Final report on key comparison EURAMET.M.P-K1.c in the range 0.7 MPa to 7.0 MPa of gas gauge pressure

EURAMET 1179 KC- EURAMET.M.P-K1.c

Aykurt Altıntaş[1], Ilknur Koçaş[2], Yasin Durgut[2], Joseph Bartolo[3], Mercede Bergoglio[4], Lovorka Grgec Bermanec[5], Alen Bošnjaković[6], Sanja Burzić[6], Antoine Condereys[7], Miruna Dobre[7], Peter Farar[8], Paul Hetherington[9], Nieves Medina[10], Wladimir Sabuga[11], Oliver Ott[11], Thomas Konczak[11], Ion Sandu[12], Janez Setina[13], Dietmar Steindl[14], Csilla Vámossy[15], Bernard Waller[16], Christian Wuethrich[17], Adam Brzozowski[18], Jan van Geel[19], Sari Saxholm[20], Fredrik Arrhén[21]

[1] FORCE, Park Alle 345, DK-2605 Brøndby, Denmark
[2] UME, P.O. 54, TR-41470 Gebze / KOCAELI, Turkey
[3] MCCAA-SMI, Kordin Business Incubation Center, Kordin Industrial Estate, Kordin, PLA 3000, Malta
[4] INRIM, Strada delle Cacce 91, IT-10135 Torino, Italy
[5] FSB-LPM, Faculty of Mechanical Engineering, Ivana Luccia 5, HR-10000 Zagreb, Croatia
[6] IMBiH Institute of Metrology of Bosnia and Herzegovina, Dolina 6, 71000 Sarajevo, Bosnia and Herzegovina
[7] SMD, North Gate - office 05A30 Koning Albert II-laan 16 - 1000 Brussels Belgium
[8] SMU Slovakia Institute of Metrology, Karloveská 63, SK-84255 Bratislava, Slovakia
[9] NSAI NML National Metrology Laboratory, Glasnevin, Dublin 9, Ireland
[10] CEM, Alfar 2, Tres Cantos, ES-28019 Madrid, Spain
[11] PTB, Bundesallee 100, 38116 Braunschweig, Germany
[12] INM, National Institute of Metrology, Sos Vitanm Barzesti 11, sect 4, RO-042122 Bucharest, Romania
[13] MIRS/IMT/LMT, Lepi pot 11, SI-1000 Ljubljana, Slovenia
[14] BEV, Arltgasse 35, AT-1160 Wien
[15] MKEH, Magyar Kereskedelmi, Engedélyezési Hivatal, Németvölgyi út 37-39, HU-1124 Budapest, Hungary
[16] NPL, Teddington, Middlesex, UK, TW11 0LW, United Kingdom
[17] METAS, Lindenweg 50, CH-3003 Bern-Wabern, Switzerland
[18] GUM, 00-139 Warsaw, 2 Elektoralna Str., Poland
[19] VSL, Thijsseweg 11, NL-2629 JA Delft, Netherland
[20] VTT MIKES, Tekniikantie 1, FI-02151 Espoo, Finland
[21] RISE, Box 857, SE-501 15 Borås, Sweden

March 2020

Abstract

A EURAMET key comparison of the national pressure standards in the range 0.7 MPa to 7.0 MPa of gas gauge pressure was carried out. The circulation of the transfer standard began in November 2011 and lasted until November 2016.

The measurand of the comparison was the effective area of the piston-cylinder assembly determined by gauge pressure measurements in the range from 0.7 MPa to 7.0 MPa.

As the comparison reference value, the weighted mean of the results of the laboratories with primary pressure standards was used.

With this reference value, all the participants who delivered the results demonstrated equivalence respective to the reference value within expanded uncertainties (k = 2) on all the range.

The results of this comparison were linked to CCM key comparison CCM.P-K1.c. Also in relation to the reference values of CCM.P-K1.c, all participants demonstrated agreement within expanded uncertainties (k = 2) at all pressure points.

Content

1 Introduction

At EURAMET TC-M meeting in 2010, it was decided to realize a comparison in gas media and gauge mode in the range 0.7 MPa to 7.0 MPa and to establish a link to the CCM.P-K1.c. There was high interest of National Metrology Institutes (NMI) to participate in this comparison. The project would confirm the calibration and measurement capabilities of the participating laboratories.

FORCE volunteered for the role as Pilot laboratory. UME provided the transfer standard and PTB monitored the transfer standard's performance.

PTB accepted the invitation to join the key comparison in order to link it to the CCM key comparison CCM.P-K1.c.

The comparison was registered as EURAMET key comparison EURAMET.M.P-K1.c in the BIPM KCDB and as EURAMET Project 1179 in the EURAMET projects' database.

The project started with 21 participants, where three of them did not submit results, but three other participants joined during the project.

The transfer standard (TS) was a pressure balance with a piston-cylinder assembly (PCA) and masses produced by DH Instruments, USA. The quantity to be measured was the effective area of the PCA. At each calibration point, the parameter to be compared was the effective area of the piston cylinder assembly determined by each participant and corrected to 20 °C.

Unless otherwise stated, all uncertainties are standard ones with a coverage factor of k = 1.

2 Participants

The list of the participants is given with the time of the measurement in Table 1. EIM (Hellenic Institute of Metrology, Greece), NIS (National Institute of Standard, Egypt) and LCAE-CME (Central Laboratory for Testing and Analysis – Metrology Center, Tunisia) did not send any results.

Table 1. List of the laboratories, which took part in the comparison with the responsible person at the time of measurement

Laboratory	Country	Responsible	Measurement period	Traceability
UME	Turkey	Ilknur Kocas	08-09-2011 – 14-09-2011	PTB
PTB	Germany	Wladimir Sabuga	19-10-2011 – 25-10-2011	Primary
FORCE	Denmark	Aykurt Altintas	16-11-2011 – 23-11-2011	PTB
BEV	Austria	Dietmar Steindl	14-12-2011 – 19-12-2011	PTB
SMD	Belgium	Antoine Condereys	20-02-2012 – 23-02-2012	PTB
METAS	Switzerland	Christian Wüthrich	18-01-2012 – 23-01-2012	Primary
MCCAA-SMI	Malta*	Joseph Bartolo	12-03-2012 – 21-03-2012	NIST, PTB and LNE
MIRS/IMT/LMT	Slovenia	Janez Setina	03-09-2012 – 07-09-2012	PTB
INM	Romania	Ion Sandu	16-01-2013 – 17-01-2013	PTB
MKEH	Hungary	Csilla Vámossy	11-02-2013 – 18-02-2013	PTB
CEM	Spain	Nieves Medina	26-04-2012 – 03-05-2012	Primary
UME Intermediate measurements	Turkey	Yasin Durgut	13-06-2012 – 18-06-2012	PTB
FSB-LPM	Croatia	Lovorka Grgec Bermanec	16-07-2012 – 20-07-2012	PTB
SMU	Slovakia	Peter Farar	05-10-2012 – 01-11-2012	Primary
IMBiH	Bosnia-Herzegovina*	Sanja Burzić	27-11-2012 – 03-12-2012	IMT
INRIM	Italy	M. Bergoglio	05-07-2013 – 12-07-2013	Primary
RISE (formerly SP)	Sweden	Fredrik Arrhén	October 2013	LNE
NPL	United Kingdom	Bernard Waller	09-12-2013 – 08-01-2014	Primary
NSAI NML	Ireland	Paul Hetherington	04-02-2014 – 10-02-2014	PTB
GUM	Poland	A. Brzozowski	04-03-2014 – 19-03-2014	PTB
VSL	Netherland	Jan van Geel	26-03-2014 – 21-04-2014	Primary
PTB Intermediate measurements	Germany	Wladimir Sabuga, Oliver Ott	05-02-2015 – 11-02-2015	Primary
VTT MIKES	Finland	Sari Saxholm	16-11-2015 - 03-12-2015	Primary
PTB Final measurements	Germany	Oliver Ott, Wladimir Sabuga	07-01-2016 – 14-01-2016	Primary
UME Final measurements	Turkey	Yasin Durgut	18-12-2016 – 24-01-2017	PTB

Countries marked with * are associate members, rest of the countries are member states of the CIPM.

3 Laboratory standards and measurements methods

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

3.1 Pilot and co-pilot laboratory

FORCE and TÜBITAK UME coordinated the project. TÜBITAK UME, acting as a co-pilot of the comparison, provided the transfer standard.

3.1.1 FORCE

The traceability of the LS is established by calibration by PTB. Calibration and uncertainty calculation are in accordance with EURAMET cg-3 version 1.0 "Calibration of pressure balances" [1].

Manufacturer	Desgranges & Huot
Measurement range in MPa	20
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Re-entrant
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.024400
The relative uncertainty of A_0 in 10^{-6}	12.5
Pressure distortion coefficient (λ) in MPa^{-1}	0
The uncertainty of λ in MPa^{-1}	2.50×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	5.0
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.81548
The relative uncertainty of g in 10^{-6}	1
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	85.5
The uncertainty of h in mm	20

3.1.2 Co-Pilot laboratory UME

The traceability of the LS is established by calibration by PTB. Calibration and uncertainty calculation are in accordance with EURAMET cg-3 version 1.0 "Calibration of pressure balances" [1].

Manufacturer	DH Instruments
Measurement range in MPa	7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.015810
The relative uncertainty of A_0 in 10^{-6}	16.2
Pressure distortion coefficient (λ) in MPa^{-1}	-2.40×10^{-6}
The uncertainty of λ in MPa^{-1}	8.00×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	5.0
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80231
The relative uncertainty of g in 10^{-6}	8
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1

3.2 Laboratory with a link to CCM.P-K1c

3.2.1 PTB

The PTB LS used in this KC is a gas-operated pressure balance Model PG-7601 equipped with a 0.5 cm^2 PCA serial number 0302 produced by DH Instruments. The zero-pressure effective area (A_0) of this PCA is traceable to a group of 5 primary PCAs of 20 cm^2 and 2 cm^2 effective areas based on dimensional measurements [2]. The pressure distortion coefficient (λ) is that given by the manufacturer on the basis of the PCA material elastic properties and the Lamé theory. This value of λ was confirmed by the cross-float measurements against the primary pressure balances [2] and [3] whose λ were determined using the finite element method [4] on the experimentally measured elastic constants of their materials [5].

Manufacturer	DH Instruments
Measurement range in MPa	0.7 – 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Re-entrant
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.01928
The relative uncertainty of A_0 in 10^{-6}	7.4
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}
The uncertainty of λ in MPa^{-1}	1.0×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	0.8
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8125330
The relative uncertainty of g in 10^{-6}	0.54
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0.15
The uncertainty of h in mm	0.37

3.3 Laboratories with a primary definition

3.3.1 INRIM

Traceability starts from dimensional measurements. A_0 and λ are calculated as reported in EURAMET 1125 report [6].

Manufacturer	DHI
Measurement range in MPa	0.04 - 10
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.02174
The relative uncertainty of A_0 in 10^{-6}	10
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}
The uncertainty of λ in MPa^{-1}	4.7×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80533
The relative uncertainty of g in 10^{-6}	1
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1

3.3.2 METAS

The pressure laboratory of METAS uses almost exclusively primary instruments for the dissemination of the pressure scale. The PCAs used as a reference in this comparison are DH-Instrument type PC-7100/7600-200 like the TS circulated. The traceability to the length is made with two piston-cylinder of 10 cm^2 measured by the length laboratory of METAS. The calibration chain is built calibrating a pair of 2 cm^2 piston-cylinder against the pair of 10 cm^2 piston-cylinder. The 0.5 cm^2 piston-cylinders are then calibrated against the 2 cm^2 piston-cylinders.

Manufacturer	DH Instruments	
Measurement range in MPa	11	
Material of piston	Tungsten carbide	
Material of cylinder	Tungsten carbide	
Operation mode, free-deformation or controlled-clearance	Negative free deformation	
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.01378	49.02041
The relative uncertainty of A_0 in 10^{-6}	9.5	
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}	
The uncertainty of λ in MPa^{-1}	2.50×10^{-7}	
The relative uncertainty of mass pieces in 10^{-6}	1	
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}	
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}	
Reference temperature (t_0) in °C	20	
Local gravity (g) in m/s^2	9.80589	
The relative uncertainty of g in 10^{-6}	1	
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0	
The uncertainty of h in mm	3	
Piston-cylinder serial no.	521	781

3.3.3 CEM

CEM performed the comparison by cross-floating using two piston-cylinder assemblies as reference standards whose properties are given below together with measurement conditions. The uncertainties included are standard uncertainties.

CEM obtains its primary traceability from its Mercury Column Manobarometer, which is transferred to piston-cylinder assemblies with different effective areas via a series of cross-float comparisons.

Manufacturer	Desgranges et Huot	
Measurement range in MPa	0.5 – 5	
Material of piston	Tungsten carbide	
Material of cylinder	Tungsten carbide	
Operation mode, free-deformation or controlled-clearance	Controlled-clearance	
Zero-pressure effective area (A_0) at a reference temperature in mm^2	98.0447	98.0518
The relative uncertainty of A_0 in 10^{-6}	10	
Pressure distortion coefficient (λ) in MPa^{-1}	6.05×10^{-7}	3.96×10^{-6}
The uncertainty of λ in MPa^{-1}	3.5×10^{-8}	2.1×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	1.5	
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}	
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}	
Reference temperature (t_0) in °C	20	
Local gravity (g) in m/s^2	9.799485	
The relative uncertainty of g in 10^{-6}	0.5	
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0	
The uncertainty of h in mm	0.5	
Piston-cylinder serial no.	3485	5845

3.3.4 SMU

SMUs traceability to SI is done by Mercury Column Manobarometer, which is transferred to piston-cylinder assemblies with effective area via a series of cross-float comparisons.

Furthermore the piston-cylinder geometry and its traceability to the SI was evaluated by means of dimensional calibration by SMUs Length Laboratory.

Manufacturer	SMU
Measurement range in MPa	0.2 – 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	98.1132
The relative uncertainty of A_0 in 10^{-6}	10
Pressure distortion coefficient (λ) in MPa^{-1}	1.0×10^{-6}
The uncertainty of λ in MPa^{-1}	1.0×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	1
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	5.0×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	5.0×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80873
The relative uncertainty of g in 10^{-6}	1
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-49.4
The uncertainty of h in mm	1

3.3.5 NPL

Traceability to SI is via dimensioned PCA. A_0 of LS determined through the hierarchy of PCAs (cross-floating) and λ is determined through elastic theory.

Manufacturer	Ruska Corp
Measurement range in MPa	0.1 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.3888
The relative uncertainty of A_0 in 10^{-6}	8
Pressure distortion coefficient (λ) in MPa^{-1}	0.86×10^{-6}
The uncertainty of λ in MPa^{-1}	0.12×10^{-6}
The relative uncertainty of mass pieces in 10^{-6}	1(2 for the piston)
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.81181
The relative uncertainty of g in 10^{-6}	5
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-57.6
The uncertainty of h in mm	0.1

3.3.6 VTT MIKES

Traceability to SI is via dimensional calibration by VTT MIKES Length Laboratory. Traceability is disseminated through the hierarchy of PCAs by cross-floating.

Manufacturer	Desgranges et Huot	
Measurement range in MPa	0.1 - 5	0.2 - 16
Material of piston	Tungsten carbide	
Material of cylinder	Tungsten carbide	
Operation mode, free-deformation or controlled-clearance	Re-entrant	
Zero-pressure effective area (A_0) at a reference temperature in mm^2	98.04899	49.026640
Relative uncertainty of A_0 in 10^{-6}	7.5	10.5
Pressure distortion coefficient (λ) in MPa^{-1}	0.00	1.50×10^{-6}
Uncertainty of λ in MPa^{-1}	$3.00\text{x}10^{-6}$	1.00×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2.5	
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}	
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}	
Reference temperature (t_0) in °C	20	
Local gravity (g) in m/s^2	9.819073	
The relative uncertainty of g in 10^{-6}	0.2	
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-114	-110
The uncertainty of h in mm	1.2	
Piston-cylinder serial no.	4012	6804

3.3.7 VSL

The LS is traceable to a 5 kPa/kg PCA with dimensional calibration from the VSL length department and a 10 kPa/kg PCA calibrated by LNE. Uncertainty and calculations are in accordance with EURAMET cg-3 version 1.0 “Calibration of pressure balances” [1].

Manufacturer	Desgranges & Huot
Measurement range in MPa	0.04 – 8
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.02601
The relative uncertainty of A_0 in 10^{-6}	10
Pressure distortion coefficient (λ) in MPa^{-1}	8.00×10^{-7}
The uncertainty of λ in MPa^{-1}	4.00×10^{-8}
The relative uncertainty of mass pieces in 10^{-6}	0.6
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.812407
The relative uncertainty of g in 10^{-6}	0.5
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1.5

3.4 Laboratories with a secondary definition

3.4.1 SMD

The traceability of the laboratory standard is established by calibration by PTB. Calibration certificate 0054 PTB 09 of 2009-08-17.

Manufacturer	RUSKA
Measurement range in MPa	0.014 – 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.38582
The relative uncertainty of A_0 in 10^{-6}	14
Pressure distortion coefficient (λ) in MPa^{-1}	2×10^{-6}
The uncertainty of λ in MPa^{-1}	0.8×10^{-6}
The relative uncertainty of mass pieces in 10^{-6}	10
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.811461
The relative uncertainty of g in 10^{-6}	1.1
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	2

3.4.2 MCCAA

Traceability is provided through a calibration certificate by Fluke, which is an accredited laboratory with pressure standards traceable to NIST, PTB and LNE, and mass standards calibrated by Troemner Calibration Services traceable to NIST.

Manufacturer	DHI
Measurement range in MPa	0.04 – 10
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.0192
The relative uncertainty of A_0 in 10^{-6}	8
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}
The uncertainty of λ in MPa^{-1}	2.4×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.5×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.79850
The relative uncertainty of g in 10^{-6}	2
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	5

3.4.3 MKEH

Traceability of the LS is to PTB. Certificate No.: PTB 30041/10.

Traceability of the mass is to the Mass Laboratory of MKEH.

Calibration and uncertainty calculation are in accordance with EURAMET cg-3 version 1.0 "Calibration of pressure balances" [1].

Manufacturer	Ruska Instrument Corporation
Measurement range in MPa	0.014 – 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.394230
The relative uncertainty of A_0 in 10^{-6}	9.5
Pressure distortion coefficient (λ) in MPa^{-1}	2.0×10^{-6}
The uncertainty of λ in MPa^{-1}	0.8×10^{-6}
The relative uncertainty of mass pieces in 10^{-6}	0.7 - 1.7
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.808293
The relative uncertainty of g in 10^{-6}	1.2
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-34.1
The uncertainty of h in mm	1

3.4.4 BEV

The traceability of the laboratory standard is established by calibration by PTB.

Manufacturer	DH Instruments. Phoenix. USA
Measurement range in MPa	0.04 – 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.01670
The relative uncertainty of A_0 in 10^{-6}	10
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}
The uncertainty of λ in MPa^{-1}	3.00×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8083779
The relative uncertainty of g in 10^{-6}	0.04
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1

3.4.5 INM

The INM standard used in this Project was Ruska piston gauge, type 2465-753, with the piston-cylinder unit serial No. V-1621, traceable to PTB - Calibration Certificate No. PTB 30046/12. A_0, λ and their uncertainties were determined in accordance with EURAMET cg-03 version 1.0 “Calibration of pressure balances” [1]. A digital thermometer measured the temperature of the piston-cylinder unit with a 0.025 ºC standard uncertainty. The ambient pressure, ambient temperature and ambient humidity were measured with proper devices and proper uncertainties.

Manufacturer	Ruska
Measurement range in MPa	0.014 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.39247
The relative uncertainty of A_0 in 10^{-6}	21
Pressure distortion coefficient (λ) in MPa^{-1}	1.51×10^{-6}
The uncertainty of λ in MPa^{-1}	0.48×10^{-6}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80540
The relative uncertainty of g in 10^{-6}	4
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-2
The uncertainty of h in mm	1

3.4.6 MIRS/IMT/LMT

LS is traceable to PTB. A_0 and λ were determined according to EURAMET cg-3 version 1.0 “Calibration of pressure balances” [1].

Manufacturer	DH Instruments (model PG 7601)
Measurement range in MPa	7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.0243
The relative uncertainty of A_0 in 10^{-6}	8
Pressure distortion coefficient (λ) in MPa^{-1}	-2.40×10^{-6}
The uncertainty of λ in MPa^{-1}	6.50×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.50×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.50×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.806128
The relative uncertainty of g in 10^{-6}	0.2
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1

3.4.7 FSB-LPM

A_0 and λ and their uncertainties were determined from cross-float results with our LS traceable to PTB (cert No: PTB 30240/11). Dimensional measurements were made with the good agreement, but results were taken from PTB certificate.

Manufacturer	DHI
Measurement range in MPa	0.1 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.01892
The relative uncertainty of A_0 in 10^{-6}	16
Pressure distortion coefficient (λ) in MPa^{-1}	-2.35×10^{-6}
The uncertainty of λ in MPa^{-1}	3×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	5
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.5×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80662
The relative uncertainty of g in 10^{-6}	50
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	5

3.4.8 RISE

PCA is calibrated at LNE/France, which also gives A_0 and λ and their uncertainties in the certificate. The values used in this calibration were evaluated and the uncertainties increased due to historical results.

Manufacturer	Ruska
Measurement range in MPa	0.14 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.390642
The relative uncertainty of A_0 in 10^{-6}	18.7
Pressure distortion coefficient (λ) in MPa^{-1}	3.91×10^{-6}
The uncertainty of λ in MPa^{-1}	7.50×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	5
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2 at 1.15 metres above floor.	9.81680066
The relative uncertainty of g in 10^{-6}	0.031
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	1

3.4.9 NSAI NML

The calibration of the transfer standard pressure balance was carried out following the guidelines set out in section 5.4 of EURAMET cg-3 version 1.0 “Calibration of pressure balances” [1]. The reference standard used was a Ruska 2465 pressure balance together with a differential pressure null detector, comprising a differential pressure transducer and an electronic null indicator. The effective area of the pressure balance and the associated mass standards were calibrated by PTB. A_0 and λ and associated uncertainties were calculated as per EURAMET cg-3 version 1.0 “Calibration of pressure balances” [1].

Manufacturer	Ruska
Measurement range in MPa	0.014 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.39040
The relative uncertainty of A_0 in 10^{-6}	24
Pressure distortion coefficient (λ) in MPa^{-1}	3.10×10^{-6}
The uncertainty of λ in MPa^{-1}	7.00×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	5
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.81387
The relative uncertainty of g in 10^{-6}	1
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	-62.3
The uncertainty of h in mm	0.3

3.4.10 IMBiH

The traceability of the LS is established by calibration by IMT. Calibration and uncertainty calculation are in accordance with EURAMET cg-3 version 1.0 [1].

Manufacturer	DH Instruments; PG 7601; PC 200 kPa/kg
Measurement range in MPa	0.1 to 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Negative free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	49.01900
The relative uncertainty of A_0 in 10^{-6}	16
Pressure distortion coefficient (λ) in MPa^{-1}	-2.5×10^{-6}
The uncertainty of λ in MPa^{-1}	5.5×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	2
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.5×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.80317
The relative uncertainty of g in 10^{-6}	10
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	0
The uncertainty of h in mm	0.5

3.4.11 GUM

LS PCA is traceable to PTB; the mass set was calibrated at Mass Laboratory in GUM. Uncertainty calculation is in accordance with EURAMET cg-3 version 1.0 “Calibration of pressure balances” [1]. A_0 uncertainty was calculated including uncertainties of following components: laboratory standard, mass, assembly temperature, thermal coefficient, gravity, air density, mass density, height difference, medium density, piston verticality and measurement results. λ uncertainty calculation was based on measurements’ results. The standard uncertainties of the estimate $u(A_p)$ were calculated as the uncertainties of the effective area expanded by uncertainty due to deviation from the best fit straight line of ($A(p_i)$; p_i).

Manufacturer	RUSKA Instrument Corporation. Houston. USA
Measurement range in MPa	0.014 - 7
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode, free-deformation or controlled-clearance	Free deformation
Zero-pressure effective area (A_0) at a reference temperature in mm^2	8.38870
The relative uncertainty of A_0 in 10^{-6}	23
Pressure distortion coefficient (λ) in MPa^{-1}	1.9×10^{-6}
The uncertainty of λ in MPa^{-1}	3×10^{-7}
The relative uncertainty of mass pieces in 10^{-6}	1.6
The linear thermal expansion coefficient of the piston (α_p) in °C^{-1}	4.55×10^{-6}
The linear thermal expansion coefficient of the cylinder (α_c) in °C^{-1}	4.55×10^{-6}
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.8122475
The relative uncertainty of g in 10^{-6}	0.34
The height difference between LS and TS (h, pos. if LS is higher than TS) in mm	74
The uncertainty of h in mm	1

4 Transfer standard

The TS was a PCA of 50 mm^2 nominal effective area with serial number 440. According to the information provided by the TS owner – UME, the piston and cylinder of TS are made of tungsten carbide. The PCA was operated in a base PG-7601, serial no. 430, and with masses whose conventional masses and densities were given known by the TS owner – UME. The properties of the TS are presented in Table 2.

Table 2. Characteristics of the circulated transfer standard

Transfer Standard	Piston Cylinder
TÜBITAK-UME Inventory Number	08583
Type	PG-7100/7600-200
DH Instruments Part Number	401564
Serial Number	440
Nominal Area	50 mm^2
Area Thermal Expansion Coefficient (α_p+α_c)	$9 \cdot 10^{-6}$ °C^{-1}
Conventional mass	199.995 g (u = 1.0 mg)
Mean piston density	8030 kg/m^3 (u = 80 kg/m^3)
Fall rate at 0.3 MPa	< 0.05 mm/min
Fall rate at 7.0 MPa	< 0.50 mm/min
Deceleration (70 rpm to 30 rpm) at 0.3 MPa	> 5 min
Base	
Type	PG-7601
Part Number	400480
Serial Number	430
TÜBITAK-UME Inventory Number	20272
Terminal	
Type	PG TERMINAL (PG7000)
Serial Number	N/A
Part Number	401284
Mass Set	
Serial Number	2067
Density of 5 kg, 4.5 kg, 2 kg and 1 kg weights	8000 kg/m^3 (u = 40 kg/m^3)
Density of 500 g, 200 g and 100 g weights	7920 kg/m^3 (u = 40 kg/m^3)
TÜBITAK-UME Inventory Number	01043
Mass Carrying Bell	
Serial Number	654
Conventional mass	299.9719 g (u = 1.0 mg)
Density	5013 kg/m^3 (u = 50 kg/m^3)

During the comparison, the TS was performing properly, mostly without technical problems. In January 2015, the piston height position and the rotation speed were not displayed on the terminal. PTB tested the terminal with their base, and it was working correctly. The authorized service centre solved the issue and returned the instrument to PTB. The KC was resumed.

One important issue observed during the comparison refers to the piston rotation speed. In the Technical Protocol [7] of the KC, it was recommended to be (40 to 50) rpm at pressures (0.7 to 4.1) MPa and (30 to 40) rpm at pressures (5.3 to 6.8) MPa. However, as it was found out by SMU and PTB, reported at the EURAMET TC-M annual meeting in Cavtat in 2013, these recommended rotation speeds were too high and affected the measured effective area, particularly at low pressures. Non-linearity of the effective area observed in the results of some participants may deal with this effect of the piston rotation speed.

Traceability of the transfer standard

Certificates have been provided by the owner of the TS – UME for the set of masses, the value of the mass of the piston and the value of the mass of the carrying bell.

5 Measurement instructions

The measurement technique is described in the EURAMET.M.P-K1.c Technical Protocol [7] like the criterions that would need a new cleaning of the piston and the fall rate that had to be achieved in a system leak tight.

5.1 Measurement points

The measurement had to be made from 0.7 MPa up to 7.0 MPa at 8 steps, upward and downward. The measurements had to be repeated five times for a total of 80 measurements.

The results were collected by the pilot laboratory during the time of the comparison. A worksheet was provided for the collection of the results to facilitate the integration in the calculation of the reference value.

5.2 Calculation of the effective area

The effective area A_p is derived from the well-known formula used to calculate the gauge pressure p_e measured by a gas-operated pressure balance at its reference level:

Equation 1

$$p_{\mathrm{e}} = \frac{g \sum_i \left[m_i \left(1 - {}^{\rho_{\mathrm{a}}}/_{\rho_{m_i}}\right) \right]}{A_p \left[1 + (\alpha_{\mathrm{p}} + \alpha_{\mathrm{c}})(t - 20\,^\circ\mathrm{C}) \right]}$$

where

g is local gravity acceleration;

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

ρ_{m_i} are densities of the parts with masses m_i;

ρ_a is air density;

α_p and α_c are thermal expansion coefficients of the piston and cylinder materials, respectively;

t is PCA temperature.

By reversing the formula and using the pressure measured by the laboratory standard at the reference level of the transfer standard, the effective area at a given pressure is given by:

Equation 2

$$A_p = \frac{g \sum_i \left[m_i \left(1 - {}^{\rho_{\mathrm{a}}}/_{\rho_{m_i}}\right) \right]}{p_{\mathrm{e}} \left[1 + (\alpha_{\mathrm{p}} + \alpha_{\mathrm{c}})(t - 20\,^\circ\mathrm{C}) \right]}$$

6 Results

6.1 Stability of the transfer standard

The transfer standard was chosen for the well-known long-term stability of a piston-cylinder made of tungsten carbide. Plastic deformation is not an issue, while the change of shape due to abrasion should be minimal.

Prior to the project, it was agreed that the owner of the TS - UME - would do the measurements for the stability of the TS. The first time the transfer standard was returned to UME for the intermediate check, it was not possible for UME to make measurements as the time allocated for this was used to compensate for the accumulated delay. Only the ATA Carnet was renewed. The second-time UME supposed to make intermediate measurements, UME's LS was in disorder, therefore it was agreed that PTB did the intermediate and the final measurements instead of UME as given in Table 3, Figure 1 and Figure 2. As start measurements for the stability determination, PTB's main results measured 2011 were taken. Measurements were done with special rotational speed as specified in the Technical Protocol [7].

Table 3. Effective areas measured by PTB

Nominal pressure	PTB		PTB2		PTB3		Maximal difference	
p	A_p (20 °C)	Stdev	A_p (20 °C)	Stdev	A_p (20 °C)	Stdev		
MPa	mm^2	ppm	mm^2	ppm	mm^2	ppm	mm^2	ppm
0.74	49.01447	2.1	49.01412	2.9	49.01436	5.5	0.00035	7.1
1.08	49.01479	2.0	49.01495	2.2	49.01488	3.4	0.00016	3.3
1.77	49.01490	1.0	49.01509	1.1	49.01495	2.1	0.00019	3.9
2.94	49.01499	1.0	49.01502	0.4	49.01498	0.7	0.00004	0.8
4.10	49.01489	0.7	49.01490	0.3	49.01487	0.2	0.00003	0.6
5.27	49.01480	0.4	49.01476	0.6	49.01475	0.4	0.00005	1.0
6.44	49.01464	0.4	49.01463	0.4	49.01461	0.4	0.00003	0.6
6.79	49.01461	0.3	49.01458	0.1	49.01457	0.4	0.00004	0.8

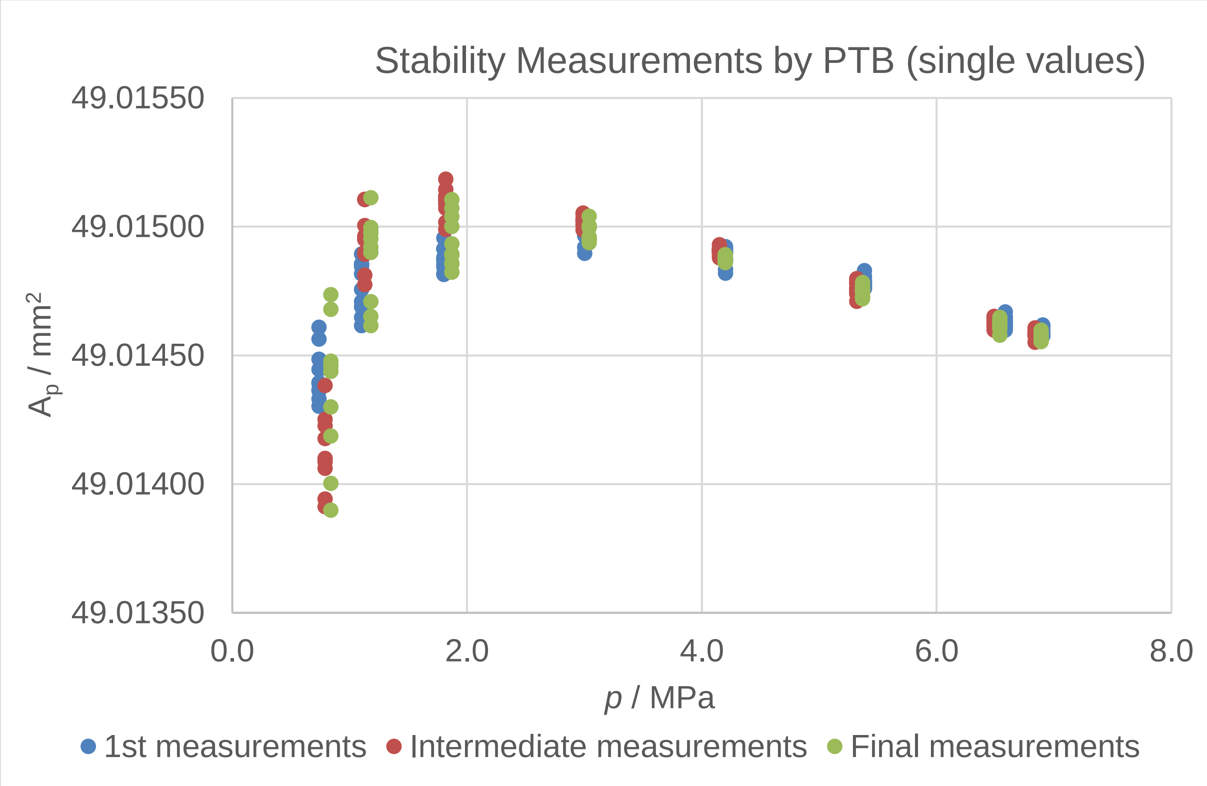

Figure 1. Stability of the transfer standard. Single values of the effective area measured by PTB in October 2011 (1st measurement), February 2015 (intermediate measurement) and January 2016 (final measurement)

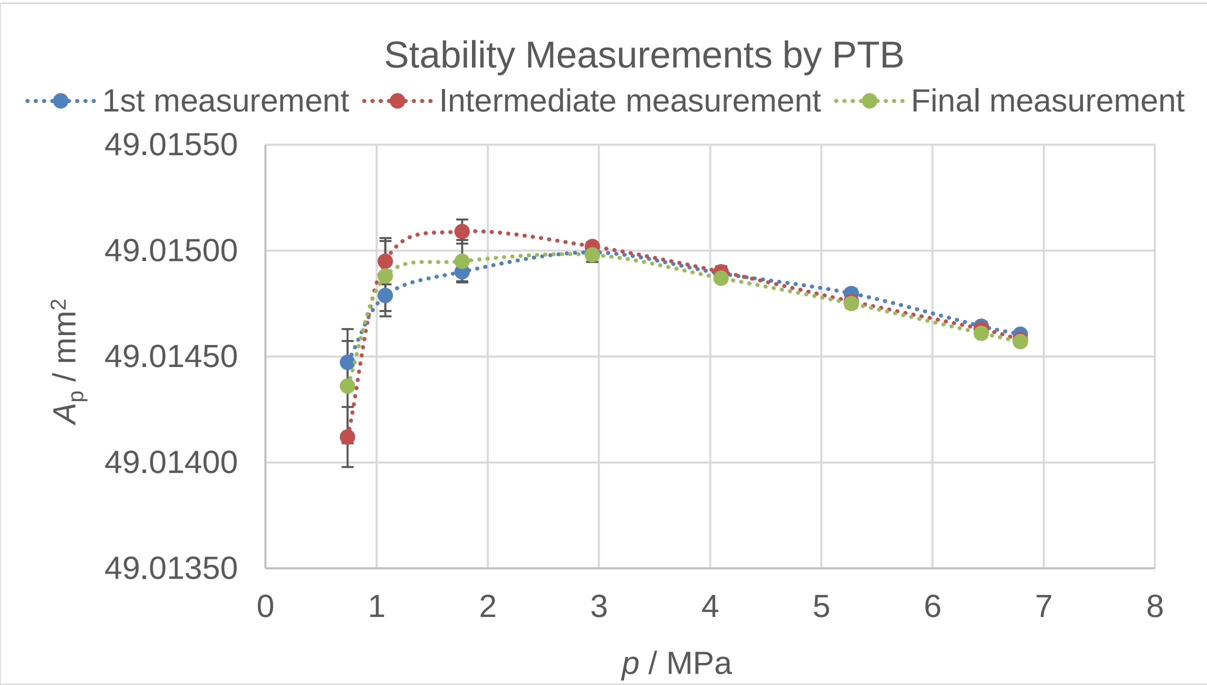

Figure 2. Stability of transfer standard. Mean effective areas measured by PTB in October 2011, February 2015 and January 2016. Vertical bars depict standard deviations of effective area measurements by PTB (Type A uncertainty contribution)

6.1.1 Correction for time-drift

There is no significance of a time-depending behaviour of the TS within the accuracy of the stability measurements: In its entirety, the stability data do not show any correlation between values and corresponding measuring dates. The maximum difference between the effective areas at the nominal pressures is not larger than expected by the statistical spread. Therefore, no correction for a drift was applied.

The standard uncertainty due to long-term instability is estimated from the maximal difference of A_p values given in Table 3, see equation 3.

Equation 3

$$\frac{u(\Delta A_{p,T})}{A_p} = \sqrt{\frac{1}{3} \cdot \left(\frac{\text{Max. Difference}(A_{p,i,\text{PTB},T})}{2 \cdot \text{Average}(A_{p,i,\text{PTB},T})}\right)^2}$$

The standard uncertainties for the pressure steps in increasing order are 2.1 ppm, 1.0 ppm, 1.1 ppm, 0.2 ppm, 0.2 ppm, 0.3 ppm, 0.2 ppm and 0.2 ppm.

These uncertainty values are taken into account as the TS instability contribution in equations 8 and 9.

6.2 Results of the participants

Effective areas and uncertainty values (k = 1) in mm^2 reported by participants are given in Table 4 and Table 5, respectively.

Table 4. Effective areas in mm^2 reported by participants

p MPa	FORCE - Denmark	UME - Turkey	PTB - Germany	BEV - Austria	METAS - Switzerland	SMD - Belgium
0.74	49.01517	49.01525	49.01447	49.01470	49.01453	49.01524
1.08	49.01507	49.01509	49.01479	49.01515	49.01474	49.01571
1.77	49.01519	49.01506	49.01490	49.01505	49.01465	49.01574
2.94	49.01519	49.01497	49.01499	49.01495	49.01450	49.01572
4.10	49.01507	49.01489	49.01489	49.01480	49.01439	49.01559
5.27	49.01503	49.01478	49.01480	49.01465	49.01431	49.01546
6.44	49.01490	49.01463	49.01464	49.01455	49.01412	49.01534
6.79	49.01480	49.01459	49.01461	49.01455	49.01412	49.01522
p MPa	MCCAA - SMI Malta	CEM - Spain	FSB-LPM - Croatia	MIRS/IMT/LMT - Slovenia	SMU - Slovakia	IMBiH - Bosnia and Herzegovina
0.74	49.01434	49.01475	49.01393	49.01556	49.01448	49.01551
1.08	49.01440	49.01480	49.01425	49.01526	49.01465	49.01534
1.77	49.01435	49.01505	49.01442	49.01524	49.01473	49.01536
2.94	49.01416	49.01525	49.01454	49.01515	49.01480	49.01524
4.10	49.01415	49.01520	49.01456	49.01509	49.01466	49.01503
5.27	49.01407	49.01510	49.01450	49.01494	49.01453	49.01484
6.44	49.01393	49.01505	49.01450	49.01478	49.01428	49.01477
6.79	49.01386	49.01505	49.01448	49.01472	49.01420	49.01473
p MPa	INM - Romania	MKEH - Hungary	INRIM - Italy	RISE - Sweden	NPL - United Kingdom	NSAI NML - Ireland
0.74	49.01358	49.01433	49.01497	49.01475	49.01533	49.01490
1.08	49.01380	49.01462	49.01507	49.01500	49.01518	49.01485
1.77	49.01367	49.01454	49.01509	49.01488	49.01516	49.01483
2.94	49.01413	49.01457	49.01503	49.01481	49.01508	49.01476
4.10	49.01431	49.01453	49.01491	49.01473	49.01497	49.01471
5.27	49.01433	49.01445	49.01485	49.01481	49.01482	49.01463
6.44	49.01439	49.01435	49.01468	49.01467	49.01464	49.01459
6.79	49.01427	49.01432	49.01464	49.01471	49.01458	49.01461
p MPa	GUM - Poland	VSL - Netherlands	VTT MIKES-Finland			
0.74	49.01597	49.01521	49.01424			
1.08	49.01591	49.01508	49.01417			
1.77	49.01577	49.01499	49.01424			
2.94	49.01556	49.01497	49.01422			
4.10	49.01552	49.01492	49.01412			
5.27	49.01529	49.01475	49.01412			
6.44	49.01524	49.01477	49.01408			
6.79	49.01517	49.01482	49.01405			

Table 5. Measurement uncertainty (k = 1) in mm^2 reported by participants

p MPa	FORCE - Denmark	UME - Turkey	PTB - Germany	BEV - Austria	METAS - Switzerland	SMD - Belgium
0.74	0.00130	0.00069	0.00061	0.00060	0.00053	0.00108
1.08	0.00117	0.00069	0.00051	0.00060	0.00052	0.00101
1.77	0.00107	0.00069	0.00043	0.00060	0.00051	0.00095
2.94	0.00101	0.00069	0.00040	0.00060	0.00050	0.00093
4.10	0.00098	0.00069	0.00039	0.00060	0.00050	0.00090
5.27	0.00096	0.00069	0.00039	0.00060	0.00050	0.00091
6.44	0.00096	0.00069	0.00039	0.00060	0.00050	0.00092
6.79	0.00095	0.00069	0.00039	0.00060	0.00050	0.00092
p MPa	MCCAA - SMI Malta	CEM - Spain	FSB-LPM - Croatia	MIRS/IMT/LMT - Slovenia	SMU - Slovakia	IMBiH - Bosnia and Herzegovina
0.74	0.00068	0.00060	0.00072	0.00054	0.00062	0.00087
1.08	0.00066	0.00060	0.00073	0.00048	0.00062	0.00087
1.77	0.00065	0.00060	0.00071	0.00046	0.00062	0.00086
2.94	0.00064	0.00060	0.00076	0.00045	0.00062	0.00086
4.10	0.00064	0.00060	0.00068	0.00046	0.00062	0.00086
5.27	0.00063	0.00060	0.00067	0.00047	0.00062	0.00086
6.44	0.00063	0.00060	0.00068	0.00048	0.00062	0.00087
6.79	0.00063	0.00060	0.00067	0.00049	0.00062	0.00087
p MPa	INM - Romania	MKEH - Hungary	INRIM - Italy	RISE - Sweden	NPL - United Kingdom	NSAI NML - Ireland
0.74	0.00142	0.00072	0.00056	0.00098	0.00044	0.00099
1.08	0.00142	0.00062	0.00056	0.00099	0.00044	0.00083
1.77	0.00147	0.00057	0.00055	0.00096	0.00044	0.00070
2.94	0.00152	0.00055	0.00055	0.00096	0.00045	0.00064
4.10	0.00157	0.00056	0.00055	0.00102	0.00045	0.00064
5.27	0.00162	0.00057	0.00055	0.00097	0.00045	0.00064
6.44	0.00170	0.00058	0.00055	0.00098	0.00045	0.00064
6.79	0.00170	0.00059	0.00054	0.00098	0.00045	0.00064
p MPa	GUM - Poland	VSL - Netherlands	VTT – MIKES Finland			
0.74	0.00079	0.00054	0.00070			
1.08	0.00079	0.00054	0.00065			
1.77	0.00079	0.00054	0.00061			
2.94	0.00079	0.00054	0.00058			
4.10	0.00079	0.00054	0.00057			
5.27	0.00079	0.00054	0.00103			
6.44	0.00079	0.00054	0.00102			
6.79	0.00079	0.00054	0.00102			

6.3 Reference Values (RV)

As reference values (key comparison reference values RV), the effective areas were used calculated by the weighted mean method.

The reference values were calculated based on the measurement results of the participants having primary pressure standards, see Table 1.

6.3.1 Weighted mean

Equation 4

$$A_{p,\mathrm{ref,weighted\ mean}} = \left. \sum_{j=1}^{N} \frac{A_{p,j}}{u^2(A_{p,j})} \middle/ \sum_{j=1}^{N} \frac{1}{u^2(A_{p,j})} \right.$$

where $u^2(A_{p,j})$ is the standard uncertainty associated with the effective area $A_{p,j}$ of laboratory j.

The standard uncertainty is given by:

Equation 5

$$u(A_{p,\mathrm{ref,weighted\ mean}}) = \left[\sum_{j=1}^{N} \frac{1}{u^2(A_{p,j})}\right]^{-0.5}$$

The consistency of the determination of the reference value must be checked using the chi-squared test as described by Cox in [8]. Results are considered as consistent if the observed chi-squared value χ^2_{obs} calculated by equation 6 is smaller than the value of chi-square distribution calculated for the degree of freedom $v = N\text{-}1$ at probability Pr = 0.05, $\chi^2(v, \mathrm{Pr})$.

Equation 6

$$\chi^2_{\mathrm{obs}} = \sum_{j=1}^{N} \frac{\left(A_{p,j} - A_{p,\mathrm{ref,weighted\ mean}}\right)^2}{u^2(A_{p,j})}$$

6.3.2 Results

Results for calculation of the reference values are given in Table 6 and in Figure 3.

Table 6. Proposed reference values of effective areas calculated as weighted-means ($A_{p,\mathrm{ref,weighted\ mean}}$) including relative and absolute standard uncertainties, observed chi-squared values (χ^2_{obs}) and values of the chi-square distribution calculated for degree of freedom v at the probability Pr = 0.05 ($\chi^2_{v=7}$)

p	$A_{p,\mathrm{ref,weighted\ mean}}$	$\frac{u(A_{p,\mathrm{ref,weighted\ mean}})}{A_{p,\mathrm{ref,weighted\ mean}}}$	$u(A_{p,\mathrm{ref,weighted\ mean}})$	χ^2_{obs}	$\chi^2_{v=7}$
MPa	mm^2	ppm	mm^2		
0.74	49.01483	4.1	0.00020	3.5	14.1
1.08	49.01486	3.9	0.00019	2.2	14.1
1.77	49.01488	3.8	0.00019	2.1	14.1
2.94	49.01487	3.7	0.00018	2.6	14.1
4.10	49.01477	3.7	0.00018	2.9	14.1
5.27	49.01472	3.8	0.00019	1.7	14.1
6.44	49.01457	3.8	0.00019	2.1	14.1
6.79	49.01455	3.8	0.00019	2.3	14.1

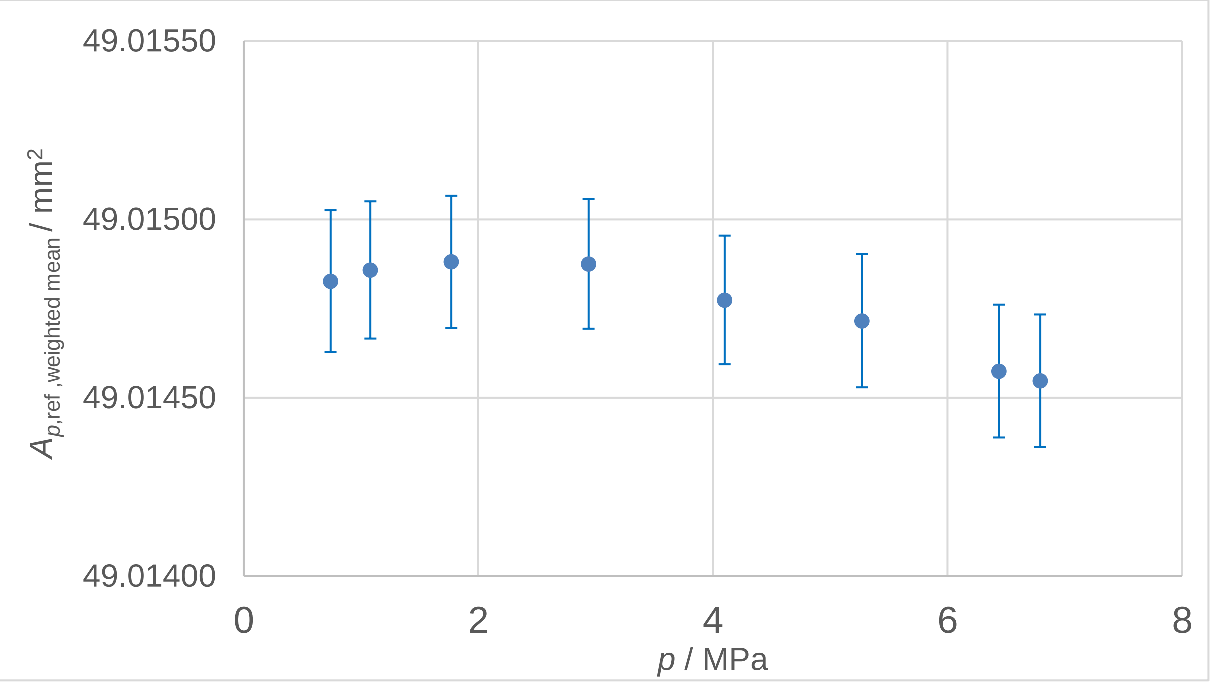

Figure 3.Reference values and their standard uncertainties evaluated as weighted means $A_{p,\mathrm{ref,weighted\ mean}}$

As the weighted mean based on the results from the primary laboratories passes the consistency check, we take it as a reference value for the comparison before establishing the link.

These values have been chosen as the reference values $A_{p,\mathrm{RV}} = A_{p,\mathrm{ref,weighted\ mean}}$.

6.4 Degrees of equivalence

The degrees of equivalence of the laboratories are expressed by the differences of the laboratories' results from the RV and the expanded (k = 2) uncertainties of these differences.

The difference between the result of laboratory j and the key comparison reference value is calculated as:

Equation 7

$$d_j = A_{p,j} - A_{p,\mathrm{RV}}$$

The expanded uncertainty (k = 2) of d_j is given, for a laboratory contributing to the reference value, by:

Equation 8

$$U(d_j) = 2 \cdot \sqrt{u^2(A_{p,j}) - u^2(A_{p,\mathrm{RV}}) + u^2(\Delta A_{p,T})}$$

while for a laboratory not contributing to the reference value it is given by:

Equation 9

$$U(d_j) = 2 \cdot \sqrt{u^2(A_{p,j}) + u^2(A_{p,\mathrm{RV}}) + u^2(\Delta A_{p,T})}$$

where $u(\Delta A_{p,T})$ is the uncertainty value due to TS instability, see section 6.1.1.

The degree of equivalence is the offset respective to the reference value and the associated uncertainty of this offset, see Table 7.

Table 7. Degrees of equivalence for all the participants, k = 2

	FORCE - Denmark		UME - Turkey		PTB - Germany	
p	d_j	$U(d_j)$	d	$U(d)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	0.00034	0.00264	0.00043	0.00145	-0.00035	0.00117
1.08	0.00021	0.00238	0.00023	0.00144	-0.00007	0.00095
1.77	0.00031	0.00217	0.00018	0.00144	0.00002	0.00078
2.94	0.00032	0.00204	0.00009	0.00143	0.00012	0.00071
4.10	0.00029	0.00199	0.00011	0.00143	0.00012	0.00070
5.27	0.00031	0.00196	0.00006	0.00144	0.00008	0.00068
6.44	0.00032	0.00195	0.00006	0.00144	0.00007	0.00068
6.79	0.00026	0.00194	0.00005	0.00143	0.00006	0.00068
	BEV - Austria		METAS - Switzerland		SMD - Belgium	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	-0.00013	0.00127	-0.00030	0.00099	0.00041	0.00220
1.08	0.00029	0.00126	-0.00012	0.00096	0.00085	0.00206
1.77	0.00017	0.00126	-0.00023	0.00095	0.00086	0.00194
2.94	0.00008	0.00125	-0.00037	0.00093	0.00085	0.00190
4.10	0.00003	0.00125	-0.00039	0.00093	0.00082	0.00184
5.27	-0.00007	0.00126	-0.00040	0.00092	0.00074	0.00186
6.44	-0.00002	0.00126	-0.00045	0.00092	0.00077	0.00188
6.79	0.00000	0.00126	-0.00043	0.00092	0.00067	0.00188
	MCCAA - SMI Malta		CEM - Spain		FSB-LPM - Croatia	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	-0.00048	0.00143	-0.00008	0.00114	-0.00089	0.00150
1.08	-0.00046	0.00138	-0.00006	0.00114	-0.00061	0.00150
1.77	-0.00053	0.00135	0.00017	0.00114	-0.00047	0.00146
2.94	-0.00072	0.00133	0.00038	0.00114	-0.00034	0.00156
4.10	-0.00062	0.00132	0.00043	0.00114	-0.00021	0.00141
5.27	-0.00064	0.00132	0.00038	0.00114	-0.00021	0.00140
6.44	-0.00064	0.00132	0.00048	0.00114	-0.00007	0.00140
6.79	-0.00069	0.00132	0.00050	0.00114	-0.00007	0.00140
	MIRS/IMT/LMT - Slovenia		SMU - Slovakia		IMBiH - Bosnia and Herzegovina	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	0.00073	0.00116	-0.00034	0.00118	0.00068	0.00179
1.08	0.00040	0.00103	-0.00021	0.00117	0.00048	0.00178
1.77	0.00036	0.00099	-0.00016	0.00118	0.00048	0.00176
2.94	0.00027	0.00098	-0.00007	0.00118	0.00037	0.00175
4.10	0.00032	0.00099	-0.00012	0.00118	0.00025	0.00175
5.27	0.00023	0.00102	-0.00019	0.00117	0.00013	0.00176
6.44	0.00021	0.00102	-0.00030	0.00117	0.00019	0.00177
6.79	0.00017	0.00104	-0.00035	0.00117	0.00018	0.00178

	INM - Romania		MKEH - Hungary		INRIM - Italy	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	-0.00125	0.00287	-0.00050	0.00150	0.00015	0.00105
1.08	-0.00105	0.00287	-0.00024	0.00130	0.00021	0.00104
1.77	-0.00121	0.00296	-0.00034	0.00120	0.00021	0.00105
2.94	-0.00074	0.00306	-0.00030	0.00116	0.00016	0.00104
4.10	-0.00046	0.00316	-0.00024	0.00118	0.00014	0.00104
5.27	-0.00039	0.00326	-0.00027	0.00120	0.00013	0.00104
6.44	-0.00018	0.00342	-0.00022	0.00122	0.00011	0.00103
6.79	-0.00028	0.00342	-0.00023	0.00124	0.00009	0.00102
	RISE - Sweden		NPL - United Kingdom		NSAI NML - Ireland	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	-0.00008	0.00201	0.00050	0.00081	0.00007	0.00203
1.08	0.00014	0.00201	0.00032	0.00080	-0.00001	0.00170
1.77	0.00000	0.00196	0.00028	0.00081	-0.00005	0.00145
2.94	-0.00006	0.00195	0.00021	0.00081	-0.00011	0.00133
4.10	-0.00005	0.00207	0.00019	0.00082	-0.00006	0.00133
5.27	0.00010	0.00197	0.00011	0.00081	-0.00009	0.00134
6.44	0.00010	0.00199	0.00006	0.00081	0.00002	0.00134
6.79	0.00016	0.00200	0.00003	0.00081	0.00006	0.00134
	GUM - Poland		VSL - Netherlands		VTT MIKES - Finland	
p	d_j	$U(d_j)$	d_j	$U(d_j)$	d_j	$U(d_j)$
MPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
0.74	0.00114	0.00164	0.00038	0.00102	-0.00059	0.00136
1.08	0.00105	0.00163	0.00023	0.00102	-0.00069	0.00124
1.77	0.00089	0.00163	0.00011	0.00103	-0.00064	0.00116
2.94	0.00069	0.00162	0.00009	0.00103	-0.00065	0.00110
4.10	0.00075	0.00162	0.00015	0.00103	-0.00065	0.00108
5.27	0.00057	0.00162	0.00004	0.00102	-0.00060	0.00204
6.44	0.00067	0.00162	0.00019	0.00102	-0.00049	0.00202
6.79	0.00062	0.00162	0.00027	0.00102	-0.00050	0.00201

The difference d_j between the results of laboratories and the RV with the expanded uncertainty $U(d_j)$ is shown from Figure 4 to Figure 11.

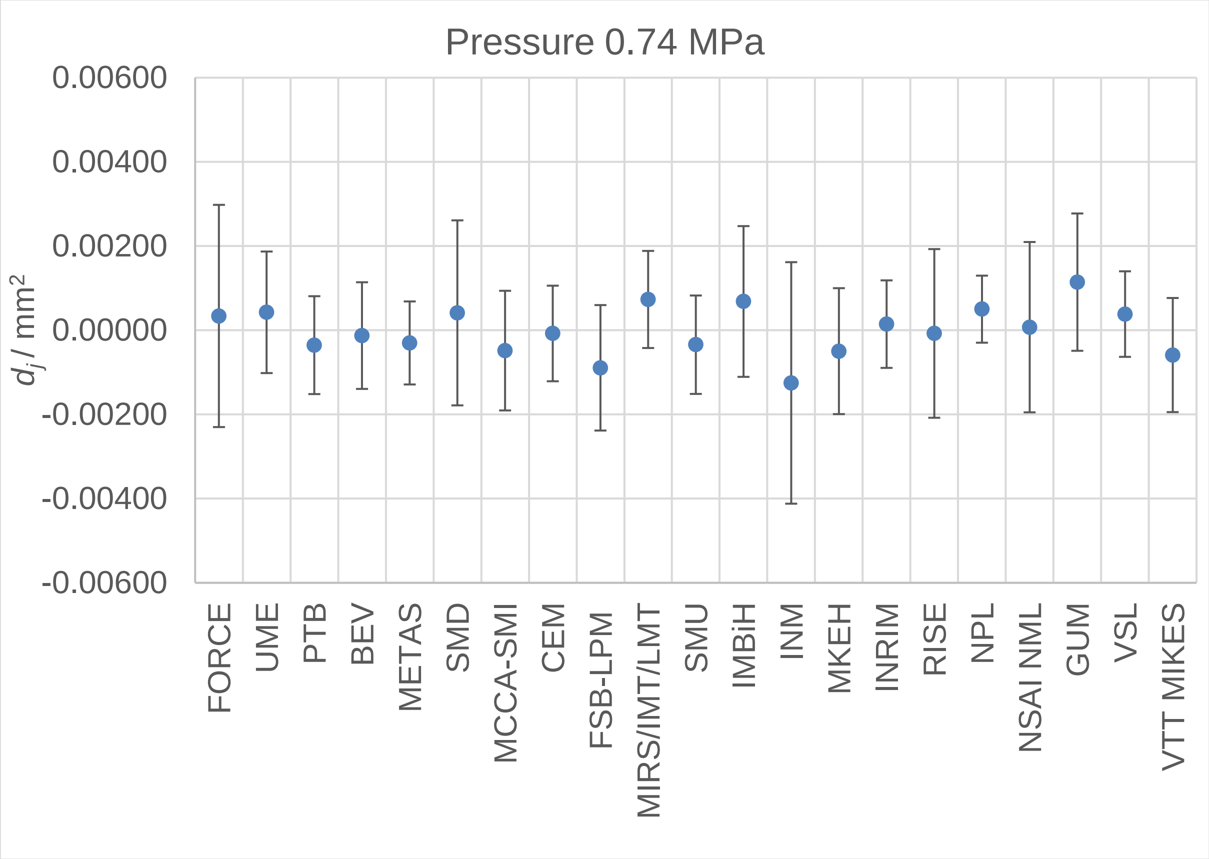

Figure 4. The differences d_j with expanded uncertainties $U(d_j)$ at 0.74 MPa.

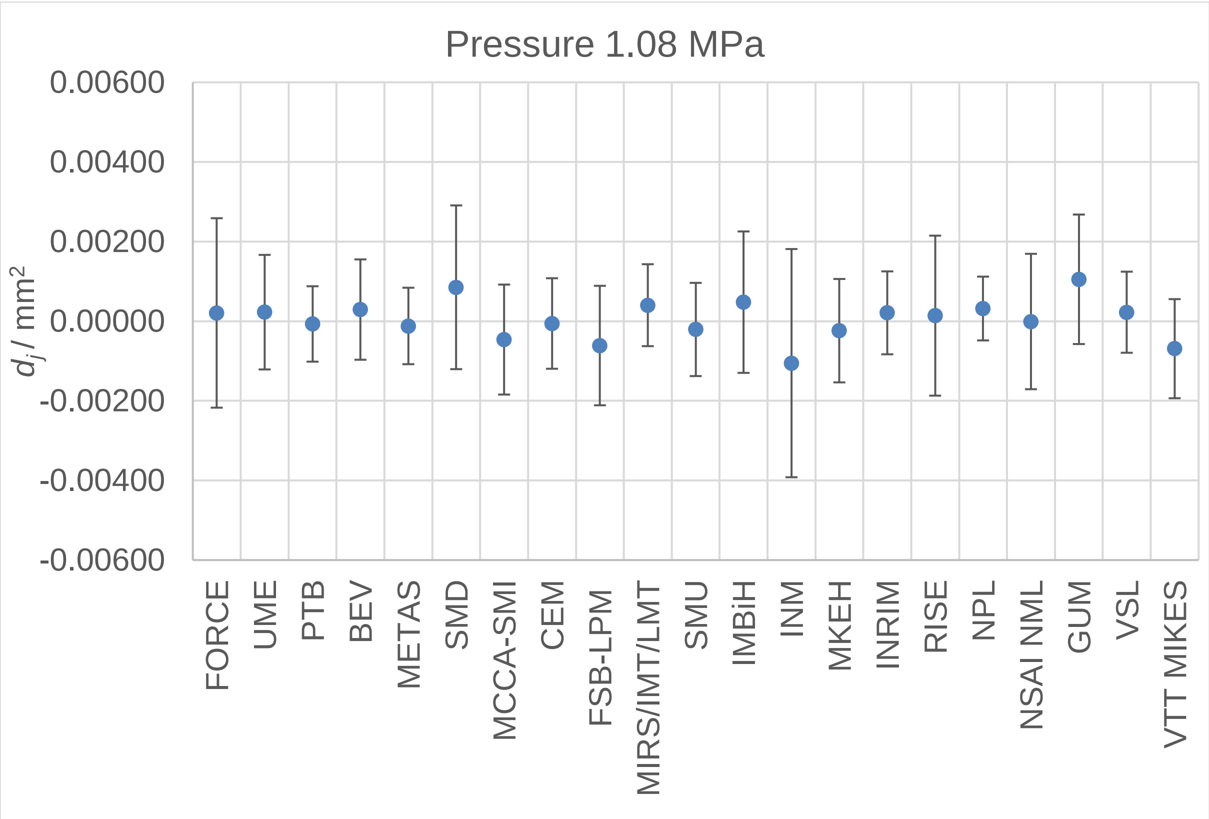

Figure 5. The differences d_j with expanded uncertainties $U(d_j)$ at 1.08 MPa.

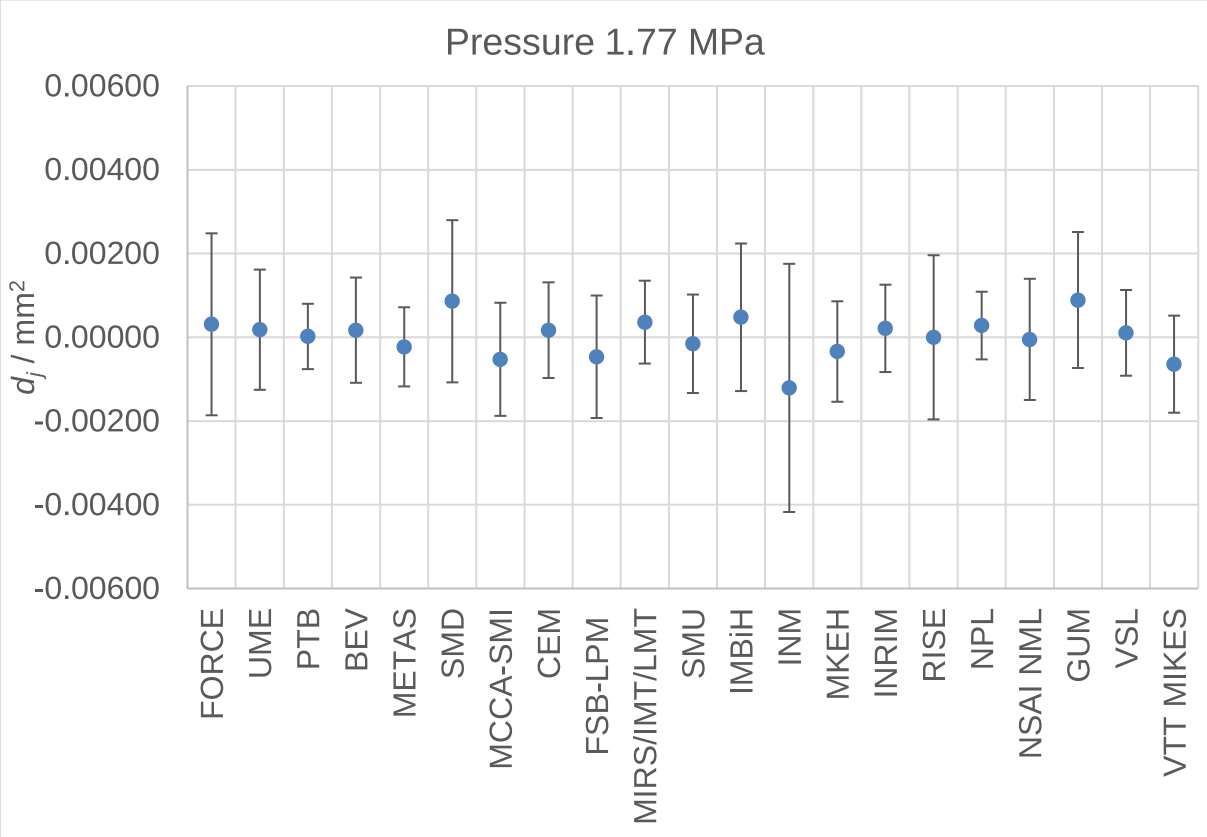

Figure 6. The differences d_j with expanded uncertainties $U(d_j)$ at 1.77 MPa

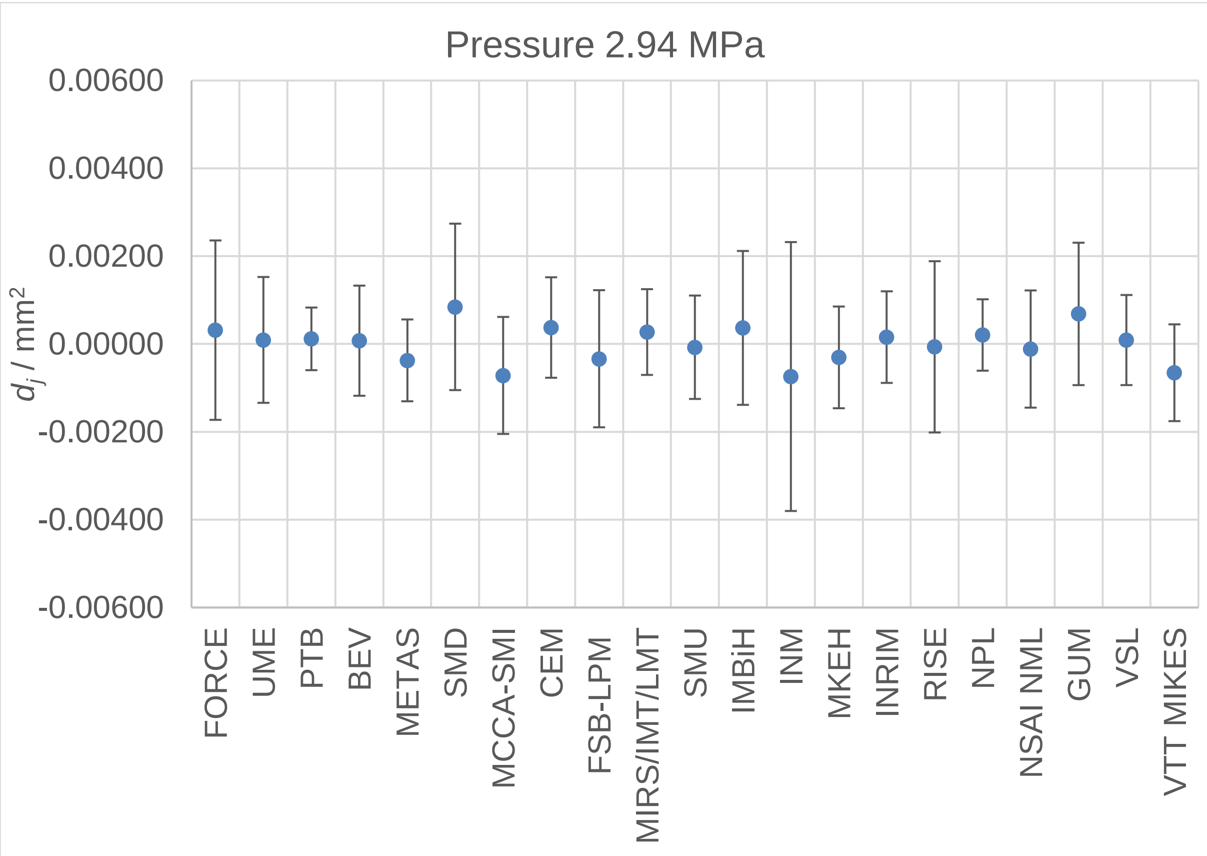

Figure 7. The differences d_j with expanded uncertainties $U(d_j)$ at 2.94 MPa

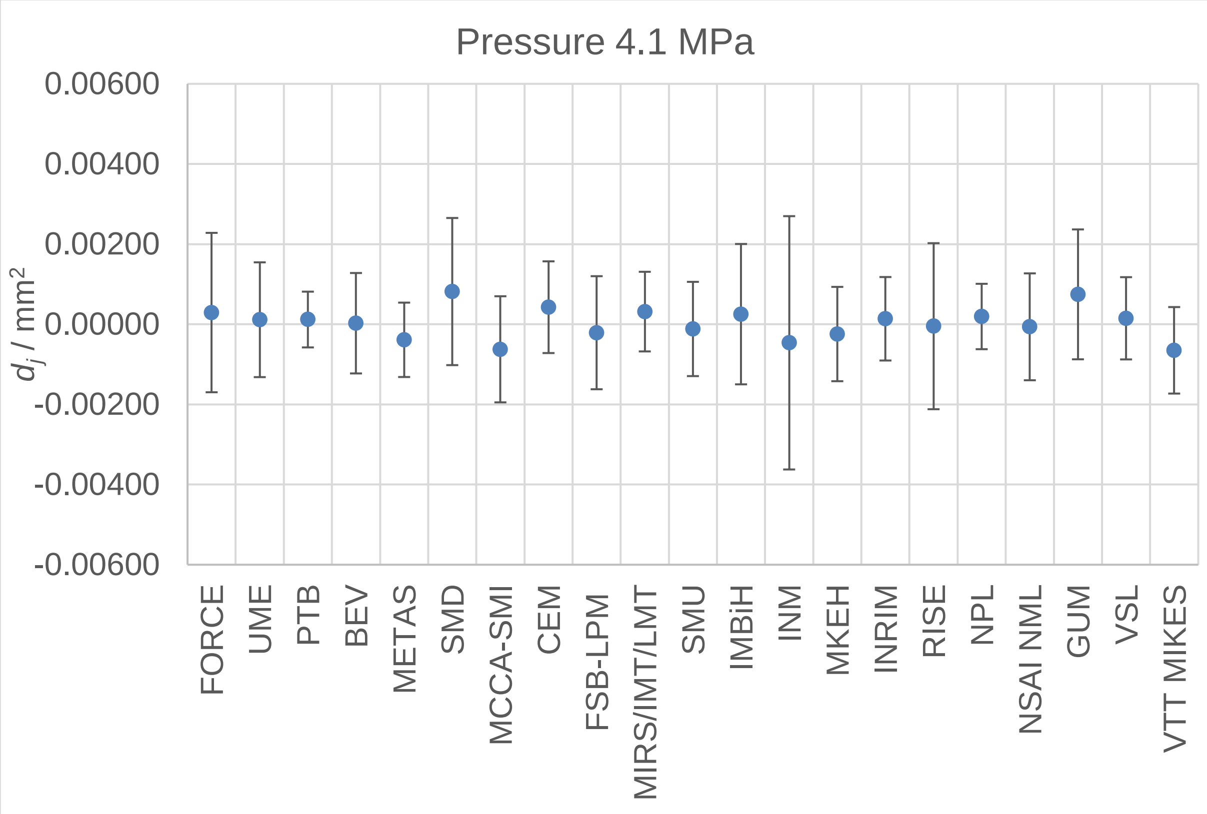

Figure 8. The differences d_j with expanded uncertainties $U(d_j)$ at 4.1 MPa

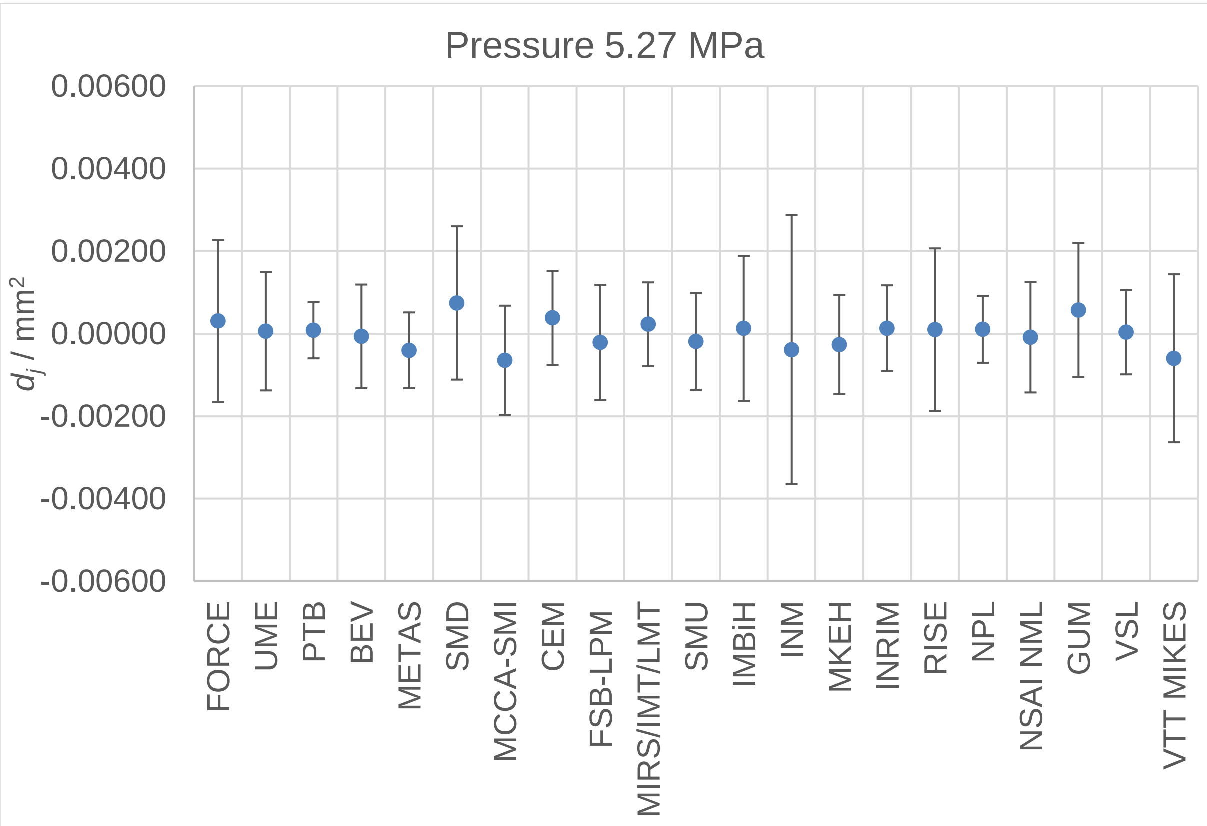

Figure 9. The differences d_j with expanded uncertainties $U(d_j)$ at 5.27 MPa

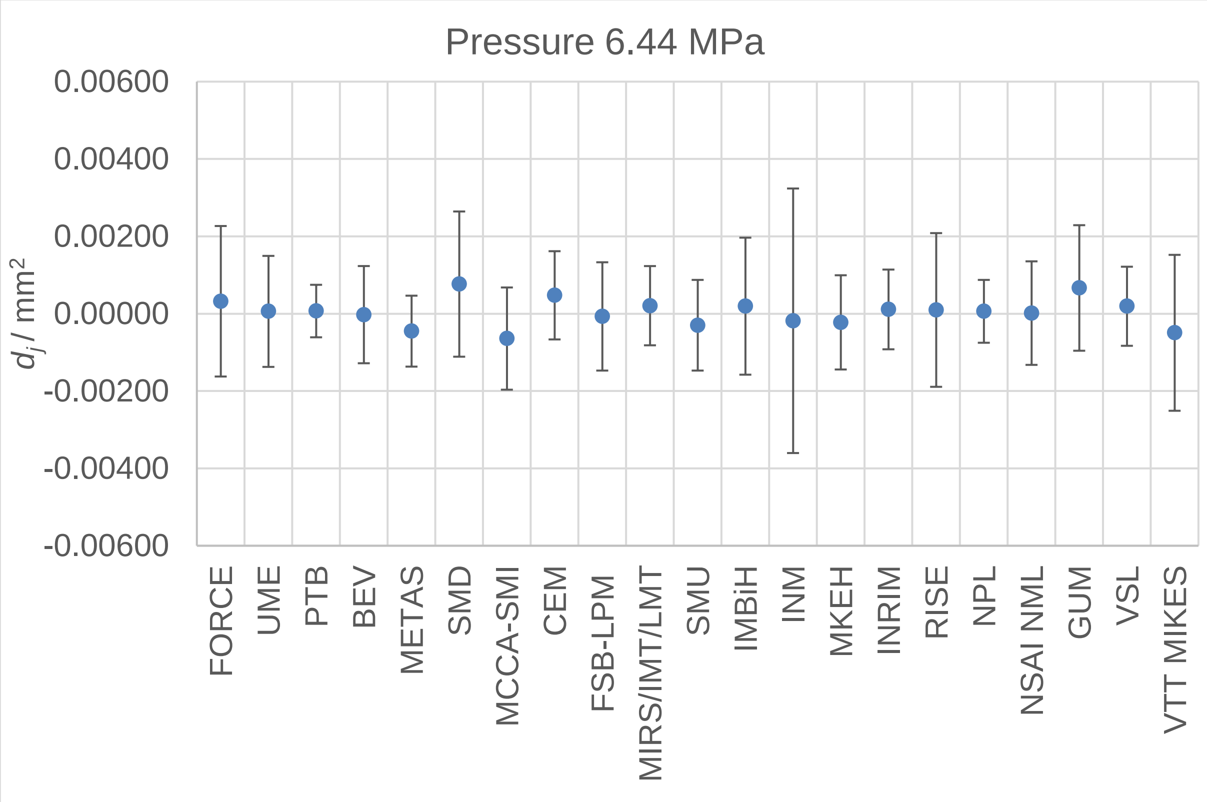

Figure 10. The differences d_j with expanded uncertainties $U(d_j)$ at 6.44 MPa

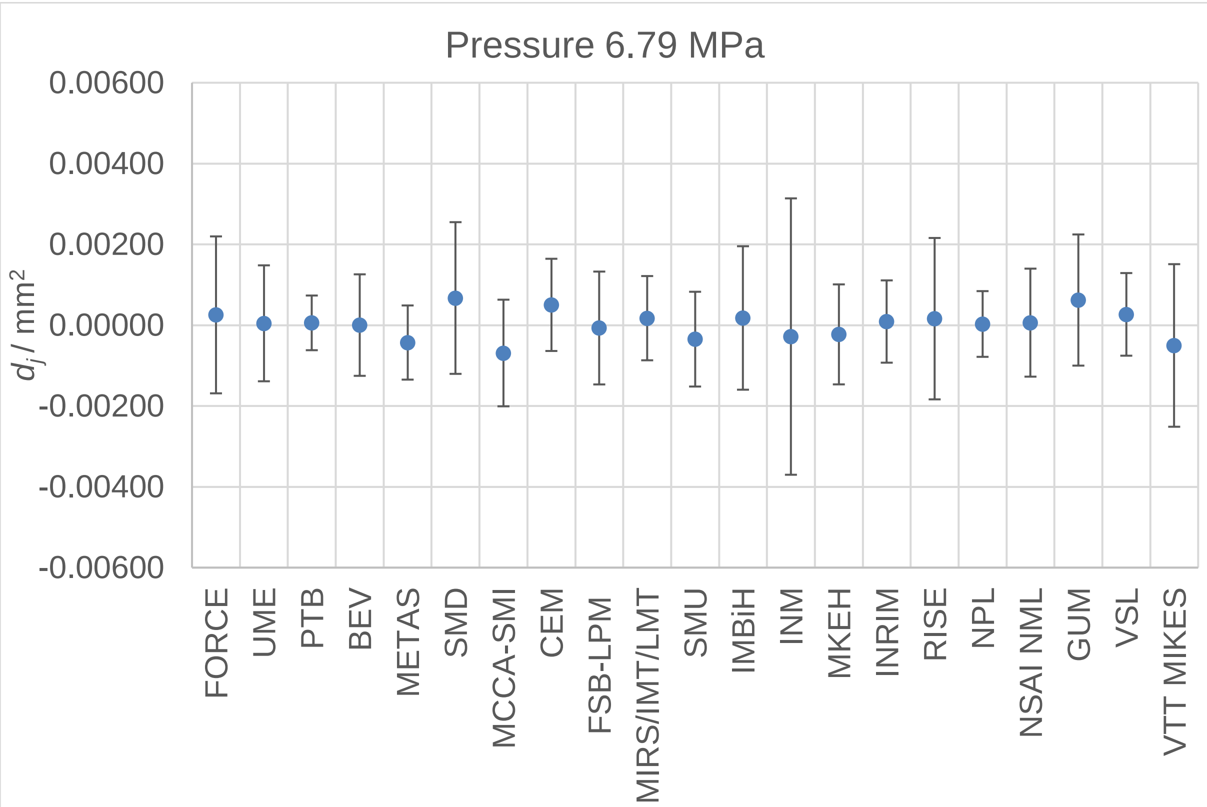

Figure 11. The differences d_j with expanded uncertainties $U(d_j)$ at 6.79 MPa

7 Linking the EURAMET.M.P-K1.c (EURAMET 1179) KC to CCM.P-K1.c KC

Key comparisons carried out by regional metrology organizations (RMO) must be linked to the corresponding CCM key comparisons by means of joint participants, see CIPM MRA-D-05 “Measurements comparisons in the CIPM MRA” [9]. In this comparison, we have the opportunity to link this EURAMET.M.P-K1.c (EURAMET 1179) key comparison to CCM.P-K1.c key comparison through PTB.

The procedure is described in “Proposal for linking the results of CIPM and RMO key comparisons” [10].

The link is established through PTB that has taken part in both the EURAMET and CCM key comparisons.

CCM key comparison reference values and results for PTB presented in the CCM.P-K1.c final report [11] are shown below.

CCM.P-K1.c final report, Table 5

p' nom / kPa	PTB data Av. A'(p', 20 °C) / mm^2	REF. VALUE A'(p', 20 °C) lin. fit / mm^2	Estimate of Unc. Ref. VALUE u_{REF} std. unc. / ppm	PTB diff. / ppm	PTB std. unc. / ppm	PTB std. unc. of difference / ppm
621,7	8,388525	8,38854	7,2	-1,9	4,8	8,7
738,5	8,388539	8,38855	7,2	-0,8	4,7	8,6
1077,5	8,388562	8,38856	7,2	0,4	4,6	8,5
1767	8,38861	8,38859	7,2	2,8	4,6	8,5
2935,7	8,388694	8,38863	7,2	7,3	7,4	10,3
4104,4	8,388738	8,38868	7,2	7,1	7,4	10,3
5273,1	8,388768	8,38872	7,2	5,2	7,4	10,3
6441,8	8,388801	8,38877	7,2	3,6	8,2	10,9
6792,4	8,388811	8,38878	7,2	3,1	8,3	11,0

7.1 Stability of the linking standard

A laboratory can provide a link between comparisons if its reference standard is stable between the two comparisons. The stability of the reference standard needs to be known to calculate the uncertainty.

PTB has informed that the stability of reference standard 0302 is 2.7 ppm.

In CCM.P-K1.c comparison, PTB used 3 different reference standards:

- Reference standard with serial number 6222 at 0.73 MPa, 1.07 MPa and 1.76 MPa.
- Reference standard with serial number 1310 at 2.93 MPa, 4.10 MPa and 5.27 MPa.
- Reference standard with serial number 0302 at 6.44 MPa and 6.79 MPa.

In EURAMET.M.P-K1.c comparison, PTB used:

- Reference standard with a serial number of DHI 0302 at all pressure points.

For linking purpose, PTB performed an additional comparison between the reference standards used in the comparisons in the range 0.73 MPa to 5.27 MPa. The uncertainty of the linkage between 0302 and 6222 in the range 0.73 MPa to 1.76 MPa is 1.0 ppm, and the uncertainty of the linkage between 0302 and 1310 in the range 2.93 MPa to 5.27 MPa is

1.0 ppm. With these results, the relative uncertainties of these standards due to instability were combined resulting in $u_{\text{stability of linking standard}}$ as given in Table 8.

Table 8. The linkage between 0302, 1310 and 6222

The reference standard used in CCM.P-K1.c	6222	1310	0302
Reference standard used in EURAMET.M.P-K1.c	0302	0302	0302
Link of standards used	0302-6222	0302-1310	-
$u_{\text{stability of linking standard}}$ / ppm	2.9	2.9	2.7
Pressure / MPa	0.73, 1.07, 1.76	2.93, 4.10, 5.27	6.44, 6.79

7.2 Linking procedure

The relative difference between the CCM PTB result, $A_{p,\text{PTB,CCM}}$, and the RV in the CCM KC, $A_{p,\text{ref,CCM}}$, is calculated according to equation 10.

Equation 10

$$D_{\text{PTB,CCM}} = \frac{(A_{p,\text{PTB,CCM}} - A_{p,\text{ref,CCM}})}{A_{p,\text{ref,CCM}}}.$$

The relative deviation of the EURAMET PTB result, $A_{p,\text{PTB,EURAMET}}$, from the EURAMET RV, $A_{p,\text{ref,EURAMET}}$, is calculated according to equation 11.

Equation 11

$$D_{\text{PTB,EURAMET}} = \frac{(A_{p,\text{PTB,EURAMET}} - A_{p,\text{ref,EURAMET}})}{A_{p,\text{ref,EURAMET}}}.$$

The link between EURAMET.M.P-K1.c and CCM.P-K1.c KC $D_{\text{EURAMET,CCM}}$ at each pressure point is given by:

Equation 12

$$D_{\text{EURAMET,CCM}} = D_{\text{PTB,CCM}} - D_{\text{PTB,EURAMET}}$$

The standard uncertainty of the $D_{\text{EURAMET,CCM}}$ can be calculated as:

Equation 13

$$u(D_{\text{EURAMET,CCM}}) = \sqrt{u^2(A_{p,\text{ref,CCM}})/A^2_{p,\text{ref,CCM}} + u^2_{\text{stability of linking standard}}}$$

The relative deviation of EURAMET laboratories' results from the CCM RV is calculated according to equation 14.

Equation 14

$$D_{j,\text{CCM}} = d_{j,\text{EURAMET}} + D_{\text{EURAMET,CCM}}$$

where

$d_{j,\mathrm{EURAMET}}$ designates the relative deviation of the EURAMET laboratory result from the EURAMET RV,

j designates laboratories participating in the EURAMET KC,

$D_{j,\mathrm{CCM}}$ represents the offset of the EURAMET laboratory *j* result respective to the CCM reference value for a particular pressure.

The uncertainty of the relative deviation from the CCM RV is obtained taking root-of-sum-of-squares of uncertainty of the CCM RV, stability of the PTB linking standard, participants' uncertainty, as well as instabilities of the transfer standards of the EURAMET ($u(\Delta A_{p,T})$) and the CCM ($u(\Delta A_{p,T,\mathrm{CCM}})$) KCs, as given by equation 15.

Equation 15

$$U(D_{j,\mathrm{CCM}}) = 2 \cdot \left[u^2\left(D_{\mathrm{EURAMET,CCM}}\right) + u^2\left(A_{p,j}\right)/A^2_{p,\mathrm{ref,EURAMET}} + u^2(\Delta A_{p,T})/A^2_{p,\mathrm{ref,EURAMET}} + u^2(\Delta A_{p,T,\mathrm{CCM}})/A^2_{p,\mathrm{ref,CCM}}\right]^{0.5}$$

Uncertainty of the CCM RV and stability of the PTB linking standard are included in $u\left(D_{\mathrm{EURAMET,CCM}}\right)$ as given by equation 13. Uncertainties of participants are taken from Table 5. Instability of the EURAMET TS is given in Section 6.1.1. The relative instability of the CCM TS is given in the CCM.P-K1c Final report [11], page 13, by $3{\cdot}10^{-6}$ for all pressures.

The degrees of equivalence and their uncertainties are calculated by equations 14 and 15 and are given in Table 9 and Figures 12 to 19. There, D_j means $D_{j,\mathrm{CCM}}$ and $U(D_j)$ means $U(D_{j,\mathrm{CCM}})$.

Table 9. The degrees of equivalence of EURAMET.M.P-K1.c participants linked to CCM.P-K1c.

	FORCE - Denmark		UME - Turkey		PTB - Germany	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	12.2	55.4	14.0	32.2	-1.9	29.4
1.08	4.9	50.4	5.3	32.2	-0.8	26.0
1.77	8.7	46.3	6.1	32.2	2.8	23.4
2.94	11.3	43.8	6.8	32.2	7.3	22.5
4.10	10.6	42.8	7.0	32.2	7.1	22.3
5.27	9.8	42.3	4.7	32.2	5.2	22.2
6.44	8.8	41.9	3.4	32.2	3.6	22.0
6.79	7.1	41.8	2.9	32.2	3.1	22.0
	BEV - Austria		METAS - Switzerland		SMD - Belgium	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	2.7	29.0	-0.8	26.6	13.7	46.7
1.08	6.6	29.0	-1.8	26.2	18.0	44.0
1.77	5.9	29.0	-2.3	25.9	19.9	41.7
2.94	6.4	29.0	-2.7	25.6	22.2	41.0
4.10	5.2	29.0	-3.2	25.6	21.3	39.9
5.27	2.2	29.0	-4.7	25.5	18.7	40.2
6.44	1.7	28.9	-7.0	25.4	17.8	40.6
6.79	2.0	28.9	-6.8	25.4	15.6	40.6
	MCCAA - SMI Malta		CEM - Spain		FSB-LPM - Croatia	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	-4.6	31.8	3.8	29.0	-12.9	33.1
1.08	-8.8	31.2	-0.6	29.0	-11.9	33.4
1.77	-8.3	30.7	5.9	29.0	-7.1	32.8
2.94	-9.7	30.4	12.6	29.0	-1.9	34.6
4.10	-8.1	30.3	13.4	29.0	0.4	31.9
5.27	-9.6	30.2	11.4	29.0	-0.8	31.5
6.44	-10.9	30.1	11.9	28.9	0.8	31.5
6.79	-12.1	30.1	12.2	28.9	0.5	31.5
	MIRS/IMT/LMT - Slovenia		SMU - Slovakia		IMBiH - Bosnia and Herzegovina	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	20.2	26.9	-1.7	29.5	19.3	38.8
1.08	8.8	24.9	-3.6	29.5	10.4	38.6
1.77	9.8	24.3	-0.8	29.5	12.1	38.4
2.94	10.5	24.1	3.4	29.5	12.4	38.3
4.10	11.1	24.4	2.3	29.5	9.8	38.3
5.27	8.2	24.7	-0.3	29.5	6.1	38.3
6.44	6.4	24.8	-3.9	29.4	6.2	38.5
6.79	5.5	25.1	-5.1	29.4	5.6	38.6

	INM - Romania		MKEH - Hungary		INRIM - Italy	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	-20.2	60.0	-4.8	33.2	8.3	27.4
1.08	-20.9	60.0	-4.2	29.7	4.9	27.4
1.77	-22.3	62.0	-4.5	28.0	6.7	27.4
2.94	-10.2	63.9	-1.3	27.3	8.1	27.3
4.10	-4.8	65.9	-0.3	27.6	7.5	27.3
5.27	-4.4	67.9	-1.9	28.0	6.2	27.4
6.44	-1.5	71.1	-2.4	28.2	4.5	27.1
6.79	-3.8	71.1	-2.7	28.6	3.8	26.9
	RISE - Sweden		NPL - United Kingdom		NSAI NML - Ireland	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	3.8	42.9	15.5	23.8	6.8	43.3
1.08	3.5	43.1	7.1	23.8	0.5	37.2
1.77	2.4	42.2	8.1	23.8	1.4	32.5
2.94	3.6	42.1	9.1	23.9	2.6	30.4
4.10	3.7	44.4	8.7	23.9	3.4	30.4
5.27	5.5	42.4	5.7	23.9	1.8	30.5
6.44	4.2	42.7	3.5	23.9	2.5	30.4
6.79	5.2	42.9	2.5	23.9	3.2	30.4
	GUM - Poland		VSL - Netherlands		VTT MIKES - Finland	
p	D_j	$U(D_j)$	D_j	$U(D_j)$	D_j	$U(D_j)$
MPa	ppm	ppm	ppm	ppm	ppm	ppm
0.74	28.6	35.8	13.2	27.1	-6.7	32.7
1.08	22.1	35.8	5.2	27.1	-13.5	30.8
1.77	20.5	35.8	4.6	27.1	-10.7	29.3
2.94	18.9	35.8	6.7	27.1	-8.4	28.3
4.10	19.9	35.8	7.7	27.1	-8.6	27.9
5.27	15.2	35.8	4.2	27.1	-8.7	45.0
6.44	15.8	35.7	6.1	27.0	-7.9	44.6
6.79	14.6	35.7	7.4	27.0	-8.3	44.5

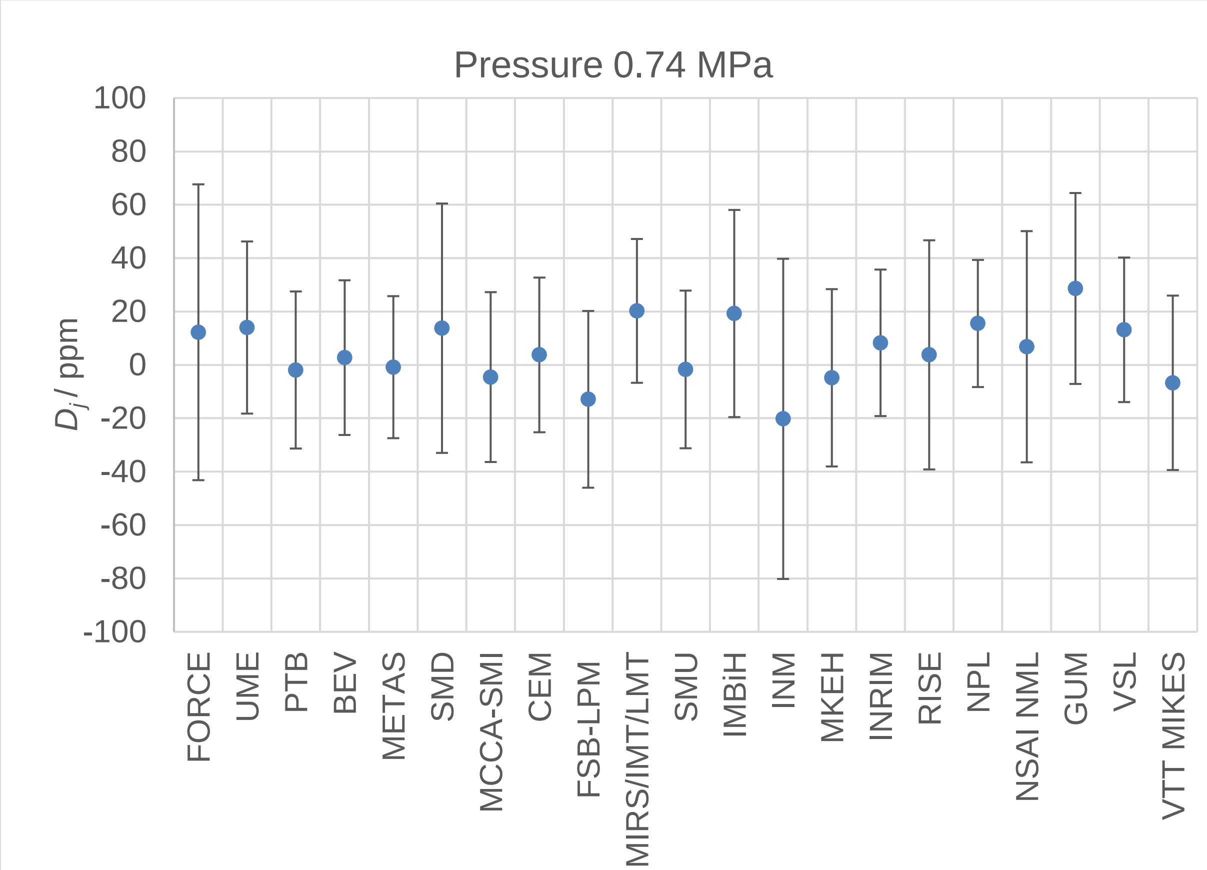

Figure 12. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 0.74 MPa

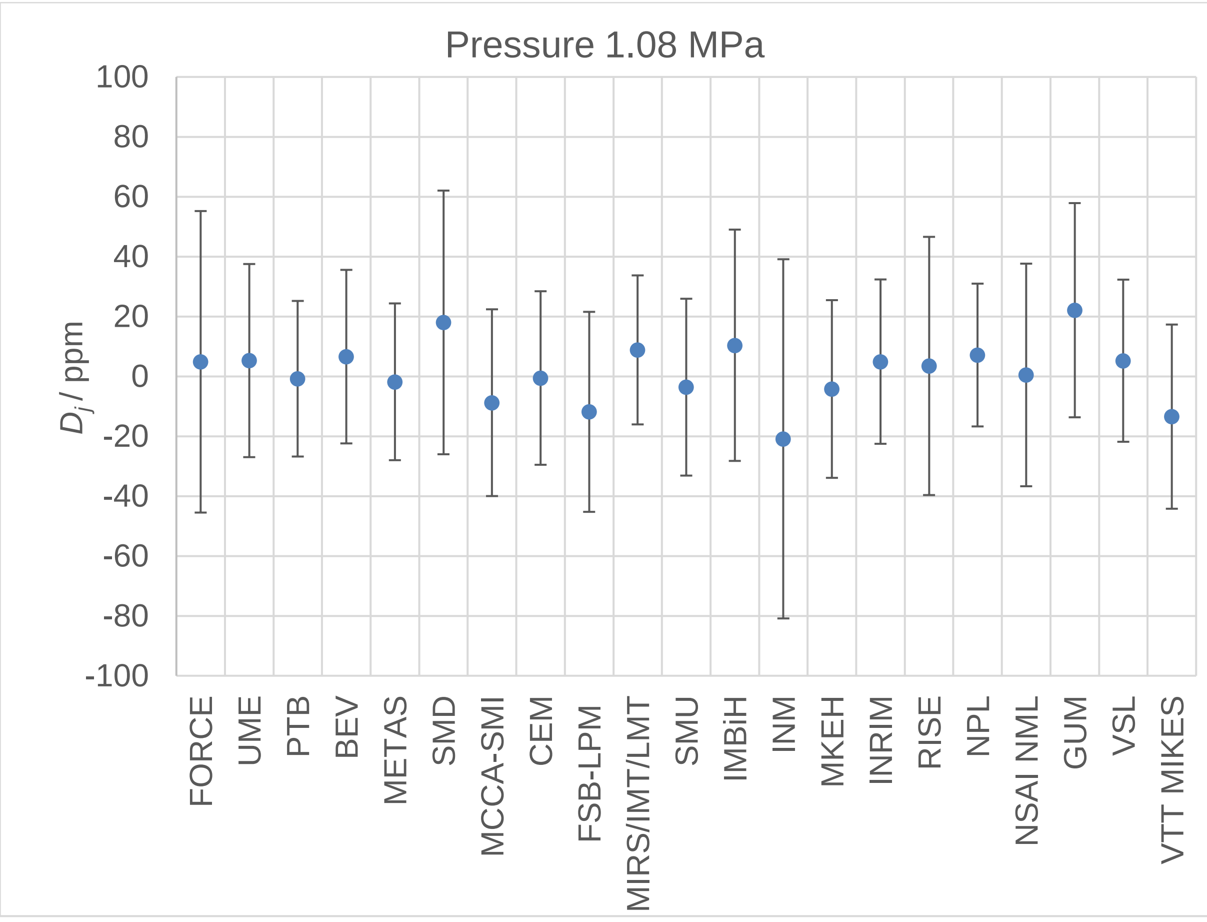

Figure 13. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 1.08 MPa

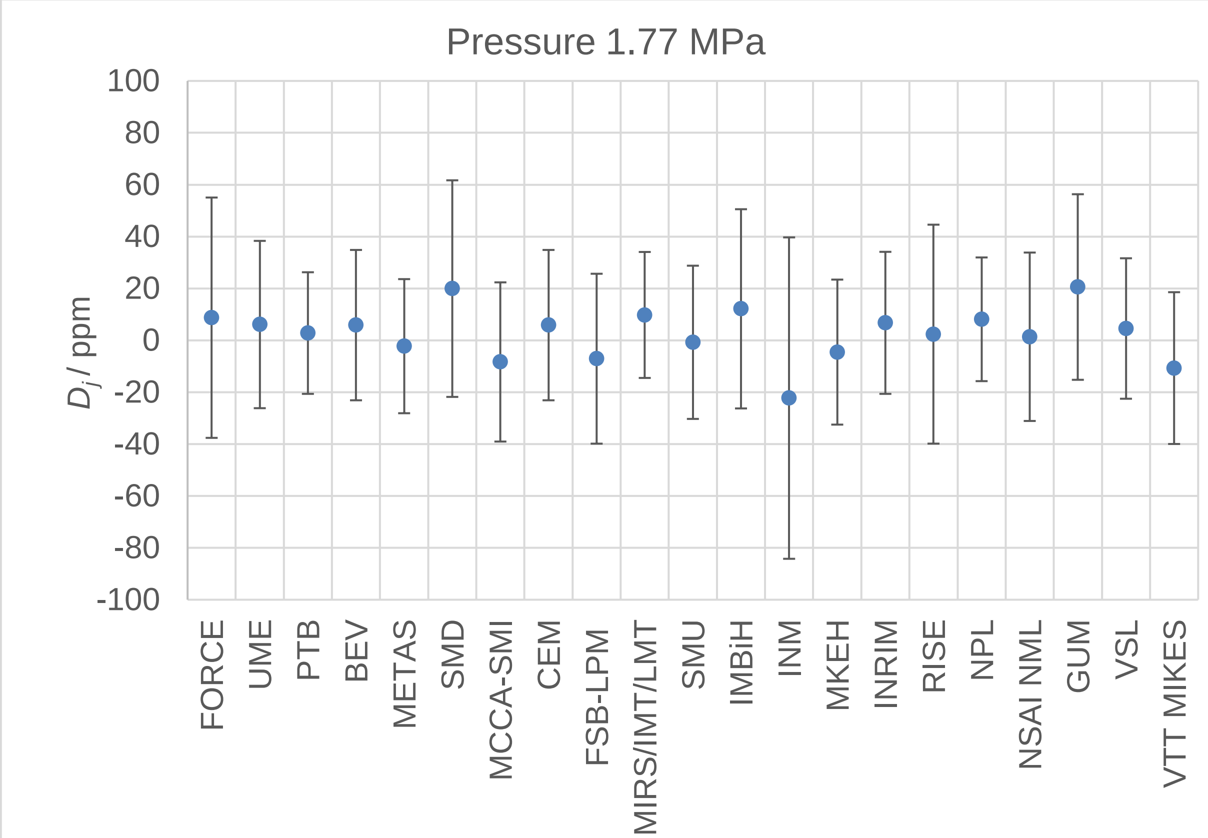

Figure 14. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 1.77 MPa

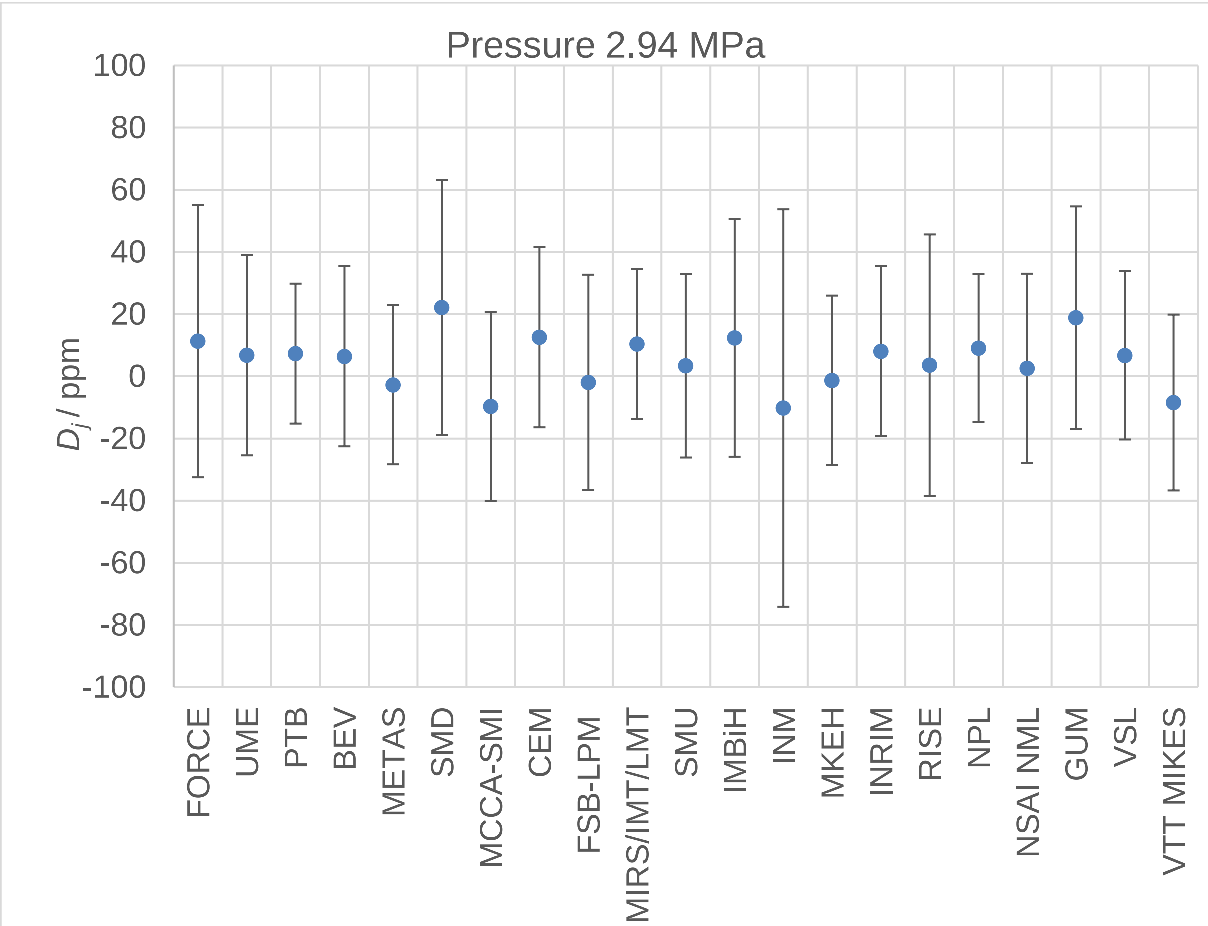

Figure 15. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 2.94 MPa

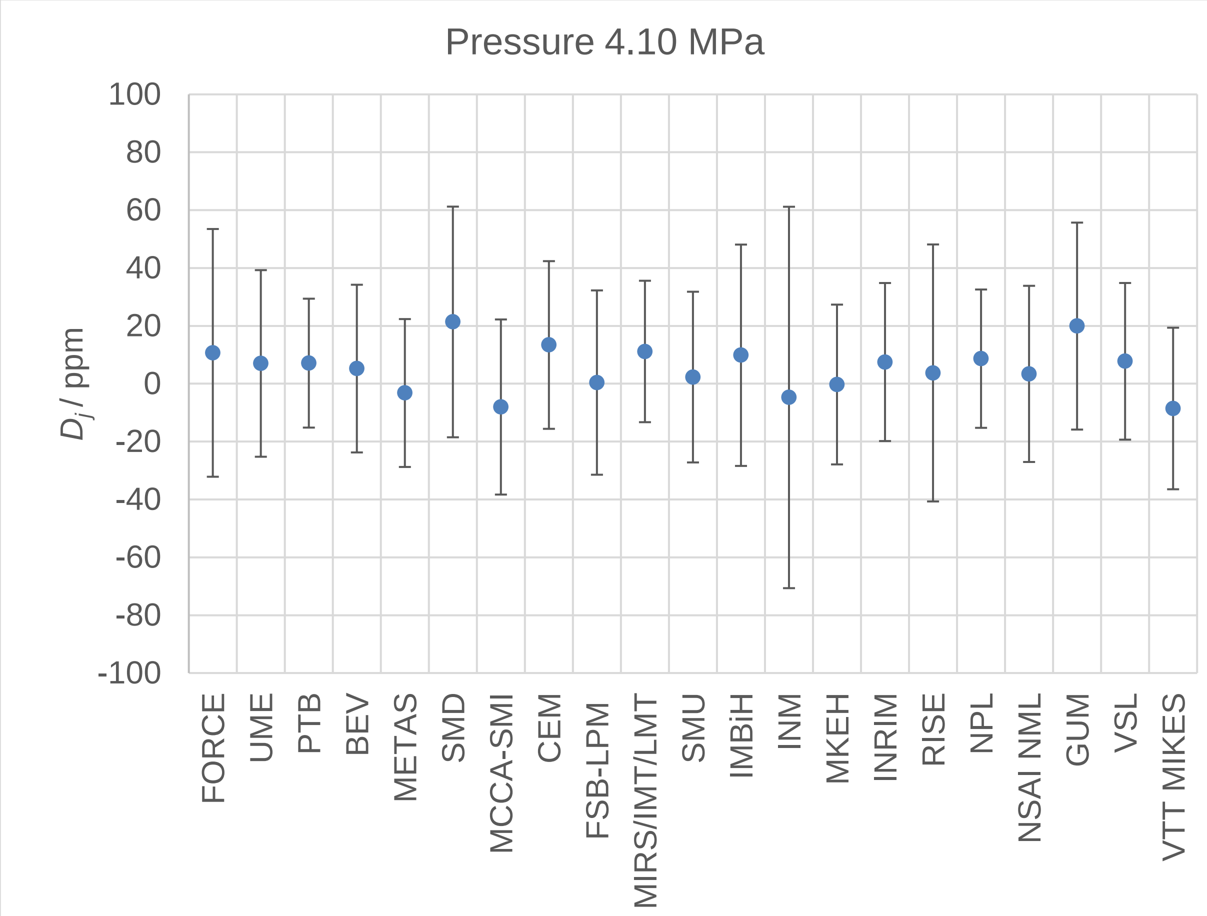

Figure 16. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 4.10 MPa

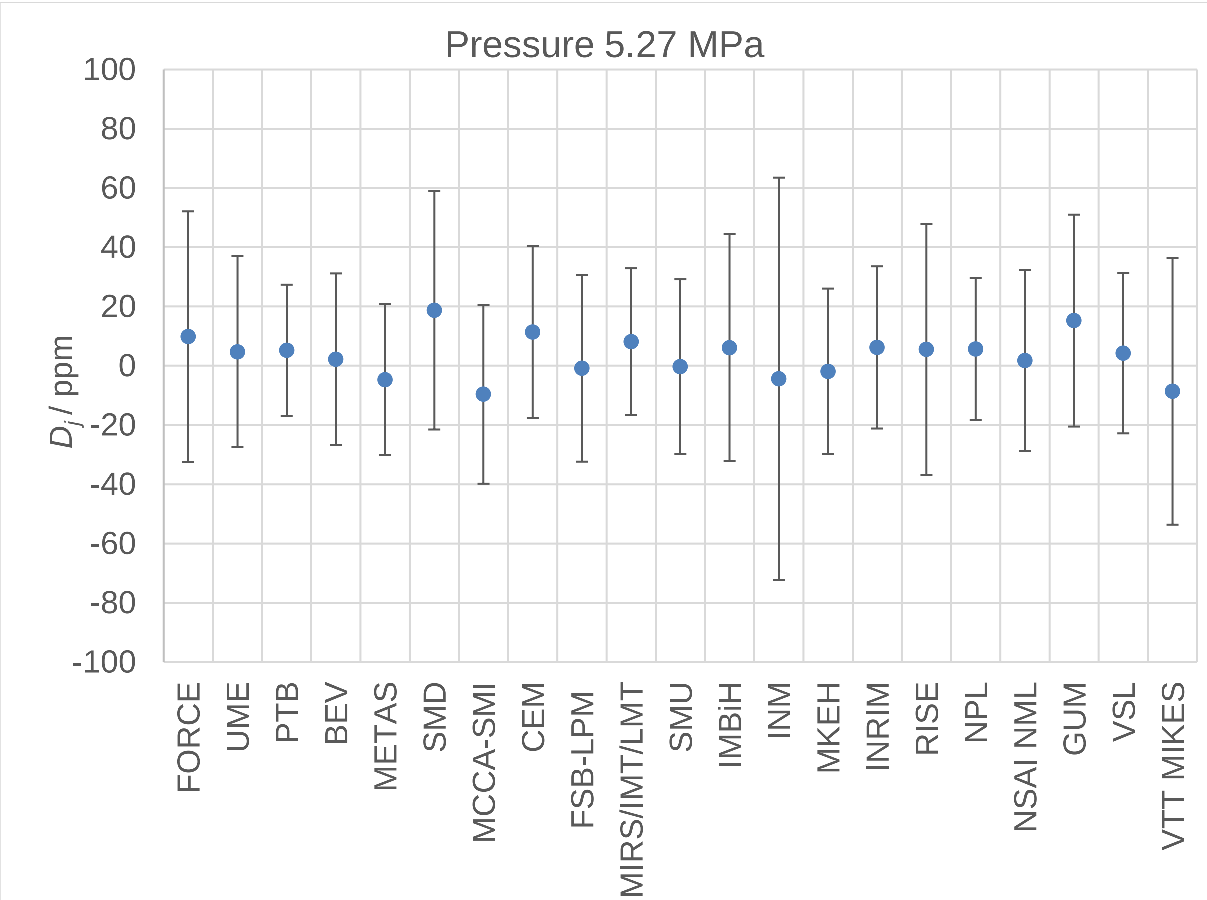

Figure 17. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 5.27 MPa

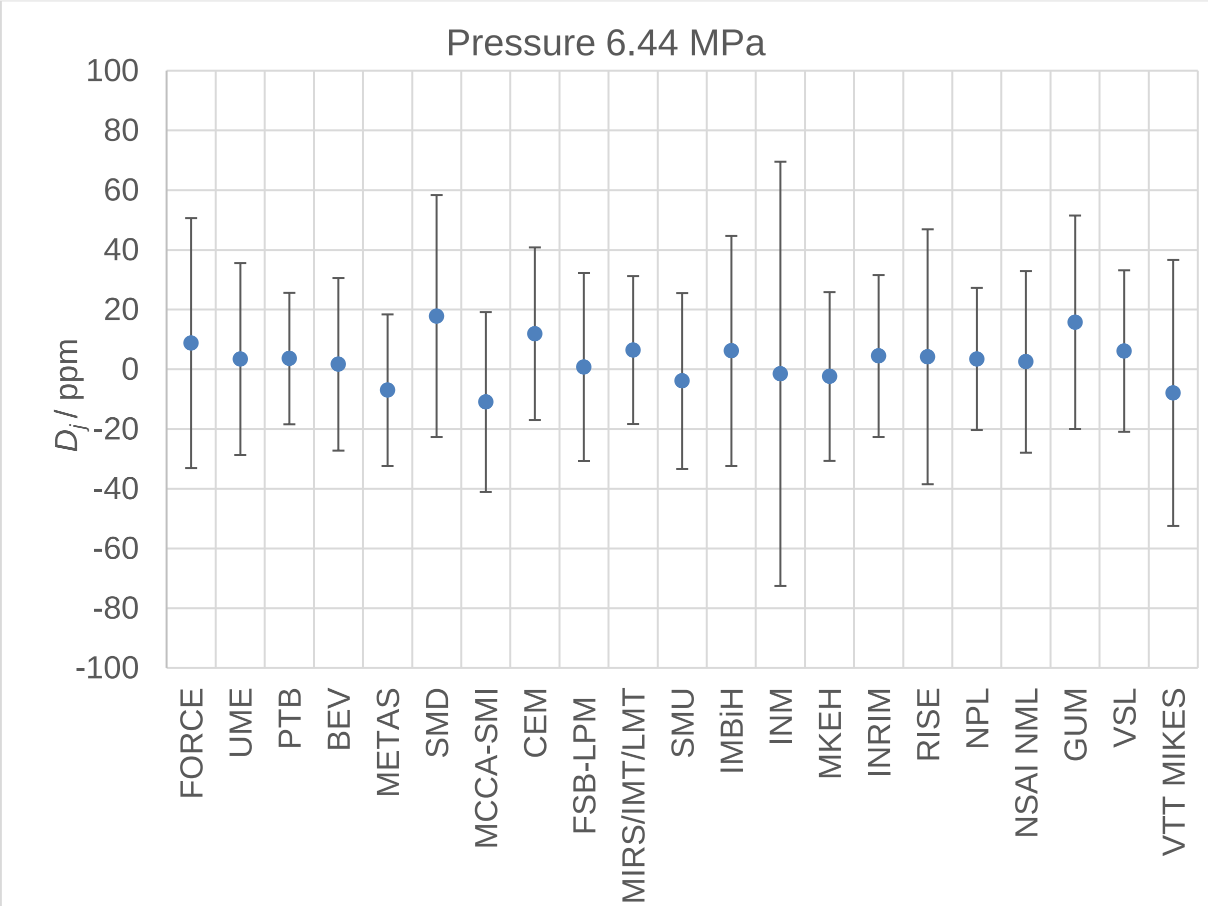

Figure 18. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 6.44 MPa

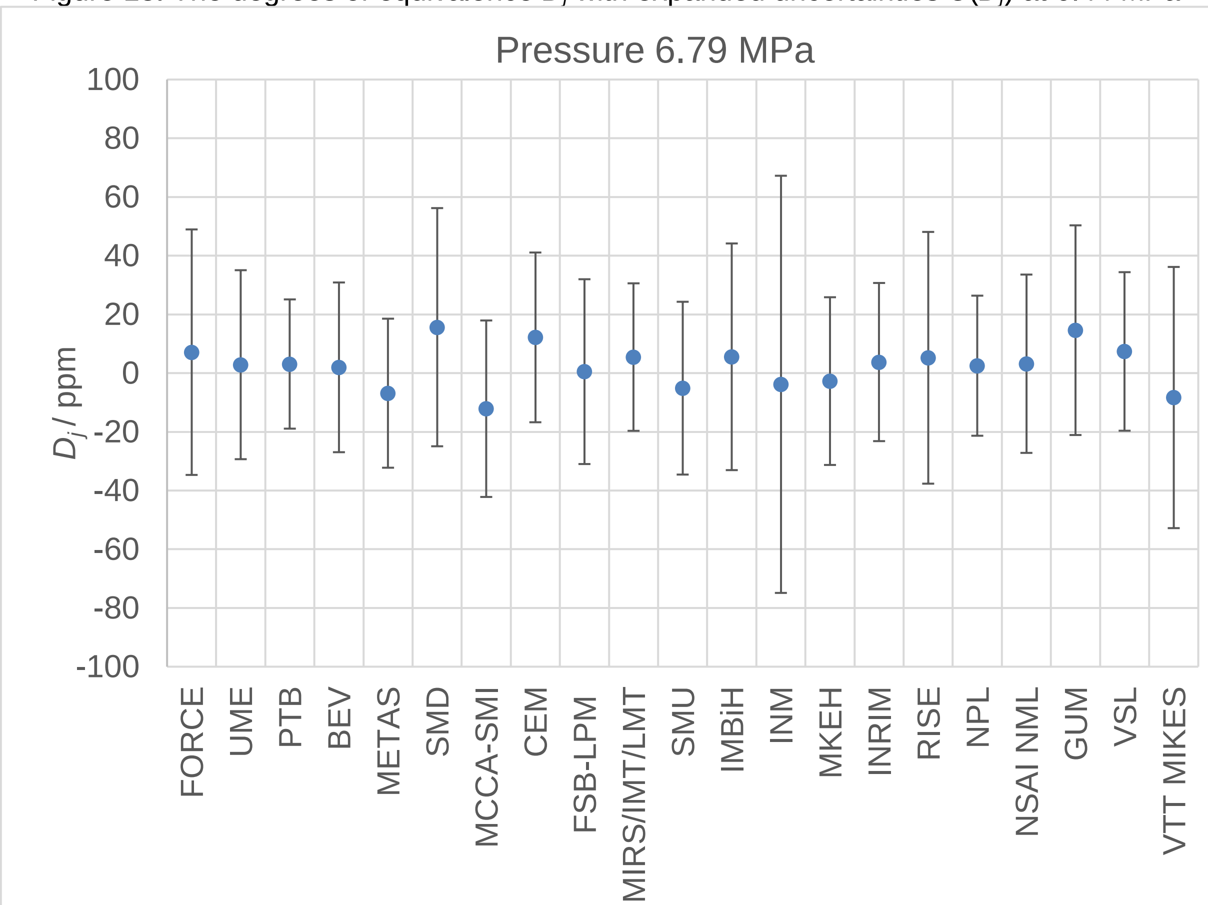

Figure 19. The degrees of equivalence D_j with expanded uncertainties $U(D_j)$ at 6.79 MPa

8 Conclusion

The EURAMET key comparison EURAMET.M.P-K1.c in gas media and gauge mode in the range 0.7 MPa to 7.0 MPa was organized by EURAMET with the project no. 1179.

24 laboratories, mainly from EURAMET, participated in the project. Due to either missing resources or failure with their laboratory standard difficulties, 3 participants, EIM, NIS and LCAE-CME, did not submit results.

The transfer standard was a piston-cylinder unit with a nominal effective area of 50 mm^2, provided with a complete pressure balance and a mass set. The transfer standard and the associated parts were circulated without any major problems. Both the transfer standard's pressure-dependent effective area and the weights were stable within the uncertainty of the check measurements during the project.

The reference values were calculated as the weighted mean of the results submitted by the 8 participating primary laboratories.

PTB measured 3 times in order to determine a potential drift of the transfer standard. There was no need to apply a time-drift correction.

The linkage to CCM.P-K1.c was performed through PTB that has taken part in both the EURAMET and CCM key comparisons.

The results of the participants are consistent with the reference values of CCM.P-K1.c at all pressure points.

9 References

[1] EURAMET, Technical Committee for Mass, "Calibration of pressure balances", EURAMET cg-3 Version 1.0, ISBN 978-3-942992-02-2, 03/2011.

[2] Sabuga W., "Pressure measurements in gas media up to 7.5 MPa for the Boltzmann constant redetermination", in "*Proceedings of the 5th CCM international conference on pressure and vacuum metrology" and 4th international conference IMEKO TC16"*, Berlin, 2011, *PTB-Mitteilungen*, 2011, vol. 121, pp. 247-255.

[3] Sabuga W., Priruenrom T., Haines R., Bair M., "Design and evaluation of pressure balances with $1 \cdot 10^{-6}$ uncertainty for the Boltzmann constant project", in "*Proceedings of the 5th CCM international conference on pressure and vacuum metrology and 4th international conference IMEKO TC16*", Berlin, 2011, *PTB-Mitteilungen*, 2011, vol. 121, pp. 256-259.

[4] Sabuga W., Priruenrom T., Molinar G., Buonanno G., Rabault T., Wongthep P., Pražák D., "FEA calculation of pressure distortion coefficients of gas-operated pressure balances – EURAMET project 1039", in "*Proceedings of the 5th CCM international conference on pressure and vacuum metrology and 4th international conference IMEKO TC16*", Berlin, 2011, *Measurement*, 2012, vol. 45, pp. 2464-2468.

[5] Salama D., Sabuga W., Ulbig P., "Measurement of the elastic constants of pressure balance materials using resonance ultrasound spectroscopy", in "*Proceedings of the 5th CCM international conference on pressure and vacuum metrology and 4th international conference IMEKO TC16*", Berlin, 2011, *Measurement*, 2012, vol. 45, pp. 2472-2475.

[6] Otal P., Morgado I., Steindl D., Medina Martín N., Lefkopoulos A., Altintas A., Grgec Bermanec L., Bursic S., Setina J., Bergoglio M., Spohr I., Wüthrich C., Rantanen M., Vámossy C., Sabuga, W., Koçaş I., "Evaluation of cross-float measurements with pressure balances – Results of EURAMET project 1125", in "*Proceedings of the 5th CCM international conference on pressure and vacuum metrology and 4th international conference IMEKO TC16*", Berlin, 2011, *PTB-Mitteilungen*, 2011, vol. 121, pp. 294-297.

[7] Altıntaş A., "Pressure standard comparison gas media and gauge mode from 0.7 MPa to 7 MPa", Technical Protocol to EURAMET.M.P-K1.c in the frame of EURAMET project no. 1179, http://kcdb.bipm.org/appendixB/appbresults/EURAMET.M.P-K1.c/EURAMET.M.P-K1.c_Technical_Protocol.pdf, 2011.

[8] Cox M. G., "The evaluation of key comparison data", *Metrologia*, 2002, vol. 39, pp. 589-595.

[9] C. MRS-D-05, "Measurements comparisons in the CIPM MRA", March 2016.

[10] Elster C., Link A., Wolfgang W., "Proposal for the linking the results of CIPM and RMO key comparisons", *Metrologia*, 2003, vol. 40, pp. 189-194

[11] Final report, CCM Key Comparison 7 MPa, Phase B (CCM.P-K1c), October 2000.