RMO SC COMPARISON
COOMET M.H-S5

Final Report

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Abstract:
This report describes the results of comparison COOMET.M.H-S5. The comparison measurements between the five participants NSC “IM” (pilot laboratory), PTB, CMI, BelGIM, RSE “KazInMetr” were started in November 2013 and ended in May 2015.
In the RMO KC, one set of hardness reference blocks were used consisting of 5 (five) blocks of the Rockwell scales and hardness levels 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC.
Agreement between results of participants is good.

1 Introduction

The present key comparisons of Rockwell hardness scales were organized by the COOMET and registered in BIPM under the cipher COOMET.M.H-S5. This regional comparison was between hardness laboratories of the national metrological institutes of Germany, Ukraine, Belarus, Kazakhstan and Czech Republic.

2 Organization

In October 2013, during TC 1.6 COOMET meeting (Kharkiv, Ukraine), it was decided to entrust the organization of the comparisons on Rockwell hardness scales to the National Scientific Centre “Institute of Metrology” (NSC IM, Ukraine) as a pilot laboratory. Dr. Vladimir Skliarov and J. Dovshenko (NSC IM, Ukraine) were appointed the coordinators of the comparisons.

The draft of the technical protocol was agreed upon between the participants of the comparison in 2013. The comparison started in November 2013 and ended in May 2015.

2.1 Participants

The list of participants is given in table 1.

Table 1– Participants of comparisons

№	NMI	Address for sending the sample	Acronym	Contact person
1	National Scientific Centre “Institute of Metrology” ***(pilot laboratory)***	42, Myronosytska str., Kharkiv, 61002, Ukraine	NSC IM	V. Skliarov, J. Dovshenko skliarov69@mail.ru
2	Physikalisch-Technische Bundesanstalt	100, Bundesallee, Braunschweig, 38116, Germany	PTB	F. Menelao febo.menelao@ptb.de
3	Czech metrology institute	4, V Botanice 15072 Praha 5 Czech Republic	CMI	J. Borovský jborovsky@cmi.cz
4	Belarusian State Institute of Metrology	93, Starovilensky trakt, Minsk,220053, Belarus	BelGIM	N. Kamkova kamkova@belgim.by E. Obozny obozny@belgim.by
5	Kazakhstan Institute of Metrology	22/2, Angerskaja str., Karaganda, 100009, Kazakhstan,	KazInMetr	M. Zhamanbalin zhamanbalin@kazinmetr.kz

2.2 Time schedule

Table 2 shows the scheduled measuring time.

Table 2 -Time schedule

Institute/Country	**Date of measurements**
NSC “IM”, Ukraine	November 2013
PTB, Germany	January 2014
CMI, Czech Republic	May 2014
BelGIM, Belarus	June 2014
RSE “KazInMetr”, Kazakhstan	December 2014
NSC “IM”, Ukraine	May 2015

3 Transfer standards

3.1 Description

In the RMO KC, one set of hardness reference blocks were used consisting of 5 (five) blocks of the Rockwell scales and hardness levels 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC (fig. 1)

Figure 1 Set of Rockwell hardness reference blocks

Hardness blocks were manufactured by “Centre “MET” Ltd (Russia) and have a length of 60 mm, width of 40 mm and a thickness of 6 mm (fig. 2).

The upper surface of the block, which is the measurement surface, is finished. The measurement area is defined to be within an engraved grid. A 5 by 7 cell grid (7 mm x 7 mm cell size) is engraved on the block surface in order to define the coordinates of the test locations. The sizes of the test area and grid allow 35 possible test locations (fig. 3). The participants instructed how to avoid testing near edges of indentations.

Figure 2 Hardness reference blocks used for the HRB RKC with the logo of the manufacturer

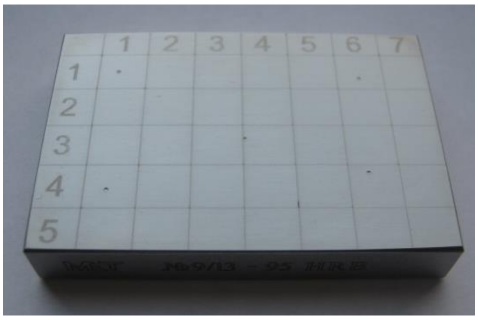

Figure 3 Layout of the grid on the measurement surface of the hardness reference blocks

3.2 Transportation and Handling

The pilot laboratory was responsible for purchasing the blocks for the regional comparison, while each participating institute assumed the costs for transport, customs and related administrative fees.

The pilot laboratory made measurements at the beginning and at the end of the RMO KC in order to evaluate the stability of the hardness reference blocks used in the RMO KC.

It was recommended for each institute to clean the blocks after unpacking with alcohol and then mark all fields reserved for the institute with a fibre pen on the left top corner. After the measurement all dots on the blocks were to be removed before packing in order to avoid corrosion.

4 Measurand

The measurements were carried out following the Rockwell scale and Superficial - Rockwell scale definition developed for adoption by National Metrology Institutes (NMIs). Before conducting the measurements, each participant was required to carry out the calibration of the primary hardness machine.

Each participant made 5 (five) measurement indentations on each hardness reference block. Each indentation was to be made at the center of the open square within the engraved grid lines such that the indentation does not contact an engraved line. The 5 (five) indentation measurements were used to evaluate the stochastic deviations occurring during the measurements, including the evaluation of the in homogeneity of the hardness distribution across the test surface of the hardness reference blocks.

The test locations on the blocks will be provided to participants as grid coordinates (Figs. 4 - 8).

№ 7/13-83 HRA

	1	2	3	4	5	6	7
1	m 1	m 1	m 2	m 7	m 5	m 5	m 5
2	m 1	m 1	m 3	m 7	m 7	m 7	m 5
3	m 6	m 6	m 3	m 2	m 4	m 3	m 7
4	m 3	m 2	m 6	m 2	m 3	m 4	m 5
5	m 1	m 2	m 6	m 6	m 4	m 4	m 4

Figure 4 Test locations on the 80-86 HRA block

№ 9/13-95 HRB

	1	2	3	4	5	6	7
1	m 1	m 1	m 1	m 6	m 4	m 4	m 4
2	m 1	m 6	m 4	m 3	m 6	m 7	m 4
3	m 1	m 2	m 3	m 3	m 3	m 6	m 5
4	m 2	m 2	m 2	m 7	m 6	m 5	m 5
5	m 2	m 7	m 7	m 7	m 3	m 5	m 5

Figure 5 Test locations on the 80-100 HRB block

№ 1/13-25 HRC

	1	2	3	4	5	6	7
1	m 1	m 1	m 2	m 3	m 7	m 4	m 6
2	m 1	m 1	m 3	m 6	m 4	m 4	m 4
3	m 1	m 7	m 7	m 3	m 6	m 4	m 7
4	m 2	m 2	m 6	m 3	m 5	m 5	m 3
5	m 2	m 7	m 2	m 6	m 5	m 5	m 5

Figure 6 Test locations on the 20-30 HRC block

№ 3/13-45 HRC

	1	2	3	4	5	6	7
1	m 1	m 2	m 1	m 6	m 7	m 5	m 4
2	m 1	m 6	m 1	m 3	m 6	m 4	m 4
3	m 1	m 3	m 6	m 3	m 7	m 5	m 4
4	m 2	m 6	m 3	m 5	m 3	m 4	m 7
5	m 2	m 2	m 2	m 7	m 5	m 7	m 5

Figure 7 Test locations on the 40-50 HRC block

№5/13-65 HRC

	1	2	3	4	5	6	7
1	m 1	m 1	m 1	m 7	m 6	m 4	m 4
2	m 1	m 6	m 1	m 3	m 3	m 6	m 4
3	m 2	m 6	m 3	m 3	m 4	m 5	m 4
4	m 2	m 7	m 7	m 5	m 5	m 5	m 5
5	m 2	m 2	m 2	m 3	m 7	m 7	m 6

Figure 8 Test locations on the 60-70 HRC block

In addition to the 5 (five) measurement locations, two additional test locations were allocated to each institute to be used for a test measurement or in case a measurement error occurs and the measurement must be repeated. The additional two test locations were indicated as “repeat measurements”.

Due to the number of fields on the hardness block surface (35) and the number of indentations to be carried out by each laboratory (5 plus two), the maximum number of participants for each regional comparison is 5 (35/5=5+2 for possible errors or test indentation). The Pilot laboratory performed the measurements twice.

5 Methods of measurement

Short descriptions with pictures of the Rockwell Primary Hardness Standard Machines (PHSM) used for the measurements by the participants are described in Appendix A.

6 Stability of the standards

In order to evaluate the stability of the standards the pilot laboratory carried out measurements at the beginning and at the end of the comparison. The results are summarised in table 3.

Table 3 -Measurement results at the beginning and at the end of the comparison by the pilot laboratory

Measurand,HR	Result at the begin (1), HR	Result at the end (2), HR	Diff. Δ_{2-1},HR	Meas. Unc. U, HR	$\lvert\Delta_{2-1}\rvert$/ U, HR
80-86 HRA	82,98	82,90	-0,08	0,27	0,28
80-100 HRBW	95,85	95,91	0,07	0,34	0,20
20-30 HRC	28,67	28,61	-0,06	0,26	0,24
40-50 HRC	45,82	45,73	-0,09	0,38	0,24
60-70 HRC	63,29	63,20	-0,10	0,40	0,24

In the last row the difference between the first and the second measurement Δ_{2-1} is compared to the measurement uncertainty. If the difference is $\lvert\Delta_{2-1}\rvert$/U> 1, it means that the difference Δ_{2-1} cannot be explained by the uncertainty but can be traced back to any change of the hardness reference blocks during the period of the comparison.

Since $\lvert\Delta_{2-1}\rvert$/U <1 for each of the reference blocks, the drift of the test blocks did not significantly influence the uncertainty of measurement results and can be omitted while processing the comparison results.

Therefore, one can conclude that the used hardness reference blocks remained stable.

7 Measurement results

In the following table 4, the results for the hardness reference blocks with hardness levels of 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC are summarised. The results are expressed by mean values, the standard deviations S_5 of each set of 5 repetition measurements and the standard deviations between the institutes s_{Inst}.

Table 4 - Results of the measurements for the hardness reference blocks with hardness level 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC

Institute	80-86 HRA		80-100 HRBW		20-30 HRC		40-50 HRC		60-70 HRC	
	Mean value	Std.dev.	Mean value	Std. dev.	Mean value .	Std. dev.	Mean value	Std.dev.	Mean value	Std.dev.
NSC IM	82,90	0,18	95,91	0,13	28,61	0,21	45,73	0,14	63,20	0,09
PTB	83,09	0,16	95,86	0,08	28,60	0,19	45,88	0,17	63,31	0,09
CMI	82,68	0,14	95,75	0,12	29,04	0,10	46,01	0,07	63,25	0,18
BelGIM	82,93	0,08	96,24	0,11	28,52	0,08	45,68	0,04	63,28	0,11
KazInMetr	82,56	0,11	96,28	0,08	28,50	0,34	45,50	0,19	63,08	0,22
Mean value	82,83		96,01		28,65		45,76		63,22	
Std.dev, S_i	0,21		0,24		0,22		0,19		0,09	

8 Uncertainty budgets

8.1 Calculation scheme

The calculation of uncertainty for all the participants was carried out according to [1-4].The calculation scheme can be seen from the example in table 5 and table 6.

Table 5 - Calculation scheme for HRA and HRC scales for the unified estimation of the measurement uncertainty

Quantity, X_i	Symbol, Unit	Estimated value, Δx_i	Standard uncertainty, $u(x_i)=\frac{\Delta x_i}{\sqrt{3}}$	Sensitivity coefficient, $c_i=\frac{\Delta H}{\Delta x_i}$	Single hardness deviation, $\Delta H_i=\Delta x_i \cdot c_i$, HR	Uncertainty contribution, $u_i(H)=c_i \cdot u(x_i)$ HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,11	0,022	0,013	2,89239 E-09
Total test force	F , N	1,5	0,866	-0,03	-0,045	-0,026	5,06309 E-08
Indenter cone angle	α_m ,^{0}	0,1	0,058	0,14	0,014	0,008	4,74327 E-10
Indenter radius	R_α , μm	1,0	0,577	0,14	0,14	0,081	4,74327 E-06
Indentation depth	l , μm	0,1	0,058	0,5	0,05	0,029	7,71695 E-08
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	0,7	0,404	-0,014	-0,0098	-0,006	1,13886 E-10
Preliminary test force duration time	T_p , c	0,2	0,115	0,01	0,002	0,001	1,97554 E-13
Total test force duration time	T_{df} , c	0,2	0,115	0,01	0,002	0,001	1,97554 E-13
Deformation of frame	d , μm	0,3	0,173	0,5	0,15	0,087	6,25073 E-06
Total					0,325	0,188	
Combined standard uncertainty, $u(H)=\sqrt{\sum_i u_i^2(H)}$, HR						0,126	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertantiy $U=k \cdot u(H)$, HR						0,251	

Table 6 - Calculation scheme for HRBW scale for the unified estimation of the measurement uncertainty

Quantity, X_i	Symbol, Unit	Estimated value, Δx_i	Standard uncertanty, $u(x)_i = \frac{\Delta x_i}{\sqrt{3}}$	Sensitivity coefficient, $c_i = \frac{\Delta H}{\Delta x_i}$	Single hardness deviation, $\Delta H_i = \Delta x_i \cdot c_i$,HRBW	Uncertainty contribution, $u_i(H) = c_i \cdot u(x_i)$ HRBW	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,07	0,014	0,008	4,74327 E-10
Total test force	F , N	1,5	0,866	0,1	0,15	0,087	6,25073 E-06
Indenter ball diametr	R_β , μm	1,0	0,577	0,1	0,1	0,058	1,23471 E-06
Indentation depth	l , μm	0,1	0,058	0,5	0,05	0,029	7,71695 E-08
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	0,7	0,404	-0,2	-0,14	-0,081	4,74327 E-06
Preliminary test force duration time	T_p , s	0,2	0,115	0,1	0,02	0,012	1,97554 E-09
Total test force duration time	T_{df} , s	0,2	0,115	0,1	0,02	0,012	1,97554 E-09
Deformation of frame	d , μm	0,3	0,173	0,5	0,15	0,087	6,25073 E-06
Total					0,364	0,210	
Combined standard uncertainty, $u(H) = \sqrt{\sum_i u_i^2(H)}$, HRBW						0,161	
Coverage factor *k* for confidence level p=0,95						2	
Expanded uncertantiy $U = k \times u(H)$, HRBW						0,323	

From the influencing quantities X_i measurement deviations Δx_i and uncertainties in the form of standard deviation S_i (type A) and A_i (type B) are considered.

Sensitivity coefficients:

$c_i = \frac{\Delta H}{\Delta x_i}$	Quantity, X_i	Symbol, Unit
$\frac{\Delta HR}{\Delta F_0}$	Preliminary test force	F_0, N
$\frac{\Delta HR}{\Delta F}$	Total test force	F , N
$\frac{\Delta HR}{\Delta \alpha}$	Indenter cone angle	α , º

$c_i = \frac{\Delta H}{\Delta x_i}$	Quantity, X_i	Symbol, Unit
$\frac{\Delta HR}{\Delta R_\alpha}$	Indenter radius	R_α , μm
$\frac{\Delta HR}{\Delta R_\beta}$	Indenter ball diametr	R_β μm
$\frac{\Delta HR}{\Delta l}$	Indentation depth	l , μm
$\frac{\Delta HR}{\Delta V_{fis}}$	Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$
$\frac{\Delta HR}{\Delta T_p}$	Preliminary test force duration time	T_p , s
$\frac{\Delta HR}{\Delta T_{df}}$	Total test force duration time	T_{df} , s

Single hardness deviation:

$$\Delta H_i = c_i \cdot \Delta x_i \, , \tag{1}$$

where Δx_i - estimated value

Variances:

$$u^2(y_i) = c_i^2 u^2(x_i) \tag{2}$$

Combined standard uncertainty:

$$u(H) = \sqrt{\sum_{i=1}^{n} u^2(y_i)} \tag{3}$$

Sum of hardness deviations:

$$\Delta H = \sum_{i=1}^{n} \Delta H_i \tag{4}$$

Effective degrees of freedom, according to the Welch-Satterthwaite formula:

$$\nu_{eff} = \frac{u^4(y)}{\sum_{i=1}^{\nu} \frac{u_i^4(y)}{\nu_i}} \tag{5}$$

Coverage factor:

$$k = f(\nu_{eff}, P) \tag{6}$$

Expanded standard uncertainty:

$$U(H) = k \cdot u(H) \tag{7}$$

According to this unified procedure for the estimation of measurement uncertainty, the following measurement uncertainties for the participants were received.

8.2 Calculation of measurement uncertainty

As a basis for the determination of the measurement uncertainty, the draft guideline to the estimation of the uncertainty of the Rockwell measuring method was recommended [1-6].

The uncertainty budgets of the participants based on a unified procedure as presented in clause 8.1 appear in Appendix B. Table 7 shows mean values of hardness measurements and expanded uncertainties of the measurement results for hardness level 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC.

Table 7 – Mean hardness values and expanded uncertainties.

Institutes	80-86 HRA		80-100 HRBW		20-30 HRC		40-50 HRC		60-70 HRC	
	Mean value	Exp.un cert.	Mean value	Exp.un cert.	Mean value	Exp.un cert.	Mean value	Exp.un cert.	Mean value	Exp.un cert.
NSC IM	82,90	0,27	95,91	0,34	28,61	0,26	45,73	0,38	63,20	0,40
PTB	83,09	0,17	95,86	0,19	28,60	0,19	45,88	0,15	63,31	0,19
CMI	82,68	0,40	95,75	0,40	29,04	0,30	46,01	0,30	63,20	0,30
BelGIM	82,93	0,35	96,24	0,43	28,52	0,44	45,68	0,31	63,28	0,36
KazInMetr	82,56	0,39	96,28	0,43	28,50	0,38	45,50	0,47	63,08	0,48

9 Analyzing Method of Comparison Results

The measurement results are used to compute the degree of equivalence in Comparison Reference Value (CRV) and En ratio. The calculation is shown in following formulas:

a) calculation of CRV, the Pilot laboratory determined CRV by calculating the weighted mean of measurements of all participants (x_{ref}):

$$x_{ref} = \frac{x_1/u^2(x_1) + x_2/u^2(x_2) + ... + x_n/u^2(x_n)}{1/u^2(x_1) + 1/u^2(x_2) + ... + 1/u^2(x_n)}; \quad (8)$$

b) the uncertainty of the CRV was calculated by following expression:

$$\frac{1}{u^2(x_{ref})} = \frac{1}{u^2(x_1)} + \frac{1}{u^2(x_2)} + ... + \frac{1}{u^2(x_n)} , \quad (9)$$

where x_i - the measured value of participating institute i $(i = 1,2,...,n)$;

$u(x_i)$ - the standard uncertainty of x_i .

Table 8 – Mean hardness values and expanded uncertainties with x_{ref}

Hardness level	80-86 HRA	80-100 HRBW	20-30 HRC	40-50 HRC	60-70 HRC
x_{ref}	**82,95**	**95,95**	**28,66**	**45,84**	**63,26**
$\frac{1}{u^2(x_{ref})}$	69,31	53,42	65,70	77,41	57,12
$u^2(x_{ref})$	0,01	0,02	0,02	0,01	0,02
$u(x_{ref})$	0,12	0,14	0,12	0,11	0,13

In Figures 9-13 reference values x_{ref} are shown by a red line, the dashed blue line shows the expanded uncertainty of the reference value x_{ref} . Expanded uncertainties are shown by black vertical bars. The total length of black vertical bars equals 2U.

Figure 9 shows mean values and expanded uncertainties of hardness measurement results by national laboratories for level 80-86 HRA.

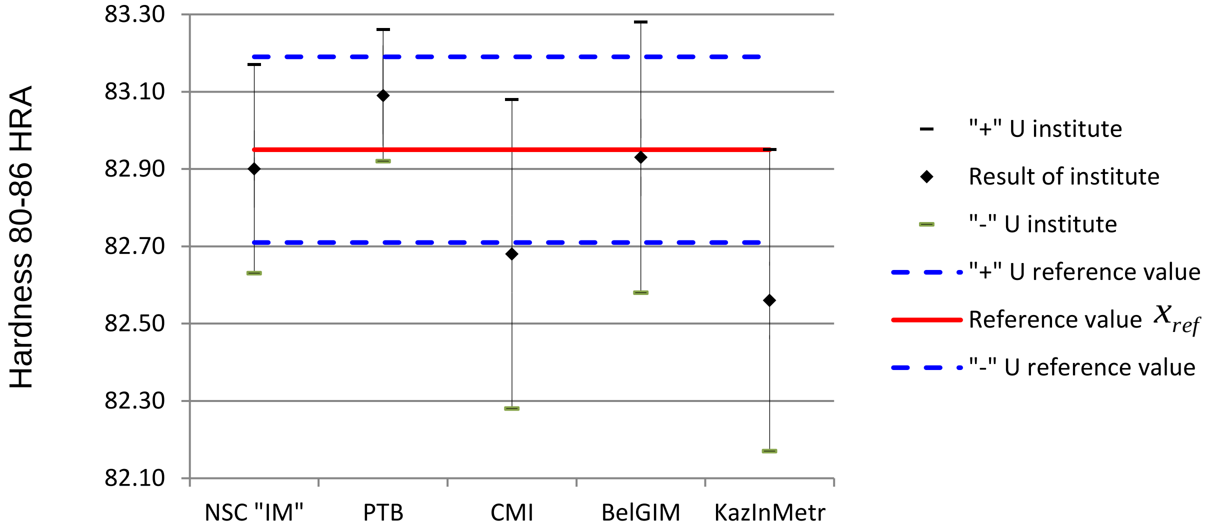

Figure 9 Comparisons results for hardness level 80-86 HRA

Figure 10 shows mean values and expanded uncertainties of hardness measurement results by national laboratories for level 80-100 HRBW.

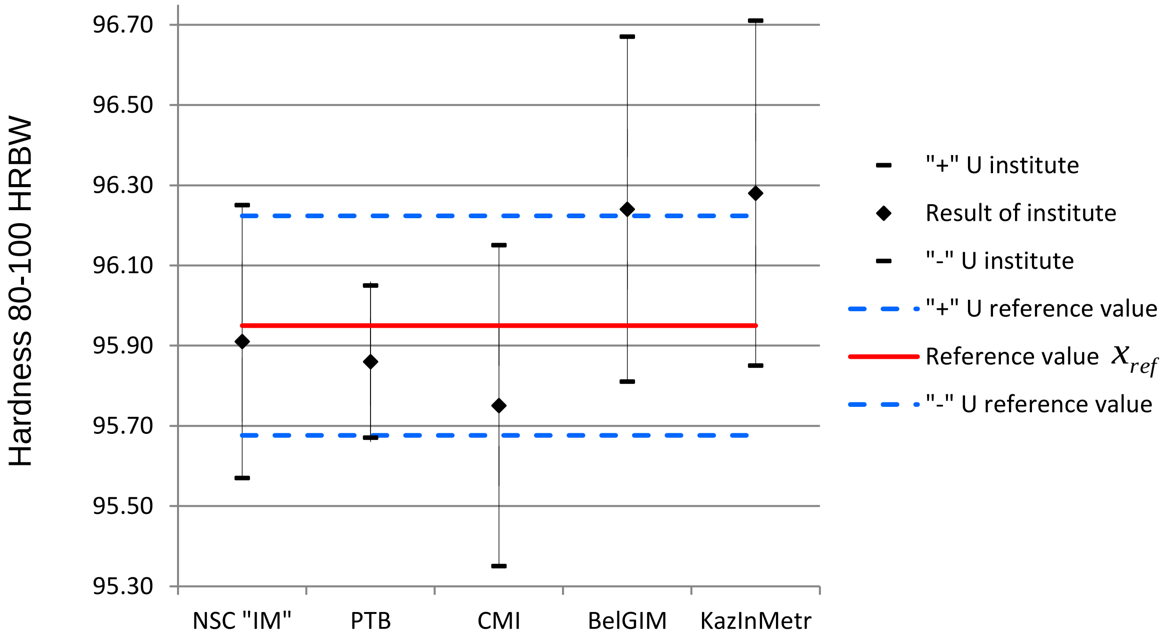

Figure 10 Comparisons results for hardness level 80-100 HRBW

Figure 11 shows mean values and expanded uncertainties of hardness measurement results by national laboratories for level 20-30 HRC.

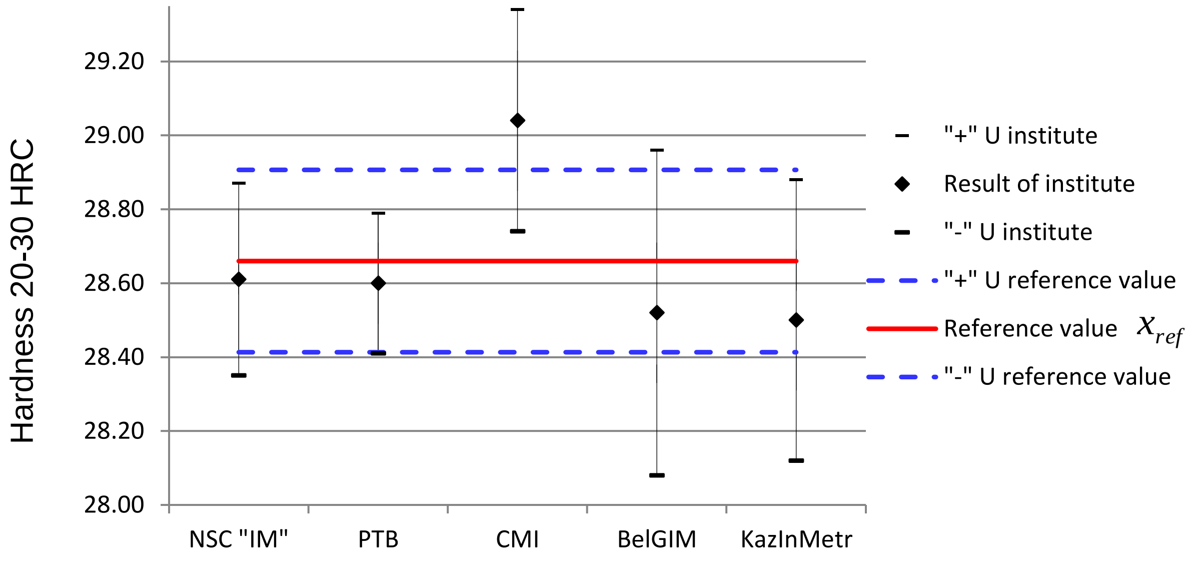

Figure 11 Comparisons results for hardness level 20-30 HRC

Figure 12 shows mean values and expanded uncertainties of hardness measurement results by national laboratories for level 40-50 HRC.

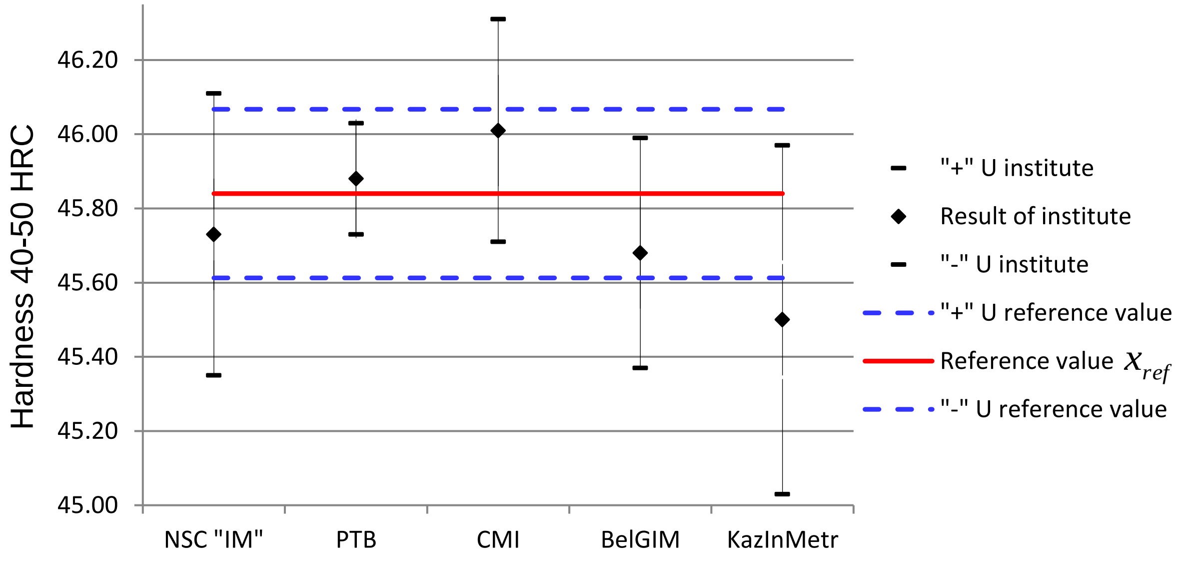

Figure 12 Comparisons results for hardness level 40-50 HRC

Figure 13 shows mean values and expanded uncertainties of hardness measurement results by national laboratories for level 60-70 HRC.

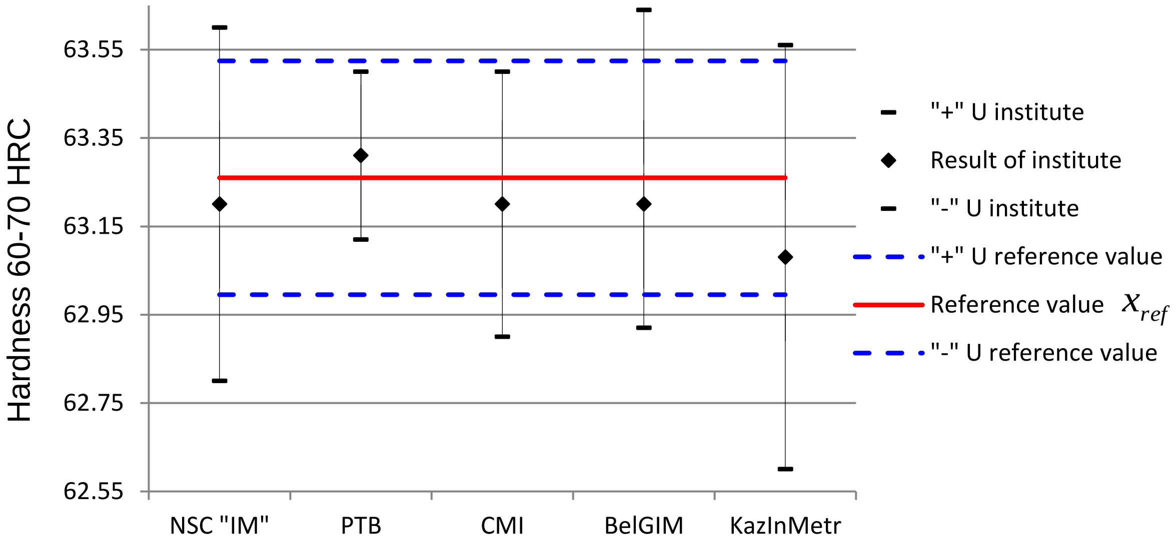

Figure 13 Comparisons results for hardness level 60-70 HRC

The results shown in Figures 14 to 18 indicate that the measurement results obtained by the majority of the comparison participants correlate well with mean hardness values.

a) The deviation from CRV:

$$d_i = x_i - x_{ref} \tag{10}$$

The uncertainty of this deviation at a 95% level of confidence:

$$U(d_i) = k \cdot u(d_i) \quad , \tag{11}$$

where $u(d_i)$ was given by ($k = 2$)

$$u(d_i) = \sqrt{u^2(x_i) + u^2(x_{ref})} \tag{12}$$

b) Evaluation of Coefficient E_n :

the equivalence between the measurements of participating institutes was expressed by coefficient E_n as well:

$$E_n = \left| \frac{x_i - x_{ref}}{\sqrt{U^2(x_i) + U^2(x_{ref})}} \right| \quad , \tag{13}$$

Where

$$U(x_i) = k \cdot u(x_i),$$
$$U(x_{ref}) = k \cdot u(x_{ref}) \tag{14}$$

The x_i is considered equivalent with the CRV x_{ref} at 95% confidence level, if $|E_n| \le 1$.

Table 9 shows the intermediate result for next Table 11 and evaluation the deviations.

Table 9– The intermediate results for further evaluations.

		80-86 HRA	80-100 HRBW	20-30 HRC	40-50 HRC	60-70 HRC
NMIs	$U(x_{ref}) = k \cdot u(x_{ref})$	0,24	0,28	0,25	0,23	0,26
	$U^2(x_{ref})$	0,06	0,07	0,06	0,05	0,07
NSC IM	$U(x_1) = k \cdot u(x_1)$	0,27	0,34	0,26	0,38	0,40
	$U^2(x_1)$	0,07	0,12	0,07	0,14	0,16
PTB	$U(x_2) = k \cdot u(x_2)$	0,17	0,19	0,19	015	0,19
	$U^2(x_2)$	0,03	0,04	0,04	0,02	0,04
CMI	$U(x_3) = k \cdot u(x_3)$	0,40	0,40	0,30	0,30	0,30
	$U^2(x_3)$	0,16	0,16	0,09	0,09	0,09
BelGIM	$U(x_4) = k \cdot u(x_4)$	0,35	0,43	0,44	0,31	0,36
	$U^2(x_4)$	0,12	0,18	0,19	0,10	0,13
KazIn Metr	$U(x_5) = k \cdot u(x_5)$	0,39	0,43	0,386	0,47	0,48
	$U^2(x_5)$	0,15	0,18	0,14	0,22	0,23

10 Comparison Results

The comparison results, comparison reference value (CRV), the deviation value of each NMIs from CRV as well as their uncertainty and E_n ratio, are calculated and shown in Table 10, Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19 for the Rockwell scales with hardness levels 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC.

Table 10 – Comparison results for evaluation

		80-86 HRA	80-100 HRBW	20-30 HRC	40-50 HRC	60-70 HRC
NMIs	*Nominal*	80-86 HRA	80-100 HRBW	20-30 HRC	40-50 HRC	60-70 HRC
	CRV x_{ref}	82,95	95,94	28,66	45,84	63,26
	$u^2(x_{ref})$	0,01	0,02	0,02	0,01	0,02
NSC IM	*deviation from CRV* $d_i = x_i - x_{ref}$	-0,05	-0,04	-0,05	-0,11	-0,06
	$U(d_i)$	0,27	0,34	0,26	0,38	0,40
	Evaluation of Coefficient E_n	-0,14	-0,09	-0,14	-0,25	-0,13
PTB	*deviation from CRV* $d_i = x_i - x_{ref}$	0,14	-0,09	-0,06	0,04	0,05
	$U(d_i)$	0,17	0,19	0,19	0,15	0,19
	Evaluation of Coefficient E_n	0,47	-0,28	-0,19	0,15	0,15

NMIs	Nominal	80-86 HRA	80-100 HRBW	20-30 HRC	40-50 HRC	60-70 HRC
CMI	*deviation from CRV* $d_i = x_i - x_{ref}$	-0,27	-0,20	0,38	0,17	-0,06
	$U(d_i)$	0,40	0,40	0,30	0,30	0,30
	Evaluation of Coefficient E_n	-0,58	-0,42	0,98	0,45	-0,15
BelGIM	*deviation from CRV* $d_i = x_i - x_{ref}$	-0,02	0,29	-0,14	-0,16	0,02
	$U(d_i)$	0,35	0,43	0,44	0,31	0,36
	Evaluation of Coefficient E_n	-0,05	0,57	-0,28	-0,42	0,04
KazInMetr	*deviation from CRV* $d_i = x_i - x_{ref}$	-0,39	0,33	-0,16	-0,34	-0,18
	$U(d_i)$	0,39	0,43	0,38	0,47	0,48
	Evaluation of Coefficient E_n	-0,85	0,65	-0,35	-0,65	-0,33

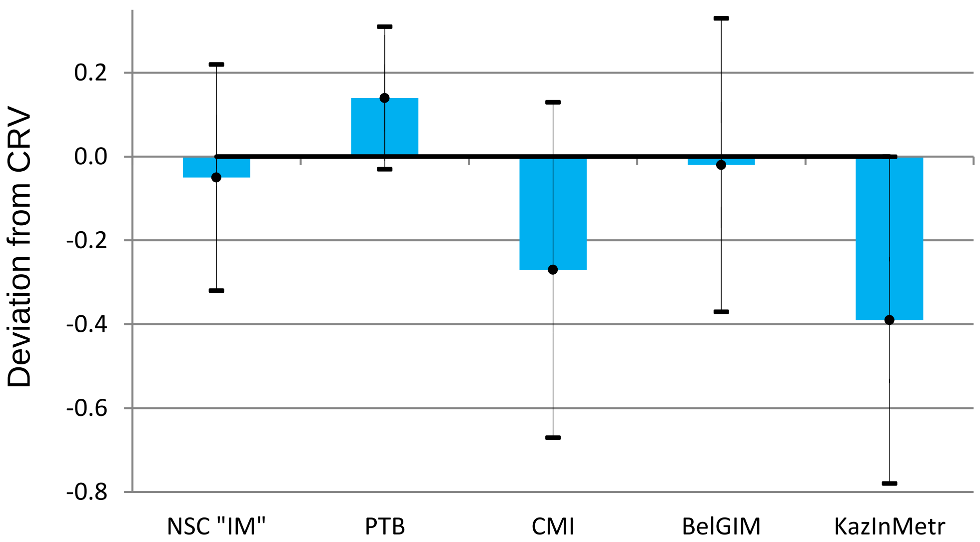

Figure 14 Deviation from reference value of 80-86 HRA measurement comparison

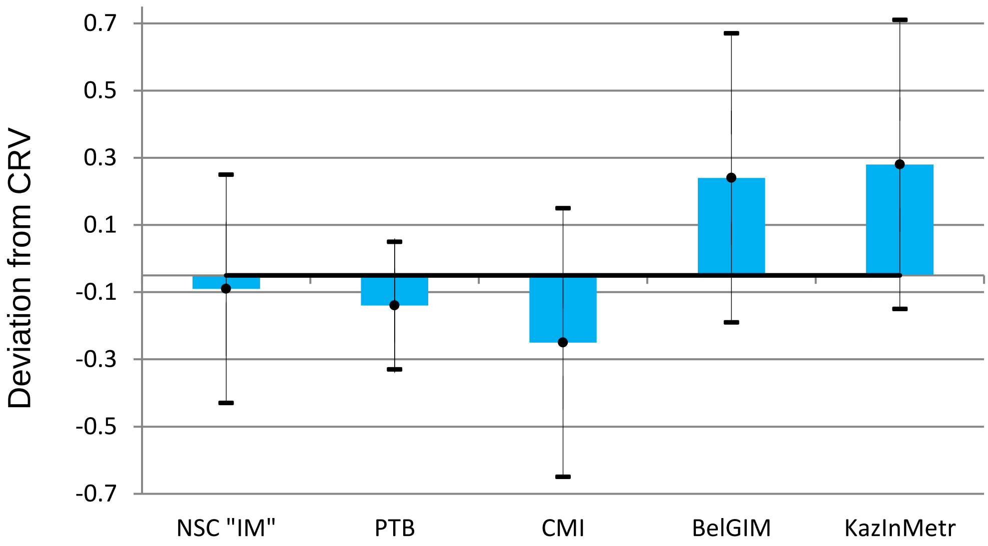

Figure 15 Deviation from reference value of 80-100 HRBW measurement comparison

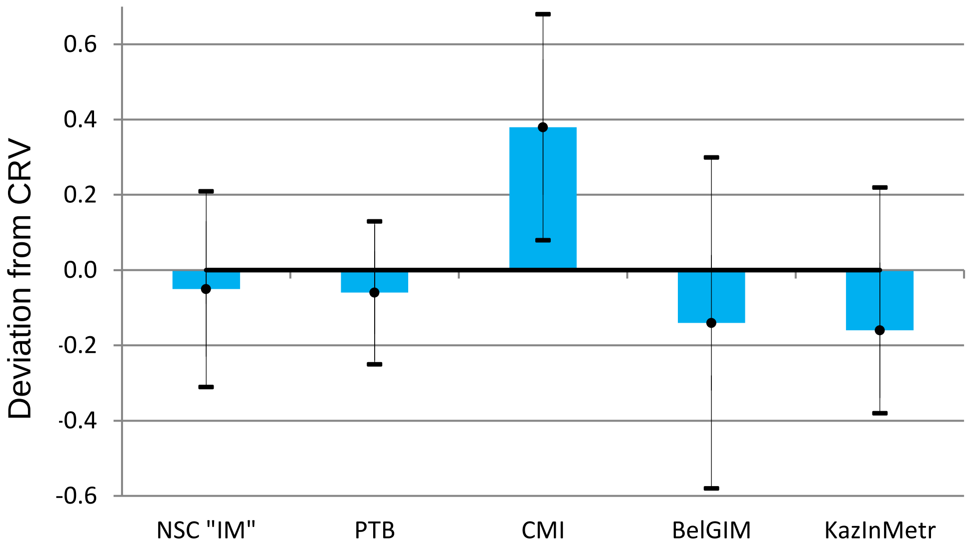

Figure 16 Deviation from reference value of 20-30 HRC measurement comparison

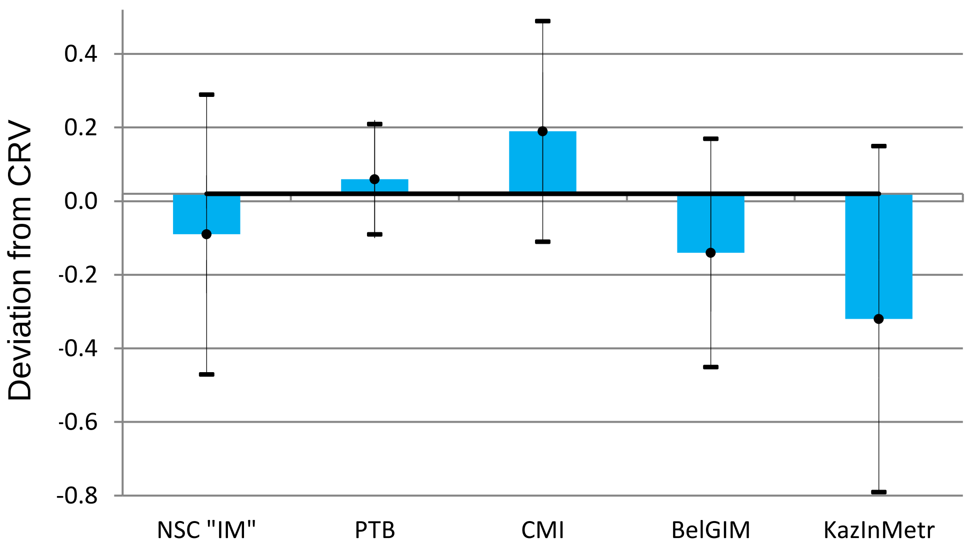

Figure 17 Deviation from reference value of 40-50 HRC measurement comparison

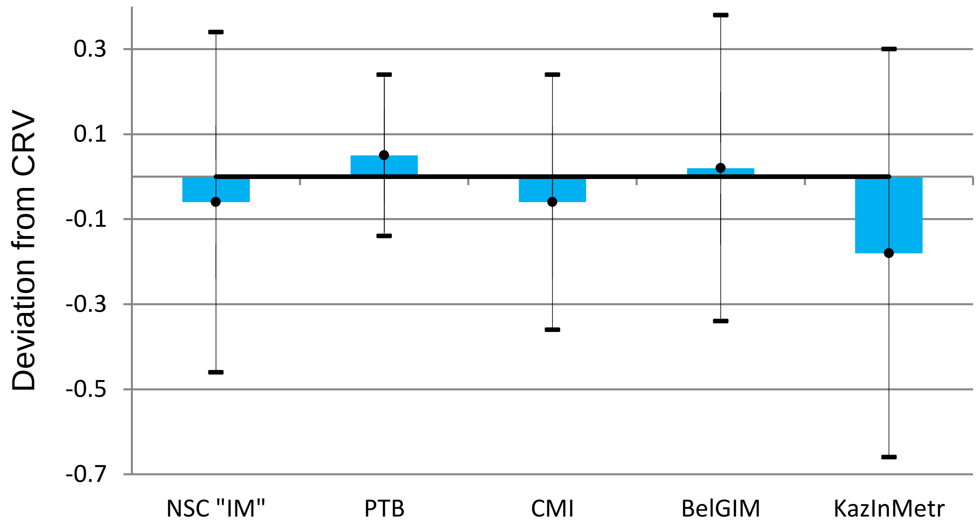

Figure 18 Deviation from reference value of 60-70 HRC measurement comparison

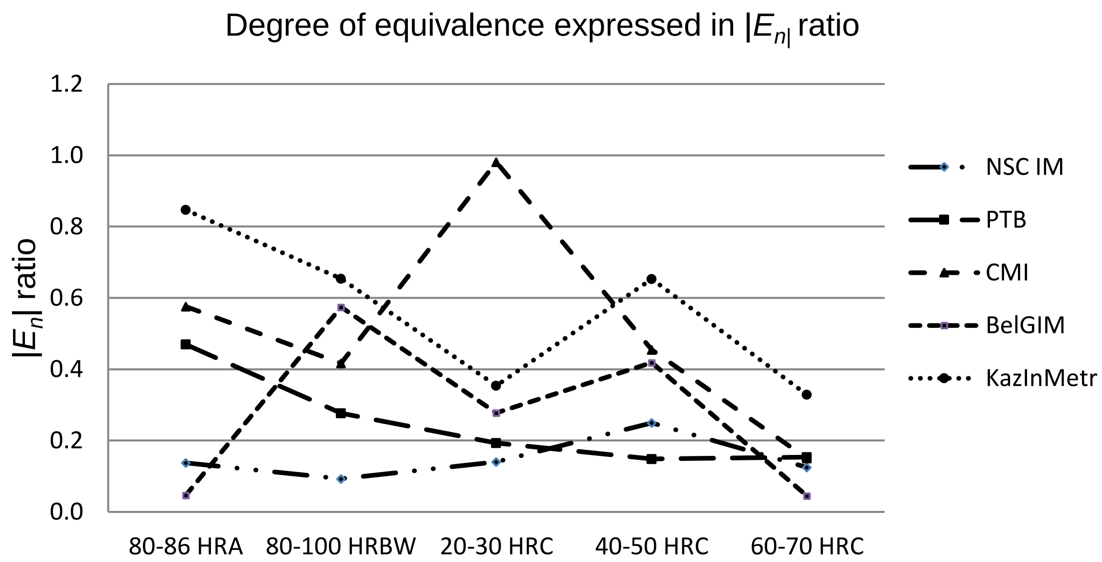

Figure 19 $\left|E_n\right|$ ratio of hardness level 80-86 HRA, 80-100 HRBW, 20-30 HRC, 40-50 HRC, 60-70 HRC measurement comparison

11 Discussions, conclusions and remarks

The COOMET.M.H-S5.comparison can be considered as a successful metrological exercise. At present, Rockwell hardness reference blocks with high time-dependent stability and high local homogeneity, including high surface quality are available.

The contribution of this comparison would be quite important because other COOMET countries need the confirmation of traceability by a key comparison.

12 References

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AppendixA

Description of the Primary Hardness Standard Machine (PHSM)

NSC “Institute of Metrology”

Name	National primary standards according to Rockwell, hardness scales
Manufacturer	NSC “Institute of Metrology”
Model	DETU 02-04-99
S/n	DETU 02-04-99
Year of construction (and following significant upgrades)	1999
Hardness Scales	Rockwell scales
HR, $U_{95\%}$	80-86 HRA = 0,3 HR 80-100 HRBW = 0,3 HR 20-30 HRC = 0,3 HR 40-50 HRC = 0,3 HR 60-70 HRC = 0,3 HR
Force generation system and $U_{95\%}$	Dead weight, 0,28 N
Depth measuring system and $U_{95\%}$	0,058µm
Indenter (manufacturer, model, s/n)	“Instrument Service” (Ukraine), model NC, s/n 2111
Picture	

Czech metrology institute

<table>
<tr><td>Name</td><td colspan="4">National primary standards according to Rockwell hardness</td></tr>
<tr><td>Manufacturer</td><td colspan="4">PGH – Kraftmessgeräte, Germany</td></tr>
<tr><td>Model</td><td colspan="4">RNGT 150</td></tr>
<tr><td>S/n</td><td colspan="4">007/1962</td></tr>
<tr><td>Year of construction (and following significant upgrades)</td><td colspan="4">1962, the last general overhaul and reconstruction in 2003, replacing the measuring system in 2014</td></tr>
<tr><td>Hardness Scales</td><td colspan="4">Rockwell scales</td></tr>
<tr><td rowspan="6">HR, $U_{95\%}$
(with own indenter, as results from Annex C)</td><td>scale</td><td>measured</td><td>uncertainty</td><td>inhomogeneity</td></tr>
<tr><td>80-86 HRA</td><td>82,7 HRA</td><td>0,4 HRA</td><td>0,4 HRA</td></tr>
<tr><td>80-100 HRBW</td><td>95,7 HRBW</td><td>0,4 HRBW</td><td>0,4 HRBW</td></tr>
<tr><td>20-30 HRC</td><td>29,0 HRC</td><td>0,3 HRC</td><td>0,8%</td></tr>
<tr><td>40-50 HRC</td><td>46,0 HRC</td><td>0,3 HRC</td><td>0,4%</td></tr>
<tr><td>60-70 HRC</td><td>63,2 HRC</td><td>0,3 HRC</td><td>0,3 HRC</td></tr>
<tr><td>Force generation system and $U_{95\%}$</td><td colspan="4">Dead weight, 0,30 N</td></tr>
<tr><td>Depth measuring system and $U_{95\%}$</td><td colspan="4">0,05μm</td></tr>
<tr><td>Indenter (manufacturer, model, s/n)</td><td colspan="4">Manufacturer Zeiss, s/n 5417</td></tr>
<tr><td>Pictures</td><td colspan="4"> </td></tr>
</table>

Kazakhstan Institute of Metrology

Name	National primary standards according to Rockwell and Superficial Rockwell hardness scales
Manufacturer	Indentec Hardness Testing Machines Ltd, United Kindom
Model	8150TK
S/n	032808
Year of construction (and following significant upgrades)	2003
Hardness Scales	Rockwell A, B, C and Superficial Rockwell N, T scales
HR, $U_{95\%}$	80-86 HRA = 0,5 HR 80-100 HRBW = 0,8 HR 20-30 HRC = 0,5 HR 40-50 HRC = 0,5 HR 60-70 HRC = 0,5 HR
Force generation system and $U_{95\%}$	Dead weight, 0,28 N
Depth measuring system and $U_{95\%}$	0,289µm
Indenter (manufacturer, model, s/n)	Indentec Hardness Testing Machines Ltd, United Kindom, s/n 23672
Picture	

Physikalisch-TechnischeBundesanstalt

Name	Hardness standard machine RNG 10
Manufacturer	PGH Kraftmessgeräte Halle/Saale (Germany)
Model	RNG 10
S/n	017-66
Year of construction (and following significant upgrades)	1966 System update in 2000 with laser interferometer and electrical motoring
Hardness Scales	All Standard Rockwell Scales
HR, $U_{95\%}$	20 HRA - 93 HRA, 0,3 HRA 20 HRBW - 100 HRBW, 0,5 HRBW 20 HRC - 70 HRC, 0,3 HRC
Force generation system and $U_{95\%}$	Dead weight system, 0,1 N for total force
Depth measuring system and $U_{95\%}$	Laser interferometer from SIOS company, 0,058 µm
Indenter (manufacturer, model, s/n)	Manufacturer Stroh, s/n 839
Picture	  

Belarusian State Institute ofMetrology

Name	Hardness tester
Manufacturer	Indentec
Model	8150SK
S/n	063266
Year of construction (and following significant upgrades)	2006
Hardness Scales	Rockwell scales
HR, $U_{95\%}$	80-86 HRA = 0,35 HR 80-100 HRBW = 0,45 HR 20-30 HRC = 0,45 HR 40-50 HRC = 0,35 HR 60-70 HRC = 0,40 HR
Force generation system and $U_{95\%}$	According to the verification scheme in accordance with GOST 8.064-94 for hardness comparator standardized SεΣ = 0,2. The accuracy of load and indentation depth measurement system is not monitored.
Depth measuring system and $U_{95\%}$	
Indenter (manufacturer, model, s/n)	Indentec, № 06194
Picture	

AppendixB

Uncertainty budgets of the participants based on a unified procedure

NSC "Institute of Metrology"; hardness level 80-86 HRA

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,060	0,012	0,007	2,56E-10
Total test force	F, N	1,5	0,866	-0,041	-0,0615	-0,036	1,76E-07
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,15	0,015	0,009	6,25E-10
Indenter radius	R_α, μm	1,0	0,577	0,15	0,15	0,087	6,25E-06
Indentation depth	l, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,064	-0,0448	-0,026	4,97E-08
Preliminary test force duration time	T_p, s	0,2	0,115	-0,01	-0,002	-0,001	1,97E-13
Total test force duration time	T_{df}, s	0,2	0,115	-0,01	-0,002	-0,001	1,97E-13
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,266	0,154	
Standard uncertainty						0,134	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,268**	

NSC “Institute of Metrology”; hardness level 80-100 HRBW

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,07	0,014	0,008	4,74E-10
Total test force	F, N	1,5	0,866	0,1	0,15	0,087	9,15E-06
Indenter ball diametr	R_β, μm	1,0	0,577	0,1	0,1	0,058	1,80E-06
Indentation depth	l, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,2	-0,14	-0,081	4,74E-06
Preliminary test force duration time	T_p, s	0,2	0,115	0,1	0,02	0,012	1,97E-09
Total test force duration time	T_{df}, s	0,2	0,115	0,1	0,02	0,012	1,97E-09
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,364	0,210	
Standard uncertainty						0,161	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,337**	

NSC “Institute of Metrology”; hardness level 20-30 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,11	0,022	0,013	2,89E-09
Total test force	F, N	1,5	0,866	-0,04	-0,06	-0,035	1,60E-07
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,14	0,014	0,008	4,74E-10
Indenter radius	R_α, μm	1,0	0,577	0,14	0,14	0,081	4,74E-06
Indentation depth	l, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,014	-0,0098	-0,006	1,13E-10
Preliminary test force duration time	T_p, s	0,2	0,115	0,01	0,002	0,001	1,97E-13
Total test force duration time	T_{df}, s	0,2	0,115	0,01	0,002	0,001	1,97E-13
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,310	0,179	
Standard uncertainty						0,128	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,256**	

NSC “Institute of Metrology”; hardness level 40-50 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,15	0,03	0,017	1,00E-08
Total test force	F, N	1,5	0,866	-0,15	-0,225	-0,130	3,16E-05
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,17	0,017	0,010	1,03E-09
Indenter radius	R_α, μm	1,0	0,577	0,17	0,17	0,098	1,03E-05
Indentation depth	l, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,04	-0,028	-0,016	7,58E-09
Preliminary test force duration time	T_p, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Total test force duration time	T_{df}, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,176	0,102	
Standard uncertainty						0,188	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,377**	

NSC “Institute of Metrology”; hardness level 60-70 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	-0,17	-0,034	-0,020	1,65E-08
Total test force	F, N	1,5	0,866	-0,16	-0,24	-0,139	4,09E-05
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,19	0,019	0,011	1,60E-09
Indenter radius	R_α, μm	1,0	0,577	0,19	0,19	0,110	1,60E-05
Indentation depth	l, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,05	-0,035	-0,020	1,85E-08
Preliminary test force duration time	T_p, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Total test force duration time	T_{df}, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,112	0,065	
Standard uncertainty						0,201	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,403**	

Kazakhstan Institute of Metrology; hardness level 80-86 HRA

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,056	0,0112	0,006	1,94E-10
Total test force	F, N	1,5	0,866	-0,041	-0,0615	-0,036	1,76E-07
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,15	0,015	0,009	6,25E-10
Indenter radius	R_α, μm	1,0	0,577	0,15	0,15	0,087	6,25E-06
Indentation depth	l, μm	0,5	0,289	0,5	0,25	0,144	4,82E-05
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,064	-0,0448	-0,026	4,97E-08
Preliminary test force duration time	T_p, s	0,2	0,115	-0,01	-0,002	-0,001	1,97E-13
Total test force duration time	T_{df}, s	0,2	0,115	-0,01	-0,002	-0,001	1,97E-13
Deformation of frame	d, μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,269	0,269	
Standard uncertainty						**0,195**	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,389**	

Kazakhstan Institute of Metrology; hardness level 80-100 HRBW

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,07	0,014	0,008	4,74E-10
Total test force	F , N	1,5	0,866	-0,1	-0,15	-0,087	6,25E-06
Indenter ball diametr	R_β , μm	1,0	0,577	-0,1	-0,1	-0,058	1,23E-06
Indentation depth	l , μm	0,5	0,289	0,5	0,25	0,144	4,82E-05
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	0,7	0,404	-0,2	-0,14	-0,081	4,74E-06
Preliminary test force duration time	T_p , s	0,2	0,115	0,1	0,02	0,012	1,97E-09
Total test force duration time	T_{df} , s	0,2	0,115	0,1	0,02	0,012	1,97E-09
Deformation of frame	d , μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,064	0,037	
Standard uncertainty						0,215	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,429**	

Kazakhstan Institute of Metrology; hardness level 20-30 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,11	0,022	0,013	2,89E-09
Total test force	F , N	1,5	0,866	-0,03	-0,045	-0,026	5,06E-08
Indenter cone angle	α_m , ^{0}	0,1	0,058	0,14	0,014	0,008	4,74E-10
Indenter radius	R_α , μm	1,0	0,577	0,14	0,14	0,081	4,74E-06
Indentation depth	l , μm	0,5	0,289	0,5	0,25	0,144	4,82E-05
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	0,7	0,404	-0,014	-0,0098	-0,006	1,13E-10
Preliminary test force duration time	T_p , s	0,2	0,115	0,01	0,002	0,001	1,97E-13
Total test force duration time	T_{df} , s	0,2	0,115	0,01	0,002	0,001	1,97E-13
Deformation of frame	d , μm	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,525	0,303	
Standard uncertainty						0,189	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,378**	

Kazakhstan Institute of Metrology; hardness level 40-50 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,15	0,03	0,017	1,00E-08
Total test force	F, N	1,5	0,866	-0,15	-0,225	-0,130	3,16E-05
Indenter cone angle	$\alpha_m, ^0$	0,1	0,058	0,17	0,017	0,010	1,03E-09
Indenter radius	$R_\alpha, \mu m$	1,0	0,577	0,17	0,17	0,098	1,03E-05
Indentation depth	$l, \mu m$	0,5	0,289	0,5	0,25	0,144	4,82E-05
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,04	-0,028	-0,016	7,58E-09
Preliminary test force duration time	T_p, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Total test force duration time	T_{df}, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Deformation of frame	$d, \mu m$	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,376	0,217	
Standard uncertainty						0,236	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,471**	

Kazakhstan Institute of Metrology; hardness level 60-70 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	-0,17	-0,034	-0,020	1,64E-08
Total test force	F, N	1,5	0,866	-0,15	-0,225	-0,130	3,16E-05
Indenter cone angle	$\alpha_m, ^0$	0,1	0,058	0,19	0,019	0,011	1,60E-09
Indenter radius	$R_\alpha, \mu m$	1,0	0,577	0,19	0,19	0,110	1,60E-05
Indentation depth	$l, \mu m$	0,5	0,289	0,5	0,25	0,144	4,82E-05
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,7	0,404	-0,05	-0,035	-0,020	1,85E-08
Preliminary test force duration time	T_p, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Total test force duration time	T_{df}, s	0,2	0,115	0,03	0,006	0,003	1,60E-11
Deformation of frame	$d, \mu m$	0,3	0,173	0,5	0,15	0,087	6,25E-06
Total					0,327	0,189	
Standard uncertainty						0,241	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,482**	

Czech metrology institute; hardness level 80-86 HRA

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,050	0,00996	0,006	1,21E-10
Total test force	F , N	1,5	0,866	-0,026	-0,03945	-0,023	2,99E-08
Indenter cone angle	α_m ,^{0}	0,1	0,058	0,180	0,018	0,010	1,29E-09
Indenter radius	R_α , μm	1,0	0,577	0,058	0,058	0,033	1,39E-07
Indentation depth	l , μm	0,1	0,058	1,000	0,1	0,058	1,23E-06
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	1,0	0,577	0,267	0,267	0,154	6,27E-05
Preliminary test force duration time	T_p , s	1,2	0,693	-0,004	-0,004284	-0,002	4,15E-12
Total test force duration time	T_{df} , s	1,5	0,866	-0,030	-0,04455	-0,026	4,86E-08
Deformation of frame	d , μm	0,1	0,058	0,500	0,05	0,029	7,71E-08
Total					0,239	0,239	
Standard uncertainty						0,174	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,35**	

Czech metrology institute; hardness level 80-100 HRBW

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,0023	0,00045	0,0001	5,06E-16
Total test force	F , N	1,5	0,866	0,143	0,2145	0,124	2,61E-05
Indenter ball diametr	R_β , μm	2,0	1,155	-0,025	-0,0498	-0,029	7,59E-08
Indentation depth	l , μm	0,1	0,058	1,5	0,15	0,087	6,25E-06
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	1,0	0,577	0,1	0,1	0,058	1,23E-06
Preliminary test force duration time	T_p , s	1,2	0,693	0,0753	0,09036	0,052	8,23E-07
Total test force duration time	T_{df} , s	1,5	0,866	-0,017	-0,0255	-0,015	5,22E-09
Deformation of frame	d , μm	0,1	0,058	0,5	0,05	0,029	5,35E-14
Total					0,530	0,306	
Standard uncertainty						0,175	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,35**	

Czech metrology institute; hardness level 20-30 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,25	0,05	0,029	7,71E-08
Total test force	F , N	1,5	0,866	-0,099	-0,14985	-0,087	6,22E-06
Indenter cone angle	α_m ,^{0}	0,1	0,058	0,18	0,018	0,010	1,29E-09
Indenter radius	R_α , μm	1,0	0,577	0,058	0,058	0,033	1,39E-07
Indentation depth	l , μm	0,1	0,058	0,4	0,04	0,023	3,16E-08
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	1,0	0,577	-0,104	-0,104	-0,060	1,44E-06
Preliminary test force duration time	T_p , s	1,2	0,693	0,0555	0,0666	0,038	2,42E-07
Total test force duration time	T_{df} , s	1,5	0,866	-0,116	-0,174	-0,100	1,13E-05
Deformation of frame	d , μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Total					-0,145	-0,084	
Standard uncertainty						0,162	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,32**	

Czech metrology institute; hardness level 40-50 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,186	0,0372	0,021	2,36E-08
Total test force	F , N	1,5	0,866	-0,076	-0,1149	-0,066	2,15E-06
Indenter cone angle	α_m ,^{0}	0,1	0,058	0,18	0,018	0,010	1,29E-09
Indenter radius	R_α , μm	1,0	0,577	0,058	0,058	0,033	1,39E-07
Indentation depth	l , μm	0,1	0,058	0,4	0,04	0,023	3,16E-08
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	1,0	0,577	-0,151	-0,151	-0,087	6,41E-06
Preliminary test force duration time	T_p , s	1,2	0,693	0,0368	0,04416	0,025	4,69E-08
Total test force duration time	T_{df} , s	1,5	0,866	-0,088	-0,1326	-0,077	3,81E-06
Deformation of frame	d , μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Total					-0,087	-0,087	
Standard uncertainty						0,147	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,29**	

Czech metrology institute; hardness level 60-70 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,2	0,115	0,122	0,0244	0,014	4,37E-09
Total test force	F, N	1,5	0,866	-0,053	-0,0795	-0,046	4,93E-07
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,18	0,018	0,010	1,29E-09
Indenter radius	R_α, μm	1,0	0,577	0,058	0,058	0,033	1,39E-07
Indentation depth	l, μm	0,1	0,058	0,4	0,04	0,023	3,16E-08
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	1,0	0,577	-0,199	-0,199	-0,115	1,93E-05
Preliminary test force duration time	T_p, s	1,2	0,693	0,0179	0,02148	0,012	2,62E-09
Total test force duration time	T_{df}, s	1,5	0,866	-0,061	-0,09135	-0,053	8,59E-07
Deformation of frame	d, μm	0,1	0,058	0,5	0,05	0,029	7,71E-08
Total					-0,158	-0,091	
Standard uncertainty						0,145	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,29**	

Belarusian State Institute of Metrology

The uncertainty value of the hardness reference blocks has been calculated according to the calibration procedure MRP MK 47 03.29-2013, which was developed by BelGIM on the basis of ISO 6508-3:2005. The use of a custom BelGIM calibration procedure is due to the fact that ISO 6508-3:2005 is currently not implemented in the Republic of Belarus and hence it cannot be applied directly.

Since BelGIM does not possess appropriate equipment to realize hardness units on its own, the calibration was conducted by using both reference hardness blocks calibrated at the D.I. Mendeleyev Institute (VNIIFTRI) and hardness comparators. For the same reason, the calibration procedure specified above was used instead of the one given in the technical report (any direct calibration of our hardness machines makes no sense, because they are being adjusted against the reference hardness blocks).
As the hardness value of the reference block under calibration a median value was taken inclusive of an appropriate correction obtained by using a 1st class reference hardness block.
A rather large expanded uncertainty was resulting from the uncertainty value specified in the calibration certificate for the relevant 1st class hardness block.
National standards for hardness units, which are planned to be established in 2017-2019, will allow avoiding the use of hardness comparators and provide means for our stand-alone realization of hardness units with the smallest uncertainty value.

The measurement results for each hardness block together with their uncertainty calculation are presented below.

№ hardness block	Result
1/13-25HRC	28,52 ± 0,44
3/13-45 HRC	45,68 ± 0,31
5/13-65 HRC	63,28±0,36
7/13-83HRA	82,93± 0,35
9/13-95HRB	96,24 ± 0,43

Measurements for hardness block№5/13-65 HRC

Measurements on a reference hardness block 1st category

Actual value of the hardness block 1st category, H_d, HR		63,2
Results of measurements on hardness block 1st category, H_{1i}, HR	1	62,5
	2	62,4
	3	62,5
	4	62,6
	5	62,6
arithmetic mean value of hardness, $\overline{H}$, HR		62,52
Standard uncertainty, $u(\overline{H})$, HR		0,037
combined standard uncertainty of hardness block 1st category, *U,* HR		0,3
Standard uncertainty of hardness block 1st category, $u(H_d)$, HR		0,15
Standard uncertainty, $u(\delta_{ms})$, HR		0,03

Measurements on calibrated hardness block

m6 – 62,7 HRC – test measurement

m2 – 62,8HRC– not used in the calculation

Number of measurements		5				
Measurement results Hi, HR		m1	m7	m3	m4	m5
		62,6	62,6	62,5	62,4	62,7
Ranging measurements hardness, HR	1	62,4				
	2	62,5				
	3	62,6				
	4	62,6				
	5	62,7				
Median, Hmes , HR		62,6				
Value | Hi – Hmes|, HR		0,2	0,1	0	0	0,1
Ranging results | Hi – Hmes |, HR	1	0				
	2	0				
	3	0,1				
	4	0,1				
	5	0,2				
Median | Hi – Hmes | S*, HR		0,1				
Standard deviation, s*,HR		0,15				
Standard uncertainty, $u(H_{mes})$,HR		0,08				
combined standard uncertainty, *u,* HR		0,18				
coverage factor		2				
expanded uncertainty, U, HR		**0,36**				
Range, HR		0,3				
Hardness calibrated block, HR		**63,28±0,36**				

Measurements for hardness block № 1/13-25HRC

Measurements on a reference hardness block 1st category

Actual value of the hardness block 1st category, H_d, HR		27,4
Results of measurements on hardness block 1st category, H_{1i}, HR	1	26
	2	25,9
	3	26
	4	25,9
	5	26,1
arithmetic mean value of hardness, $\overline{H}$, HR		25,98
Standard uncertainty, $u(\overline{H})$, HR		0,04
combined standard uncertainty of hardness block 1st category, *U*, HR		0,40
Standard uncertainty of hardness block 1st category, $u(H_d)$, HR		0,20
Standard uncertainty, $u(\delta_{ms})$, HR		0,03

Measurements on calibrated hardness block

m6 – 27,1HRC – test measurement

m7 – 27,1HRC – not used in the calculation

Number of measurements		5				
Measurement results Hi, HR		m1	m2	m3	m4	m5
		27,0	27,2	27,1	27,0	27,1
Ranging measurements hardness, HR	1	27,0				
	2	27,0				
	3	27,1				
	4	27,1				
	5	27,2				
Median, Hmes , HR		27,1				
Value | Hi – Hmes |, HR		0,1	0,1	0	0	0,1
Ranging results | Hi – Hmes |, HR	1	0				
	2	0				
	3	0,1				
	4	0,1				
	5	0,1				
Median | Hi – Hmes | S*, HR		0,1				
Standarddeviation, s*,HR		0,15				
Standard uncertainty, $u(H_{mes})$,HR		0,08				
combined standard uncertainty, *u*, HR		0,24				
coverage factor		2				
expanded uncertainty, U, HR		**0,44**				
Range, HR		0,2				
Hardness calibrated block, HR		**28,52 ± 0,44**				

Measurements for hardness block № 3/13-45 HRC

Measurements on a reference hardness block 1st category

Actual value of the hardness block 1st category, H_d, HR		45,2
Results of measurements on hardness block 1st category, H_{1i}, HR	1	43,9
	2	43,9
	3	43,9
	4	44
	5	43,9
arithmetic mean value of hardness, $\overline{H}$, HR		43,92
Standard uncertainty, $u(\overline{H})$, HR		0,02
combined standard uncertainty of hardness block 1st category, *U,* HR		0,30
Standard uncertainty of hardness block 1st category, $u(H_d)$, HR		0,15
Standard uncertainty, $u(\delta_{ms})$, HR		0,03

Measurements on calibrated hardness block

m6 – 44,6 HRC – test measurement

m7 – 44,5 HRC – not used in the calculation

Number of measurements		5				
Measurement resultsHi, HR		m1	m2	m3	m4	m5
		44,4	44,4	44,4	44,4	44,3
Ranging measurements hardness, HR	1	44,3				
	2	44,4				
	3	44,4				
	4	44,4				
	5	44,4				
Median, Hmes , HR		44,4				
Value | Hi – Hmes |, HR		0,1	0	0	0	0
Ranging results | Hi – Hmes |, HR	1	0				
	2	0				
	3	0				
	4	0				
	5	0,1				
Median | Hi – Hmes | S*, HR		0				
Standard deviation, s*,HR		0				
Standard uncertainty, $u(H_{mes})$,HR		0				
combined standard uncertainty, *u,* HR		0,15				
coverage factor		2				
expanded uncertainty, U, HR		**0,31**				
Range, HR		0,1				
Hardness calibrated block, HR		**45,68 ± 0,31**				

Measurements for hardness block № 7/13-83HRA

Measurements on a reference hardness block 1st category

Actual value of the hardness block 1st category, H_d, HR		83,1
Results of measurements on hardness block 1st category, H_{1i} , HR	1	82,4
	2	82,4
	3	82,3
	4	82,4
	5	82,4
arithmetic mean value of hardness, $\overline{H}$, HR		82,38
Standard uncertainty, $u(\overline{H})$, HR		0,02
combined standard uncertainty of hardness block 1st category, *U,* HR		0,3
Standard uncertainty of hardness block 1st category, $u(H_d)$, HR		0,15
Standard uncertainty, $u(\delta_{ms})$, HR		0,03

Measurements on calibrated hardness block

m6 - 82,2 HRA – test measurement

m7 – 82,0 HRA – not used in the calculation

Number of measurements		5				
Measurement resultsHi, HR		m1	m2	m3	m4	m5
		82,1	82,2	82,1	82,3	82,2
Ranging measurements hardness, HR	1	82,1				
	2	82,1				
	3	82,2				
	4	82,2				
	5	82,3				
Median, Hmes , HR		82,2				
Value | Hi – Hmesм |, HR		0,1	0,1	0	0,1	0,2
Ranging results | Hi – Hmes |, HR	1	0				
	2	0,1				
	3	0,1				
	4	0,1				
	5	0,2				
Median | Hi – Hmes | S*, HR		0,1				
Standard deviation, s*,HR		0,15				
Standard uncertainty, $u(H_{mes})$,HR		0,08				
combined standard uncertainty, *u,* HR		0,18				
coverage factor		2				
expanded uncertainty, U, HR		**0,35**				
Range, HR		0,2				
Hardness calibrated block, HR		**82,93± 0,35**				

Measurements for hardness block № 9/13-95HRB

Measurements on a reference hardness block 1st category

Actual value of the hardness block 1st category, H_d, HR		98,5
Results of measurements on hardness block 1st category, H_{1i}, HR	1	98,6
	2	98,8
	3	98,6
	4	98,4
	5	98,4
arithmetic mean value of hardness, $\overline{H}$, HR		98,56
Standard uncertainty, $u(\overline{H})$, HR		0,07
combined standard uncertainty of hardness block 1st category, U, HR		0,40
Standard uncertainty of hardness block 1st category, $u(H_d)$, HR		0,20
Standard uncertainty, $u(\delta_{ms})$, HR		0,03

Measurements on calibrated hardness block

m6 – 96,5 HRB – test measurement

m7 – 96,4 HRB – not used in the calculation

Number of measurements		5				
measurement results H_i, HR		m1	m2	m3	m4	m5
		96,3	96,4	96,5	96,3	96,3
Ranging measurements hardness, HR	1	96,3				
	2	96,3				
	3	96,3				
	4	96,4				
	5	96,5				
Median, H_{mes}, HR		96,3				
Value $\mid H_i - H_{mes} \mid$, HR		0	0	0	0,1	0,2
Ranging results $\mid H_i - H_{mes} \mid$, HR	1	0				
	2	0				
	3	0				
	4	0,1				
	5	0,2				
Median $\mid H_i - H_{mes} \mid$ S^*, HR		0				
standard deviation, s^*, HR		0				
Standard uncertainty, $u(H_{mes})$, HR		0				
combined standard uncertainty, u, HR		0,21				
coverage factor		2				
expanded uncertainty, U, HR		**0,43**				
Range, HR		0,2				
Hardness calibrated block, HR		**96,24 ± 0,43**				

Physikalisch-Technische Bundesanstalt; hardness level 80-86 HRA

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	$u_i(H)$, HR
Preliminary test force	F_0, N	0,05	0,0289	0,04864	0,0014
Total test force	F , N	0,3	0,1732	-0,02589	-0,0045
Indenter cone angle	α_m ,^{0}	0,1	0,0577	0,18	0,0104
Indenter radius	R_α , μm	1	0,5774	0,058	0,0335
Indentation depth	l , μm	0,1	0,0577	0,5	0,0289
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	10	5,7735	0,00665	0,0384
Preliminary test force duration time	T_p , s	0,2	0,1155	-0,0039	-0,0005
Total test force duration time	T_{df} , s	0,2	0,1155	-0,0292	-0,0034
Deformation of frame	d , μm	0,2	0,1155	0,5	0,0577
Standard uncertainty					0,08
Coverage factor k for confidence level p=0,95					2
Expanded uncertainty					**0,17**

Physikalisch-Technische Bundesanstalt; hardness level 80-100 HRBW

Influencing Quantity, X_i	Symbol,Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	$u_i(H)$, HR
Preliminary test force	F_0, N	0,05	0,0289	0,0218	0,0006
Total test force	F , N	0,5	0,2887	-0,05068	-0,0146
Indenter ball diametr	R_β , μm	0,1	0,0577	-0,02504	-0,0014
Indentation depth	l , μm	0,1	0,0577	0,5	0,0289
Indentation velocity	V_{fis} , $\mu m \cdot s^{-1}$	10	5,7735	-0,00324	-0,0187
Preliminary test force duration time	T_p , s	0,2	0,1155	0,07396	0,0085
Total test force duration time	T_{df} , s	0,2	0,1155	-0,017	-0,0020
Deformation of frame	d , μm	0,3	0,1732	0,5	0,0866
Standard uncertainty					0,09
Coverage factor k for confidence level p=0,95					2
Expanded uncertainty					**0,19**

Physikalisch-Technische Bundesanstalt; hardness level 20-30 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i , HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,01	0,006	0,120	0,001	0,001	1,152E-14
Total test force	F, N	0,15	0,087	-0,040	-0,006	-0,003	7,2E-12
Indenter cone angle	α_m ,^{0}	0,1	0,058	1,300	0,130	0,075	1,5867E-06
Indenter radius	R_α , μm	0,001	0,001	0,015	0,000	0,000	2,8125E-22
Indentation depth	l, μm	0,03	0,017	0,500	0,015	0,009	2,8125E-10
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,5	0,289	-0,020	-0,010	-0,006	7,4074E-11
Preliminary test force duration time	T_p , s	0,2	0,115	0,010	0,002	0,001	1,1852E-13
Total test force duration time	T_{df} , s	0,2	0,115	-0,070	-0,014	-0,008	2,8456E-10
Deformation of frame	d, μm	0,2	0,115	0,500	0,500	0,058	7,4074E-07
Total						0,13	
Standard uncertainty						0,10	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,19**	

Physikalisch-Technische Bundesanstalt; hardness level 40-50 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i , HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,01	0,006	0,070	0,000	0,000	1,3339E-15
Total test force	F, N	0,15	0,087	-0,030	0,000	-0,003	2,2781E-12
Indenter cone angle	α_m ,^{0}	0,1	0,058	0,800	0,037	0,046	2,2756E-07
Indenter radius	R_α , μm	0,001	0,001	0,030	0,000	0,000	4,5E-21
Indentation depth	l, μm	0,03	0,017	0,500	0,004	0,009	2,8125E-10
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,5	0,289	0,000	0,000	0,000	0
Preliminary test force duration time	T_p , s	0,2	0,115	0,005	0,000	0,001	7,4074E-15
Total test force duration time	T_{df} , s	0,2	0,115	-0,040	0,000	-0,005	3,0341E-11
Deformation of frame	d, μm	0,2	0,115	0,500	0,029	0,058	7,4074E-07
Total						0,11	
Standard uncertainty						0,07	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,15**	

Physikalisch-Technische Bundesanstalt; hardness level 60-70 HRC

Influencing Quantity, X_i	Symbol, Unit	Δx_i	$u(x_i)$	$\tilde{n}_i$	ΔH_i, HR	$u_i(H)$, HR	$u_i^4(H)/\nu_i$
Preliminary test force	F_0, N	0,01	0,006	0,050	0,000	0,001	1,152E-14
Total test force	F, N	0,15	0,087	-0,020	0,000	-0,003	7,2E-12
Indenter cone angle	α_m, ^{0}	0,1	0,058	0,400	0,009	0,075	1,5867E-06
Indenter radius	R_α, μm	0,001	0,001	0,050	0,000	0,000	2,8125E-22
Indentation depth	l, μm	0,03	0,017	0,500	0,004	0,009	2,8125E-10
Indentation velocity	V_{fis}, $\mu m \cdot s^{-1}$	0,5	0,289	0,030	0,000	-0,006	0,4074E-11
Preliminary test force duration time	T_p, s	0,2	0,115	0,004	0,000	0,001	1,1852E-13
Total test force duration time	T_{df}, s	0,2	0,115	-0,030	0,000	-0,008	2,8456E-10
Deformation of frame	d, μm	0,2	0,115	0,500	0,029	0,058	7,4074E-07
Total						0,13	
Standard uncertainty						0,01	
Coverage factor k for confidence level p=0,95						2	
Expanded uncertainty						**0,19**	