uncertainty of this deviation, $u(D_{i,\text{CCM}})$, can be calculated as:

$$u(D_{i,\text{CCM}}) = \left[u_i^2 + u_{\text{CCM}}^2 + u_{\text{PTB\_stabilty}}^2 + u_{\text{CCM\_drift}}^2 + u_{\text{EURAMET\_drift}}^2\right]^{0.5} \qquad (18)$$

where

u_i is the relative standard uncertainty of laboratory i in EURAMET.M.P-K13 as given in Table 14;

u_{CCM} is the relative standard uncertainty of the CCM.P-K13 KCRV;

$u_{\text{PTB\_stability}}$ is the stability of the PTB standard used in both KCs. In first approximation the highest standard deviation of the PTB measurements can be taken for this, which is equal to $4 \cdot 10^{-6}$;

$u_{\text{CCM\_drift}}$ is the relative standard uncertainty of the TS drift correction in CCM.P-K13. For simplicity, the highest of the uncertainties determined for each individual pressure can be taken which is equal to $2.2 \cdot 10^{-6}$ [11];

$u_{\text{EURAMET\_drift}}$ is the relative standard uncertainty of the TS drift correction in EURAMET.M.P-K13 equal to $u(A_{p,\text{drift}}) / A_{0,\text{nom}} = 3.6 \cdot 10^{-6}$.

The relative deviation of laboratory *i* participated in EURAMET.M.P-K13 from laboratory *j* participated in CCM.P-K13 (D_{ij}) can be calculated as:

$$D_{ij} = D_{i,\text{EURAMET}} + D_{\text{EURAMET,CCM}} - D_{j,\text{ CCM}}. \quad (19)$$

The standard uncertainty of this deviation, $u(D_{ij})$, is given by:

$$u(D_{ij}) = \left[u_i^2 + u_j^2 + u_{\text{PTB\_stabilty}}^2 + u_{\text{CCM\_drift}}^2 + u_{\text{EURAMET\_drift}}^2\right]^{0.5}, \quad (20)$$

where u_j is the relative standard uncertainty of laboratory *j* in CCM.P-K13.

The data required for the link are summarised in Table 29.

Table 29. Linkage between key comparisons EURAMET.M.P-K13 and CCM.P-K13

p / MPa	PTB results in EURAMET.M.P-K13		PTB results in CCM.P-K13		u_{CCM}
	$D_i \times 10^6$	$U_i \times 10^6$	$D_i \times 10^6$	$U_i \times 10^6$	$\times 10^6$
50	8.4	36	-2.0	40	13.5
100	9.8	30	0.0	31	4.6
150	12.9	34	0.7	33	3.4
200	10.4	38	0.0	35	3.4
250	9.8	39	-0.4	38	5.4
300	12.2	44	-1.6	42	5.9
350	5.4	48	-1.2	47	7.7
400	6.3	55	-1.2	50	6.7
450	9.9	61	-1.0	55	8.8
500	11.1	70	-0.2	61	11.1
$u_{\text{PTB\_stability}} \times 10^6 = 4.0$ $u_{\text{EURAMET\_drift}} \times 10^6 = 3.6$ $u_{\text{CCM\_drift}} \times 10^6 = 2.2$					

The results of the EURAMET participants linked to the CCM.P-K13 KCRV are presented in Table 30.

Table 30. Relative deviations of EURAMET.M.P-K13 participants' results from the CCM.P-K13 reference value ($D = D_{i,\mathrm{CCM}}$) and relative expanded uncertainties (k = 2) of these deviations ($U = 2u(D_{i,\mathrm{CCM}})$), all in 10^{-6}

p / MPa	PTB		INRIM		NIS		NMISA		SMU		IMT		NPL		UME	
	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$	$D_{i,\mathrm{CCM}}$	$U(D_{i,\mathrm{CCM}})$
50	-2.0	40.6	7.2	56.3	-18.8	45.9	9.7	59.4	1.6	43.5	-19.9	39.0	-40.8	43.5	-37.0	41.3
100	0.0	31.7	-17.0	50.6	-14.3	41.2	-6.6	59.3	5.7	40.8	-10.1	30.6	-9.6	35.3	-19.8	30.8
150	0.7	32.9	-36.1	51.4	-12.4	45.0	-17.6	36.2	0.0	46.0	-11.9	32.3	5.1	34.7	-22.8	32.9
200	0.0	36.6	-44.1	53.1	-7.7	50.2	-33.6	36.6	-1.6	46.0	-13.0	35.5	21.1	34.7	-22.5	34.2
250	-0.4	39.3	-48.0	55.1	-3.9	56.8	-61.7	77.3	-3.9	54.4	-16.3	39.9	35.9	35.7	-20.8	40.4
300	-1.6	43.3	-52.8	57.8	0.4	63.5	-71.2	74.3	-6.2	64.2	-21.5	44.2	45.9	36.0	-22.5	41.6
350	-1.2	48.1	-53.9	61.3	6.9	71.2	-66.6	54.0	-2.5	74.6	-21.2	49.4	63.9	37.4	-10.7	48.1
400	-1.2	51.2	-53.9	63.9	10.6	78.0	-69.3	54.4	-2.9	83.9	-26.7	53.2	74.0	36.6	-12.2	51.2
450	-1.0	56.1	-53.4	68.0	12.4	86.3	-63.8	37.4	-4.9	102.2	-34.2	59.1	81.7	38.4	-16.9	58.0
500	-0.2	61.4	-56.9	72.7	19.2	94.8	-76.7	38.8	-4.3	112.8	-39.4	66.2	90.7	40.7	-18.2	61.7

Most results of the EURAMET.M.P-K13 participants are consistent with the CCM.P-K13 KCRV.

8. Conclusion

The regional key comparison for pressure in liquid media covering the range from 50 MPa to 500 MPa was organized with the participation of 8 NMIs. The key comparison reference value was calculated as a median. In a great majority, the results of the participants are consistent with their uncertainty (k = 2) claims. Exceptions are NPL results at (250 - 500) MPa and NMISA results at (350 - 500) MPa whose deviations from the EURAMET.M.P-K13 and CCM.P-K13 key comparison reference values are higher than the uncertainties of the deviations.

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