Physikalisch-Technische Bundesanstalt Braunschweig

CCM Vickers key comparison

Final Report

Braunschweig, March 2005 / K. Herrmann

Content

1 Introduction

The metrological equivalence of national measurement standards is determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM or by the Regional Metrology Organisations (ROM's) in collaboration with the Consultative Committees.
At its meeting in May 1999, the Working Group on Hardness (WGH) of the Consultative Committee for Mechanical Measurements, CCM, identified several key comparisons in the field of hardness measurements and decided upon the general content.
In particular, the WGH has decided that a key comparison on the main Vickers hardness scales should be carried out with the Physikalisch-Technische Bundesanstalt (PTB) as the pilot laboratory.
As the rules for key comparisons were followed it may be declared as such and thus be included in the MRA App. B data base.

2 Organisation

Following the rules set up by the BIPM[1)] a small group from the provisional list of participating laboratories has drafted the technical protocol. The group was composed of the pilot laboratory (Konrad Herrmann from PTB, Germany) and Alessandro Germak from IMGC, Italy.
The draft of the technical protocol was agreed upon between the participants of the comparison in March 2001. The comparison started in March 2001 and ended in March 2003.
The participants were invited according to a questionnaire of the ad hoc Working Group on Hardness about hardness laboratories in National Metrology Institutes from June 1998.

2.1 Participants

The list of participants is given in Table 1.

[1)] T. J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, BIPM, Paris

Table 1: *List of participants*

Participant	Institute	Adress
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2.2 Time schedule and measurements carried out by the participants

The comparison started in February 2001 with the initial measurements at PTB. Due to problems with the availability and necessary repair of the hardness standard machines at several participants the foreseen period of measurement for each partner of one month could not be kept. Moreover, during the transport of the hardness reference blocks as standards for the measurements the accompanying customs documents were lost, so that the pilot laboratory had to care about this customs problem. Therefore, considerable delay in the measurements occurred so that the originally scheduled measurement period for the whole comparison of one year was not realistic.
The following table shows the scheduled measuring time, the date of reception of the standards and the date when the results were received by the pilot laboratory.

Table 2: *Time schedule*

Laboratory	Original schedule	Confirmation of reception	Results received
PTB	02/2001	-	01.03.2001
IMGC	03/2001	19.03.2001	15.05.2001
INMETRO	06/2001	31.05.2001	30.08.2001
NIST	08/2001	19.08.2001	15.09.2001
AIST	09/2001	10.09.2001	26.02.2003
NIM	10/2001	05.02.2002	07.03.2002
KRISS	11/2001	30.03.2002	07.11.2002
CMI	12/2001	22.05.2002	05.09.2002
GUM	01/2002	17.09.2002	25.10.2002
NPL	02/2002	20.10.2002	16.01./25.02.2003
PTB	03/2002	20.02.2003	18.03.2003

Moreover, because not all participants were able to measure the three hardness scales HV0,2, HV1 and HV30, which is justified by different economical needs, it was allowed to participate only in a part of the scheduled measurement programme. Accordingly, Table 3 gives an overview over the measurements carried out by the participants.

Table 3: *Overview over the measurements carried out by the participants*

Laboratory	HV0,2	HV1	HV30	Ref. indent HV0,2	Ref. indent HV1	Ref. indent HV30
PTB	x	x	x	x	X	x
IMGC	x	x	x	x	X	x
INMETRO			x			x
NIST	x	x		x	X	
AIST	x	x	x	x	X	x
NIM	x	x	x	x	X	x
KRISS	x	x	x	x	X	x
CMI	x	x	x	x	X	x
GUM	x	x	x	x	X	x
NPL	x	x	x	x	X	x
PTB	x	x	x	x	X	x

3 Standards

3.1 Description

In the key comparison three sets of hardness reference blocks for the Vickers hardness scales HV0,2, HV1 and HV30 consisting each of three hardness reference blocks with the hardness levels 240 HV, 540 HV and 840 HV (that is altogether nine blocks) are used. The dimensions are length 60 mm, width 60 mm, thickness 10 mm. The upper side of the blocks which is the measurement surface is finished. The blocks are manufactured as commercial products by Buderus Co., Germany. For the comparison on the hardness reference blocks on the measurement surface was engraved a grid with 13 x 13 = 169 fields. At the left and the lower edge of the blocks are engraved numbers from 1 to 13 in order to define coordinates of the fields. The direction along the lower edge of the blocks defines the X-direction (lines), correspondingly the direction along the left edge of the blocks defines the Y-direction (rows) (see Fig. 1).

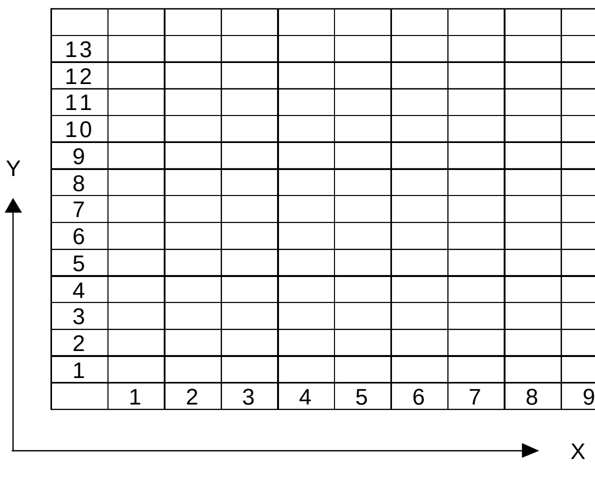

Fig. 1: Layout of the grid on the measurement surface of the hardness reference blocks

3.2 Handling

It is recommended to clean the blocks after unpacking with alcohol and then sign all fields reserved for your institute with a fiber pen on the left top corner. After measurement all dots on the blocks must be removed before packing in order to avoid corrosion.

4 Measurand

The measurands used in this comparison were of two kinds. Firstly, the mean value each of eight hardness measurements on a hardness reference block had to be determined. The hardness measurements were made in the hardness scales HV0,2, HV1 and HV30 each for the nominal hardness levels 240 HV, 540 HV and 840 HV. The procedure of the hardness measurement is defined in ISO 6507-1 and -3. Secondly, the mean diagonal length of nine reference indents had to be determined according to ISO 6507-1 and -3. The reference indents represent indents for the hardness levels 240 HV, 540 HV and 840 HV, each for the Vickers scales HV0,2, HV1 and HV30.

5 Methods of measurement

The methods of measurement and the measuring devices used by the participants are described in Appendix A1.

6 Stability of the standards

In order to evaluate the stability of the standards, the hardness reference blocks, the pilot laboratory has carried out measurement in the beginning and in the end of the comparison. The results are summarised in Table 4.

Table 4: *Measurement results in the beginning and in the end of the comparison by the pilot laboratory*

Measurand	Result in the begin. (1)	Result in the end (2)	Diff. Δ_{1-2}	Meas. Uncert. U	$\lvert\Delta_{1-2}\rvert$/ U
240 HV0,2, HV	248,19	252,27	-4,08	5,03	0,81
540 HV0,2, HV	528,42	540,63	-12,21	16,25	0,75
840 HV0,2, HV	839,78	858,07	-18,29	31,33	0,58
240 HV1, HV	244,06	243,15	+0,91	2,18	0,42
540 HV1, HV	539,03	537,76	+1,27	7,18	0,18
840 HV1, HV	831,49	835,79	-4,30	13,86	0,31
240 HV30, HV	-	238,00	-	-	-
540 HV30, HV	-	522,89	-	-	-
840 HV30, HV	-	817,86	-	-	-
r.i.240 HV0,2, µm	38,52	38,36	+0,16	0,2	0,80
r.i.540 HV0,2, µm	26,38	26,01	+0,37	0,2	1,85
r.i.840 HV0,2, µm	21,08	20,90	+0,18	0,2	0,90
r.i.240 HV1, µm	87,55	87,41	+0,14	0,6	0,23
r.i.540 HV1, µm	58,58	58,59	-0,01	0,4	0,03
r.i.840 HV1, µm	47,38	47,20	+0,18	0,3	0,60
r.i.240 HV30, µm	482,48	482,47	+0,01	1,1	0,01
r.i.540 HV30, µm	326,03	326,65	-0,62	1,1	0,56
r.i.840 HV30, µm	259,35	258,88	+0,47	1,1	0,43

In the last row the difference between first and second measurement Δ_{1-2} is compared with the measurement uncertainty. If the difference $|\Delta_{1-2}|/U > 1$, it means, that the difference Δ_{1-2} 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. The exceeding at the reference indent for 540 HV0,2 is insignificant.
Therefore, one can conclude that the used hardness reference blocks remained stable.
Although the conclusion about the stability according to the difference between the first and the last measurement seems to be justified, the analysis of the measurement results in dependence on the time of the comparison revealed, that in the course of the measurements eight of the nine used hardness reference blocks showed like a quadratic function first a tendency to lower hardness values and then the hardness values rose approximately to the original level.
Fig. 2 shows this change on the example of the hardness reference block 240 HV1.

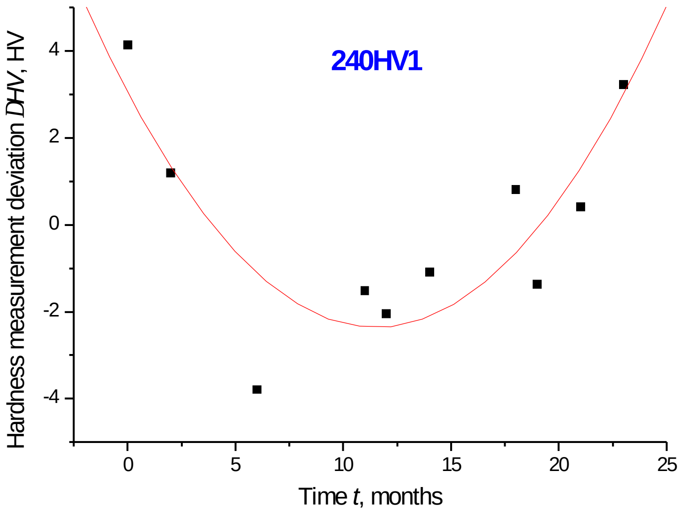

Fig. 2: Apparent hardness change of the hardness reference block 240 HV1 over the time of the comparison

From the fitted quadratic function a maximum hardness change of 8,9 HV = 3,7 % was derived. An overview of the change of all hardness reference blocks is given in Table 5.

Table 5:
Evaluation of the apparent hardness change of the used hardness reference blocks over the time of the comparison

Hardness reference block	Hardness change, HV	Relative hardness change, %
240HV0,2	8,9	3,7
240HV1	5,4	2,3
240HV30	--	--
540HV0,2	6,8	1,3
540HV1	8,3	1,5
540HV30	4,7	0,9
840HV0,2	32,8	3,9
840HV1	14,7	1,8
840HV30	6,3	0,8

The apparent hardness changes shown in Table 5 differ with the test force. For the scales with smaller test forces (HV0,2 and HV1) the hardness changes are larger than in the case of the hardness scale HV30. This means that the found quadratic course of the hardness change over the time only to a very small part can be attributed to a real hardness change. Also the mechanism of a reversible hardness change in the hardness reference blocks is not clear. Because the transport box of the blocks did not contain monitoring sensors for temperature and other environment influences, afterwards we can not determine whether intolerable temperature shocks and other events having negative effects happened during the transport of the blocks.
Therefore, the above conclusion about the stability of the hardness reference blocks can be maintained.

7 Measurement results

In the following tables 6 to 8 the results for the hardness reference blocks with hardness levels of 240 HV, 540 HV and 840 HV are summarised. The results are expressed by the mean values, the standard deviations s_8 of each 8 repetition measurements and the standard deviations between the institutes s_{Inst}.

Table 6:
Results of the measurements for the hardness reference blocks with hardness level 240 HV

	HV0,2		HV1		HV30	
Institute	**Mean value**	**Std.dev.**	**Mean value**	**Std. dev.**	**Mean value**	**Std. dev.**
PTB	248,19	2,67	244,06	1,79		
IMGC	254,30	4,34	241,11	3,18	237,83	0,88
INMETRO					244,83	0,77
NIST	244,88	3,31	236,13	1,81		
NMIJ	241,59	3,92	238,41	1,71	236,11	1,21
NIM	242,36	2,77	237,88	0,86	236,40	0,44
KRISS	247,58	3,48	238,83	1,88	241,96	0,46
CMI	245,21	3,00	240,73	0,66	238,73	0,39
GUM	242,14	2,56	238,56	2,28	242,58	0,77
NPL	253,65	2,92	240,33	3,55	238,55	0,53
PTB	252,27	2,99	243,15	2,46	238,00	0,56
Mean value	247,20		239,92		239,44	
Std.dev.	4,83		2,44		2,99	

Table 7:
Results of the measurements for the hardness reference blocks with hardness level 540 HV

	HV0,2		HV1		HV30	
Institute	**Mean val.x_8**	**Std.dev.s_8**	**Mean val.x_8**	**Std. dev.s_8**	**Mean val.x_8**	**Std. dev.s_8**
PTB	528,42	5,81	539,03	5,97		
IMGC	548,16	6,12	544,84	5,71	525,45	1,35
INMETRO					534,94	2,08
NIST	528,50	3,34	522,50	1,77		
NMIJ	529,34	6,24	524,45	5,71	516,68	1,90
NIM	536,63	1,87	528,56	2,10	518,88	0,79
KRISS	538,79	4,61	533,89	2,94	528,41	1,57
CMI	522,83	5,50	535,38	1,30	520,73	0,57
GUM	529,76	6,11	535,55	2,72	527,90	1,30
NPL	547,36	13,07	536,63	4,34	524,86	1,06
PTB	540,63	5,22	537,76	1,59	522,89	2,50
M.val.x_{Inst}	535,04		533,86		524,53	
Std.dev.s_{Inst}	8,61		6,84		5,55	

Table 8:
Results of the measurements for the hardness reference blocks with hardness level 840 HV

CCM Vickers key comparison
Results for 840 HV hardness reference blocks

	HV0,2		**HV1**		**HV30**	
Institute	**Mean val.x_8**	**Std.dev. s_8**	**Mean val.x_8**	**Std. dev. s_8**	**Mean val.x_8**	**Std. dev. s_8**
PTB	839,78	9,38	831,49	6,14		
IMGC	864,20	44,79	875,40	10,05	820,85	2,15
INMETRO					841,55	1,43
NIST	827,00	7,09	815,38	6,35		
NMIJ	832,18	13,40	825,54	7,39	811,59	5,93
NIM	833,96	5,00	828,80	3,24	815,91	1,71
KRISS	840,25	3,77	839,75	5,77	831,86	1,68
CMI	813,37	4,02	826,82	4,45	810,64	1,08
GUM	830,00	5,77	831,77	3,26	818,03	2,20
NPL	897,57	13,60	839,32	7,54	837,17	1,55
PTB	858,07	10,22	835,79	6,62	817,86	3,39
M.val.x_{Inst}	843,64		835,01		822,83	
Std.dev. s_{Inst}	23,97		15,91		11,25	

Fig. 3 presents as an extract from tables 6 to 8 the reproducibility s_{Inst} over the hardness in absolute hardness values and Fig. 4 the same relationship in relative values of reproducibility.

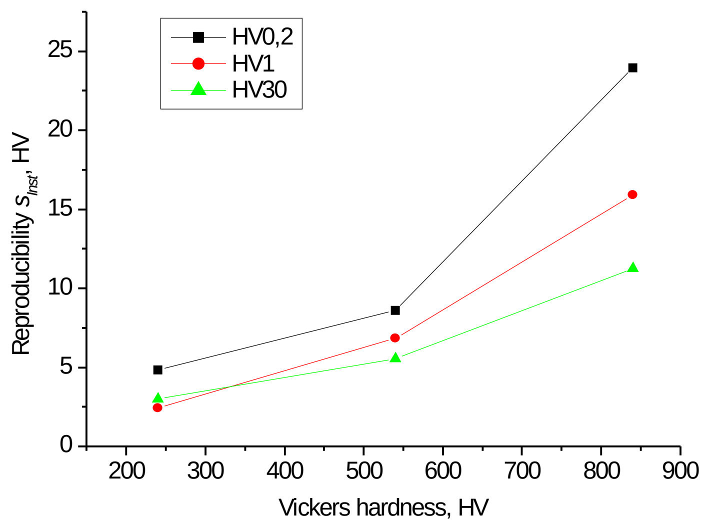

Fig. 3: Reproducibility s_{Inst} over Vickers hardness for the three scales HV0,2, HV1 and HV30

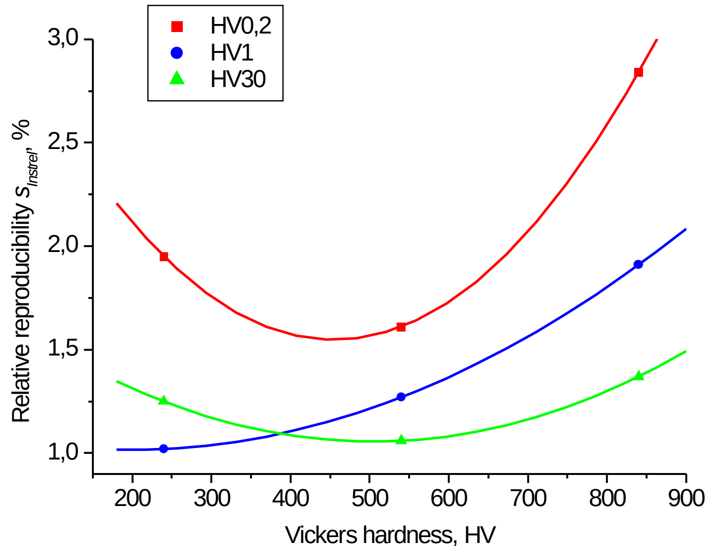

Fig.4: Relative reproducibility $s_{Instrel}$ over Vickers hardness for the three scales HV0,2, HV1 and HV30 (fitted curves)

The Fig. 3 and 4 illustrate the presently achievable degree of agreement for Vickers measurements in the scales HV0,2, HV1 and HV30 carried out by the participating national metrology institutes. Whereas for the high hardness level of 840 HV the uncertainty (expressed by the reproducibility) increases with decreasing test force, for the low hardness level of 240 HV the influence from the diagonal measurements becomes more evident. This may be the reason that $s_{Instrel}$ at 240 HV for HV30 is higher than for HV1.

8 Analysis

8.1 Reference values on the basis of the uncertainty determined by the participants

For the calculation of the reference values two ways were tried:

1) Reference values based on the arithmetic mean
2) Reference values based on the weighted mean

In the following these two evaluation methods are compared with each other.

8.1.1 Reference values based on the arithmetic mean

The arithmetic mean value is calculated as follows:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

with

$x_1, x_2,\ldots,x_n$ = measurement results of n participants

n = number of participants

The uncertainty of the arithmetic mean value is expressed by the confidence interval:

$$u_{\bar{x}} = \frac{t \cdot s}{\sqrt{n}} \qquad (2)$$

with
t = factor of Student distribution (t = f(α,n))
s = standard deviation of the measurement results of n participants
Finally, the coefficient E_n, which evaluates the agreement between the measurement deviations found in the comparison and the uncertainties stated by the participants, is calculated with the following expression:

$$E_n = \frac{x_{lab} - x_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}} \quad (3)$$

where x_{lab} is the measurement result of the participating laboratory, x_{ref} is the reference value calculated by the weighted mean value, U_{lab} is the uncertainty stated by the participating laboratory and U_{ref} is the uncertainty of x_{ref} calculated by the uncertainty of the weighted mean value.
For the reference values only the measurement results with $E_n \leq 1$ are considered. Using the uncertainties in Appendix A2 one gets the following references values.

Table 9:
Reference values and their uncertainties for the hardness measurements (evaluation by the participants)

Hardness scale	Ref. value x_{ref}	Uncertainty of reference value U_{ref}	
		Absolute unc., HV	Relative unc., %
240 HV0,2	247,09	4,57	1,85
240 HV1	239,46	1,70	0,71
240 HV30	239,44	2,44	1,02
540 HV0,2	535,78	7,17	1,34
540 HV1	533,28	6,25	1,17
540 HV30	524,53	4,52	0,86
840 HV0,2	844,07	20,69	2,45
840 HV1	835,40	13,71	1,64
840 HV30	822,83	9,17	1,11

8.1.2 Reference values based on the weighted mean

The reference values are calculated as the weighted mean based on the uncertainties of the participants. The weighted mean is calculated as follows:

$$\bar{x}_w = \frac{x_1 u_1^{-2} + x_2 u_2^{-2} + \ldots + x_n u_n^{-2}}{u_1^{-2} + u_2^{-2} + \ldots + u_n^{-2}} \quad (4)$$

with
$x_1, x_2, \ldots, x_n$ = measurement results of n participants
$u_1, u_2, \ldots, u_n$ = measurement uncertainties of n participants
The uncertainty of the weighted mean according to the law of error propagation follows from:

$$U_{xw} = \sqrt{(u_1 S)^{-2} + (u_2 S)^{-2} + \ldots + (u_n S)^{-2}} \quad (5)$$

with

$$S = u_1^{-2} + u_2^{-2} + \ldots + u_n^{-2}$$

Using the uncertainties in Table 14 (see paragraph 8.2) one gets the following references values.

Table 10:
Reference values and their uncertainties for the hardness measurements (evaluation by the participants)

Hardness scale	Ref. value x_{ref}	Uncertainty of reference value U_{ref}	
		Absolute unc., HV	Relative unc., %
240 HV0,2	246,00	2,54	0,45
240 HV1	238,48	1,37	0,42
240 HV30	238,58	0,54	0,23
540 HV0,2	531,29	6,65	1,13
540 HV1	534,89	4,36	0,82
540 HV30	524,97	1,39	0,26
840 HV0,2	827,76	11,86	1,36
840 HV1	828,36	6,86	0,83
840 HV30	813,48	3,04	0,37

In the case of 840 HV30 the measurement results showed a distribution with two peaks. Because 6 values where distributed around 815 HV and 3 values around 835 HV, the reference value was taken from the majority of the measurement results.
Fig. 5 depicts the dependency of the uncertainty on the hardness level and the test force (resp. hardness scale).

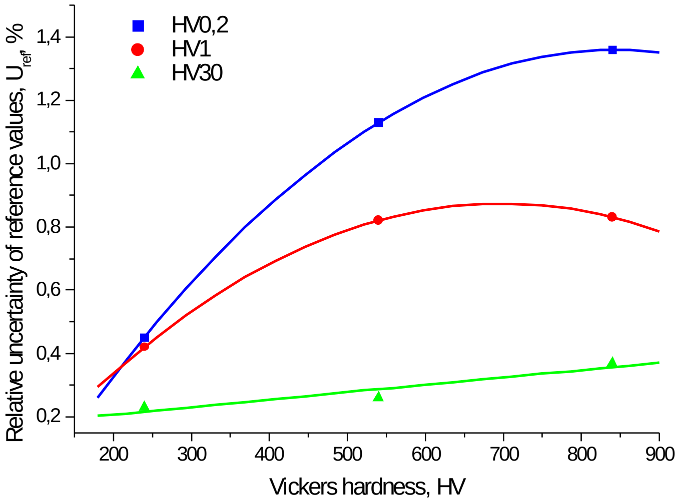

Fig. 5: Dependency of the relative uncertainty of the reference values on the hardness level and the test force (resp. hardness scale)

Fig. 5 clarifies that the relative uncertainty of the reference values – as expected – increases with the hardness, whereby smaller test forces deliver higher uncertainties than larger test forces. This reflects the fact that the Vickers hardness uncertainty is strongly influenced by the uncertainty of the diagonal measurement (see also ch. 8.4).
It should be noted that the uncertainties of the reference values are obviously the smallest uncertainties reached in the field of Vickers measurements worldwide so far. These uncertainties can be interpreted as the present limits of Vickers

measurements in the investigated range of hardness scales. This is one important outcome of this Vickers key comparison.
In the following Fig. 6 to 14 the measurement results are shown in connection with the reference values and the uncertainties stated by the participants.

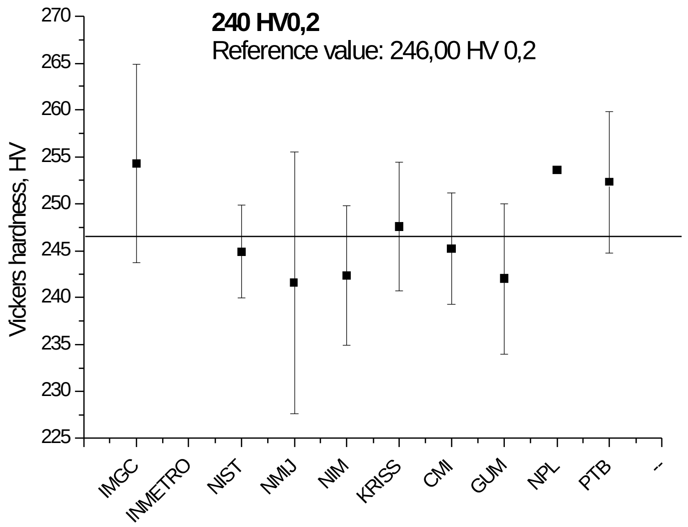

Fig. 6: Measurement results for the hardness scale 240 HV0,2 related to the reference value

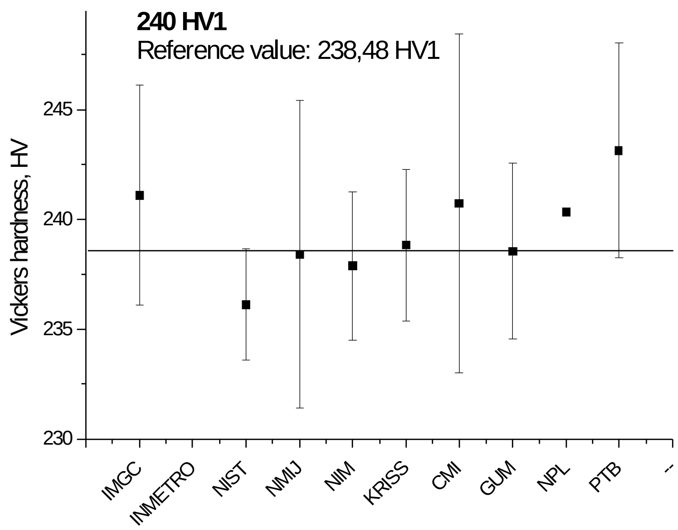

Fig. 7: Measurement results for the hardness scale 240 HV1 related to the reference value

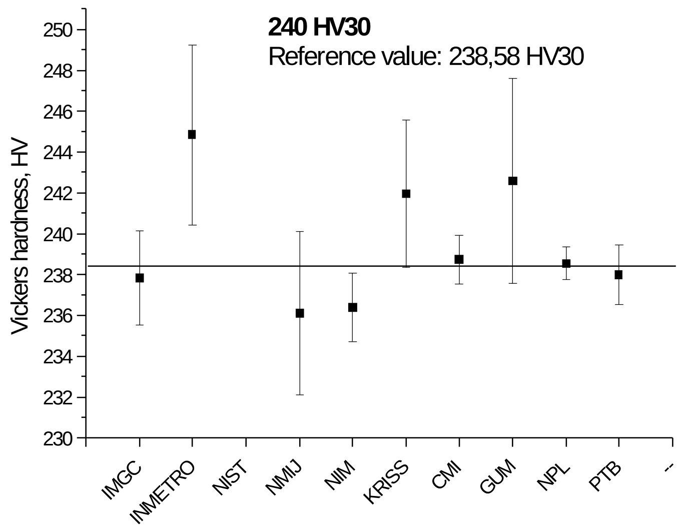

Fig. 8: Measurement results for the hardness scale 240 HV30 related to the reference value

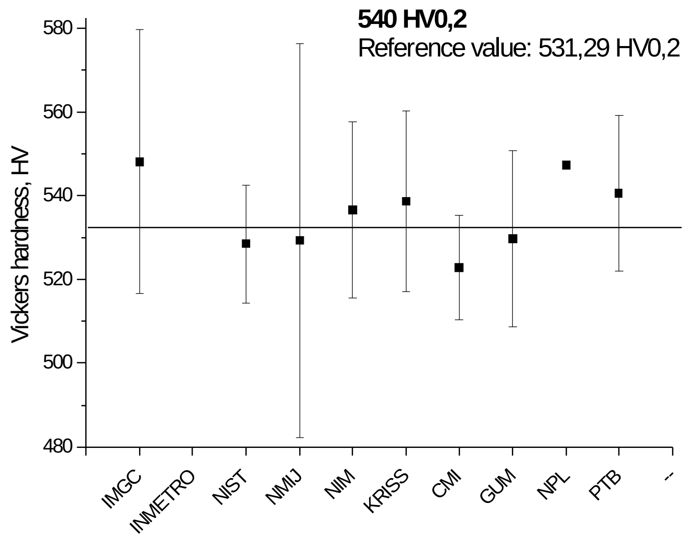

Fig. 9: Measurement results for the hardness scale 540 HV0,2 related to the reference value

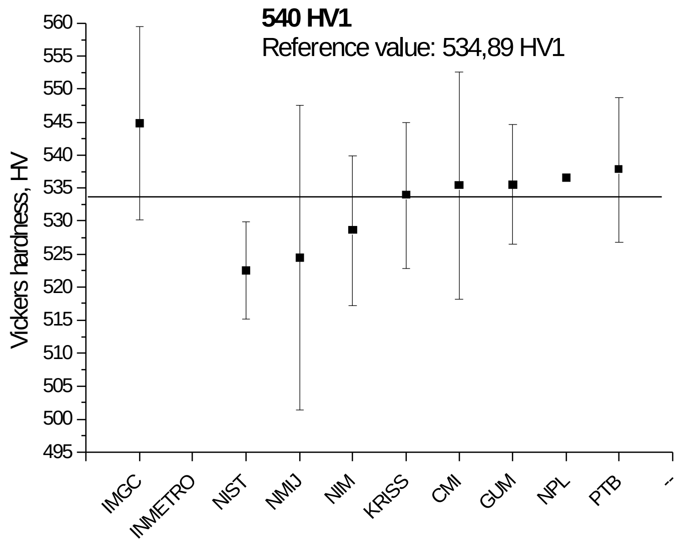

Fig. 10: Measurement results for the hardness scale 540 HV1 related to the reference value

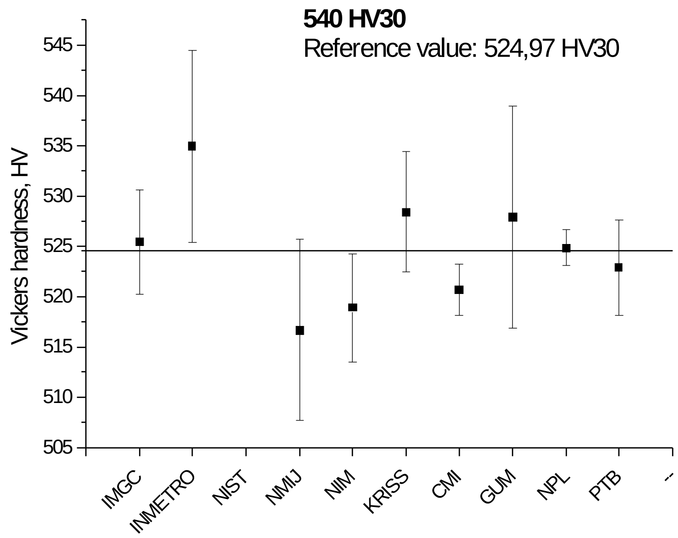

Fig. 11: Measurement results for the hardness scale 540 HV30 related to the reference value

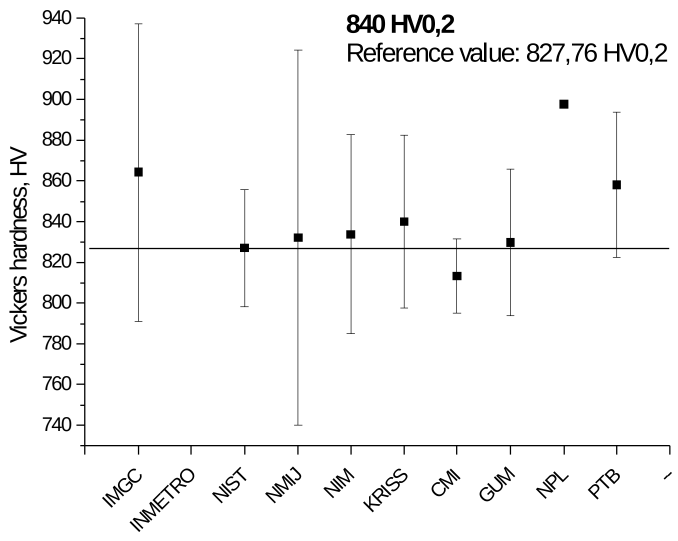

Fig. 12: Measurement results for the hardness scale 840 HV0,2 related to the reference value

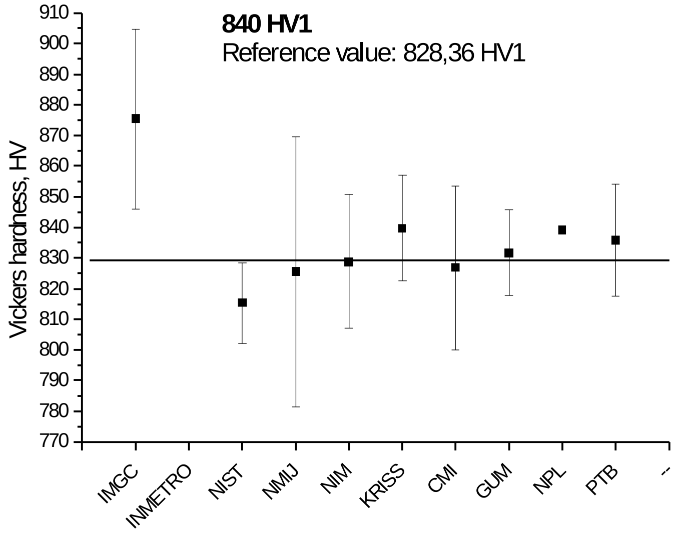

Fig. 13: Measurement results for the hardness scale 840 HV1 related to the reference value

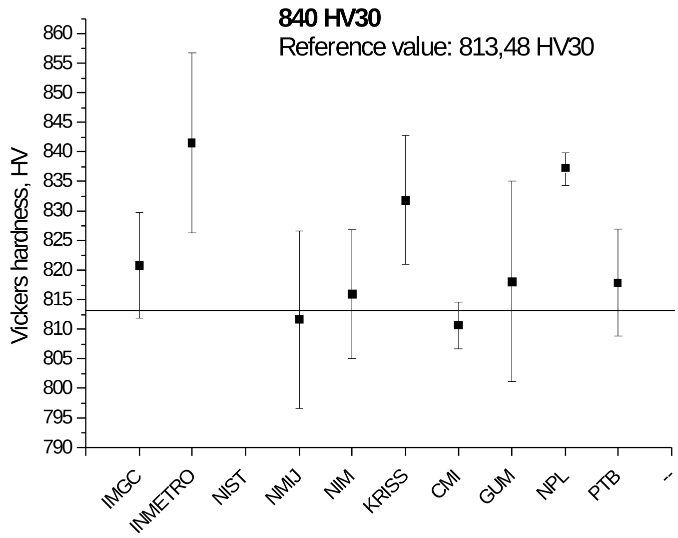

Fig. 14: Measurement results for the hardness scale 840 HV30 related to the reference value

The question whether the measurement deviations found in the comparison can be explained by the uncertainties stated by the participants is evaluated with the coefficient E_n. In the following Tables 11 and 12 the coefficients E_n are summarised for all participants and hardness scales, first for reference values based on the arithmetic mean and then based on the weighted mean.

Table 11:
Coefficients E_n for all participants and all hardness scales (based on arithmetic mean)

E_n values									
	240 HV			**540 HV**			**840 HV**		
	240HV0,2	240HV1	240HV30	540HV0,2	540HV1	540HV30	840HV0,2	840HV1	840HV30
IMGC	0,67	0,37	0,50	0,39	0,76	0,14	0,31	1,28	0,16
INMETRO			1,06			0,99			1,05
NIST	0,33	1,09		0,46	1,12		0,48	1,05	
NMIJ	0,37	0,15	1,06	0,14	0,39	1,04	0,13	0,22	0,78
NIM	0,54	0,42	1,03	0,04	0,37	0,82	0,19	0,26	0,49
KRISS	0,06	0,17	0,58	0,13	0,06	0,52	0,08	0,20	0,64
CMI	0,25	0,16	0,26	0,90	0,11	0,73	1,11	0,29	1.22
GUM	0,55	0,21	0,56	0,27	0,21	0,28	0,34	0,19	0,25
NPL			0,35			0,07			1,51
PTB	0,57	0,70	0,51	0,24	0,35	0,26	0,33	0,02	0,39
Mean value	0,42	0,41	0,66	0,32	0,42	0,54	0,37	0,44	0,72

Table 12:
Coefficients E_n for all participants and all hardness scales (based on weighted mean)

En values									
	240 HV			**540 HV**			**840 HV**		
	240HV0,2	240HV1	240HV30	540HV0,2	540HV1	540HV30	840HV0,2	840HV1	840HV30
IMGC	0,84	0,61	0,22	0,53	0,92	0,35	0,58	1,54	0,79
INMETRO			1,45			1,18			0,89
NIST	0,22	0,81		0,18	1,11		0,02	1,06	
NMIJ	0,31	0,01	1,07	0,04	0,32	1,14	0,05	0,13	1,45
NIM	0,47	0,17	1,11	0,24	0,27	0,89	0,12	0,10	1,10
KRISS	0,22	0,10	1,00	0,33	0,23	0,80	0,28	0,47	0,37
CMI	0,13	0,29	0,33	0,60	0,21	1,04	0,66	0,15	3,87
GUM	0,49	0,02	0,85	0,07	0,40	0,39	0,06	0,05	0,57
NPL			0,28			0,62			2,98
PTB	0,78	0,91	0,20	0,47	0,53	0,16	0,79	0,25	1,10
Mean value	0,42	0,37	0,72	0,31	0,50	0,73	0,32	0,47	1,46

As the mean values of E_n for the hardness scales express the degree of difficulty to measure in the corresponding hardness scales, Tables 11 and 12 deliver the somewhat astonishing result that the uncertainties with increasing test force (resp. with increasing diagonal length) in the mean are underestimated. On the other side, the uncertainties for HV0,2 as compared with the uncertainties for HV30 generally are estimated more realistically. This result is also confirmed by the investigation of the influence of the diagonal measurement uncertainty.
The comparison of the E_n values derived from the arithmetic and from the weighted mean yield the result that the En values based on the arithmetic mean deliver less exceedings of the limit E_n = 1 than the E_n values based on the weighted mean. **This clarifies that the weigthed mean is not well suited for a small number of participants (*n* = 10)**, because under the point of view of statistics it is difficult to declare the results of 4 or 5 participants out of 10 to outliers.

8.2 Reference values on the basis of a unified estimation of the hardness measurement uncertainty

The application of the EA draft "Guideline to the estimation of the uncertainty of the Brinell and the Vickers measuring method" already guaranteed a rather uniform approach of all participants to the estimation of the measurement uncertainty. Nevertheless, the amount of considered influence quantities was different, and the type of distribution was also not always considered. So the individual application of this guideline in several cases led to uncertainty values which are not sufficiently comparable.
Therefore a unified estimation of the measurement uncertainty was made on the following basis.
The calculation scheme can be seen from the following example.

Table 13:
Calculation scheme for the unified estimation of the measurement uncertainty

Influencing quantity X_i	**Symbol**	**Unit**	**Value**	$D x_i$	s_i	a_i	$u^2(x_i)$	c_i	DH	$u^2(y_i)$	n_i	$u_i^4(y)/n_i$
Test force *F*	***F***	N	**1,96**	0,000		9,80E-03	3,2E-05	1,3E+02	0,0E+00	5,1E-01	8	3,3E-02
Indentation diagonal length	***d***	mm	**0,039**	0		0,0004	5,3E-08	-1,3E+04	0,0E+00	8,7E+00	9	8,5E+00
Plane angle *a*	*a*	°	136	-8,7E-04		0,00175	1,0E-06	5,0E+01	-4,4E-02	2,5E-03	10	6,4E-07
Tip radius *D r*	*r*	mm		3,0E-04		1,0E-04	3,3E-09	-7,1E+03	-2,1E+00	1,7E-01	10	2,8E-03
Length of line of junction *D c*	*c*	mm		4,0E-04		1,0E-04	3,3E-09	9,0E+03	3,6E+00	2,7E-01	10	7,1E-03
Total									**1,41**	9,7E+00		8,5E+00
Combined standard uncertainty *u (H)*										3,1E+00	ν_{eff}	11
Confidence level										95%		
Coverage factor										2,2		
Expanded standard uncertainty *U (H)*										**6,8**	**HV**	
Expanded standard uncertainty *U(H)+I D HI*										**8,3**	**HV**	
Relative Expanded standard uncertainty $U_{rel}(H)$										**3,3**	**%**	
Hardness	**247,5**	**HV**										

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.
Standard uncertainty:

$$u^2(x_i) = s_i^2 \vee \frac{a_i^2}{3} \tag{6}$$

Sensitivity coefficients:

$$c_1 = \frac{\partial HV}{\partial F} = \frac{0{,}204 \cdot \sin a / 2}{d^2}$$

$$c_2 = \frac{\partial HV}{\partial d} = \frac{-0{,}408 \cdot F \cdot \sin a / 2}{d^3}$$

$$c_3 = \frac{\partial HV}{\partial a} = \frac{0{,}102 \cdot F \cdot \cos a / 2}{d^2} \tag{7}$$

$$c_4 = \frac{\partial HV}{\partial r} = \frac{-0{,}204 \cdot F \cdot \sin a / 2}{d^3} \cdot (1{,}099 + 1{,}1515 \cdot \frac{r}{d})$$

$$c_5 = \frac{\partial HV}{\partial c} = -\frac{0{,}2856 \cdot F \cdot \sin a / 2}{d^3}$$

Single hardness deviation:

$$\Delta H_i = c_i \cdot \Delta x_i \tag{8}$$

Variances:

$$u^2(y_i) = c_i^2 u^2(x_i) \tag{9}$$

Combined standard uncertainty:

$$u(H) = \sqrt{\sum_{i=1}^{n} u^2(y_i)} \tag{10}$$

Sum of hardness deviations:

$$\Delta H = \sum_{i=1}^{n} \Delta H_i \tag{11}$$

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

$$n_{eff} = \frac{u^4(y)}{\sum_{i=1}^{n} \frac{u_i^4(y)}{n_i}} \tag{12}$$

Coverage factor:

$$k = f(v_{eff}, P) \tag{13}$$

Expanded standard uncertainty:

$$U(H) = k \cdot u(H) + |\Delta H| \quad (14)$$

Relative expanded standard uncertainty:

$$U_{rel}(H) = \frac{U(H)}{H} \cdot 100, \% \quad (15)$$

According to this unified procedure for the estimation of measurement uncertainty, the following measurement uncertainties for the participants were received. If the participants had omitted the indenter tip radius because they did not have the facility to measure it, a value of r = 0,5 µm with an uncertainty of 0,2 µm was set in.

Table 14:

Results of the relative measurement uncertainty (in %) according to the estimation of the participant (part) and to the unified procedure (unif)

Institute	240HV0,2		240HV1		240HV30		540HV0,2		540HV1		540HV30		840HV0,2		840HV1		840HV30	
	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif
IMGC	3,9	4,9	1,7	2,0	0,9	0,4	5,7	7,2	2,5	3,2	1,0	0,6	7,1	9,0	3,2	4,0	1,0	0,7
INMETRO					1,8	3,3					1,8	2,2					1,8	2,7
NIST	2,0	4,4	1,1	2,0			2,7	6,5	1,4	3,0			3,5	8,2	1,6	3,6		
NMIJ	5,8	4,9	2,9	2,5	0,9	0,7	8,9	7,3	4,2	3,7	1,2	1,1	11,1	9,2	5,2	4,6	1,4	1,3
NIM	3,1	5,6	1,4	2,5	0,7	0,7	3,9	8,5	2,1	3,8	1,0	1,1	5,9	10,6	2,6	4,7	1,3	1,3
KRISS	2,9	5,3	1,4	2,4	1,5	0,9	4,0	8,1	1,6	3,2	1,1	0,7	5,0	9,5	2,1	4,6	1,3	1,1
CMI	2,4	6,4	3,2	2,7	0,5	0,9	2,3	9,3	3,2	4,1	0,5	1,1	2,2	11,8	3,2	5,1	0,5	1,3
GUM	3,3	5,0	1,7	3,1	2,1	2,5	3,9	7,5	1,7	3,8	2,0	2,5	4,3	9,3	1,7	3,8	2,1	2,5
NPL					0,3	0,6					0,3	0,9					0,3	1,1
PTB	3,1	5,1	2,0	3,1	0,6	0,9	3,4	5,6	2,0	3,3	0,9	1,3	4,3	6,9	2,2	3,6	1,1	1,6
Mean value	3,3	5,2	1,9	2,5	1,0	1,2	4,4	7,5	2,3	3,5	1,1	1,3	5,4	9,3	2,7	4,3	1,2	1,5
Variation	3,8	2	2,1	1,1	1,8	2,9	6,6	3,7	2,8	1,1	1,7	1,9	8,9	4,9	3,6	1,5	1,8	2

Table 14 elucidates that the application of the unified procedure for the measurement uncertainty in most cases led to a reduction of the variation (difference between maximum and minimum value of the uncertainty). An increase of the variation is observed for the scale HV30 which is due to a relatively big change of uncertainty in one single case. On the other hand, the level of uncertainty, as expressed by the mean value, increased. The reason is that the hardness deviations due to the indenter calibration are rather large. This fact underlines that it is necessary to improve the calibration methods of the indenter.

In Tables 15 and 16 the coefficients E_n for all participants and all hardness scales according to the evaluation by the unified procedure for the estimation of the measurement uncertainty and the corresponding reference values are summarised, first for the weighted mean and then for the arithmetic mean.

Table15:
Coefficients E_n in the case of the unified procedure for the estimation of the measurement uncertainty (based on arithmetic mean)

	E_n values								
	240 HV			540 HV			840 HV		
	HV0,2	HV1	HV30	HV0,2	HV1	HV30	HV0,2	HV1	HV30
IMGC	0,55	0,32	0,62	0,31	0,63	0,17	0,26	1,06	0,18
INMETRO			0,66			0,84			0,76
NIST	0,19	0,67		0,20	0,63		0,24	0,62	
NMIJ	0,44	0,17	1,12	0,16	0,44	1,10	0,15	0,24	0,79
NIM	0,33	0,25	1,02	0,02	0,22	0,77	0,11	0,16	0,48
KRISS	0,04	0,11	0,78	0,07	0,03	0,68	0,05	0,11	0,70
CMI	0,12	0,19	0,22	0,26	0,09	0,51	0,31	0,19	0,85
GUM	0,39	0,12	0,48	0,15	0,11	0,24	0,17	0,11	0,22
NPL			0,31			0,05			1,12
PTB	0,39	0,48	0,45	0,16	0,24	0,20	0,23	0,01	0,31
Mean	0,31	0,29	0,63	0,17	0,30	0,51	0,19	0,31	0,60

Table16:
Coefficients E_n in the case of the unified procedure for the estimation of the measurement uncertainty (based on weighted mean)

	E_n values								
	240 HV			540 HV			840 HV		
	HV0,2	HV1	HV30	HV0,2	HV1	HV30	HV0,2	HV1	HV30
IMGC	0,61	0,39	0,20	0,31	0,65	0,30	0,30	1,10	0,25
INMETRO			0,87			0,90			0,83
NIST	0,12	0,57		0,17	0,59		0,18	0,60	
NMIJ	0,37	0,10	1,08	0,14	0,41	1,35	0,10	0,22	0,96
NIM	0,27	0,18	0,92	0,03	0,20	0,92	0,07	0,13	0,56
KRISS	0,10	0,04	1,80	0,08	0,06	1,03	0,00	0,13	0,97
CMI	0,06	0,24	0,32	0,24	0,12	0,60	0,27	0,17	1,03
GUM	0,32	0,06	0,75	0,12	0,13	0,26	0,12	0,08	0,22
NPL			0,32			0,09			1,53
PTB	0,45	0,53	0,02	0,17	0,26	0,22	0,28	0,05	0,34
Mean	0,29	0,26	0,70	0,16	0,30	0,63	0,17	0,31	0,74

Compared with the uncertainty estimation by the participants (Tables 11 and 12) the E_n values in Table 15 and 16 are a little bit smaller. This is due to the harmonisation of the uncertainty estimation by the unified procedure. The values in Table 15 exhibit the same tendency as those in Table 11 that the E_n values are increasing with the test force as can be seen by the mean values. This means that the uncertainty for the largest test force (and the largest indentation size) in several cases is underestimated.
The comparison of the E_n values according to the unified method based on the weighted mean and the arithmetic mean shows clearly that the use of the arithmetic mean delivers the smallest number of exceedings of the limit E_n = 1 (5 exceedings for the arithmetic mean against 7 exceedings for the weighted mean). Obviously, the use of the weighted mean leads to an overestimation of single results if the number of the participants is small (n = 10 in the case of this key comparison). Therefore the use of

the arithmetic mean for the calculation of the reference values and the E_n values seems to be most suited in order to evaluate this key comparison.
On the basis of the measurement uncertainties according to the unified procedure based on the arithmetic mean the reference values were recalculated. Measurement results with En ≥ 1 have been excluded. The calculation of the reference values according to the estimation of the participants and to the unified method is given in Appendix A2. The results are shown in the following Table 17.

Table 17:
Reference values and their uncertainties for the hardness measurements (evaluation by the unified procedure based on the arithmetic mean, values with E_n ≤ 1)

Hardness scale	**Reference value x_{ref}, HV**	**Uncertainty of reference value U_{ref}**	
		Abs. unc., HV	**Rel. unc., %**
240 HV0,2	246,28	4,57	1,86
240 HV1	239,81	2,08	0,87
240 HV30	239,15	1,97	0,82
540 HV0,2	534,33	8,80	1,65
540 HV1	534,35	6,10	1,14
540 HV30	525,51	5,03	0,96
840 HV0,2	840,81	25,38	3,02
840 HV1	831,41	16,82	2,02
840 HV30	819,35	11,25	1,37

The following Fig. 15 until 23 show the measurement results under consideration of the uncertainty according to the unified procedure.

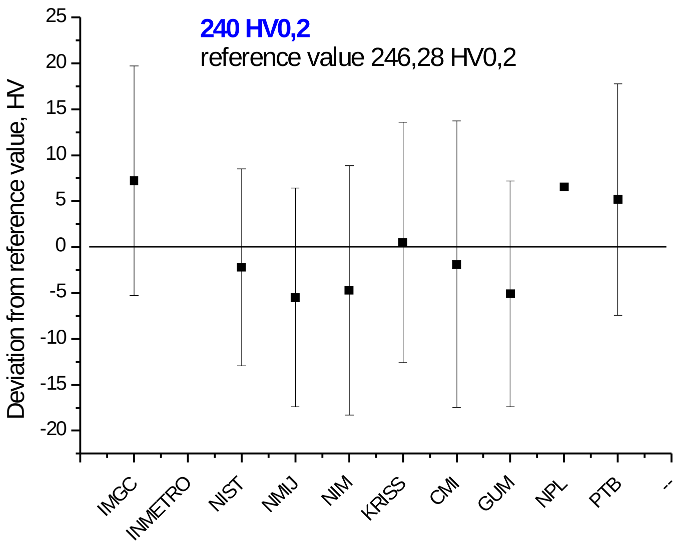

Fig. 15: Measurement results for the hardness scale 240 HV0,2 related to the reference value (unified procedure)

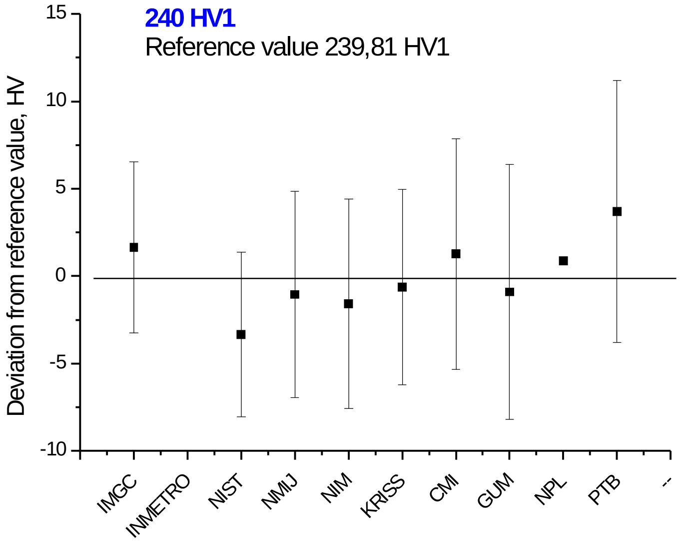

Fig. 16: Measurement results for the hardness scale 240 HV1 related to the reference value (unified procedure)

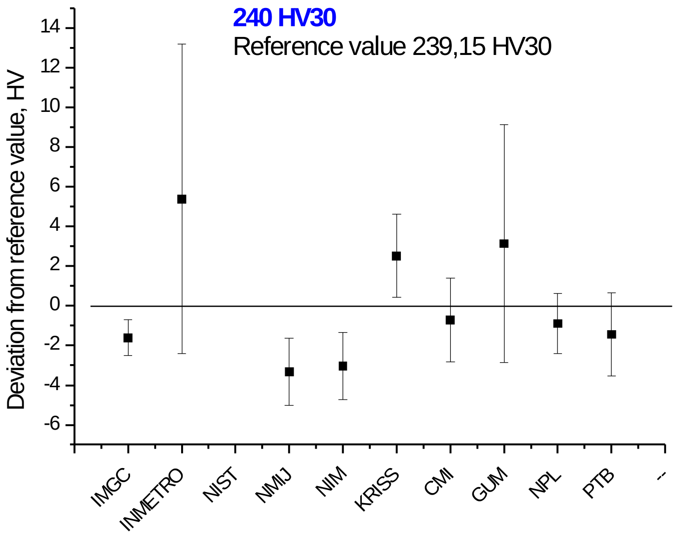

Fig. 17: Measurement results for the hardness scale 240 HV30 related to the reference value (unified procedure)

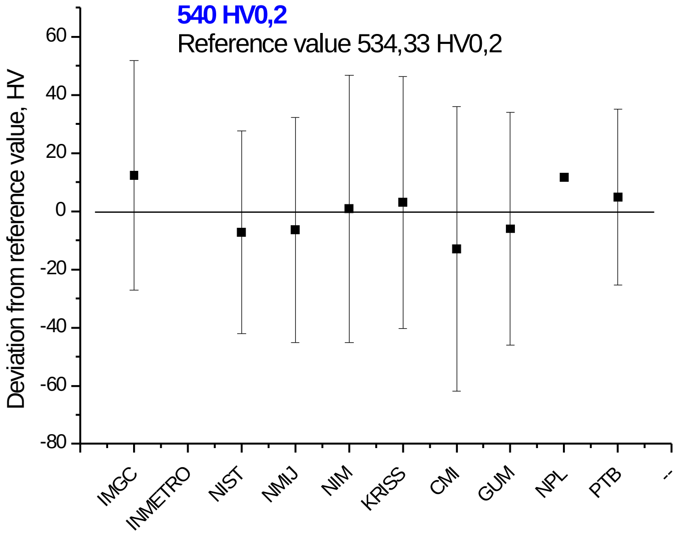

Fig. 18: Measurement results for the hardness scale 540 HV0,2 related to the reference value (unified procedure)

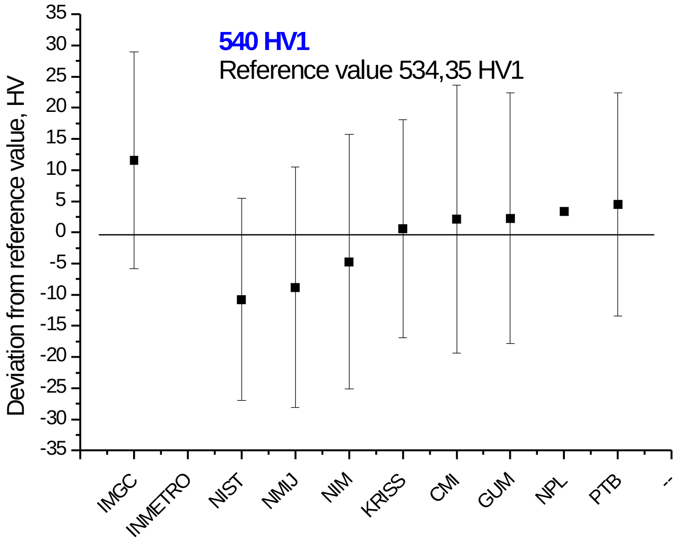

Fig. 19: Measurement results for the hardness scale 540 HV1 related to the reference value (unified procedure)

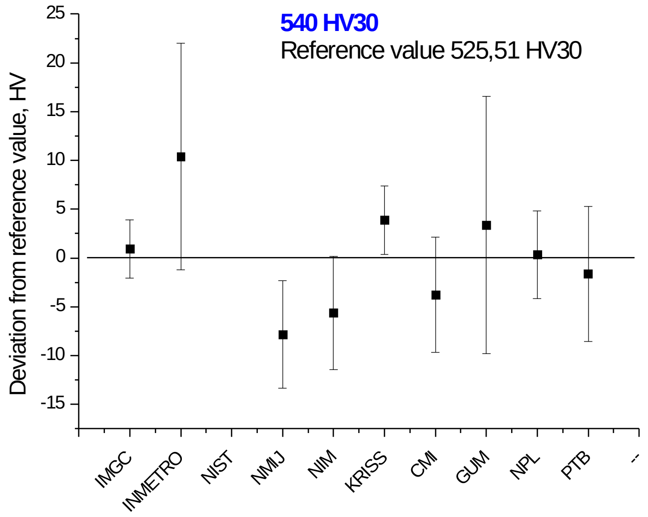

Fig. 20: Measurement results for the hardness scale 540 HV30 related to the reference value (unified procedure)

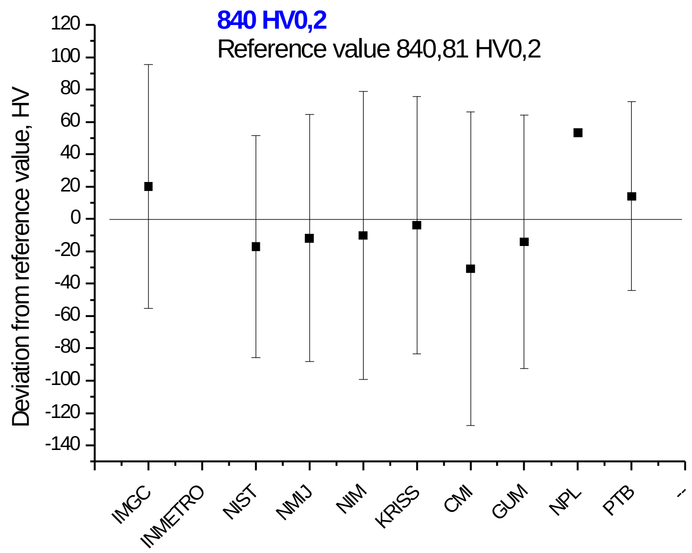

Fig. 21: Measurement results for the hardness scale 840 HV0,2 related to the reference value (unified procedure)

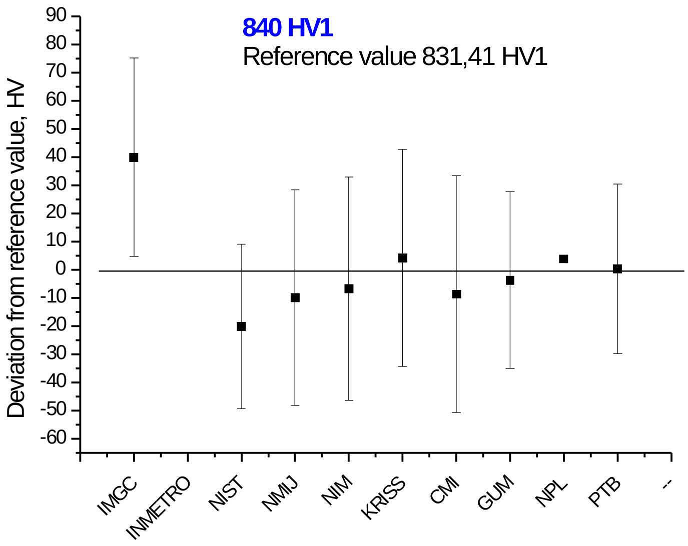

Fig. 22: Measurement results for the hardness scale 840 HV1 related to the reference value (unified procedure)

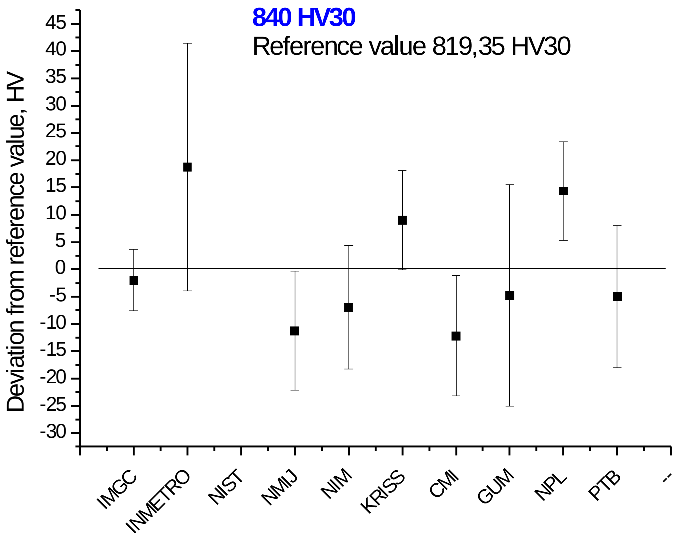

Fig. 23: Measurement results for the hardness scale 840 HV30 related to the reference value (unified procedure)

8.3 Influence of the inhomogeneity of hardness of the hardness reference blocks

The inhomogeneity of the hardness distribution on the hardness reference blocks is evaluated on the following basis. According to the technical protocol each participant had to carry out eight measurements on each hardness reference block. The distribution of these eight measurement locations on the block was such that two consecutive locations were rather near to each other so that one can assume that the hardness change between these two locations is sufficiently small as compared with the hardness change due to the repeatability of the hardness standard machine. Therefore, the standard deviation based on the differences between the four groups of each two neighbouring locations can be used to express the inhomogeneity of hardness distribution on the hardness reference blocks.

If the measuring values on the eight locations are denominated as:
x_1, x_2, ... x_8,
then the differences of the four groups of neighbouring locations are:

$$\Delta_1 = (x_1 - x_2)/2$$
$$\Delta_2 = (x_3 - x_4)/2$$
$$\Delta_3 = (x_5 - x_6)/2$$
$$\Delta_4 = (x_7 - x_8)/2 \qquad (16)$$

Further, the standard deviation due to inhomogeneity of hardness is expressed by:

$$s_{Inh} = \sqrt{\frac{1}{3}(\Delta_1^2 + \Delta_2^2 + \Delta_3^2 + \Delta_4^2)} \qquad (17)$$

Table 18 summarises the results of the inhomogeneity of the hardness reference blocks, as derived from the measuring results of CMI. The values of this institute were chosen because the repeatability of their results is sufficiently small. Therefore one can suppose that the influences from the inhomogeneity and the repeatability are rather well separated.

Table 18:
Results of the inhomogeneity of the hardness reference blocks, as derived from the measuring results of CMI

	Standard deviation due to inhomogeneity s_{Inh}		
	Related to diagonal length *d*	Related to hardness *HV*	Relative inhomo-geneity s_{Inh}/HV, %
240HV0,2	0,14	0,83	0,35
240HV1	0,12	0,64	0,27
240HV30	0,27	0,27	0,11
540HV0,2	0,10	4,01	0,74
540HV1	0,02	0,44	0,08
540HV30	0,17	0,54	0,10
840HV0,2	0,05	3,33	0,40
840HV1	0,12	4,11	0,49

Table 18 shows that the relative inhomogeneity depends less on the hardness level, but more on the hardness scale. The relative inhomogeneity increases with decreasing test force resp. with decreasing indent size. This fact clarifies that the inhomogeneity is still superposed by the repeatability of the length measurement. As a rough estimate one can conclude that the relative inhomogeneity of hardness distribution on the used hardness reference blocks is not larger than 0,5 %.

8.4 Influence of the length measuring deviation

Because at Vickers measurements the length measuring deviation significantly influences the uncertainty of measurements, in the technical protocol the measurement of reference indents was included.

In the Tables 19 to 21 the results for the measurements of the reference indents are summarised. At this the repeatability of the measurements is expressed by s_r and calculated as follows:

$$s_r = \frac{s_h + s_v}{2} \qquad (18)$$

with
s_h = standard deviation of the diagonal measurements in horizontal direction
s_v = standard deviation of the diagonal measurements in vertical direction

The standard deviation s_{Inst} represents the reproducibility of measurements between the participating laboratories.

Table 19:
Results for 240 HV reference indents

	HV0,2		HV1		HV30	
Institute	**Mean value**	**Std.dev. s_r**	**Mean value**	**Std. dev. s_r**	**Mean value**	**Std. dev. s_r**
PTB	38,52	0,09	87,55	0,05	482,48	0,68
IMGC	38,19	0,12	87,70	0,16	483,66	0,62
INMETRO					479,40	0,7
NIST	38,90	0,09	87,90	0,05		
NMIJ	39,18	0,03	88,19	0,06	485,39	0,15
NIM	39,19	0,05	88,29	0,08	485,95	0,14
KRISS	38,65	0,41	88,65	0,09	480,89	0,00
CMI	38,96	0,13	88,01	0,17	483,96	0,58
GUM	38,95	0,06	87,92	0,03	482,55	0,06
NPL	38,17	0,11	87,27	0,23	484,37	0,02
PTB	38,36	0,16	87,41	0,23	482,47	0,88
Mean value	38,71	0,13	87,89	0,12	483,11	0,38
Std.dev. s_{Inst}	0,38		0,42		1,99	

Table 20:
Results for 540 HV reference indents

	HV0,2		HV1		HV30	
Institute	**Mean value**	**Std.dev. s_r**	**Mean value**	**Std. dev. Sr**	**Mean value**	**Std. dev. s_r**
PTB	26,38	0,14	58,58	0,12	326,03	0,82
IMGC	26,01	0,15	58,31	0,12	325,39	0,35
INMETRO					321,80	0,22
NIST	26,30	0,06	58,80	0,06		
NMIJ	26,47	0,03	59,47	0,03	328,14	0,00
NIM	26,24	0,08	59,25	0,09	327,85	0,09
KRISS	26,30	0,07	58,65	0,00	323,30	0,00
CMI	26,61	0,06	59,24	0,20	326,30	0,48
GUM	26,25	0,05	59,07	0,03	325,47	0,08
NPL	25,43	0,13	58,34	0,09	325,87	0,01
PTB	26,01	0,09	58,59	0,13	326,65	0,28
Mean value	26,20	0,09	58,83	0,09	325,68	0,23
Std.dev. s_{Inst}	0,33		0,41		1,92	

Table 21:
Results for 840 HV reference indents

	HV0,2		HV1		HV30	
Institute	**Mean value**	**Std.dev. s_r**	**Mean value**	**Std. dev. s_r**	**Mean value**	**Std. dev. s_r**
PTB	21,08	0,08	47,38	0,11	259,35	0,22
IMGC	20,74	0,14	46,03	0,12	260,34	0,26
INMETRO					255,50	0,56
NIST	21,10	0,03	47,50	0,03		
NMIJ	21,11	0,00	47,40	0,06	261,81	0,03
NIM	21,23	0,09	47,33	0,07	261,30	0,10
KRISS	21,01	0,11	47,12	0,08	257,85	0,00
CMI	21,21	0,09	47,33	0,20	260,54	0,40
GUM	21,00	0,06	47,42	0,91	259,40	0,09
NPL	20,51	0,29	46,87	0,16	257,79	0,02
PTB	20,90	0,21	47,20	0,10	258,88	0,33
Mean value	20,99	0,11	47,16	0,18	259,28	0,20
Std.dev. s_{Inst}	0,22		0,44		1,88	

Fig. 24 shows the relative reproducibility of the diagonal measurement expressed by the standard deviation $s_{Instrel}$ over the hardness.

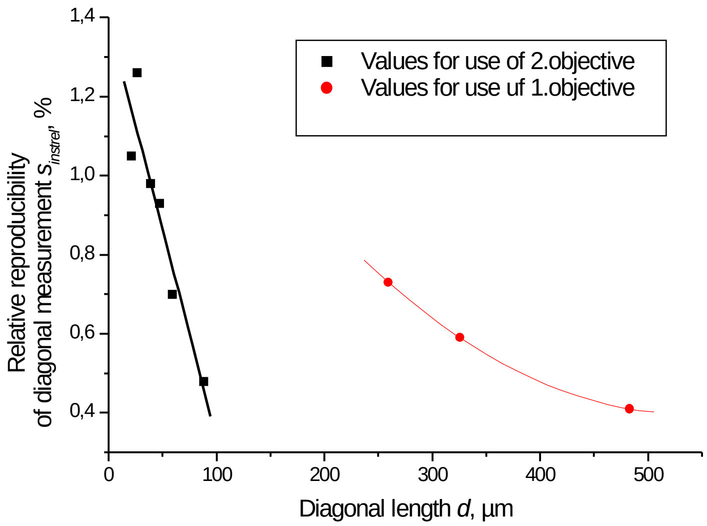

Fig. 24: Relative reproducibility of the diagonal measurement expressed by the standard deviation $s_{Instrel}$ over the diagonal length.

In Fig. 24 two groups of data attract the attention. These two groups of data correspond to two different objectives used for the diagonal measurement, one with higher magnification for smaller indents with diagonals d < 100 µm and the other with smaller magnification for indents with diagonals 250 µm < d < 500 µm. For both groups the relative reproducibility $s_{instrel}$ decreases with increasing diagonal length d. But for the smaller diagonals the reproducibility increases much more sharply with

decreasing diagonal length than for the larger diagonals. For the smaller diagonals (d < 100 µm) the relative reproducibility is in a range $s_{instrel}$ = 0,5 % to 1,3 % and for the larger diagonals in a range $s_{instrel}$ = 0,4 % to 0,7 %.
The part of the uncertainty of the diagonal measurement in the measured hardness deviations for the two extreme scales 840 HV0,2 and 240 HV30 is depicted in Fig. 25 and 26. At this the uncertainty of diagonal measurement was converted by

$$dHV = -2\frac{\Delta d}{d} \tag{19}$$

in hardness units. The measured hardness deviations from the arithmetic mean value of all participants are an approximate expression of the hardness uncertainty.

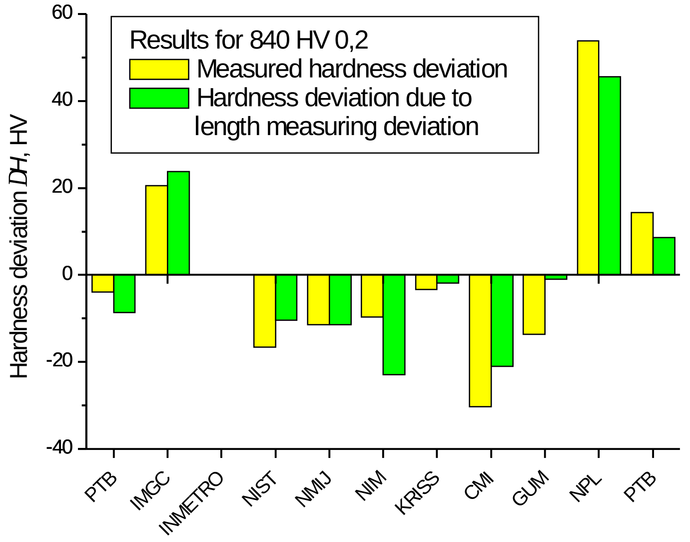

Fig. 25: Comparison of the measured hardness deviation from the mean value of all participants with the hardness deviation due to length measuring deviation for the hardness scale 840 HV0,2

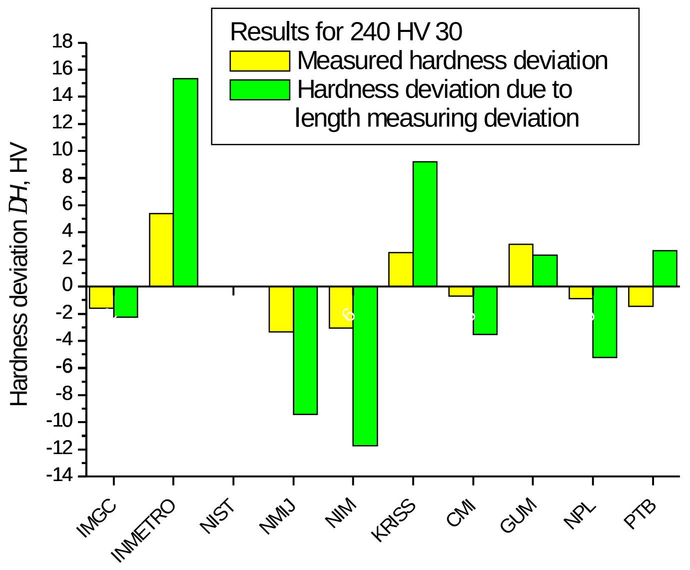

Fig. 26: Comparison of the measured hardness deviation from the mean value of all participants with the hardness deviation due to length measuring deviation for the hardness scale 240 HV30

Fig. 25 and 26 show that the hardness deviation clearly depends on the hardness deviation due to the length measuring deviation, but this dependence becomes still more significant for small indent sizes, as in the case of the hardness scale 840 HV0,2.

8.5 Influence of the numerical aperture of the objective

Depending on the used equipment the participants have used optical length measuring systems with different magnifications and numerical apertures. Tab. 22 delivers an overview of the characteristics of the used optical length measuring systems.

Table 22:
Overview of the numerical aperture of the used optical length measuring systems

Scale	HV0,2			HV1			HV30		
Block	240	540	840	240	540	840	240	540	840
Institute									
IMGC	0,5	0,5	0,5	0,4	0,4	0,5	0,2	0,2	0,2
INMETRO	-	-	-	-	-	-	0,32	0,32	0,32
NIST	0,9	0,9	0,9	0,8	0,8	0,8	-	-	-
NMIJ	0,65	0,65	0,65	0,45	0,45	0,45	0,1	0,25	0,25
NIM	0,8	0,8	0,8	0,8	0,8	0,8	0,5	0,5	0,5
KRISS	0,65	0,65	0,65	0,65	0,4	0,4	0,3	0,25	0,25
CMI	0,5	0,5	0,5	0,5	0,5	0,5	0,35	0,35	0,35
GUM	0,32	0,32	0,32	0,32	0,32	0,32	0,3	0,3	0,3
NPL	0,9	0,9	0,9	0,8	0,9	0,9	0,9	0,9	0,9
PTB	0,75	0,75	0,75	0,75	0,75	0,75	0,2	0,2	0,2
ΔNA_{max}	0,58	0,58	0,58	0,48	0,58	0,58	0,8	0,7	0,7

In the last line of Table 19 one can see that the largest difference of numerical aperture ΔNA_{max} between the participants for the different indents was between 0,58 and 0,8. Therefore one can assume that the numerical aperture of the used objectives can influence the results of the length measurement.
In order to investigate this influence, partner IMGC made the following investigation. The reference indents were measured with a microscope to which belongs a set of five objectives. These objectives have the following magnifications and numerical apertures:

Magnification	32x	20x	10x	5x	2,5x
Numerical aperture	0,5	0,4	0,2	0,09	0,07

The result of the measurement of the reference indents with the 5 different objectives is shown in Table 23.

Table 23:
Result of the measurement of the reference indents with the 5 different objectives

Block	Objective/N.A.					
(indentations 8-8)	*32x*	*20x*	*10x*	*5x*	*2.5x*	*Ref.*
	0,5	*0,4*	*0,2*	*0,09*	*0,07*	*0,5*
240HV0,2	38,69	38,50	38,39			38,69
540HV0,2	26,15	25,94				26,15
840HV0,2	20,50	20,79				20,50
240HV1	87,77	87,47	87,29			87,77
540HV1	58,32	59,01	58,59			58,32
840HV1	46,60	46,64	46,25			46,60
240HV30		482,98	483,46	488,55		486,98
540HV30		325,04	324,96	325,35		325,46
840HV30	258,63	258,31	259,40	259,71	260,18	258,63

On the basis of the data in Table 19, Fig. 27 shows the relative length measuring deviations in dependence on the diagonal length and the numerical aperture.

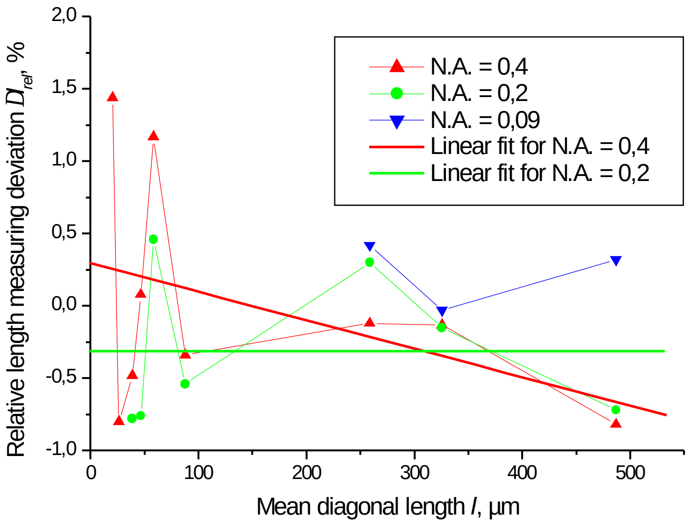

Fig. 27: Relative length measuring deviations in dependence on the diagonal length and the numerical aperture (for *N.A.* = 0,5 the length measurement deviations are set = 0)

Fig. 27 clarifies that the effect of numerical aperture does not have a well defined slope and sign. Changing the objectives (and the numerical aperture), the measurements change very much (about ± 1 %), but in a random way.
From this analysis it is not possible to correct for the effect of the numerical aperture. One can only conclude that variations of the diagonal length of ±1 % can be justified, if different objectives and numerical apertures are used.

9 Uncertainty budgets

9.1 Results of calibrations

As basis for the calculation of the measurement uncertainty all participants carried out a calibration of the used Vickers standard machines. The results of the calibrations are summarised in Table 24.

Table 24:
Results of the calibrations of Vickers standard machines used by the participants

	u_F			u_d, µm		u_α, °	r, µm	c, µm
	HV0,2	HV1	HV30	d<40 µm	d>40 µm			
IMGC	0,02 mN	0,098 mN	0,003 N	0,01 µm	0,01 µm	0,008°		
INMETRO	-	-	0,15 N	-	1,4 µm	1°	-	2 µm
NIST	0,9 mN	4 mN		(0,09...0,12)µr	(0,15...0,18)µr	0,075°		
NMIJ	0,98 mN	17 mN	0,076 N	(0,22..0,28)µm	(0,36...0,56)µr	0,1°	0,3 µm	0,4 µm
NIM	2,7 mN	13,7 mN	0,29 N	0,4 µm	0,5 µm	0,02°		(0,5...0,6) µm
KRISS	1,2 mN	5,9 mN	0,12 N	0,16 µm	0,4 µm	0,02°	-	
CMI	1 mN	1 mN	0,01 N	0,02 µm	0,24 µm	(0,11...0,55)°	(0,7...0,8) µm	(0,8...0,9) µm
GUM	1,9 mN	9,8 mN	0,29 N	0,2 µm	0,5 % d	<0,1°	0,3 µm	(0,2 ... 0,3) µm
NPL			0,246 N		0,14 % d	0,1°		0,37 µm
PTB	19,6 mN	9,8 mN	0,15 N	0,3 µm	0,4 µm	0,1°	0,3 µm	0,4 µm

The data in Table 24 for force *F*, diagonal length *d* and indenter plane angle *α* indicate the calibration uncertainties, whereas for tip radius *r* and length of line of junction *c* the deviation are given.
From this table one gets an overview that the calibration facilities have a rather wide range of achievable uncertainties. Whereas the facilities for force and length are well developed, for the characterisation of the indenter geometry in several cases no calibration facilities are available. Here in future corresponding facilities should be developed, set up and used.

9.2 Calculation of measurement uncertainty

As basis for the determination of the measurement uncertainty the draft guideline to the estimation of the uncertainty of the Brinell and the Vickers measuring method was recommended. [2] The uncertainty budgets of the participants based on this guideline are contained in Appendix A3.
The uncertainty budgets of the participants based on the unified procedure as presented in ch. 8.2 appear in Appendix A4.

9.3 Degree of equivalence

The degree of equivalence (*DoE*) of each participant with respect to the reference value is given by *DoE*(d_{ir}, U_{ir}) defined as:

$$d_{ir} = d_i - d_{ref}$$
$$U_{ir} = 2 \cdot \sqrt{(\left| u_i^2 - u_{ref}^2 \right|)} \qquad (30)$$

Here the corresponding uncertainties u_i and u_{ref} cannot simply be geometrically added, because the values d_i and d_{ref} are correlated.[3] The *DoE* is calculated for measurement results with E_n< 1. Because the original method in [3] is constructed for the case of the weighted mean value where u_{ref} is smaller than the smallest value of u_i, for the case of the arithmetic mean, which we have applied, for the radicand was taken the absolute value in order to avoid imaginary values.

Then the degree of equivalence between institute *i* and *j* is calculated as follows. For *i* = 1 ... N and *j* = 1 ... N with *j* not equal *i*, the degree of equivalence between institute *i* and institute *j* is formed as the pair of values (d_{ij}, $U(d_{ij})$) using

$$d_{i,j} = x_i - x_j$$
$$U(d_{i,j}) = 2u(d_{ij}) \qquad (31)$$

where $u(d_{i,j})$ is given by

$$u(d_{i,j}) = \sqrt{(u^2(x_i) + u^2(x_j)} \qquad (32)$$

Discrepant measurements are identified if

$$|d_i| > 2u(d_i) \qquad (33)$$

then x_i is classified as discrepant at the 5% level of significance.

The calculation of *DoE* according to this procedure is given in the following tables.

Table 25:

Degree of equivalence related to the reference values

1) Deviations d_{ij} from reference values

	240HV0,2	**240HV1**	**240HV30**	**540HV0,2**	**540HV1**	**540HV30**	**840HV0,2**	**840HV1**	**840HV30**
IMGC	8,03	1,30	-1,32	13,83	10,49	-0,06	23,39		1,50
INMETRO						9,43			
NIST	-1,40			-5,83			-13,81		
NMIJ	-4,69	-1,40		-4,99	-9,90		-8,63	-5,87	-7,76
NIM	-3,91	-1,93	-2,75	2,30	-5,79	-6,63	-6,85	-2,61	-3,44
KRISS	1,31	-0,98	2,81	4,46	-0,46	2,90	-0,56	8,34	12,51
CMI	-1,07	0,92	-0,42	-11,50	1,03	-4,78		-4,59	
GUM	-4,27	-1,25	3,43	-4,57	1,20	2,39	-10,81	0,36	-1,32
NPL			-0,60			-0,65			
PTB	6,00	3,34	-1,15	6,30	3,41	-2,62	17,26	4,38	-1,49

2) Values of uncertainty U_{ir}

	240HV0,2	**240HV1**	**240HV30**	**540HV0,2**	**540HV1**	**540HV30**	**840HV0,2**	**840HV1**	**840HV30**
IMGC	23,27	8,87	1,45	59,45	24,76	9,09	111,38		14,50
INMETRO						18,48			
NIST	19,35			22,09			27,77		
NMIJ	21,98	11,04		92,34	42,27		176,86	79,15	4,69
NIM	25,62	11,26	2,16	37,98	18,55	9,51	83,53	26,95	7,46
KRISS	24,56	10,40	6,10	39,35	12,57	10,98	67,80	8,11	6,21
CMI	29,83	12,53	3,14	17,57	32,10	2,92		41,55	
GUM	22,84	14,00	9,19	38,14	13,23	21,60	51,06	18,64	25,50
NPL			3,67			2,68			
PTB	23,49	14,41	2,71	32,64	18,24	8,09	52,38	14,02	13,93

Table 26:

Hardness scale 240 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INME-TRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	9,42	12,71	11,94	6,72	9,09	12,16	0	2,03
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-9,42	0	0,00	3,29	2,52	-2,70	-0,33	2,74	0	-7,39
NMIJ	-12,71	0	-3,29	0	-0,77	-5,99	-3,62	-0,55	0	-10,68
NIM	-11,94	0	-2,52	0,77	0	-5,22	-2,85	0,22	0	-9,91
KRISS	-6,72	0	2,70	5,99	5,22	0	2,37	5,44	0	-4,69
CMI	-9,09	0	0,33	3,62	2,85	-2,37	0	3,07	0	-7,06
GUM	-12,16	0	-2,74	0,55	-0,22	-5,44	-3,07	0	0	-10,13
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-2,03	0	7,39	10,68	9,91	4,69	7,06	10,13	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	32,91	34,52	36,94	36,21	39,98	35,07	0	35,50
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	32,01	34,61	37,83	37,83	32,61	0	33,06
NMIJ				0	36,14	35,40	39,24	34,23	0	34,66
NIM					0	37,77	41,39	36,67	0	37,08
KRISS						0	40,74	35,94	0	36,35
CMI							0	39,73	0	40,11
GUM								0	0	35,22
NPL									0	0
PTB										0

Table 27:

Hardness scale 240 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	2,70	3,23	2,28	0,38	2,55	0	-2,04
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-2,70	0	0	0	0,53	-0,42	-2,32	-0,15	0	-4,74
NIM	-3,23	0	0	-0,53	0	-0,95	-2,85	-0,68	0	-5,27
KRISS	-2,28	0	0	0,42	0,95	0	-1,90	0,27	0	-4,32
CMI	-0,38	0	0	2,32	2,85	1,90	0	2,17	0	-2,42
GUM	-2,55	0	0	0,15	0,68	-0,27	-2,17	0	0	-4,59
NPL	0	0	0	0	0	0	0	0	0	0
PTB	2,04	0	0	4,74	5,27	4,32	2,42	4,59	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	9,80	15,34	15,49	14,88	16,44	17,58	0	17,92
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	16,83	16,27	17,71	18,77	0	19,09
NIM					0	16,41	17,84	18,90	0	19,21
KRISS						0	17,31	18,40	0	18,72
CMI							0	19,68	0	19,98
GUM								0	0	20,93
NPL									0	0
PTB										0

Table 28:

Hardness scale 240 HV30

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	1,43	-4,13	-0,90	-4,75	-0,72	-0,17
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	0	0	0	0	0	0
NIM	-1,43	0	0	0	0	-5,56	-2,33	-6,18	-2,15	-1,60
KRISS	4,13	0	0	0	5,56	0	3,23	-0,62	3,41	3,96
CMI	0,90	0	0	0	2,33	-3,23	0	-3,85	0,18	0,73
GUM	4,75	0	0	0	6,18	0,62	3,85	0	4,03	4,58
NPL	0,72	0	0	0	2,15	-3,41	-0,18	-4,03	0	0,55
PTB	0,17	0	0	0	1,60	-3,96	-0,73	-4,58	-0,55	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	5,34	8,39	4,83	10,85	4,44	5,08
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	0	0	0	0	0	0
NIM					0	7,97	4,07	10,53	3,60	4,37
KRISS						0	7,64	12,36	7,40	7,80
CMI							0	10,28	2,78	3,72
GUM								0	10,10	10,40
NPL									0	3,20
PTB										0

Table 29:

Hardness scale 540 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	19,66	18,82	11,53	9,37	25,33	18,40	0	7,53
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-19,66	0	0,00	-0,84	-8,13	-10,29	5,67	-1,26	0	-12,13
NMIJ	-18,82	0	0,84	0	-7,29	-9,45	6,51	-0,42	0	-11,29
NIM	-11,53	0	8,13	7,29	0	-2,16	13,80	6,87	0	-4,00
KRISS	-9,37	0	10,29	9,45	2,16	0	15,96	9,03	0	-1,84
CMI	-25,33	0	-5,67	-6,51	-13,80	-15,96	0	-6,93	0	-17,80
GUM	-18,40	0	1,26	0,42	-6,87	-9,03	6,93	0	0	-10,87
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-7,53	0	12,13	11,29	4,00	1,84	17,80	10,87	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	68,13	112,61	74,81	75,51	66,80	74,89	0	72,24
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	98,15	50,50	28,24	37,62	50,61	0	46,61
NMIJ				0	102,90	103,41	97,23	102,96	0	101,05
NIM					0	60,08	48,69	59,30	0	55,92
KRISS						0	49,76	60,18	0	56,86
CMI							0	48,81	0	44,64
GUM								0	0	56,03
NPL									0	0
PTB										0

Table 30:

Hardness scale 540 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	20,39	16,28	10,95	9,46	9,29	0	7,08
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-20,39	0	0	0	-4,11	-9,44	-10,93	-11,10	0	-13,31
NIM	-16,28	0	0	4,11	0	-5,33	-6,82	-6,99	0	-9,20
KRISS	-10,95	0	0	9,44	5,33	0	-1,49	-1,66	0	-3,87
CMI	-9,46	0	0	10,93	6,82	1,49	0	-0,17	0	-2,38
GUM	-9,29	0	0	11,10	6,99	1,66	0,17	0	0	-2,21
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-7,08	0	0	13,31	9,20	3,87	2,38	2,21	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	51,94	35,42	32,69	44,06	32,95	0	35,26
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	49,28	47,36	55,81	47,54	0	49,17
NIM					0	28,28	40,89	28,58	0	31,21
KRISS						0	38,55	25,12	0	28,08
CMI							0	38,77	0	40,75
GUM								0	0	28,38
NPL									0	0
PTB										0

Table 31:

Hardness scale 540 HV30

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	-4,47	0	0	6,57	-2,96	4,72	-2,45	0,59	2,56
INMETRO	9,49	0	0	0	16,06	6,53	14,21	7,04	10,08	12,05
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	0	0	0	0	0	0
NIM	-6,57	-16,06	0	0	0	-9,53	-1,85	-9,02	-5,98	-4,01
KRISS	2,96	-6,53	0	0	9,53	0	7,68	0,51	3,55	5,52
CMI	-4,72	-14,21	0	0	1,85	-7,68	0	-7,17	-4,13	-2,16
GUM	2,45	-7,04	0	0	9,02	-0,51	7,17	0	3,04	5,01
NPL	-0,59	-10,08	0	0	5,98	-3,55	4,13	-3,04	0	1,97
PTB	-2,56	-12,05	0	0	4,01	-5,52	2,16	-5,01	-1,97	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	21,42	0	0	14,41	15,42	11,22	24,17	10,49	13,52
INMETRO		0	0	0	21,60	22,28	19,61	29,03	19,21	21,01
NIST			0	0	0	0	0	0	0	0
NMIJ				0	0	0	0	0	0	0
NIM					0	15,67	11,56	24,33	10,86	13,80
KRISS						0	12,79	24,94	12,16	14,85
CMI							0	22,58	5,99	10,42
GUM								0	22,23	23,81
NPL									0	9,64
PTB										0

Table 32:

Hardness scale 840 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	37,20	32,02	30,24	23,95	0	34,20	0	6,13
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-37,20	0	0	-5,18	-6,96	-13,25	0	-3,00	0	-31,07
NMIJ	-32,02	0	5,18	0	-1,78	-8,07	0	2,18	0	-25,89
NIM	-30,24	0	6,96	1,78	0	-6,29	0	3,96	0	-24,11
KRISS	-23,95	0	13,25	8,07	6,29	0	0	10,25	0	-17,82
CMI	0,00	0	0	0	0	0	0	0	0	0
GUM	-34,20	0	3,00	-2,18	-3,96	-10,25	0	0	0	-28,07
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-6,13	0	31,07	25,89	24,11	17,82	0	28,07	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	135,39	220,99	156,64	148,85	0	142,01	0	142,49
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	192,88	113,58	57,86	0	92,37	0	93,10
NMIJ				0	208,35	202,56	0	197,59	0	197,93
NIM					0	129,33	0	121,40	0	121,96
KRISS						0	0	111,17	0	111,78
CMI							0	0	0	0
GUM								0	0	102,49
NPL									0	0
PTB										0

Table 33:
Hardness scale 840 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	0	0	0	0	0	0
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	-3,26	-14,21	-1,28	-6,23	0	-10,25
NIM	0	0	0	3,26	0	-10,95	1,98	-2,97	0	-6,99
KRISS	0	0	0	14,21	10,95	0	12,93	7,98	0	3,96
CMI	0	0	0	1,28	-1,98	-12,93	0	-4,95	0	-8,97
GUM	0	0	0	6,23	2,97	-7,98	4,95	0	0	-4,02
NPL	0	0	0	0	0	0	0	0	0	0
PTB	0	0	0	10,25	6,99	-3,96	8,97	4,02	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	0	0	0	0	0	0
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	96,20	92,70	101,26	90,44	86,00	93,40
NIM					0	55,27	68,67	51,40	43,10	56,44
KRISS						0	63,68	44,51	34,60	50,25
CMI							0	60,35	53,46	64,70
GUM								0	28,00	45,96
NPL									0	0,00
PTB										0

Table 34:
Hardness scale 840 HV30
1) Differences d_{ij} between institutes

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	9,26	4,94	-11,01	0	2,82	0	2,99
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-9,26	0	0	0	-4,32	-20,27	0	-6,44	0	-6,27
NIM	-4,94	0	0	4,32	0	-15,95	0	-2,12	0	-1,95
KRISS	11,01	0	0	20,27	15,95	0	0	13,83	0	14,00
CMI	0	0	0	0	0	0	0	0	0	0
GUM	-2,82	0	0	6,44	2,12	-13,83	0	0	0	0,17
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-2,99	0	0	6,27	1,95	-14,00	0	-0,17	0	0

2) Uncertainty between institutes $U(d_{ij})$

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	27,93	27,32	27,63	0	38,10	0	24,65
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	30,57	30,85	0	40,50	0	28,21
NIM					0	30,29	0	40,08	0	27,61
KRISS						0	0	40,29	0	27,92
CMI							0	0	0	0
GUM								0	0	38,31
NPL									0	0
PTB										0

The consistency check delivered the result that the tables 26 to 34 do not contain discrepant values for *DoE*. As expected this consistency check concurs with the E_n values.

10 Discussions, conclusions and remarks

The CCM Vickers key comparison can be considered as a successful metrological exercise. Representatively it delivered for all three ranges of the test forces (Micro-Vickers, small load Vickers and Macro-Vickers scales) valuable metrological data. At present Vickers hardness reference blocks with high time-dependent stability and high local homogeneity, including high surface quality are available.
The uncertainties of the reference values are obviously the smallest uncertainties reached in the field of Vickers measurements worldwide so far. These uncertainties can be interpreted as the present limits of Vickers measurements in the investigated range of hardness scales. This is one important outcome of this Vickers key comparison.
In order to overcome these metrological limits in the future, it is recommended to concentrate metrological investigations on the following topics:
1) It was found that the calibration methods for the diagonal measurements, especially for diagonal lengths d > 100 µm should be improved.
2) The calibration methods for the parameters of the indenter geometry, like tip radius and length of the line of junction should be further developed.
3) The inputs from the participants to the used draft guideline for the estimation of the measurement uncertainty should be used for its further qualification. In this context it seems to be necessary to carry out experimental investigations on the determination of sensitivity coefficients for material dependent influences on the Vickers hardness measurement, especially influences of the force-time regime on the Vickers hardness.
4) For the further reduction of the uncertainty of Micro-Vickers measurements it is necessary to correct for the indenter deviations and to provide indenters with higher quality.
5) With the development of automatic Vickers indent measurements on the basis of CCD technique it is necessary to guarantee a high agreement of measurements both with CCD systems and with optical microscopes. This requires investigations about the relationships between both methods.

6) For the diagonal measurements with optical microscopes the properties of the used optical system should be further investigated.

11 References

[1] T. J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, BIPM, Paris

[2] EA Working group Hardness; Draft: Guideline to the estimation of the uncertainty of the Brinell and the Vickers measuring method, July 2002

[3] W. Bich, M.G. Cox, W.T. Estler, L. Nielsen, W. Woeger: Proposed guidelines for the evaluation of key comparison data, BIPM (2002)

Abstract
In the framework of the Working Group on Hardness (WGH) of the Consultative Committee for Mechanical Measurements (CCM) in the year 2003 the key comparison Vickers was finished. In the comparison the hardness laboratories of the following national metrology institutes participated: IMGC (Italy), NIST (USA), INMETRO (Brazil), NIM (P.R. China), KRISS (Republic of Korea), NMIJ (Japan), CMI (Czech Republic), GUM (Poland), NPL (U.K.), and PTB (Germany) served as the pilot laboratory. The comparison of the Vickers primary hardness standard machines was carried out with three sets of hardness reference blocks of the Vickers scales HV0,2, HV1 and HV 30 each with the hardness levels 240 HV, 540 HV and 840 HV. The Vickers key comparison for all used test forces ranges (Micro Vickers, Small force Vickers, Macro Vickers) delivered the following results.

Table A1:
Results of the measurements for the hardness reference blocks with hardness level 240 HV

	HV0,2		HV1		HV30	
Institute	**Mean value**	**Std.dev.**	**Mean value**	**Std. dev.**	**Mean value**	**Std. dev.**
PTB	248,19	2,67	244,06	1,79		
IMGC	254,30	4,34	241,11	3,18	237,83	0,88
INMETRO					244,83	0,77
NIST	244,88	3,31	236,13	1,81		
NMIJ	241,59	3,92	238,41	1,71	236,11	1,21
NIM	242,36	2,77	237,88	0,86	236,40	0,44
KRISS	247,58	3,48	238,83	1,88	241,96	0,46
CMI	245,21	3,00	240,73	0,66	238,73	0,39
GUM	242,14	2,56	238,56	2,28	242,58	0,77
NPL	253,65	2,92	240,33	3,55	238,55	0,53
PTB	252,27	2,99	243,15	2,46	238,00	0,56
Mean value	247,20		239,92		239,44	
Std.dev.	4,83		2,44		2,99	

Table A2:
Results of the measurements for the hardness reference blocks with hardness level 540 HV

	HV0,2		HV1		HV30	
Institute	**Mean val.x_8**	**Std.dev.s_8**	**Mean val.x_8**	**Std. dev.s_8**	**Mean val.x_8**	**Std. dev.s_8**
PTB	528,42	5,81	539,03	5,97		
IMGC	548,16	6,12	544,84	5,71	525,45	1,35
INMETRO					534,94	2,08
NIST	528,50	3,34	522,50	1,77		
NMIJ	529,34	6,24	524,45	5,71	516,68	1,90
NIM	536,63	1,87	528,56	2,10	518,88	0,79
KRISS	538,79	4,61	533,89	2,94	528,41	1,57
CMI	522,83	5,50	535,38	1,30	520,73	0,57
GUM	529,76	6,11	535,55	2,72	527,90	1,30
NPL	547,36	13,07	536,63	4,34	524,86	1,06
PTB	540,63	5,22	537,76	1,59	522,89	2,50
M.val.x_{Inst}	535,04		533,86		524,53	
Std.dev.s_{Inst}	8,61		6,84		5,55	

Table A3:
Results of the measurements for the hardness reference blocks with hardness level 840 HV

CCM Vickers key comparison
Results for 840 HV hardness reference blocks

	HV0,2		HV1		HV30	
Institute	**Mean val.x_8**	**Std.dev. s_8**	**Mean val.x_8**	**Std. dev. s_8**	**Mean val.x_8**	**Std. dev. s_8**
PTB	839,78	9,38	831,49	6,14		
IMGC	864,20	44,79	875,40	10,05	820,85	2,15
INMETRO					841,55	1,43
NIST	827,00	7,09	815,38	6,35		
NMIJ	832,18	13,40	825,54	7,39	811,59	5,93
NIM	833,96	5,00	828,80	3,24	815,91	1,71
KRISS	840,25	3,77	839,75	5,77	831,86	1,68
CMI	813,37	4,02	826,82	4,45	810,64	1,08
GUM	830,00	5,77	831,77	3,26	818,03	2,20
NPL	897,57	13,60	839,32	7,54	837,17	1,55
PTB	858,07	10,22	835,79	6,62	817,86	3,39
M.val.x_{Inst}	843,64		835,01		822,83	
Std.dev. s_{Inst}	23,97		15,91		11,25	

Table A4:
Reference values and their uncertainties for the hardness measurements (evaluation by the unified procedure)

Hardness scale	**Reference value x_{ref}, HV**	**Uncertainty of reference value U_{ref}**	
		Abs. unc., HV	**Rel. unc., %**
240 HV0,2	246,28	4,57	1,86
240 HV1	239,81	2,08	0,87
240 HV30	239,15	1,97	0,82
540 HV0,2	534,33	8,80	1,65
540 HV1	534,35	6,10	1,14
540 HV30	525,51	5,03	0,96
840 HV0,2	840,81	25,38	3,02
840 HV1	831,41	16,82	2,02
840 HV30	819,35	11,25	1,37

Table A5:
Results of the relative measurement uncertainty (in %) according to the estimation of the participant (part) and to the unified procedure (unif)

Institute	240HV0,2		240HV1		240HV30		540HV0,2		540HV1		540HV30		840HV0,2		840HV1		840HV30	
	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif	part	unif
IMGC	3,9	4,1	1,7	1,9	0,9	0,7	5,7	5,8	2,5	2,8	1,0	0,8	7,1	7,0	3,2	3,4	1,0	0,9
INMETRO					1,8	4,1					1,8	3,7					1,8	4,6
NIST	2,0	2,7	1,1	1,2			2,7	4,0	1,4	1,9			3,5	5,1	1,6	2,2		
NMIJ	5,8	3,3	2,9	1,8	0,9	0,6	8,9	4,9	4,2	2,6	1,2	1,0	11,1	6,1	5,2	3,3	1,4	1,2
NIM	3,1	4,5	1,4	2,1	0,7	0,6	3,9	6,9	2,1	3,2	1,0	1,0	5,9	8,6	2,6	3,9	1,3	1,2
KRISS	2,9	2,4	1,4	1,1	1,5	0,6	4,0	3,8	1,6	1,4	1,1	0,7	5,0	4,1	2,1	2,3	1,3	0,7
CMI	2,4	1,7	3,2	0,7	0,5	0,6	2,3	2,5	3,2	1,0	0,5	0,7	2,2	3,1	3,2	1,3	0,5	0,8
GUM	3,3	2,9	1,7	2,4	2,1	2,3	3,9	4,3	1,7	2,8	2,0	2,2	4,3	5,4	1,7	2,6	2,1	2,2
NPL					0,3	0,6					0,3	0,7					0,3	0,8
PTB	3,1	3,3	2,0	2,3	0,6	0,6	3,4	3,0	2,0	2,2	0,9	1,0	4,3	3,7	2,2	2,2	1,1	1,2
Mean value	3,3	3,1	1,9	1,7	1,0	1,2	4,4	4,4	2,3	2,2	1,1	1,3	5,4	5,4	2,7	2,7	1,2	1,5
Variation	3,8	2,8	2,1	1,7	1,8	3,5	6,6	4,4	2,8	2,2	1,7	3	8,9	5,5	3,6	2,6	1,8	3,9

Table A6:
Coefficients E_n in the case of the unified procedure for the estimation of the measurement uncertainty (based on the arithmetic mean)

	E_n values								
	240 HV			540 HV			840 HV		
	HV0,2	HV1	HV30	HV0,2	HV1	HV30	HV0,2	HV1	HV30
IMGC	0,55	0,32	0,62	0,31	0,63	0,17	0,26	1,06	0,18
INMETRO			0,66			0,84			0,76
NIST	0,19	0,67		0,20	0,63		0,24	0,62	
NMIJ	0,44	0,17	1,12	0,16	0,44	1,10	0,15	0,24	0,79
NIM	0,33	0,25	1,02	0,02	0,22	0,77	0,11	0,16	0,48
KRISS	0,04	0,11	0,78	0,07	0,03	0,68	0,05	0,11	0,70
CMI	0,12	0,19	0,22	0,26	0,09	0,51	0,31	0,19	0,85
GUM	0,39	0,12	0,48	0,15	0,11	0,24	0,17	0,11	0,22
NPL			0,31			0,05			1,12
PTB	0,39	0,48	0,45	0,16	0,24	0,20	0,23	0,01	0,31
Mean	0,31	0,29	0,63	0,17	0,30	0,51	0,19	0,31	0,60

The degree of equivalence between the participating institutes for the different hardness scales follows from the tables A7 to A16.

Table A7:
Degree of equivalence related to the reference values
1) Deviations d_{ij} from reference values

	240HV0,2	240HV1	240HV30	540HV0,2	540HV1	540HV30	840HV0,2	840HV1	840HV30
IMGC	8,03	1,30	-1,32	13,83	10,49	-0,06	23,39		1,50
INMETRO						9,43			
NIST	-1,40			-5,83			-13,81		
NMIJ	-4,69	-1,40		-4,99	-9,90		-8,63	-5,87	-7,76
NIM	-3,91	-1,93	-2,75	2,30	-5,79	-6,63	-6,85	-2,61	-3,44
KRISS	1,31	-0,98	2,81	4,46	-0,46	2,90	-0,56	8,34	12,51
CMI	-1,07	0,92	-0,42	-11,50	1,03	-4,78		-4,59	
GUM	-4,27	-1,25	3,43	-4,57	1,20	2,39	-10,81	0,36	-1,32
NPL			-0,60			-0,65			
PTB	6,00	3,34	-1,15	6,30	3,41	-2,62	17,26	4,38	-1,49

2) Values of uncertainty U_{ir}

	240HV0,2	240HV1	240HV30	540HV0,2	540HV1	540HV30	840HV0,2	840HV1	840HV30
IMGC	23,27	8,87	1,45	59,45	24,76	9,09	111,38		14,50
INMETRO						18,48			
NIST	19,35			22,09			27,77		
NMIJ	21,98	11,04		92,34	42,27		176,86	79,15	4,69
NIM	25,62	11,26	2,16	37,98	18,55	9,51	83,53	26,95	7,46
KRISS	24,56	10,40	6,10	39,35	12,57	10,98	67,80	8,11	6,21
CMI	29,83	12,53	3,14	17,57	32,10	2,92		41,55	
GUM	22,84	14,00	9,19	38,14	13,23	21,60	51,06	18,64	25,50
NPL			3,67			2,68			
PTB	23,49	14,41	2,71	32,64	18,24	8,09	52,38	14,02	13,93

Table A8:

Hardness scale 240 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INME-TRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	9,42	12,71	11,94	6,72	9,09	12,16	0	2,03
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-9,42	0	0,00	3,29	2,52	-2,70	-0,33	2,74	0	-7,39
NMIJ	-12,71	0	-3,29	0	-0,77	-5,99	-3,62	-0,55	0	-10,68
NIM	-11,94	0	-2,52	0,77	0	-5,22	-2,85	0,22	0	-9,91
KRISS	-6,72	0	2,70	5,99	5,22	0	2,37	5,44	0	-4,69
CMI	-9,09	0	0,33	3,62	2,85	-2,37	0	3,07	0	-7,06
GUM	-12,16	0	-2,74	0,55	-0,22	-5,44	-3,07	0	0	-10,13
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-2,03	0	7,39	10,68	9,91	4,69	7,06	10,13	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	32,91	34,52	36,94	36,21	39,98	35,07	0	35,50
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	32,01	34,61	37,83	37,83	32,61	0	33,06
NMIJ				0	36,14	35,40	39,24	34,23	0	34,66
NIM					0	37,77	41,39	36,67	0	37,08
KRISS						0	40,74	35,94	0	36,35
CMI							0	39,73	0	40,11
GUM								0	0	35,22
NPL									0	0
PTB										0

Table A9:

Hardness scale 240 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	2,70	3,23	2,28	0,38	2,55	0	-2,04
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-2,70	0	0	0	0,53	-0,42	-2,32	-0,15	0	-4,74
NIM	-3,23	0	0	-0,53	0	-0,95	-2,85	-0,68	0	-5,27
KRISS	-2,28	0	0	0,42	0,95	0	-1,90	0,27	0	-4,32
CMI	-0,38	0	0	2,32	2,85	1,90	0	2,17	0	-2,42
GUM	-2,55	0	0	0,15	0,68	-0,27	-2,17	0	0	-4,59
NPL	0	0	0	0	0	0	0	0	0	0
PTB	2,04	0	0	4,74	5,27	4,32	2,42	4,59	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	9,80	15,34	15,49	14,88	16,44	17,58	0	17,92
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	16,83	16,27	17,71	18,77	0	19,09
NIM					0	16,41	17,84	18,90	0	19,21
KRISS						0	17,31	18,40	0	18,72
CMI							0	19,68	0	19,98
GUM								0	0	20,93
NPL									0	0
PTB										0

Table A10:

Hardness scale 240 HV30

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	1,43	-4,13	-0,90	-4,75	-0,72	-0,17
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	0	0	0	0	0	0
NIM	-1,43	0	0	0	0	-5,56	-2,33	-6,18	-2,15	-1,60
KRISS	4,13	0	0	0	5,56	0	3,23	-0,62	3,41	3,96
CMI	0,90	0	0	0	2,33	-3,23	0	-3,85	0,18	0,73
GUM	4,75	0	0	0	6,18	0,62	3,85	0	4,03	4,58
NPL	0,72	0	0	0	2,15	-3,41	-0,18	-4,03	0	0,55
PTB	0,17	0	0	0	1,60	-3,96	-0,73	-4,58	-0,55	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	5,34	8,39	4,83	10,85	4,44	5,08
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	0	0	0	0	0	0
NIM					0	7,97	4,07	10,53	3,60	4,37
KRISS						0	7,64	12,36	7,40	7,80
CMI							0	10,28	2,78	3,72
GUM								0	10,10	10,40
NPL									0	3,20
PTB										0

Table A11:

Hardness scale 540 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	19,66	18,82	11,53	9,37	25,33	18,40	0	7,53
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-19,66	0	0,00	-0,84	-8,13	-10,29	5,67	-1,26	0	-12,13
NMIJ	-18,82	0	0,84	0	-7,29	-9,45	6,51	-0,42	0	-11,29
NIM	-11,53	0	8,13	7,29	0	-2,16	13,80	6,87	0	-4,00
KRISS	-9,37	0	10,29	9,45	2,16	0	15,96	9,03	0	-1,84
CMI	-25,33	0	-5,67	-6,51	-13,80	-15,96	0	-6,93	0	-17,80
GUM	-18,40	0	1,26	0,42	-6,87	-9,03	6,93	0	0	-10,87
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-7,53	0	12,13	11,29	4,00	1,84	17,80	10,87	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	68,13	112,61	74,81	75,51	66,80	74,89	0	72,24
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	98,15	50,50	28,24	37,62	50,61	0	46,61
NMIJ				0	102,90	103,41	97,23	102,96	0	101,05
NIM					0	60,08	48,69	59,30	0	55,92
KRISS						0	49,76	60,18	0	56,86
CMI							0	48,81	0	44,64
GUM								0	0	56,03
NPL									0	0
PTB										0

Table A12:

Hardness scale 540 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	20,39	16,28	10,95	9,46	9,29	0	7,08
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-20,39	0	0	0	-4,11	-9,44	-10,93	-11,10	0	-13,31
NIM	-16,28	0	0	4,11	0	-5,33	-6,82	-6,99	0	-9,20
KRISS	-10,95	0	0	9,44	5,33	0	-1,49	-1,66	0	-3,87
CMI	-9,46	0	0	10,93	6,82	1,49	0	-0,17	0	-2,38
GUM	-9,29	0	0	11,10	6,99	1,66	0,17	0	0	-2,21
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-7,08	0	0	13,31	9,20	3,87	2,38	2,21	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	51,94	35,42	32,69	44,06	32,95	0	35,26
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	49,28	47,36	55,81	47,54	0	49,17
NIM					0	28,28	40,89	28,58	0	31,21
KRISS						0	38,55	25,12	0	28,08
CMI							0	38,77	0	40,75
GUM								0	0	28,38
NPL									0	0
PTB										0

Table A13:

Hardness scale 540 HV30

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	-4,47	0	0	6,57	-2,96	4,72	-2,45	0,59	2,56
INMETRO	9,49	0	0	0	16,06	6,53	14,21	7,04	10,08	12,05
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	0	0	0	0	0	0
NIM	-6,57	-16,06	0	0	0	-9,53	-1,85	-9,02	-5,98	-4,01
KRISS	2,96	-6,53	0	0	9,53	0	7,68	0,51	3,55	5,52
CMI	-4,72	-14,21	0	0	1,85	-7,68	0	-7,17	-4,13	-2,16
GUM	2,45	-7,04	0	0	9,02	-0,51	7,17	0	3,04	5,01
NPL	-0,59	-10,08	0	0	5,98	-3,55	4,13	-3,04	0	1,97
PTB	-2,56	-12,05	0	0	4,01	-5,52	2,16	-5,01	-1,97	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	21,42	0	0	14,41	15,42	11,22	24,17	10,49	13,52
INMETRO		0	0	0	21,60	22,28	19,61	29,03	19,21	21,01
NIST			0	0	0	0	0	0	0	0
NMIJ				0	0	0	0	0	0	0
NIM					0	15,67	11,56	24,33	10,86	13,80
KRISS						0	12,79	24,94	12,16	14,85
CMI							0	22,58	5,99	10,42
GUM								0	22,23	23,81
NPL									0	9,64
PTB										0

Table A14:

Hardness scale 840 HV0,2

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	37,20	32,02	30,24	23,95	0	34,20	0	6,13
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	-37,20	0	0	-5,18	-6,96	-13,25	0	-3,00	0	-31,07
NMIJ	-32,02	0	5,18	0	-1,78	-8,07	0	2,18	0	-25,89
NIM	-30,24	0	6,96	1,78	0	-6,29	0	3,96	0	-24,11
KRISS	-23,95	0	13,25	8,07	6,29	0	0	10,25	0	-17,82
CMI	0	0	0	0	0	0	0	0	0	0
GUM	-34,20	0	3,00	-2,18	-3,96	-10,25	0	0	0	-28,07
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-6,13	0	31,07	25,89	24,11	17,82	0	28,07	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	135,39	220,99	156,64	148,85	0	142,01	0	142,49
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	192,88	113,58	57,86	0	92,37	0	93,10
NMIJ				0	208,35	202,56	0	197,59	0	197,93
NIM					0	129,33	0	121,40	0	121,96
KRISS						0	0	111,17	0	111,78
CMI							0	0	0	0
GUM								0	0	102,49
NPL									0	0
PTB										0

Table A15:

Hardness scale 840 HV1

1) *Differences d_{ij} between institutes*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	0	0	0	0	0	0
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	0	0	0	0	-3,26	-14,21	-1,28	-6,23	0	-10,25
NIM	0	0	0	3,26	0	-10,95	1,98	-2,97	0	-6,99
KRISS	0	0	0	14,21	10,95	0	12,93	7,98	0	3,96
CMI	0	0	0	1,28	-1,98	-12,93	0	-4,95	0	-8,97
GUM	0	0	0	6,23	2,97	-7,98	4,95	0	0	-4,02
NPL	0	0	0	0	0	0	0	0	0	0
PTB	0	0	0	10,25	6,99	-3,96	8,97	4,02	0	0

2) *Uncertainty between institutes $U(d_{ij})$*

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	0	0	0	0	0	0	0
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	96,20	92,70	101,26	90,44	86,00	93,40
NIM					0	55,27	68,67	51,40	43,10	56,44
KRISS						0	63,68	44,51	34,60	50,25
CMI							0	60,35	53,46	64,70
GUM								0	28,00	45,96
NPL									0	0,00
PTB										0

Table A16:

Hardness scale 840 HV30

1) Differences d_{ij} between institutes

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	9,26	4,94	-11,01	0	2,82	0	2,99
INMETRO	0	0	0	0	0	0	0	0	0	0
NIST	0	0	0	0	0	0	0	0	0	0
NMIJ	-9,26	0	0	0	-4,32	-20,27	0	-6,44	0	-6,27
NIM	-4,94	0	0	4,32	0	-15,95	0	-2,12	0	-1,95
KRISS	11,01	0	0	20,27	15,95	0	0	13,83	0	14,00
CMI	0	0	0	0	0	0	0	0	0	0
GUM	-2,82	0	0	6,44	2,12	-13,83	0	0	0	0,17
NPL	0	0	0	0	0	0	0	0	0	0
PTB	-2,99	0	0	6,27	1,95	-14,00	0	-0,17	0	0

2) Uncertainty between institutes $U(d_{ij})$

	IMGC	INMETRO	NIST	NMIJ	NIM	KRISS	CMI	GUM	NPL	PTB
IMGC	0	0	0	27,93	27,32	27,63	0	38,10	0	24,65
INMETRO		0	0	0	0	0	0	0	0	0
NIST			0	0	0	0	0	0	0	0
NMIJ				0	30,57	30,85	0	40,50	0	28,21
NIM					0	30,29	0	40,08	0	27,61
KRISS						0	0	40,29	0	27,92
CMI							0	0	0	0
GUM								0	0	38,31
NPL									0	0
PTB										0

The uncertainties of the reference values can be considered as the present accuracy limits of Vickers measurements in the investigated ranges of hardness scales.
In order to beat these metrological limits in the future, it is recommended to concentrate metrological investigations mainly on the following topics:

1) Improvement of the calibration methods for the diagonal measurements for diagonal lengths d > 100 µm
2) Further development of the calibration methods for the parameters of the indenter geometry, like tip radius and length of the line of junction
3) Experimental investigations for the determination of sensitivity coefficients for material dependent influences on Vickers measurements
4) Investigation of the relationships between results of Vickers measurements received with CCD systems and conventional optical microscopes
5) Further qualification of the guideline for the estimation of the uncertainty of Vickers measurements

The proposed investigations should be realised in a co-ordinated way in the framework of the WGH.