Final Report on Supplementary comparison of NIMT and LNE pressure standards in the range 50 MPa to 500 MPa of hydraulic gauge pressure

APMP.M.P-S7

July 2016

Padipat Wongthep[1], Pierre Otal[2], Thierry Rabault[2], Olivier Soyez[2]

[1]NIMT: National Institute of Metrology (Thailand), 3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120 Thailand

[2]LNE: Laboratoire National de Métrologie et d'Essais, 1, rue Gaston Boissier, 75015 Paris, France

1. INTRODUCTION

This report describes the results of a bilateral supplementary comparison of hydraulic high-pressure standards between Laboratoire National de Métrologie et d'Essais (LNE) and National Institute of Metrology (Thailand) (NIMT) in order to check their degrees of equivalence in the pressure range from 50 MPa to 500 MPa in the gauge mode.

This comparison was carried out during the period from March to December 2015. The results of this comparison will be essential to support the calibration and measurement capabilities (CMC) of NIMT. The pilot laboratory was NIMT who provided the transfer standard (TS). The TS was a Piston-Cylinder Unit (PCU) without any pressure balance nor mass set.

All the measurements were performed in accordance with the Technical Protocol [1] prepared by NIMT and accepted by LNE.

This report presents the results of NIMT and LNE. All uncertainties in this report are the standard ones ($k = 1$).

2. DESCRIPTION OF THE LABORATORY STANDARD

2.1 NIMT Laboratory Standard

The NIMT laboratory standard (LS) in this comparison was the Piston-Cylinder Unit (PCU) of 1.96 mm^2 nominal effective area, identified by number 867, Kn=5 MPa/kg. The PCU was installed in the pressure balance model PG-7302 [2]. The PCU and the pressure balance were manufactured by Fluke Corporation, DH Instrument Division (DHI), USA. The properties of the NIMT laboratory standard (LS) are summarized in Tables 1 – 2.

Table 1. Details of the NIMT reference pressure balance used for the comparison

	Manufacturer	Model/Serial	Description
Base	DH Instruments	PG-7302 serial no. 491	-
Piston-cylinder	DH Instruments	PC-7300-5 serial no. 867	Operation mode: Simple Pressure range: 500 MPa
Weights	DH Instruments	MS-7002-100 serial no. 2350, with carrying bell no. 7000	Total mass: 100 kg Typical relative uncertainty of mass pieces (k = 1): 2.5 × 10^{-6}
Thermometer	DH Instruments	-	Serial No.: 507

Table 2. Details of the NIMT reference piston-cylinder used for the comparison

	Material	Linear thermal expansion coefficient (α) in K^{-1}
Piston	Tungsten carbide	4.5×10^{-6}
Cylinder	Tungsten carbide	4.5×10^{-6}

	Value	Uncertainty (k = 1)	Traceability
Zero-pressure effective area in mm^2 at ref. temp., A_0 (Ref. temp.: t_0)	1.96142 (t_0: 20 °C)	$3.5 \times 10^{-5} \times A_0$	Measurement through Gas Primary Standard
Pressure distortion coefficient λ_1 in MPa^{-1}	7.99×10^{-7}	7.8×10^{-8}	Measurement by Hydraulic Primary standard CCPG

Note: The zero-pressure effective area (A_0) was determined by cross-float measurement against hydraulic Piston-Cylinder Unit (PCU) 100 MPa and to 200 MPa pressure standards. This standard itself is traceable to a set of primary gas pressure standards [3-4].

The value of pressure distortion coefficient (λ_1) was determined by cross-float measurement against hydraulic Control-Clearance Piston Gauge (CCPG) in the range up to 200 MPa.

2.2 LNE Laboratory Standard

The standard used by LNE for the comparison was the national standard balance Desgranges et Huot N°A equipped with a 1 GPa PCU # 2. The assembly was used in controlled-clearance mode, with a pressure jacket equal to 1/5 of the measurement pressure [5]. Its properties are summarized in Tables 3 – 4.

Table 3. Details of the LNE reference pressure balance used for the comparison

	Manufacturer	Model/Serial	Description
Base	Desgranges&Huot	A	-
Piston-cylinder	Desgranges&Huot	1 GPa n°2	Operation mode: Control-Clearance Pressure range: 1000 MPa
Weights	Desgranges&Huot	A	Total mass: 1000 kg Typical relative uncertainty of mass pieces (k = 1): 7.5×10^{-6}
Thermometer	Desgranges&Huot	A	4 wires platinum thermometer (Pt 100) connected to Agilent multimeter

Table 4. Details of the LNE reference piston-cylinder used for the comparison

	Material	Linear thermal expansion coefficient (α) in K^{-1}
Piston	tungsten carbide	4.5×10^{-6}
Cylinder	tungsten carbide	4.5×10^{-6}

	Value	Uncertainty (k = 1)	Traceability
Zero-pressure effective area in mm^2 at ref. temp., A_0 (Ref. temp.: t_0)	9.804751 (t_0: 20 °C)	6.5×10^{-6}	from LNE, mean value estimated from calibrations performed since 2002
Pressure distortion coefficient λ_1 in MPa^{-1}	1.32×10^{-7}	0.5×10^{-7}	

<u>Note</u>: The zero-pressure effective area (A_0) was determined by comparison with the 50 MPa pressure standard. This standard is itself traceable to the primary standard in the range 10 kPa to 1 MPa [5, 6].

The value of pressure distortion coefficient (λ_1) was determined using the experimental method developed at the LNE. The method is based on fall rate measurements and cross-floating experiments under variable conditions of jacket pressure.

3. TRANSFER STANDARD

The transfer standard was a piston-cylinder unit (PCU) of 1.96 mm^2 nominal effective area with serial number 9193 and manufactured by DH-Budenberg, France. The PCU had to be installed in a DH-Budenberg pressure balance model 5306 [7]. The properties of the transfer standard (TS), provided by manufactured [8], are summarized in Tables 5 – 7.

Table 5. Characteristics of piston-cylinder unit

	Material	α / K	E / GPa	μ
Piston	steel	10.5×10^{-6}	200	0.3
Cylinder	Tungsten carbide	4.5×10^{-6}	620	0.218

The thermal expansion coefficient of the piston-cylinder unit can be taken as
$\alpha'_p + \alpha'_c = (15.0 \pm 1.5) \times 10^{-6}$ K^{-1}.

The piston head is made of stainless steel. The true mass (including cap, head and screw) and the length of the piston were measured by NIMT shown in Table 6.

Table 6. Mass, density and length of the piston

	True mass in g	Equivalent density in (kg/m^3)	Length in mm
Piston	199.9989 ± 0.00011	$7920 \times (1 \pm 5 \times 10^{-2})$	85.0 ± 0.25

The reference level of the TS is referenced to the bottom of piston at the mid float position. The piston working position (mid float) is (5.2 ± 0.25) mm above its lowermost (low stop) position.

The magnetization of the piston and cylinder is negligible.

Piston fall rate of TS (v'_f) measured by NIMT at temperature around 20 °C is shown in Table 7.

Table 7. Piston fall rate at the maximum pressure measured by NIMT

p / MPa	v'_f / (mm/min)
500	0.35 ± 0.03

4. DETAILS OF THE MEASUREMENT CONDITIONS

Details of the measurement conditions of NIMT and LNE are given in Tables 8 – 10.

Table 8. Local gravity and height difference

	NIMT	LNE
Local gravity, g in m/s^2	9.7831243 ± 4.9 × 10^{-6}	9.809273 ± 1.96 × 10^{-6}
Height difference, Δh* in mm	-58.7 ± 0.58	131 ± 3

* It will be positive if the level of laboratory standard (LS) is higher.

Table 9. Piston rotation during the measurement

	NIMT	LNE
LS	Rotate by hand, with speed 20-25 rpm	Rotate by motor, with speed 28 rpm
TS	Rotate by hand, with speed 15-20 rpm	Rotate by motor, with speed 21 rpm

Table 10. Instruments for measuring environmental conditions

	Parameter	Manufacturer	Model	Uncertainty (k = 1)
NIMT	Temperature	T&D Corp.	TR-73U (F8061376)	0.15 K
	Humidity			1 %
	Ambient pressure			0.18 mbar
LNE	Temperature	Rotronic	Hygrolog	0.1 K
	Humidity	Rotronic	Hygrolog	0.8 %
	Ambient pressure	Druck	DPI 520	1.1 mbar

5. MEASUREMENT

The Piston-Cylinder Unit (PCU) of the transfer standard (TS) was installed and operated in the pressure balance, DH-Budenberg, Model 5306, that belongs to each laboratory. The

mass carrying bell and the mass set, belonging to each laboratory, were used for operation. The direct comparison method (also called the fall-rate method) was
used in the measurements.

5.1 Measurement condition and preparation

The transfer standard (TS) was installed in the laboratory at least 1 day before starting the measurement.

The TS was operated with clean di(2-ethylhexyl) sebacate (DHS) as a pressure transmitting medium. The density of DHS can be calculated from the equation given in the protocol [1].

After the installation, TS was pressurized using the laboratory's standard up to 500 MPa. Then, the leak in the calibration system had to be checked and fixed if necessary. To check the tightness of TS, the piston fall rate was measured preferably at the maximum pressure of 500 MPa. It required to wait a minimum 10 minutes after generating the pressure in the TS measurement system prior to starting the piston fall rate measurement in order to stabilize the TS temperature. The piston fall rate at 500 MPa and the rotation time at 50 MPa were recommended to checking before starting the measurement in order to eliminate the effect of the tightness, cleanness and vertical of TS. The typical piston fall rate and rotation time were (0.35 ± 0.03) mm/min and more than 5 minutes respectively as shown in the Technical Protocol [1].

The reference temperature of the comparison is 20 °C. If measurements were performed at a temperature deviating from 20 °C, the effective area of TS had to take into account the piston-cylinder thermal expansion coefficient ($\alpha'_p + \alpha'_c$) referred to 20 °C given in protocol [1].

5.2 Measurement procedure

The measurements were included three complete measuring cycles, each with the 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. Finally, 60 measurements were performed in total. Between two consequent measurements at 500 MPa was waited for at least 15 minutes. One complete measurement cycle was performed in one day.

The time between generating of the pressure and taking of the data of each pressure point corresponding to the equilibrium of the laboratory's standard and transfer standard was not shorter than 5 minutes.

5.3 Reporting of the results

The effective area (A'_p) at 20 ºC and each measured pressure of the transfer standard (TS) for each laboratory was calculated with the equation (1)

$$A'_\mathrm{p} = \frac{\sum_i m'_i\, g\,(1-\rho_\mathrm{a}/\rho'_{m_i}) + 2\sigma\sqrt{\pi A'_{0,\mathrm{nom}}}}{p'[1+(\alpha'_\mathrm{p}+\alpha'_\mathrm{c})(t'-t'_0)]}\,, \tag{1}$$

where

m'_i are the true masses of the piston, the mass loading bell and the mass pieces placed on the mass loading bell of TS;

g is the local gravity acceleration;

ρ_a is the local air density;

ρ'_{m_i} are the densities of masses m'_i;

σ is the surface tension of the TS pressure transmitting fluid;

$A'_{0,\mathrm{nom}}$ is the nominal effective area of TS;

p' is the pressure generated by the laboratory's standard at the TS reference level, that is represented by equation, $p' = p_\mathrm{s} + (\rho_\mathrm{f} - \rho_\mathrm{a})\cdot g\cdot \Delta h$, where p_s is the pressure generated by the laboratory's standard at its reference level, ρ_f is the fluid density, ρ_a is the air density, g is the local gravity acceleration and Δh is the height difference between the reference levels of the two pressure balances (It will be positive if the level of laboratory standard (LS) is higher);

α'_p and α'_c are the thermal expansion coefficients of the piston and cylinder materials of TS, respectively;

t' is the temperature of TS;

t'_0 is the reference temperature of TS, defined as 20 °C;

The values of ρ_a, ρ_f and t' as well as the masses of each laboratory were calculated or measured by the method of each laboratory.

The zero-pressure effective area of TS (A'_0) and its pressure distortion coefficient (λ') were reported from all results, based on the equation (2):

$$A'_\mathrm{p} = A'_0(1+\lambda'\cdot p)\,. \tag{2}$$

The combined standard uncertainty of A_0' and λ' as well as the description were included.

5.4 Calibration Methods

The comparison method of two laboratories is the fall rate method. NIMT measured the piston fall rate of laboratory standard using a laser displacement installed at the top of piston while an inductive sensor installed at the top of motor is used by LNE.

6. MEASUREMENTS RESULTS

6.1 Stability of transfer standard

The effective area stability of the transfer standard (TS) was measured three times, in 2013 to 2015, by NIMT. In 2013, before the comparison, the TS was calibrated by using the routine procedure of NIMT [9], every 10% of 500 MPa and 3 measurements series. In 2015, beginning the comparison, the TS was measured by using the procedure as describe in the protocol [1]. Just after the comparison, in 2015, the TS was calibrated again. The relative deviations from the average for the three measurements are presented in Fig. 1.

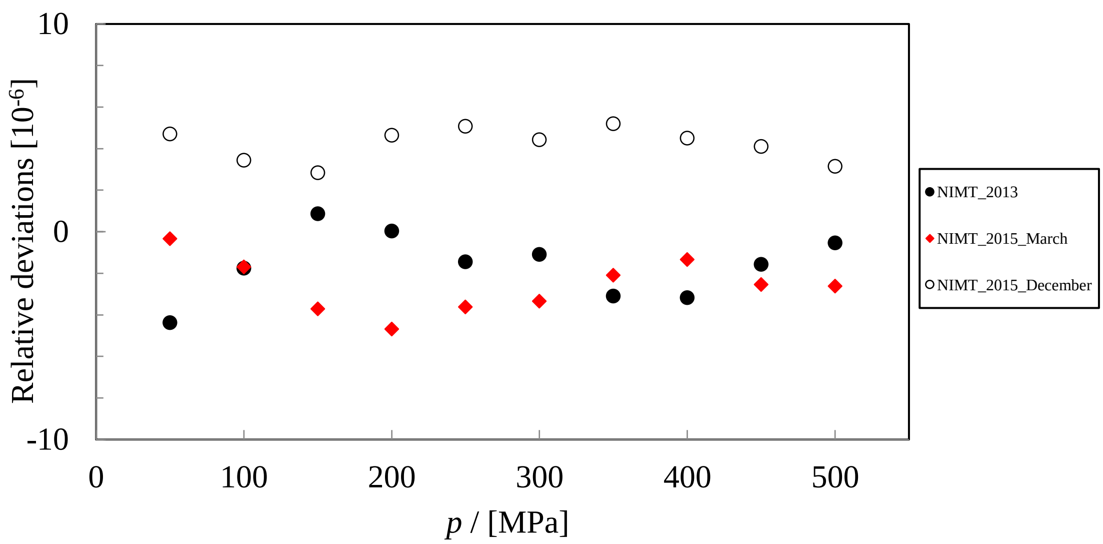

Figure 1. Stability of the transfer standard. Relative deviations of the effective areas from the average measured by NIMT from 2013 to 2015

The results show that the three measurements fully agree with the uncertainties claimed by NIMT. In addition, the drift of effective area over the time does not depend on the pressure. Therefore, the maximum drift of the effective area from the average was treated as a rectangular distribution [10] for this comparison. The standard uncertainty due to instability of TS was estimated from the maximum value divided by $2\sqrt{3}$.

The relative deviation of the three measurements from the average, the maximum value of deviation and the estimated uncertainty are listed in Table 11.

Table 11. Relative deviations of the three measurements from 2013 to 2015, maximum relative deviation and standard uncertainty due to instability of the transfer standard

p / MPa	Relative deviation from the average in 10^{-6}		
	2013	2015_March	2015_December
50	-4.4	-0.3	4.7
100	-1.7	-1.7	3.4
150	0.9	-3.7	2.8
200	0.0	-4.7	4.6
250	-1.4	-3.6	5.1
300	-1.1	-3.3	4.4
350	-3.1	-2.1	5.2
400	-3.2	-1.3	4.5
450	-1.6	-2.5	4.1
500	-0.5	-2.6	3.2

Maximum relative deviation	9.3×10^{-6}
Relative standard uncertainty	2.7×10^{-6}
Standard uncertainty in mm^2	5.3×10^{-6}

6.2 Results of measurement

Due to the insignificant drift measured by NIMT, it was decided not to apply a drift correction to the effective areas of the TS. The result of NIMT is the average of the two measurements performed on March and December 2015. The measurements of LNE were performed on August to September 2015. The mean effective areas determined by both laboratories are reported in Table 12.

Table 12. Effective areas (A_p) as reported by the laboratories

p / MPa	NIMT	LNE
	A_p / mm^2	A_p / mm^2
50	1.961985	1.962020
100	1.962056	1.962072
150	1.962124	1.962134
200	1.962193	1.962204
250	1.962262	1.962286
300	1.962335	1.962360
350	1.962408	1.962453
400	1.962481	1.962534
450	1.962554	1.962606
500	1.962628	1.962684

A'_0 / mm^2	1.961910	1.961930
λ' / MPa^{-1}	7.28×10^{-7}	7.49×10^{-7}

The effective area at zero pressure, A'_0 and the pressure distortion coefficient, λ' is determined by NIMT using the method described in EURAMET cg-3 [11] while the weighted least square method (WLS) [12] is used by LNE.

6.3 Degrees of equivalence

The relative deviations between LNE's results and NIMT's results were calculated by:

$$\Delta A_p / A_p = \frac{A_{\mathrm{p,LNE}} - A_{\mathrm{p,NIMT}}}{A_{\mathrm{p,NIMT}}} . \tag{3}$$

The results obtained from the above equation are reported in Table 13 and presented in Fig. 2.

The results show that the relative deviations are not dependent on the pressure. However, the maximum relative deviation is at the maximum pressure.

Table 13. Relative deviation ($\Delta A_p/A_p$) between LNE and NIMT

p / MPa	$(A_{p,LNE}-A_{p,NIMT})/A_{p,NIMT} \times 10^6$
50	18
100	8
150	5
200	6
250	12
300	13
350	23
400	27
450	27
500	29

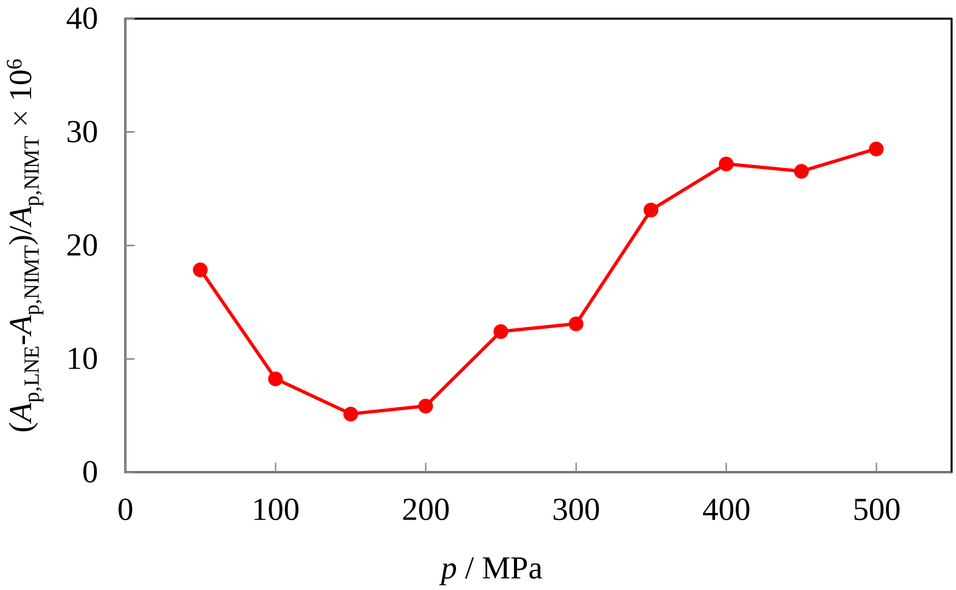

Figure 2. Relative deviations between LNE and NIMT

6.4 Uncertainty

The measurement uncertainty of the transfer standard's effective area is determined by using ISO GUM [13]. The combined standard uncertainty of the effective area is estimated by equation (4). It is the root-sum-square of two uncertainty components, the uncertainty of the effective area of the TS reported by the each laboratory, $u(A_{p,lab.})$ and the uncertainty due to the instability of the effective area of the TS, $u(A_{p,ins.})$.

$$u(A_p) = \sqrt{u^2(A_{p,lab.}) + u^2(A_{p,ins.})} \tag{4}$$

The uncertainty, $u(A_{p,lab.})$, reported by NIMT and LNE in the Table 14, includes all the uncertainty components based on equation (1) and the standard deviation of the average value. The uncertainty, $u(A_{p,ins.})$ due to the instability of the effective area of the TS was listed in the Table 11.

Table 14. Standard uncertainty $u(A_{p,lab.})$ of the transfer standard's effective area reported by NIMT and LNE

p / MPa	NIMT	LNE
	$u(A_{p,lab})/A_{p,lab} \times 10^6$	$u(A_{p,lab})/A_{p,lab} \times 10^6$
50	20.3	11.6
100	21.6	13.4
150	23.3	16.0
200	25.5	18.0
250	28.1	20.6
300	31.0	22.9
350	34.0	25.3
400	37.3	27.8
450	40.6	30.2
500	44.0	32.7

The combined standard uncertainties of the LNE and NIMT are calculated according to the equation (4) at all pressures and given in Table 15 and Fig. 3.

The maximum relative standard uncertainty is about $44 \cdot 10^{-6}$ and $33 \cdot 10^{-6}$ for NIMT and LNE respectively.

Table 15. Standard uncertainty $u(A_p)$ of the transfer standard's effective area

p / MPa	NIMT		LNE	
	$u(A_p)$ / mm²	$u(A_p)/A_p \times 10^6$	$u(A_p)$ / mm²	$u(A_p)/A_p \times 10^6$
50	0.000039	20.5	0.000024	11.9
100	0.000043	21.8	0.000026	13.6
150	0.000045	23.8	0.000031	16.2
200	0.000051	25.7	0.000035	18.2
250	0.000055	28.3	0.000041	20.7
300	0.000061	31.1	0.000045	23.0
350	0.000067	34.1	0.000049	25.5
400	0.000073	37.4	0.000055	27.9
450	0.000080	40.7	0.000059	30.3
500	0.000086	44.1	0.000065	32.8

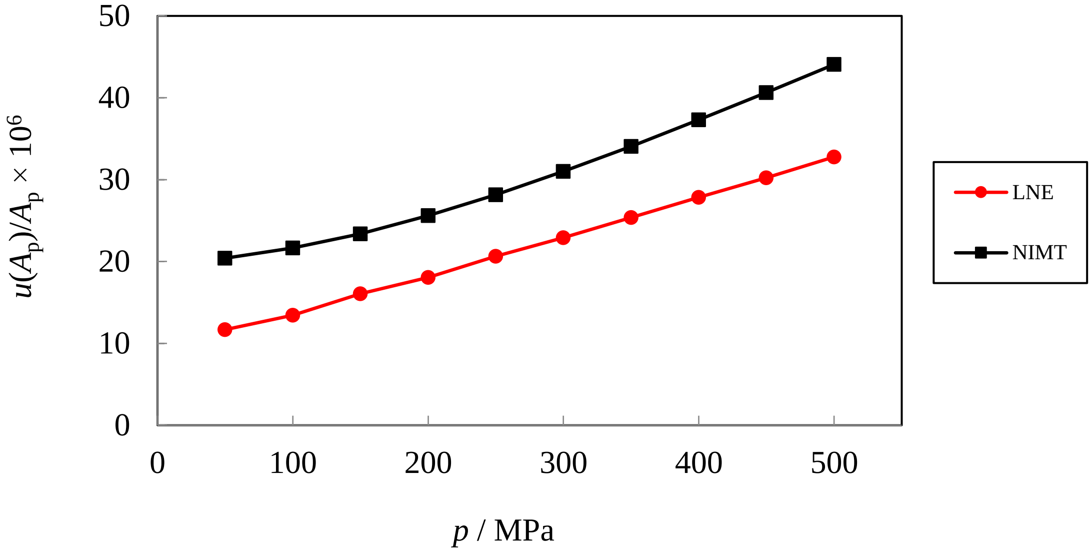

Figure 3. Relative standard uncertainties $u(A_p)/A_p$ calculated for the participants

The degree of equivalent of the National Institute of Metrology (Thailand), NIMT is expressed by the relative deviation, the relative standard uncertainties of deviations and the normalize errors (E_n). The equation of E_n for each pressure is shown below:

$$E_n = \frac{\left| A_{p,LNE} - A_{p,NIMT} \right| / A_{p,NIMT}}{2 \times \sqrt{(u(A_{p,NIMT})/A_{p,NIMT})^2 + (u(A_{p,LNE})/A_{p,NIMT})^2}} \tag{5}$$

The results of equivalence are listed in the Table 16 and shown in Fig. 4.

Table 16. Relative deviation ($\Delta A_p/A_p$) between LNE and NIMT, the standard uncertainty ($u(A_p)/A_p$) of each laboratory, combined standard uncertainty and E_n ratio

p / MPa	$(A_{p,LNE}-A_{p,NIMT})/A_{p,NIMT} \times 10^6$	$u(A_{p,i})/A_{p,NIMT} \times 10^6$		Combined uncertainty in 10^{-6}	E_n Ratio
		NIMT	LNE		
50	18	21	12	24	0.38
100	8	22	14	26	0.16
150	5	23	16	29	0.09
200	6	26	18	31	0.09
250	12	28	21	35	0.18
300	13	31	23	39	0.17
350	23	34	25	43	0.27
400	27	37	28	47	0.29
450	27	41	30	51	0.26
500	29	44	33	55	0.26

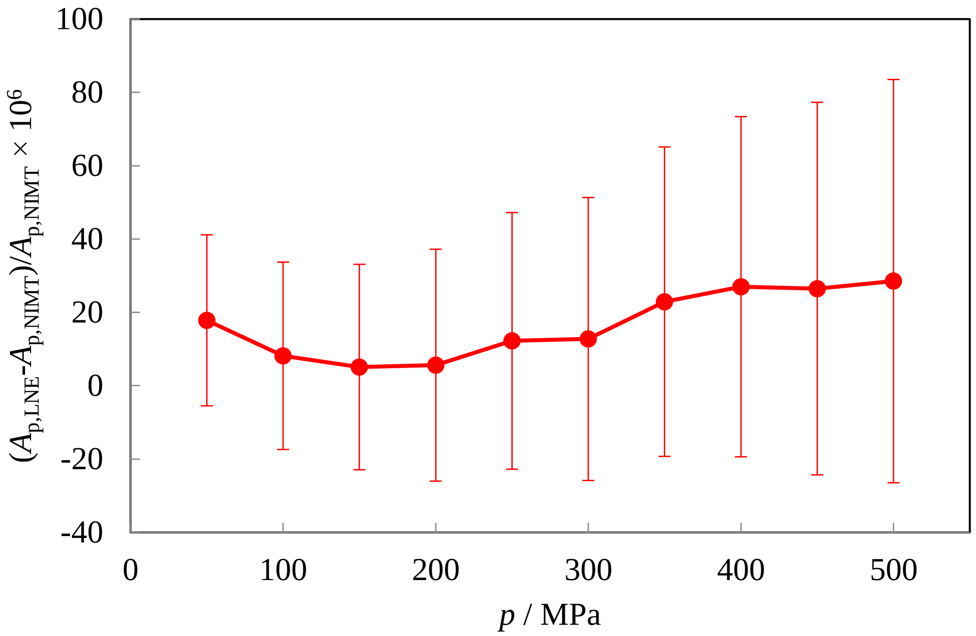

Figure 4. Relative deviation between LNE and NIMT. Error bar are the combined relative standard uncertainty

The maximum relative deviation of the transfer standard's effective area between NIMT an LNE is about $29 \cdot 10^{-6}$at maximum pressure, which corresponds to $E_n = 0.26$. However, the highest $E_n = 0.38$ occurs at the minimum pressure.

7. LINKING THE COMPARISON'S RESULTS TO CCM.P-K13

The comparison's results of NIMT and LNE in APMP.M.P-S7 are linked to CCM.P-K13 [14] through the results of LNE. The i-th deviation of NIMT and LNE's results from CCM.P-K13 reference values, $\Delta A_{p,i,ref.}$ are determined by the equation (6) [10] without the correction $\Delta A_{p,TS,j}$ for the difference in the effective areas between the piston-cylinders used in the comparison, because only one piston-cylinder was used in this case,

$$\Delta A_{p,i,\mathrm{ref}} = A_{p,i} + \Delta A_{p,\mathrm{Link}} - A_{p,\mathrm{ref}} \,, \tag{6}$$

where $A_{p,i}$ is the effective area measured by NIMT and LNE (reported in Table 12), $\Delta A_{p,Link}$ is the correction of the effective area of the transfer standard between APMP.M.P-S7 and CCM.P-K13 determined as equation below,

$$\Delta A_{p,\mathrm{Link}} = A_{p,\mathrm{LNE,CCM}} - A_{p,\mathrm{LNE,APMP}}, \tag{7}$$

when $A_{p,LNE,CCM}$ and $A_{p,LNE,APMP}$ are the effective area measured by LNE in the key comparison CCM.P-K13 and APMP.M.P-S7 respectively, and $A_{p,ref}$ is the effective area of the transfer standard from the reference values of CCM.P-K13. The values of $A_{p,LNE,CCM}$ and $A_{p,ref}$ obtained from the final report of CCM.P-K13, are listed in Table 17.

Table 17. The LNE's effective area (A_p) and the key comparison reference values of CCM.P-K13 with their standard uncertainty ($u(A_p)$)

p / MPa	$A_{p,LNE,CCM}$ / mm^2	$A_{p,ref}$ / mm^2	u ($A_{p,ref}$) / mm^2	u ($A_{p,ref}$) / $A_{p,ref}$ × 10^6
50	1.961182	1.961152	0.000026	13.5
100	1.961276	1.961269	0.000009	4.6
150	1.961380	1.961386	0.000007	3.4
200	1.961480	1.961495	0.000007	3.4
250	1.961579	1.961597	0.000011	5.4
300	1.961672	1.961692	0.000012	5.9
350	1.961766	1.961782	0.000015	7.7
400	1.961857	1.961871	0.000013	6.7
450	1.961946	1.961956	0.000017	8.8
500	1.962040	1.962041	0.000022	11.1

The combined standard uncertainty of $\Delta A_{p,i,ref}$, is evaluated by the following equation [10],

$$u_c(\Delta A_{p,i,ref}) = \sqrt{u^2(A_{p,i}) + u^2(\Delta A_{p,Link}) + u^2(A_{p,ref})}. \quad (8)$$

The standard uncertainty $u(A_{p,i})$ of NIMT and LNE are listed in the Table 15. The uncertainty, u ($\Delta A_{p,Link}$) is estimated from the combination of type A uncertainties [10] measured by LNE for CCM.P-K13 and APMP.M.P-S7 as equation below,

$$u(\Delta A_{p,Link}) = \sqrt{u_A^2(A_{p,LNE,CCM}) + u_A^2(A_{p,LNE,APMP})}. \quad (9)$$

The standard deviation (Type A uncertainty) measured by LNE for CCM.P-K13 and APMP.M.P-S7, are listed in Table 18. The standard uncertainty of the reference values obtained from the final report of CCM.P-K13, are listed in Table 17.

Table 18. Standard deviation measured by LNE for CCM.P-K13 and APMP.M.P-S7

p / MPa	$u_A(A_{\mathrm{p,LNE,CCM}})$ / mm^2	$u_A(A_{\mathrm{p,LNE,APMP}})$ / mm^2
50	0.0000022	0.0000050
100	0.0000022	0.0000044
150	0.0000031	0.0000080
200	0.0000039	0.0000044
250	0.0000041	0.0000066
300	0.0000041	0.0000048
350	0.0000041	0.0000051
400	0.0000033	0.0000048
450	0.0000027	0.0000026
500	0.0000031	0.0000046

Finally, the degree of equivalent of NIMT and LNE are shown by the relative deviation of NIMT and LNE's results from reference values and relative standard uncertainty in CCM.P-K13 as shown in Tables 19 and 20.

Table 19. Correction ($\Delta A_{p,Link}$) of LNE's results between CCM.P-K13 and APMP.M.P-S7 and deviation (ΔA_p) of participant's results from the CCM.P-K13 reference value

p / MPa	Link	NIMT		LNE	
	$\Delta A_{p,Link}$ / mm^2	$\Delta A_{p,i,ref.}$ / mm^2	$\Delta A_{p,i,ref.}$ / $A_{p,ref.}$ × 10^6	$\Delta A_{p,i,ref.}$ / mm^2	$\Delta A_{p,i,ref.}$ / $A_{p,ref.}$ × 10^6
50	-0.000838	-0.000005	-2.5	0.000030	15.3
100	-0.000796	-0.000009	-4.6	0.000007	3.6
150	-0.000754	-0.000016	-8.2	-0.000006	-3.1
200	-0.000724	-0.000026	-13.3	-0.000015	-7.6
250	-0.000707	-0.000042	-21.4	-0.000018	-9.2
300	-0.000688	-0.000045	-22.9	-0.000020	-10.2
350	-0.000687	-0.000061	-31.1	-0.000016	-8.2
400	-0.000677	-0.000067	-34.2	-0.000014	-7.1
450	-0.000660	-0.000062	-31.6	-0.000010	-5.1
500	-0.000644	-0.000057	-29.1	-0.000001	-0.5

Table 20. Standard uncertainty ($u(\Delta A_p)$) of the deviation of participant's results from the CCM.P-K13 reference value

p / MPa	NIMT		LNE	
	$u(\Delta A_{p,i,ref.})$ / mm^2	$u(\Delta A_{p,i,ref.})$ / $A_{p,ref.}$ × 10^6	$u(\Delta A_{p,i,ref.})$ / mm^2	$u(\Delta A_{p,i,ref.})$ / $A_{p,ref.}$ × 10^6
50	0.000048	25	0.000036	18
100	0.000044	23	0.000028	14
150	0.000047	24	0.000033	17
200	0.000051	26	0.000036	19
250	0.000057	29	0.000042	22
300	0.000062	32	0.000047	24
350	0.000069	35	0.000053	27
400	0.000075	38	0.000057	29
450	0.000081	42	0.000062	32
500	0.000089	45	0.000069	35

Figure 5. Relative deviation of participant's results from the reference value of CCM.P-K13. Error bar represents standard uncertainty of the relative deviation

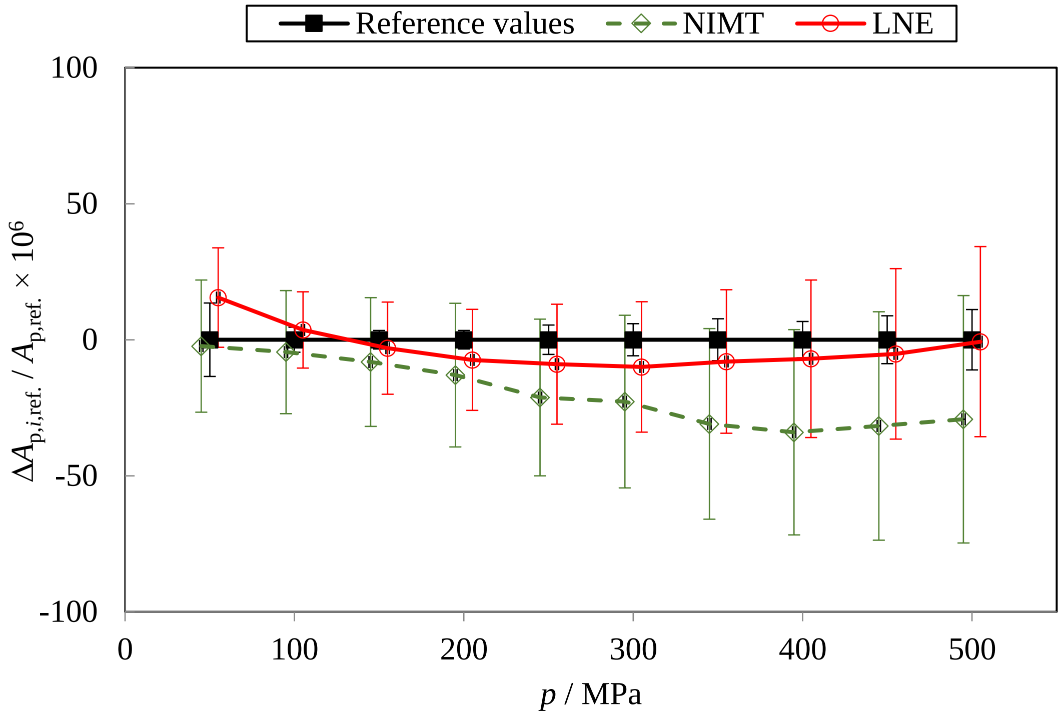

Figure 5 shows the same values as Tables 19 and 20. For visual clarity, the results are slightly shifted from the nominal pressure.

8. CONCLUSIONS

The bilateral supplementary comparison APMP.M.P-S7 was organized in order to check the equivalence of the pressure range from 50 MPa to 500 MPa in the gauge mode between NIMT and LNE. A piston-cylinder unit was used as the transfer standard. This comparison was carried out during the period of March to December 2015. LNE completed their measurements and submitted reports by April 2016. The relative deviations of the effective area of the transfer standard between NIMT and LNE were calculated. The uncertainty of effective area was evaluated by taking into account the instability of the transfer standard even if this value has an insignificant effect to the uncertainty reported by each laboratory. The results of the comparison show that the deviation of the effective area between NIMT and LNE agree with each other with in the standard uncertainties claimed by each laboratory. Therefore, it confirms that the hydraulic gauge pressure standards maintained by two laboratories in the pressure range from 50 MPa to 500 MPa are equivalent. The results of this comparison support the calibration and measurement capabilities (CMC) of NIMT.

This bilateral comparison results are linked to the CCM.P-K13 reference values through LNE. The deviations of NIMT results from CCM.P-K13 reference values were in good agreement with the uncertainties claimed by NIMT.

Acknowledgements

The invaluable advices and supports by Mr. Tawat Changpan are gratefully acknowledged. Contributions by the staffs at NIMT and LNE are also appreciated.

References

1. Technical Protocol of Supplementary comparison of NIMT and LNE pressure standards in the range 50 MPa to 500 MPa of hydraulic gauge pressure (APMP.M.P-S7), 2014
2. Fluke Corporation, DH Instruments Divition, PG7000™ PISTON GAUGES PG7102™, PG7202™, PG7302™, PG7601™ (Ver. 3.0 and Higher) Operation and Maintenance Manual, 1983
3. Priruenrom T., Changpan T. The primary gas pressure standards at NIMT, Proceedings of the 6th APMP Pressure & Vacuum Workshop, Wellington, New Zealand, 2012, 6-7
4. T. Priruenrom, *et al.*, Final report on APMP.M.P-S4: Results of the bilateral supplementary comparison on pressure measurements in the range (60 to 350) kPa of gauge pressure in gas media, Metrologia 50 07009, 2013
5. J.C. Legras - Piston gage used as high accuracy standards in the range 0,01 - 1000 MPa. BIPM, Monographie 89/1, 41-52 (1989)
6. J. Le Guinio, J.C. Legras, A. El-Tawil - The new standard of BNM-LNE for absolute pressure measurements up to 1 MPa, Metrologia, 1999, 36, 535-539
7. Desgranges *et* Huot, TYPE 5300 MODEL 5306,Operation and Maintenance Manual, 1983
8. DH Budenberg, Calibration certificate No. 18790 of piston-cylinder for pressure balance, 2005
9. Mechanical department, Pressure Laboratory, Calibration procedure for pressure CP-

MP-2001, edition 02, revision 01, 2010

10. H. Kajikawa *et al.*, Final report on key comparison APMP.M.P-K13 in the range 50 MPa to 500 MPa of hydraulic gauge pressure, Metrologia 52 07003, 2015
11. Calibration of pressure balance, EURAMET cg-3, Version 1.0 (03/2011)
12. Pierre Otal - EURAMET project 1125 "Evaluation of cross-float measurements with pressure balances", PTB-Mitteilungen 121 (2011), Heft 3
13. ISO/IEC 2008 Guide 98-3 Guide to the Expression of Uncertainty in Measurement (GUM: 1995) (Geneva: International Organization for Standardization)
14. W. Sabuga, *et al*., Final report on key comparison CCM.P-K13 in the range 50 MPa to 500 MPa of hydraulic gauge pressure, Metrologia 49 07006, 2012