EURAMET - THE EUROPEAN ASSOCIATION OF NATIONAL METROLOGY INSTITUTES
Comparison Identifier: **EURAMET 1414 (Registered in KCDB as EURAMET.M.P-S18)**

Final Report on Comparison of Hydraulic Pressure Balance Effective Area Determination in the Range up to 80 MPa

L. Grgec Bermanec[1], D. Pantić[2], B. Ramač[2]

[1] HMI/FSB-LPM – Croatian Metrology Institute, Faculty of Mechanical Engineering and Naval Architecture- University of Zagreb, Laboratory for Process Measurement, Croatia

[2] Directorate of Measures and Precious Metals (DMDM) of the Republic of Serbia Laboratory for mass, pressure and force, Serbia

Abstract

Bilateral comparison was organized between the Laboratory for Process Measurement of the Croatian Metrology Institute (HMI/FSB-LPM) and the Pressure Laboratory of the Directorate of Measures and Precious Metals of the Republic of Serbia (DMDM). Laboratory for Process Measurement of HMI acted as the pilot laboratory. The aim of the comparison was to evaluate the degree of equivalence in the determination of effective area and elastic distortion coefficient, considering respective uncertainties of the two laboratories. Measurements were done on the pressure balance in gauge mode, with oil as transmitting medium, in the gauge pressure range 10 - 80 MPa. The results of the comparison successfully demonstrated that the hydraulic gauge pressure standards are equivalent within their claimed uncertainties.

Contents:

1. Introduction

At the EURAMET TC-M meeting in 2015, it was agreed to carry out a bilateral supplementary comparison (SC) between LPM and DMDM of their hydraulic gauge pressure standards in the range up to 80 MPa. The comparison in that range was motivated by the fact that, in both National Metrology Institutes (NMI's), their pressure balances provide traceability and that DMDM does not have CMC entries published in the BIPM database. DMDM provided a transfer standard (TS) for this comparison. A pressure balance, with nominal "accuracy" of 0.015%, was circulated between the two laboratories. The measurand was the effective area of the piston-cylinder, in gauge mode.
This SC is identified as EURAMET.M.P-S18 in the BIPM key comparison database.

2. Participating Laboratories

Details about participating laboratories and responsible persons are given in Table 1.

Table 1: Details about participants

Laboratory	Address	Person responsible
Croatian Metrology Institute (HMI), Faculty of Mechanical Engineering and Naval Architecture (FSB) - University of Zagreb Laboratory for Process Measurement (LPM) Pilot Laboratory	Ivana Lučića 5 Zagreb Croatia	Prof. dr. sc. Lovorka Grgec Bermanec Tel : 01 6168 488 e-mail : lovorka.grgec@fsb.hr
Directorate of Measures and Precious Metals (DMDM) of the Republic of Serbia Laboratory for mass, pressure and force Participating laboratory	Mike Alasa 14, 11000 Beograd Serbia	Dragan Pantić, dipl.ing. Tel : +381-11-20-24-417 e-mail : pantic@dmdm.rs

3. Description of the Laboratory standards and traceability

3.1 LPM Laboratory standard

LPM has been developing temperature, pressure and humidity standards for more than 40 years. More than 15 years' traceability of pressure measurements is achieved through the German national pressure laboratory PTB (Physikalisch-Technische Bundesanstalt). To maintain compliance with MRA, LPM participated in several international comparisons (through DKD – Deutscher Kalibrierdienst, now DAkkS, Deutsche Akkreditierungsstelle and EURAMET) with other NMIs to support calibration measurement capabilities (CMCs). First, cross-float was validated with PTB measurements for accreditation purposes in 2002. LPM successfully participated in two key comparisons through EURAMET namely: EURAMET.M.P.-K8 (up to 0.2

MPa) [10] and EURAMET.M.P-K1c, (up to 7 MPa) as well as in EURAMET project 1125 whose purpose was to compare approaches to effective area and uncertainty estimation [1]. CMC entries of LPM were published in BIPM database in 2008.

LPM standard used in this SC was a commercially manufactured oil pressure balance with details described in Table 2 and Figure 1. Zero-pressure effective area,A_0, and pressure distortion coefficient (λ) were determined by cross-floating method in PTB in 2006, 2011 and 2017.

Table 2: Details of the LPM laboratory standard

Manufacturer / Type	Pressurements / P7000 Series
Measurement range	3 to 140 MPa
PCU S/N	X 0467
Nominal area of the piston	$4 \cdot 10^{-6}$ m^2
Piston-cylinder unit thermal coefficient	Tungsten carbide + Steel $16.6 \cdot 10^{-6}$ °C^{-1}
Total mass	60 kg
Weights set S/N	59689
Pressure reference level	Bottom of the piston at cross-floating position
Working liquid used	sebacate

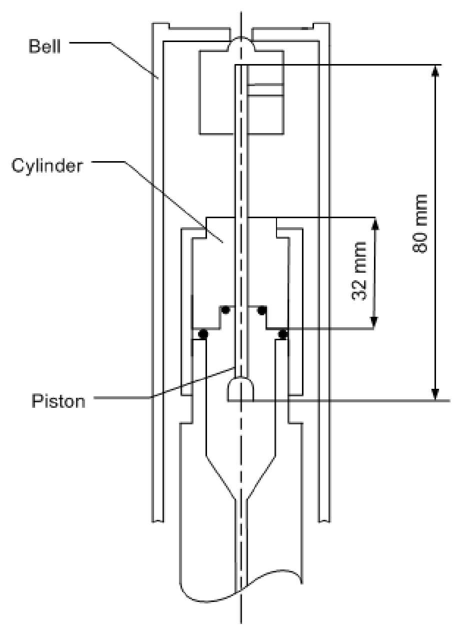

Figure 1: LPM piston-cylinder unit X 0467

3.2. DMDM Laboratory standard

The properties of the DMDM pressure standard and measurement conditions are presented in Table 3. All uncertainties in the table are standard ones. DMDM pressure balance and piston-cylinder unit are shown in Figure 2.
Laboratory standard of DMDM is traceable to Swedish National Laboratory (SP, nowadays RISE). A_0 and λ were determined by cross-floating method in SP in 2015.

Table 3: Details of the DMDM laboratory standard

Manufacturer	Desgranges et Huot 5303 S CP
PCU S/N	2496
Measurement range	2 to 80 MPa
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	Free-deformation
Zero-pressure effective area (A_0) at reference temperature in mm^2	4.90287
Relative uncertainty of A_0 in 10^{-6}	19
Pressure distortion coefficient (λ) in Pa^{-1}	$3.06 \cdot 10^{-13}$
Uncertainty of λ in MPa^{-1}	$0.91 \cdot 10^{-13}$
Relative uncertainty of mass pieces in 10^{-6}	0.75
Linear thermal expansion coefficient of piston (α_p) in ºC^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (α_c) in ºC^{-1}	$4.5 \cdot 10^{-6}$
Local gravity (g) in m/s^2	9.80582
Relative uncertainty of g in 10^{-6}	25
Height difference between pressure balances in mm	-45
Uncertainty of h in mm	1
Weights set model	40 kg
Weights set S/N	1927
Pressure reference level	Bottom of the piston at cross-floating position
Direction of the rotation	CCW
Working liquid	Di(2)-ethyl-hexyl-sebacate (DHS)
Rotation speed	30 rpm

Figure 2: DMDM pressure balance and piston-cylinder unit

4. Transfer standard

The transfer (TS) standard that was circulated between the two laboratories is a pressure balance manufactured by Desgranges et Huot, consisting of a base, a piston-cylinder unit (PCU) and a set of weights. The transfer standard was provided by DMDM.
Table 4 summarizes the basic characteristics of the transfer standard.

Table 4: Technical characteristic of transfer standard

Manufacturer	Desgranges et Huot
Pressure balance model	5304 N CP
Pressure balance S/N	3617
PCU model	HUILE
PCU S/N	8755
Nominal area of the piston	$4.9 \cdot 10^{-6}$ m^2
Linear thermal expansion coefficient of piston (α_p) in ºC^{-1}	$4.5 \cdot 10^{-6}$
Linear thermal expansion coefficient of cylinder (α_c) in ºC^{-1}	$4.5 \cdot 10^{-6}$
Weights set model	50 kg
Weights set S/N	4159
Pressure reference level	Bottom of the piston at cross-floating position
Working liquid	Di(2)-ethyl-hexyl-sebacate (DHS)
Direction of the rotation	CCW
Rotation speed	30 rpm
Piston circumference	0.007917 m

The DMDM provided calibration certificates for the following masses: discs (mass set), piston and mass carrying bell. The mass set consists of 8 mass pieces listed in the Table 5. The material density of the mass pieces is ρ_m = (7920 $\pm$ 140) kg/m^3.

Table 5: Masses of transfer standard

Nominal value	Marking	Conventional mass in g
4 kg	4159 4 kg	4000 .000
5 kg	4159 1 5kg	5000.008
5 kg	4159 2 5kg	5000.018
5 kg	4159 3 5kg	5000.013
5 kg	4159 4 5kg	5000.003
5 kg	4159 5 5kg	4999.998
5 kg	4159 6 5kg	5000.003
5 kg	4159 7 5kg	4999.998

Conventional mass for piston and mass carrying bell are 200.0254 g and 800.0065 g, respectively.

5. Circulation of the transfer standard

The measurements with the transfer standard were performed in accordance with the schedule given below. The time allocated for each laboratory for the measurements was three weeks. One week was also allocated for transportation of the artifact. The equipment to be circulated was separated in two packages, under the same ATA-carnet, and there were no problems during the comparison.

Table 6: Measurement schedule

Country	**NMI**	**Period**	**Responsible**
Croatia	FSB-LPM	December 2015	Lovorka Grgec Bermanec
Serbia	DMDM	January 2016	Pantić Dragan and Boris Ramač

6. Calibration methods and uncertainty evaluation

According to the Technical protocol [2] it was required that each laboratory finds the effective area of TS at the following nominal pressures:

100 bar, using weights 4 kg, piston and weight carrier
200 bar, using weights 4 kg, 1, piston and weight carrier
300 bar, using weights 4 kg, 1, 2, piston and weight carrier
400 bar, using weights 4 kg, 1, 2, 3, piston and weight carrier
500 bar, using weights 4 kg, 1, 2, 3, 4, piston and weight carrier
600 bar, using weights 4 kg, 1, 2, 3, 4, 5, piston and weight carrier
700 bar, using weights 4 kg, 1, 2, 3, 4, 5, 6, piston and weight carrier
800 bar, using weights 4 kg, 1, 2, 3, 4, 5, 6, 7, piston and weight carrier

Calibration methods used in both laboratories are based on [3] with specific details described in the following sections.

6.1. DMDM calibration method

During all measurements both the laboratory 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.

PCU temperature was measured by a platinum resistance thermometer (PRT) built into the laboratory standard mounting post, traced to the international temperature scale (ITS-90) at DMDM Temperature Laboratory. Its standard measurement uncertainty was 0.05 °C.

DMDM Mass Laboratory calibrated mass of the weights of the laboratory and the transfer standard with a relative standard uncertainty of $0.75 \cdot 10^{-6}$.

Position and fall rates of the laboratory and transfer standard pistons were measured by Float Position Sensors connected to Ruska 2456 Piston Gauge Monitor. Fall rates data acquisition was done with a WinPrompt software and a specific DMDM software program that perform processing of image taken by a simple camera placed in front of window for the piston position display. Each fall rate measurement has been made at each pressure at temperature around 20 °C, laboratory and transfer standard were cross-floated using the fall rates of both pistons as an equilibrium criterion. To reach the equilibrium trim masses were applied to both pressure balances. DMDM calibration setup is shown in Figure 3.

Figure 3: DMDM calibration setup

The air density was calculated from measured temperature, pressure and humidity by following equation

$$\rho_a = \frac{0.34848 \cdot p - 0.009024 \cdot h \cdot e^{0.0612 \cdot t}}{273.15 + t} \quad (1)$$

This equation has a relative uncertainty of 2×10^{-4} in the range 900 hPa < p < 1100 hPa, 10 °C < t < 30 °C and hr < 80 %.
Atmospheric pressure was measured with resolution of 1 Pa and standard uncertainty of 3 Pa. Laboratory temperature was measured with resolution of 0.01 ºC and standard uncertainty of 0.05 ºC.
Relative air humidity was measured with resolution of 0.01 % and standard uncertainty of 0.5 %. All measurements were performed with Vaisala PTU-301 traceable to FSB-LPM for atmospheric pressure and DMD for temperature and relative air humidity.

The following density (ρ) in dependence on pressure (p) and temperature (t) as well as the surface tension (σ) of DHS were used in the calculations:

$$\begin{aligned} \rho(p,t) = &\left[912.7 + 0.752(p/MPa) - 1.65 \cdot 10^{-3}\left(p/MPa\right)^2 * + 1.5 \cdot 10^{-6}\left(p/MPa\right)^3\right] \cdot \\ &\cdot \left[1 - 7.8 \cdot 10^{-4}\left(t/\ °C - 20\right)\right] \cdot \left[1 \pm 0.01\right] kg/m^3 \end{aligned} \quad (2)$$

σ =31.2·(1±0.05) *mN/m*

Uncertainty evaluation was based on ISO GUM and EURAMET procedure.

6.2. LPM calibration method

Transfer standard (pressure balance under test) was hydrostatically balanced against the LPM standard of known effective cross-sectional area. The basis of the comparison was determination of the loads at which each balance would individually reach equilibrium of the system at precisely the same pressure. State of equilibrium was identified by rate-of-fall technique, which means that load of each assembly is carefully adjusted by means of trimming weights until both pistons were falling with their natural rates [4].
Fig. 4 shows a common system configuration for a single medium hydraulic cross-float.

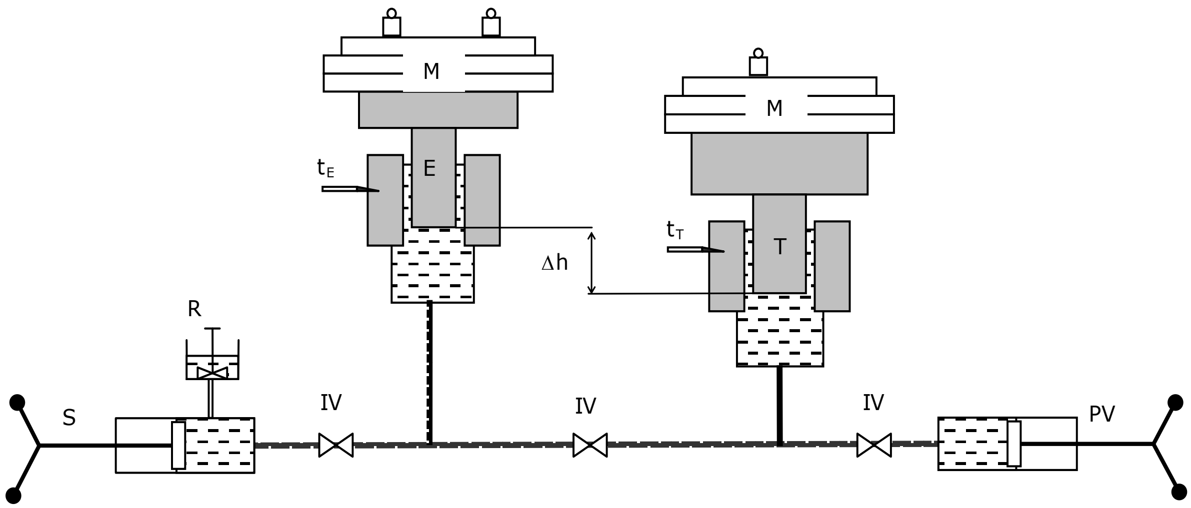

Figure 4: LPM calibration setup

The pressure balance under test, T, is connected to a standard pressure balance, E, and a pressure generator, S. The loads, M, on both pistons are adjusted until they are hydrostatically balanced at the required pressure. Difference in altitude, Δh, between the reference levels of the E and T balances as well as the temperatures of the environment, tested and standard piston-cylinder unit are measured.

Mathematical model used to calculate pressure balance effective area at zero pressure is known as the P method which requires all loading forces acting on the system to be evaluated and summed, including those due to internal 'fluid-head' and buoyancy effects.
For each calibration point the effective pressure, p_r, measured at the reference level of the E is calculated, using the known characteristic of the standard piston/cylinder assembly according to equation (3).

$$p_r = \frac{\left[\sum_i \left[m_i \cdot \left(1 - \frac{\rho_a}{\rho_{m_i}}\right)\right] - V \cdot \left(\rho_f - \rho_a\right)\right] \cdot g + \sigma \cdot c}{A_0 (1 + \lambda \cdot p) \cdot \left[1 + \left(\alpha_p + \alpha_c\right) \cdot (t - t_r)\right]} \tag{3}$$

Where:

p_r is the pressure generated by the reference pressure standard at its reference level,
m_i are the individual mass values of the weights applied on the piston, including all floating elements,
ρ_{mi} are the densities of the weights,
ρ_a is the density of air,
V additional volume due to a free volume, a conical end or a step on the piston,
ρ_f is the density of the fluid,
g is the local gravity,
σ is the surface tension of the liquid,
c is the circumference of the piston or its extension at the level where it emerges from the oil,
A_0 effective area at null pressure,
λ pressure distortion coefficient,
p is an approximate value of the measured pressure p_r,
α_p is the linear thermal expansion coefficient of the piston,
α_c is the linear thermal expansion coefficient of the cylinder,
t is the measured temperature of the piston-cylinder assembly during its use,
t_r is the reference temperature of the piston-cylinder assembly.

For each calibration point A_p was calculated as:

$$A_p = \frac{\sum_i \left[m_i \cdot \left(1 - \frac{\rho_a}{\rho_{m_i}}\right)\right] \cdot g \cdot \cos \Theta + \sigma \cdot c}{\left(p_r + \left(\rho_f - \rho_a\right) \cdot g \cdot h\right) \cdot \left[1 + \left(\alpha_p + \alpha_c\right) \cdot (t - t_r)\right]} \tag{4}$$

Where

A_p is effective area at the reference temperature t_r, of an pressure balance calibrated in gauge mode by a reference pressure balance,
h is difference between the altitude of the balance reference level and the altitude of the point where the pressure has to be measured (or reference level of the pressure balance under calibration),
Θ is the angle of deviation of the piston axis from verticality.

Following the ISO [5] and EURAMET [3] recommendations and [6], uncertainties $u(A_p)$ for each calibration point were calculated.

7. Results

The participating laboratory provided, three weeks after the completion of its measurements, results of the calibration, in the form of an EXCEL sheet, prepared for this purpose by the pilot laboratory. The results to be provided are the values of the effective area A_p at each calibration point, as well as the values of A_0 at 20°C and pressure distortion coefficient (λ), all with their respective expanded uncertainties. *En* values were calculated:

$$E_n = \frac{/M_{LPM} - M_{lab}/}{\sqrt{\left(U_{lab}^{\ 2} + U_{LPM}^{\ 2}\right)}} \qquad (5)$$

Where M_{LPM} is measurement result of LPM, M_{lab} is measurement result assigned by DMDM, U_{LPM} is uncertainty of M_{LPM}. U_{lab} is the uncertainty of M_{lab}.
Results are regarded as equivalent when the resultant E_n for any measurement is between +1 and -1.

Table 7: Summary results of the effective area obtained by LPM and DMDM:

Nominal pressure	Average of A_p A_p (LPM)	Combined uncertainty *U*(LPM)	Average of A_p A_p (DMDM)	Combined uncertainty *U*(DMDM)	*En*
MPa	mm^2	mm^2	mm^2	mm^2	
10	4.90240	0.0004	4.90264	0.00043	0.41
20	4.90251	0.0003	4.90256	0.00039	0.10
30	4.90247	0.0003	4.90251	0.00038	0.08
40	4.90245	0.0003	4.90245	0.00037	0.00
50	4.90233	0.0003	4.90237	0.00037	0.08
60	4.90227	0.0003	4.90229	0.00037	0.04
70	4.90214	0.0003	4.90220	0.00037	0.13
80	4.90209	0.0003	4.90212	0.00037	0.06

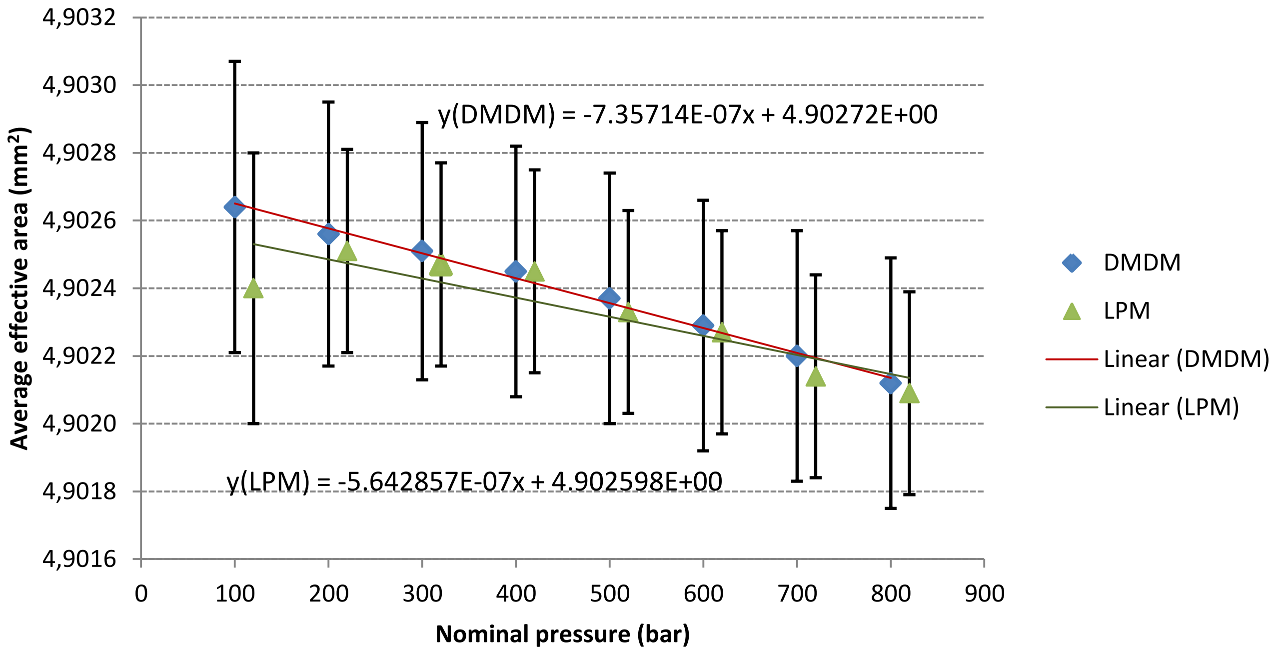

Figure 5: Average values of effective areas at each nominal pressure, LPM and DMDM

To determine zero-pressure effective area A_0 of TS and its distortion coefficient (λ), linear mode based on average reported areas is used for each laboratory:

$$A_p = A_0(1 + \lambda \cdot p) \tag{6}$$

Table 8: Results for zero-pressure effective area and distortion coefficient

	LPM		DMDM		*En*
	Value	Combined uncertainty	Value	Combined uncertainty	
A_0 (mm^2)	4,902598	0,0003	4,90272	0,0004	0,24
λ (MPa^{-1})	-1.13E-06	3.70E-07	-1.51E-06	4.80E-07	0.63

8. Conclusions and discussion

The aim of proposed comparison was to evaluate the degree of equivalence in the determination of effective area and elastic distortion coefficient, considering respective uncertainties of the two laboratories. Measurements were done on the pressure balance in gauge mode, with oil as transmitting medium, in the gauge pressure range from 10 up to 80 MPa. With the uncertainty claimed by each laboratory the *En* values for effective area determination are in the range from 0.01 to 0.41. The E_n value for A_0 is 0,24 while it is 0,63 for distortion coefficient. The results of the comparison successfully demonstrated that the hydraulic gauge pressure standards are equivalent within their claimed uncertainties.

9. References

[1] P. Otal, I. Morgado, D. Steindl, N. Medina Martín, A. Lefkopoulos, A. Altintas, L. Grgec Bermanec, S. Bursic, J. Setina, M. Bergoglio, I. Spohr, C. Wüthrich, M. Rantanen, C. Vámossy1, W. Sabuga, I. Koçaş; Evaluation of crossfloat measurements with pressure balances – Results of EURAMET project 1125. // PTB Mitteilungen. 3 (2011)

[2] Technical Protocol for EURAMET bilateral comparison of Hydraulic Pressure Balance Effective Area Determination in the Range up to 80 MPa

[3] Calibration of Pressure Balances, EURAMET cg-3 Version 1.0, European Association of National Metrology Institutes, 2011.

[4] L. Grgec Bermanec, D. Zvizdic, V. Simunovic, Development of Method for Determination of Pressure Balance Piston fall Rate. // ACTA IMEKO The e-Journal of the International Measurement Confederation (IMEKO). Vol 3 (2014).

[5] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, Guide to the expression of uncertainty in measurement (GUM), Geneva, 1995.

[6] Zvizdić D.; Grgec Bermanec L.; Bonnier G.; Renaot E.; Veliki T.: Uncertainty Budget of Pressure Balance Effective Area Determined by Comparison Method, Proceedings of XVII IMEKO World Congress, Topic 16 - Pressure and Vacuum Measurement, pp 2003-2007, Dubrovnik, 2003.