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Final Report on Supplementary Comparison No. APMP.M.H-S1

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Abstract

This report purposes the results of supplementary comparison APMP.M.H-S1 among four National Metrology Institutes (NIMT, NMIJ/AIST, VMI and SPRING). The comparison was carried out during October 2004 to January 2005 in order to determine the capability of the primary Rockwell hardness standard, including standard conditions, of each participant, to confirm the accuracy of Rockwell hardness scale C measurement declared by the participant, which includes the effect of each participant's primary indenter and determine the degrees of equivalence of hardness scale measurement in the range 20 HRC to 60 HRC. Furthermore, the comparison were carried out by common indenter, which provided by the pilot institute, in order to determine the measurement capability of participant's primary machine without the influence of the indenter, as a study of scientific purpose. The pilot institute was the National Institute of Metrology (Thailand), NIMT. There were 2 sets of artifacts for the comparison. Each set composed of 9 hardness blocks; 20 HRC, 25 HRC, 30 HRC, 35 HRC, 40 HRC, 45 HRC, 50 HRC, 55 HRC, 60 HRC. The verification of participant's primary Rockwell hardness machine was carried out according to ISO6508-3 before making the measurement. The pilot institute made measurements in the beginning and the end of the comparison in order to monitor the stability of the artifacts. The degree of equivalence of each national primary hardness standard was expressed quantitatively by two terms, the deviation from *KCRV* and the uncertainty of this deviation at a 95% level of confidence. The E_n parameter was calculated to express the equivalence between the measurements of participant as well. The degree of equivalence between pairs of participating institutes was expressed by the difference of their deviations from the key comparison reference value and the uncertainty of this difference at the 95% level of confidence.

Contents:

1. Introduction

The National Institute of Metrology (Thailand) or NIMT was requested to organize a comparison in Rockwell hardness scale C among ASEAN countries. The National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) was invited as a guest participant, due to their reputation through history and their experience.

An invitation was distributed to ASEAN countries on July 2004 by the pilot institute, NIMT. NIMJ/AIST(Japan), VMI(Vietnam) and SPRING(Singapore) responded to participate this comparison.

A protocol of the comparison was prepared by the pilot institute and was distributed to participating institutes on September 2004 to gather the comments and opinions from them. All participants accepted and approved the protocol.

The participating institutes used the primary Rockwell hardness machine as their standard. The artifacts of this comparison were 2 sets of hardness blocks. Each set composed of 9 hardness blocks: 20 HRC, 25 HRC, 30 HRC, 35 HRC, 40 HRC, 45 HRC, 50 HRC, 55 HRC, and 60 HRC. Set 1 was used for comparison with the common indenter (The common indenter was provided by pilot institute) whereas set 2 was used for comparison using the participant's primary indenter. There was the additional set (set 3) of blocks used for testing cycle adjustment and checking the machine's frame deformation as well. The additional set composed of the same-level hardness blocks as the artifact sets.

The two sets of artifacts, a set of the additional blocks and the common diamond indenter were sent from one participant to the next according to a timetable in which the date of measurement had been agreed with the participating institutes.

The participants carried out the verification of their primary Rockwell hardness machine according to ISO6508-3 before preceding the measurement on artifact blocks. The measurement results determined from the participants were submitted to the pilot institute and were used for analyzing the degrees of equivalence in this report. The comparison result of set 2 artifacts was the priority of this comparison because it showed the deviations obtained from each national standard of the participants. Whereas the result of set 1 was discussed as an "Experimental Comparison" in order to determine the performance of national primary hardness machine without the effect from indenter.

2. Participating Institutes and their Standards

2.1 List of Participating Institutes

Four National Metrology Institutes participated to this comparison including the pilot institute. The participating institutes are listed in Table 1 arranged by the order of measurement. The index number in the first column refers to the identification of the participating institute in this report.

Index	Institute	Acronym	Country
1	National Institute of Metrology (Thailand) (Pilot Institute)	NIMT	Thailand
2	Vietnam Metrology Institute	VMI	Vietnam
3	Standards, Productivity and Innovation Board	SPRING	Singapore
4	National Metrology Institute of Japan /National Advanced Institute of Science and Technology	NMIJ/AIST	Japan

Table 1: List of participating institutes

2.2 Standards of Participating Institutes

All participating institutes used primary Rockwell hardness machine as the standards. NIMT, NMIJ and SPRING used lever-amplified deadweight as the test force applying system while VMI used deadweight system. All primary Rockwell hardness machine were verified their preliminary test force, total test force, depth measuring device, tip radius of curvature and apex angle of their primary diamond indenter, testing condition, environmental condition and deformation of frame according to ISO6508-3 before measurement.

3. Circulation of the Artifacts

3.1 Chronology of Measurements

The artifacts of comparison were circulated to all participants during October 2004 to January 2005. The pilot institute made the measurement of artifacts at the beginning and the end of the comparison.

For each circulation, the pilot institute prepared ATA CARNET. The participating institute had to check the arrival artifacts according to attached checklist of artifact before make a measurement. The actual arrival time and result of inspection were informed to pilot laboratory by the participants. After the measurements were carried out, the participants reported the indentation positions that they made to the artifacts to pilot institute. The artifacts were sent to the next participant according to the sequence from technical protocol of the comparison. The actual departure time of artifacts were informed to the pilot institute as well.

Institute	Country	Arrival time	Departure time	Date of measurement
NIMT	Thailand	---	20/10/2004	13/10/2004
VMI	Vietnam	21/10/2004	29/10/2004	22/10/2004
SPRING	Singapore	8/11/2004	25/11/2004	12/11/2004
NMIJ/AIST	Japan	7/12/2004	17/12/2004	8-9/12/2004
NIMT	Thailand	22/12/2004	---	8-9/1/2005

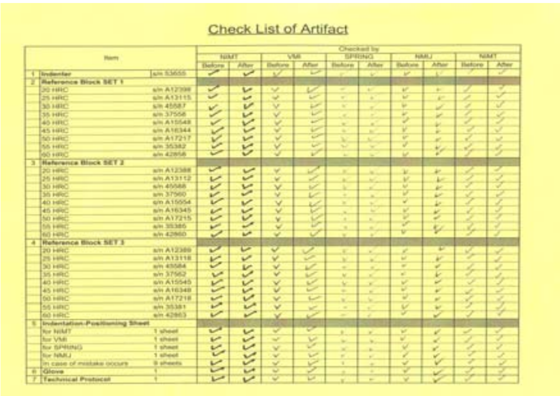
Table 2: Chronology of measurements

3.2 Transportation

Two sets of artifact blocks (set1 and set2), an additional set of blocks (set3) and common indenter were contained in the aluminum box for transportation. The technical protocol of the comparison, indentation-positioning sheet of each participant and checklist of artifact were attached with the artifacts in the aluminum boxes as well.

Fig.1: Aluminum box for transportation

Fig.2: Artifact blocks



Check List of Artifact

	Item		Checked by									
			NIMT		VMI		SPRING		NMIJ		NIMT	
			Before	After	Before	After	Before	After	Before	After	Before	After
1	Indenter	s/n 53655	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	Reference Block SET 1											
	20 HRC	s/n A12398	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25 HRC	s/n A13115	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 HRC	s/n 45587	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	35 HRC	s/n 37558	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	40 HRC	s/n A15548	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	45 HRC	s/n A16344	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	50 HRC	s/n A17217	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	55 HRC	s/n 35382	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	60 HRC	s/n 42858	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	Reference Block SET 2											
	20 HRC	s/n A12388	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25 HRC	s/n A13112	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 HRC	s/n 45588	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	35 HRC	s/n 37560	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	40 HRC	s/n A15554	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	45 HRC	s/n A16345	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	50 HRC	s/n A17215	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	55 HRC	s/n 35385	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	60 HRC	s/n 42860	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4	Reference Block SET 3											
	20 HRC	s/n A12389	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25 HRC	s/n A13118	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 HRC	s/n 45584	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	35 HRC	s/n 37562	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	40 HRC	s/n A15545	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	45 HRC	s/n A16348	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	50 HRC	s/n A17218	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	55 HRC	s/n 35381	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	60 HRC	s/n 42863	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5	Indentation-Positioning Sheet											
	for NIMT	1 sheet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	for VMI	1 sheet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	for SPRING	1 sheet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	for NMIJ	1 sheet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	In case of mistake occurs	8 sheets	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6	Glove	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
7	Technical Protocol	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fig.3: Checklist of artifacts

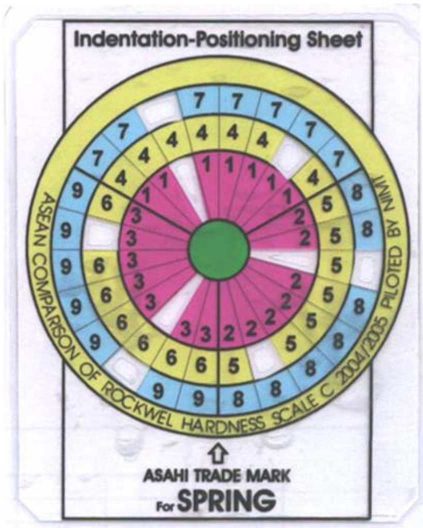


Fig. 4: Indentation positioning sheet

4. Measurements of Artifacts

4.1 Participants verified the primary Rockwell hardness machine according to ISO6508-3 and reported the following item:

- The relative error and uncertainty of preliminary test force
- The relative error and uncertainty of total test force
- The uncertainty of the depth measuring device
- The tip radius of curvature of the primary diamond cone indenter
- The apex angle of the primary diamond cone indenter
- Testing condition and uncertainty
- Environmental condition of measurement
- The deformation of the machine's frame

4.2 Participants carried out the deformation of the machine's frame verification by using the indenter with a spherical tip instead of the diamond cone indenter. The material of plunger and the dummy indenter (ideal specimen, which had high hardness-level) had the hardness of at least 60 HRC. The results of frame checking were recorded in Report Form1.

4.3 Participants adjusted the testing cycle of measurements by using the block set 3.

4.4 Participants started the measurement with common indenter by using the artifacts of set 1. Each block was made the indentation 9 points at the designated position as in the indentation-positioning sheet for each participant. All data of the measurement and the average value of each block were reported in Report Form 2.

4.5 Participants started the measurement with their primary indenters by using artifacts of set 2. All data of the measurement and the average value of each block were reported in Report Form 3.

Note: In case the participant made as incorrect indentation or was unsure about the measurement value, the spare segments on the block were used. The new position of measurement was informed to the next participant and the pilot institute immediately.

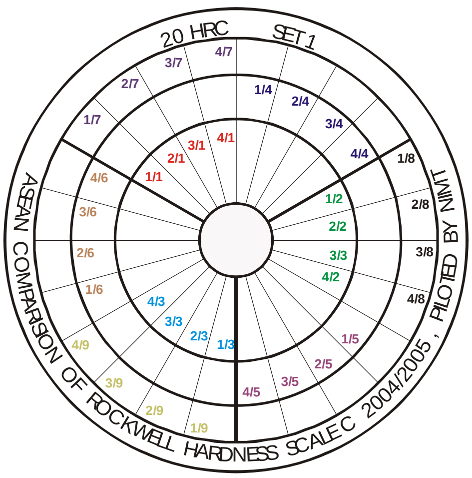


Fig.5: Indentation position of artifacts

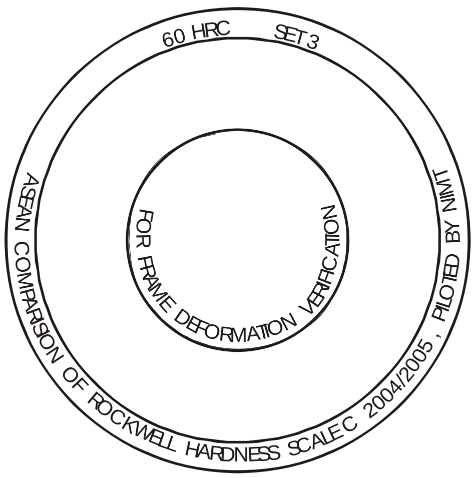


Fig.6: The 60 HRC block of set 3

5. Measurement data

The measurement data and uncertainty of artifact set 2 reported by the participants are listed in Table3.

Nominal	Measurement data of each participant				Uncertainty (k=2) of each participant			
	NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
20	20.06	19.86	20.22	19.99	0.45	0.35	0.37	0.34
25	25.04	24.96	25.10	24.88	0.45	0.35	0.37	0.34
30	30.86	30.51	30.86	30.77	0.45	0.25	0.37	0.34
35	35.78	35.69	35.82	35.86	0.45	0.27	0.37	0.34
40	40.46	40.21	40.43	40.58	0.45	0.27	0.26	0.30
45	45.01	44.87	45.01	45.15	0.45	0.27	0.26	0.30
50	50.28	50.20	50.30	50.34	0.45	0.29	0.48	0.30
55	55.65	55.73	55.68	55.80	0.45	0.27	0.48	0.30
60	60.12	60.25	60.10	60.29	0.45	0.42	0.48	0.30

Table 3: Measurement data and Uncertainty of artifact set2 (measured by participant's primary indenter)

The stability of artifact blocks was monitored by piloted institute (see topic 9: stability of artifacts during transportation). The significance of drifts in hardness value should be evaluated carefully. There were many discussions concerning with the stability of the artifact blocks. If the drifts were compared with the pilot institute's claimed uncertainty, the drift effect was not significant to the results. In this case, the drift correction to the result was not necessary.

However, in another idea, it was found that the drift in hardness value was significant compared to KCRV uncertainty at 55 HRC and 60 HRC. Therefore, with this criterion, the application of corrections due to drift error was necessary. By using the drift corrections from Table 22, new measurement data of participant after application of the drift corrections was shown in Table 4.

Nominal	Measurement data of each participant				Uncertainty (k=2) of each participant			
	1	2	3	4	1	2	3	4
20	20.06	19.86	20.23	20.00	0.45	0.35	0.37	0.34
25	25.04	24.96	25.11	24.90	0.45	0.35	0.37	0.34
30	30.86	30.52	30.89	30.82	0.45	0.25	0.37	0.34
35	35.78	35.69	35.81	35.84	0.45	0.27	0.37	0.34
40	40.46	40.20	40.41	40.55	0.45	0.27	0.26	0.30
45	45.01	44.87	45.00	45.13	0.45	0.27	0.26	0.30
50	50.28	50.19	50.28	50.30	0.45	0.29	0.48	0.30
55	55.65	55.72	55.64	55.72	0.45	0.27	0.48	0.30
60	60.12	60.24	60.07	60.23	0.45	0.42	0.48	0.30

Table 4: Measurement data corrected by drift effect and Uncertainty of artifact set 2
(measured by participant's primary indenter)

6. Analyzing method of comparison results

The results of comparison were determined by the following procedure:

6.1 Calculation of Key Comparison Reference Value (*KCRV*)

6.2 Calculation of Degree of Equivalence

6.2.1 The Degree of Equivalence of each participating institute

6.2.2 The Degree of Equivalence between pairs of institutes

6.3 Evaluation of Coefficients E_n

6.1 Calculation of Key Comparison Reference Value (*KCRV*)

Pilot laboratory determined *KCRV* by calculating the weighted mean of measurements of all participants (x_{ref}).

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

The uncertainty of the *KCRV* was calculated by following expression:

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

Where:

x_i = The measured value of participating institute i (i =1,2,…,n)

$u(x_i)$ = The standard uncertainty of x_i

6.2 Calculation of Degree of Equivalence

6.2.1 The Degree of Equivalence of each participating institute

The degree of equivalence of each participating institute was expressed by two terms,

- Its deviation from *KCRV*

$$d_i = x_i - x_{ref}$$

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

$$U(d_i) = k \cdot u(d_i)$$

Where $u(d_i)$ was given by

$$u^2(d_i) = u^2(x_i) + u^2(x_{ref})$$

And k = 2

6.2.2 The Degree of Equivalence between pairs of institutes

The degree of equivalence between pairs of participating institutes was expressed by the difference of their deviations from *KCRV* and the uncertainty of the difference at the 95% level of confidence. The following is the calculation of the degree of equivalence between pairs:

- Difference of deviations from *KCRV* between institute i and institute j

$$d_{i,j} = d_i - d_j = (x_i - x_{ref}) - (x_j - x_{ref}) = x_i - x_j$$

- Uncertainty of the difference at a 95% level of confidence

$$U(d_{i,j}) = 2u(d_{i,j})$$

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

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

Table 6 presents the degree of equivalence between pairs of the participating institutes.

6.3 Evaluation of Coefficient E_n

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

$$E_n = \frac{x_i - x_{ref}}{\sqrt{U^2(x_i) + U^2(x_{ref})}}$$

Where:

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

The x_i was equivalent with KCRV x_{ref} at 95% confidence level, if $|E_n| \le 1$.

7. Comparison Results

7.1 The Degree of Equivalence of each participating institute

By using the original measurement data (From Table 3), the key comparison reference value (*KCRV* or x_{ref}), the deviation from *KCRV* and the uncertainty of the deviation from *KCRV* of each participant were determined as shown in Table 5.

Nominal	X ref	U(x ref)	Deviation from KCRV				Uncertainty of the Deviation from KCRV (k=2)			
			NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
20	20.02	0.19	0.04	-0.16	0.20	-0.03	0.49	0.40	0.41	0.39
25	24.98	0.19	0.06	-0.02	0.12	-0.10	0.49	0.40	0.41	0.39
30	30.69	0.16	0.17	-0.18	0.17	0.08	0.48	0.30	0.40	0.38
35	35.77	0.17	0.01	-0.08	0.05	0.09	0.48	0.32	0.41	0.38
40	40.40	0.15	0.06	-0.19	0.03	0.18	0.47	0.31	0.30	0.34
45	45.00	0.15	0.01	-0.13	0.01	0.15	0.47	0.31	0.30	0.34
50	50.27	0.18	0.01	-0.07	0.03	0.07	0.48	0.34	0.51	0.35
55	55.73	0.17	-0.08	0.00	-0.05	0.07	0.48	0.32	0.51	0.35
60	60.22	0.20	-0.10	0.03	-0.12	0.07	0.49	0.46	0.52	0.36

Table 5: Deviation from KCRV and the uncertainty of the deviation without drift correction of artifact set 2 (measured by participant's primary indenter)

In case of drift corrections were applied to the results. By using the measurement data corrected by drift effect (From Table 4), the key comparison reference value (*KCRV* or x_{ref}), the deviation from *KCRV* and the uncertainty of the deviation from *KCRV* of each participant were determined as in Table 6.

Nominal	X ref	U(x ref)	Deviation from KCRV				Uncertainty of the Deviation from KCRV (k=2)			
			1	2	3	4	1	2	3	4
20	20.03	0.19	0.03	-0.17	0.20	-0.03	0.49	0.40	0.41	0.39
25	24.99	0.19	0.05	-0.03	0.12	-0.09	0.49	0.40	0.41	0.39
30	30.71	0.16	0.15	-0.19	0.18	0.11	0.48	0.30	0.40	0.38
35	35.76	0.17	0.02	-0.08	0.05	0.08	0.48	0.32	0.41	0.38
40	40.39	0.15	0.07	-0.18	0.03	0.16	0.47	0.31	0.30	0.34
45	44.99	0.15	0.02	-0.13	0.01	0.14	0.47	0.31	0.30	0.34
50	50.26	0.18	0.02	-0.06	0.02	0.05	0.48	0.34	0.51	0.35
55	55.70	0.17	-0.05	0.02	-0.06	0.02	0.48	0.32	0.51	0.35
60	60.18	0.20	-0.06	0.06	-0.12	0.04	0.49	0.46	0.52	0.36

Table 6: Deviation from KCRV and the uncertainty of the deviation with drift corrections of artifact set 2 (measured by participant's primary indenter)

The comparison results without drift correction of artifact set 2 are plotted in Fig. 7 and Fig. 9.Where as the comparison results with drift corrections of artifact set 2 are plotted in Fig. 8 and Fig. 10.

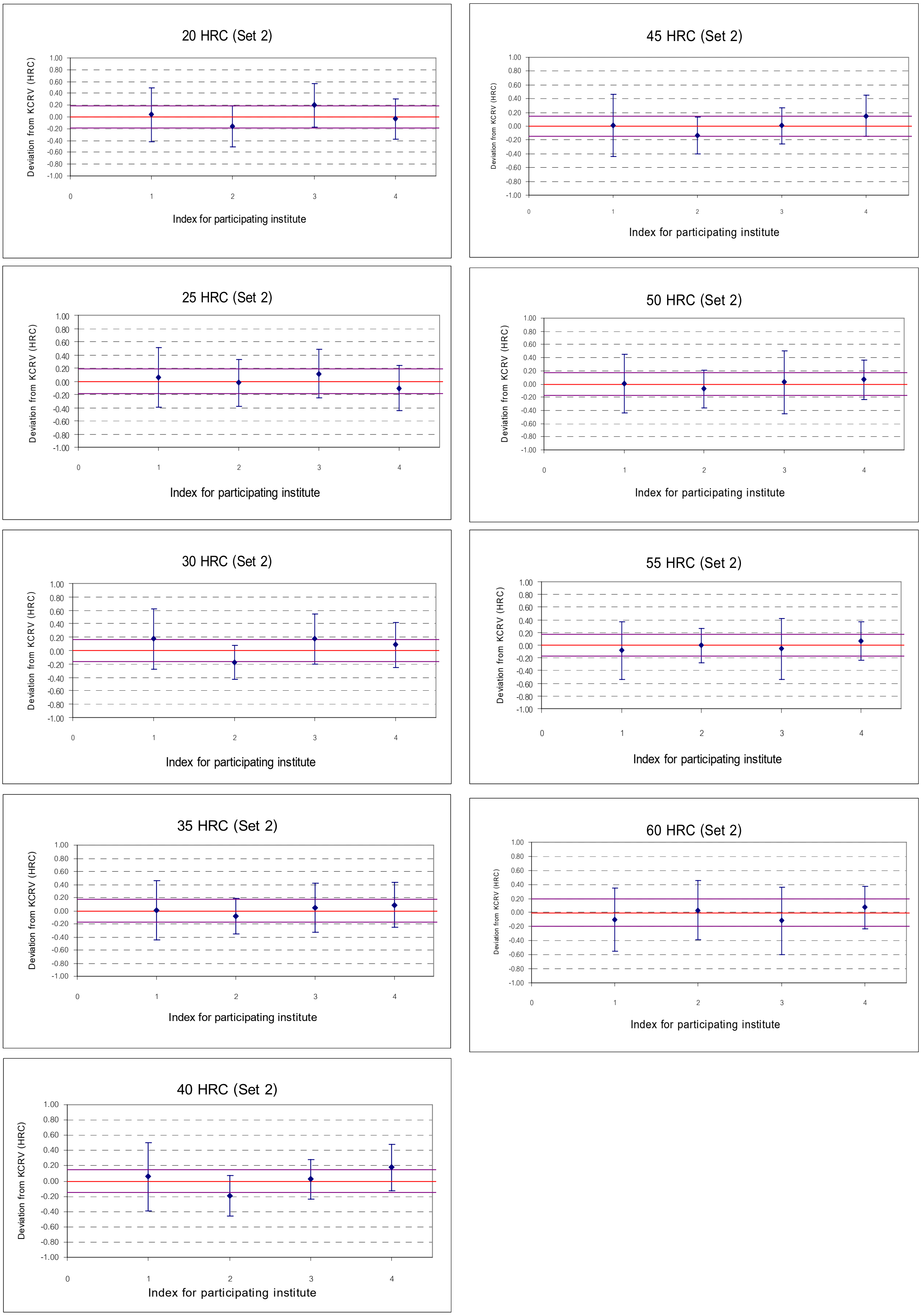


Fig. 7: Deviation from KCRV and the uncertainties of the deviation of artifact set2 (Without drift correction)

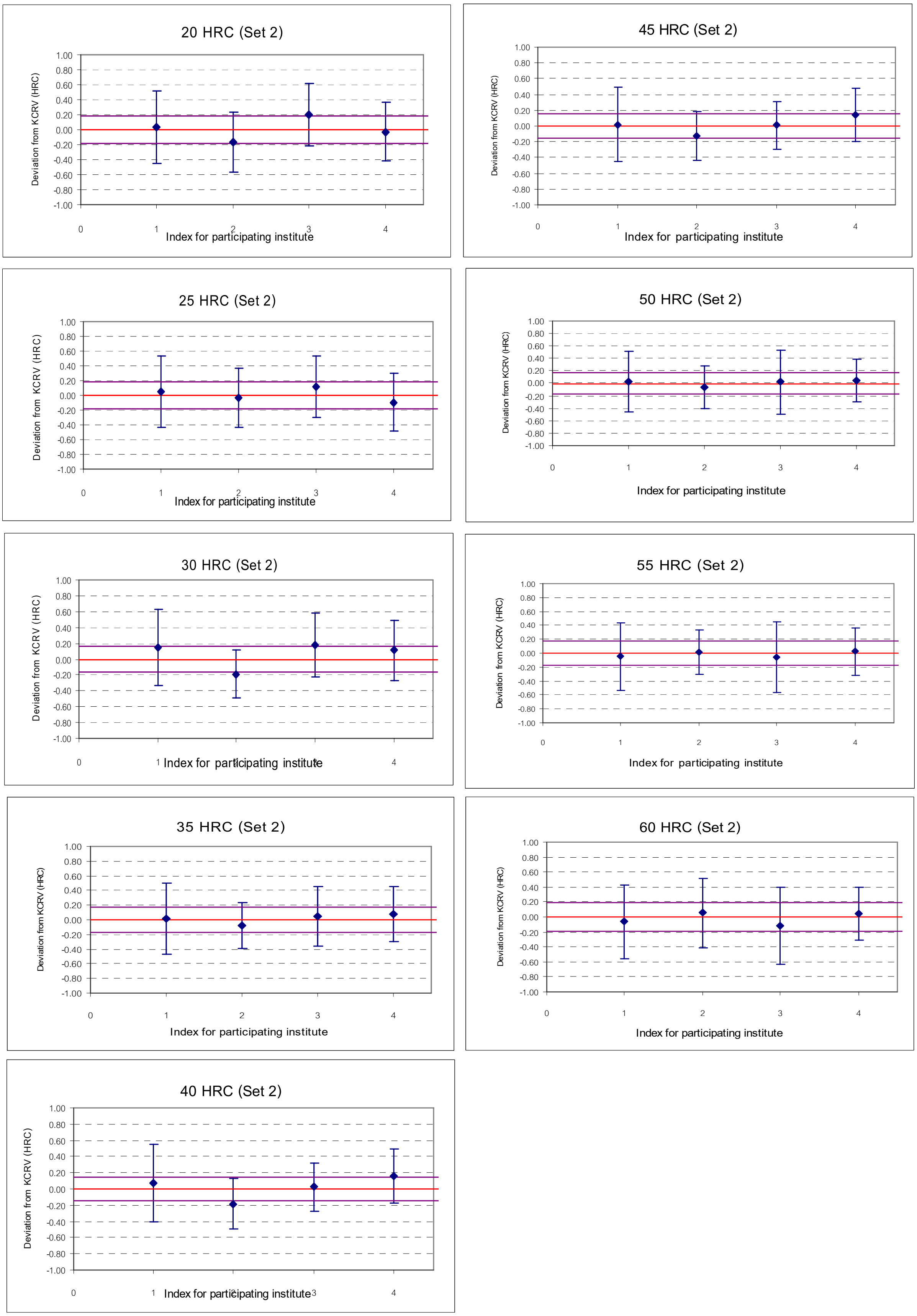


Fig. 8: Deviation from KCRV and the uncertainties of the deviation of artifact set 2 (With drift corrections)

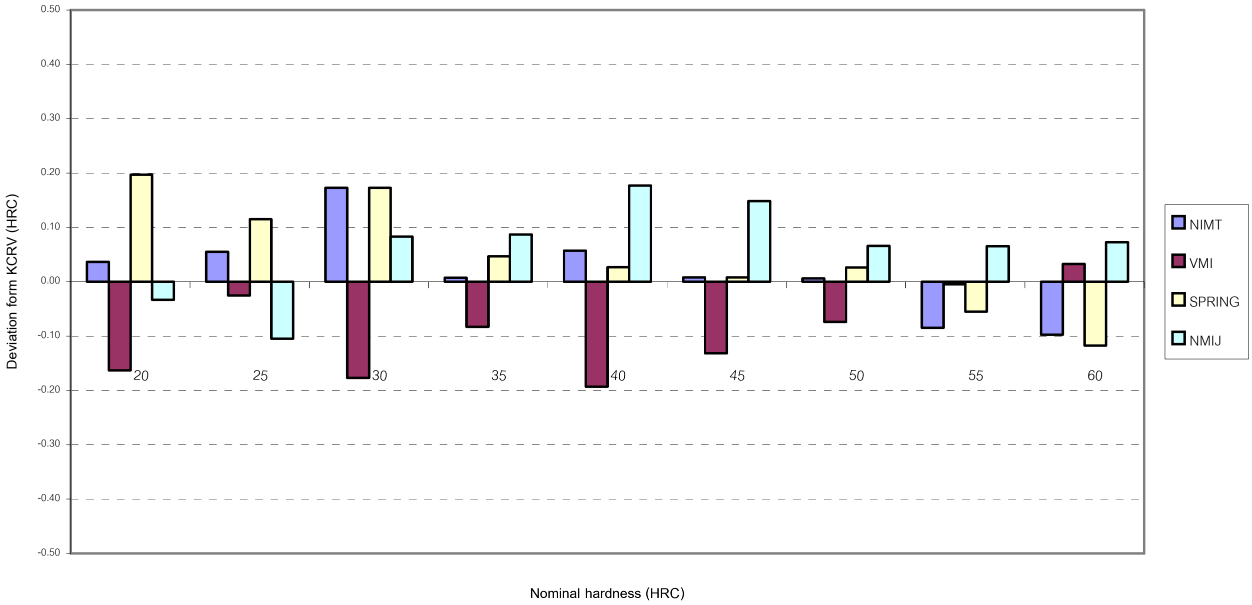


Fig. 9: Deviation from reference values (KCRV) of artifact set 2
(Without drift correction)

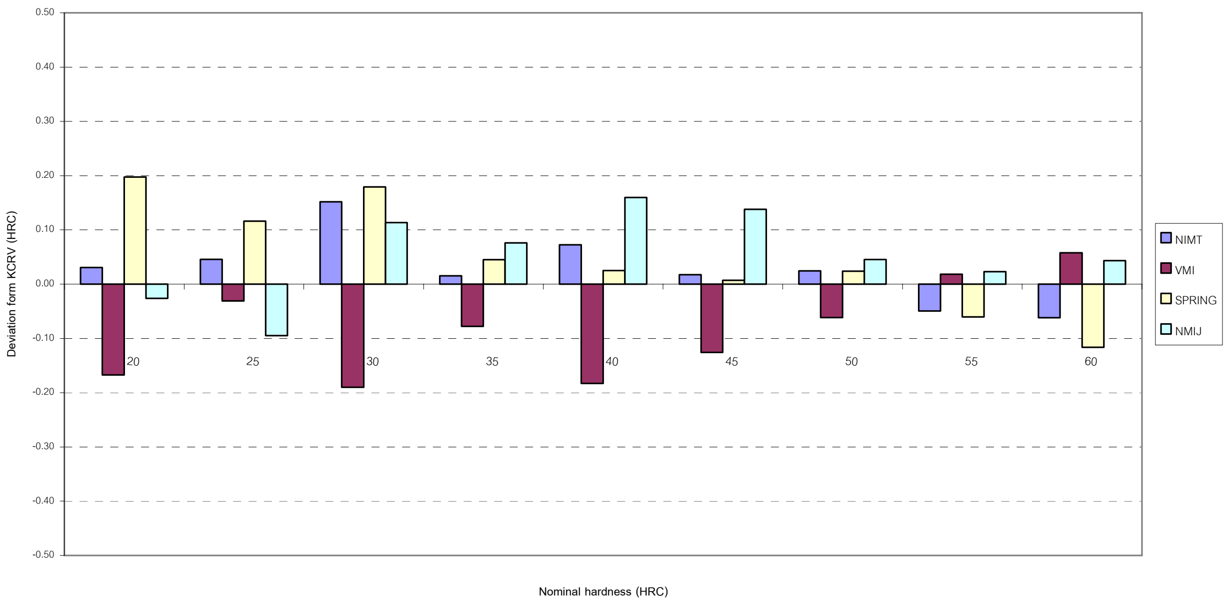


Fig. 10: Deviation from reference values (KCRV) of artifact set 2
(With drift corrections)

7.2 The Degree of Equivalence of between pairs of the institute

The degree of equivalence between pairs of participating institutes of artifact set 2 was expressed by the difference of their deviations from *KCRV* and the uncertainty of the difference at the 95% level of confidence. Table 7 and Table 8 presents the degree of equivalence between pairs of the participating institutes by using the measurement result without drift correction and with drift corrections, respectively.

Institute	Nominal	Difference between pairs				Uncertainties of the differences			
		NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
NIMT	20		0.20	-0.16	0.07		0.33	0.34	0.32
	25		0.08	-0.06	0.16		0.33	0.34	0.32
	30		0.35	0.00	0.09		0.27	0.34	0.32
	35		0.09	-0.04	-0.08		0.28	0.34	0.32
	40		0.25	0.03	-0.12		0.28	0.27	0.29
	45		0.14	0.00	-0.14		0.28	0.27	0.29
	50		0.08	-0.02	-0.06		0.29	0.43	0.29
	55		-0.08	-0.03	-0.15		0.28	0.43	0.29
	60		-0.13	0.02	-0.17		0.38	0.43	0.29
VMI	20	-0.20		-0.36	-0.13	0.33		0.26	0.24
	25	-0.08		-0.14	0.08	0.33		0.26	0.24
	30	-0.35		-0.35	-0.26	0.27		0.20	0.18
	35	-0.09		-0.13	-0.17	0.28		0.21	0.19
	40	-0.25		-0.22	-0.37	0.28		0.14	0.16
	45	-0.14		-0.14	-0.28	0.28		0.14	0.16
	50	-0.08		-0.10	-0.14	0.29		0.31	0.17
	55	0.08		0.05	-0.07	0.28		0.30	0.16
	60	0.13		0.15	-0.04	0.38		0.41	0.27
SPRING	20	0.16	0.36		0.23	0.34	0.26		0.25
	25	0.06	0.14		0.22	0.34	0.26		0.25
	30	0.00	0.35		0.09	0.34	0.20		0.25
	35	0.04	0.13		-0.04	0.34	0.21		0.25
	40	-0.03	0.22		-0.15	0.27	0.14		0.16
	45	0.00	0.14		-0.14	0.27	0.14		0.16
	50	0.02	0.10		-0.04	0.43	0.31		0.32
	55	0.03	-0.05		-0.12	0.43	0.30		0.32
	60	-0.02	-0.15		-0.19	0.43	0.41		0.32
NMIJ	20	-0.07	0.13	-0.23		0.32	0.24	0.25	
	25	-0.16	-0.08	-0.22		0.32	0.24	0.25	
	30	-0.09	0.26	-0.09		0.32	0.18	0.25	
	35	0.08	0.17	0.04		0.32	0.19	0.25	
	40	0.12	0.37	0.15		0.29	0.16	0.16	
	45	0.14	0.28	0.14		0.29	0.16	0.16	
	50	0.06	0.14	0.04		0.29	0.17	0.32	
	55	0.15	0.07	0.12		0.29	0.16	0.32	
	60	0.17	0.04	0.19		0.29	0.27	0.32	

Table 7: Degrees of equivalence between pairs of institutes (Artifact set 2)
(Without drift correction)

Institute	Nominal	Difference between pairs				Uncertainties of the differences			
		NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
NIMT	20		0.20	-0.17	0.06		0.33	0.34	0.32
	25		0.08	-0.07	0.14		0.33	0.34	0.32
	30		0.34	-0.03	0.04		0.27	0.34	0.32
	35		0.09	-0.03	-0.06		0.28	0.34	0.32
	40		0.26	0.05	-0.09		0.28	0.27	0.29
	45		0.14	0.01	-0.12		0.28	0.27	0.29
	50		0.09	0.00	-0.02		0.29	0.43	0.29
	55		-0.07	0.01	-0.07		0.28	0.43	0.29
	60		-0.12	0.05	-0.11		0.38	0.43	0.29
VMI	20	-0.20		-0.36	-0.14	0.33		0.26	0.24
	25	-0.08		-0.15	0.06	0.33		0.26	0.24
	30	-0.34		-0.37	-0.30	0.27		0.20	0.18
	35	-0.09		-0.12	-0.15	0.28		0.21	0.19
	40	-0.26		-0.21	-0.34	0.28		0.14	0.16
	45	-0.14		-0.13	-0.26	0.28		0.14	0.16
	50	-0.09		-0.09	-0.11	0.29		0.31	0.17
	55	0.07		0.08	0.00	0.28		0.30	0.16
	60	0.12		0.17	0.01	0.38		0.41	0.27
SPRING	20	0.17	0.36		0.22	0.34	0.26		0.25
	25	0.07	0.15		0.21	0.34	0.26		0.25
	30	0.03	0.37		0.07	0.34	0.20		0.25
	35	0.03	0.12		-0.03	0.34	0.21		0.25
	40	-0.05	0.21		-0.13	0.27	0.14		0.16
	45	-0.01	0.13		-0.13	0.27	0.14		0.16
	50	0.00	0.09		-0.02	0.43	0.31		0.32
	55	-0.01	-0.08		-0.08	0.43	0.30		0.32
	60	-0.05	-0.17		-0.16	0.43	0.41		0.32
NMIJ	20	-0.06	0.14	-0.22		0.32	0.24	0.25	
	25	-0.14	-0.06	-0.21		0.32	0.24	0.25	
	30	-0.04	0.30	-0.07		0.32	0.18	0.25	
	35	0.06	0.15	0.03		0.32	0.19	0.25	
	40	0.09	0.34	0.13		0.29	0.16	0.16	
	45	0.12	0.26	0.13		0.29	0.16	0.16	
	50	0.02	0.11	0.02		0.29	0.17	0.32	
	55	0.07	0.00	0.08		0.29	0.16	0.32	
	60	0.11	-0.01	0.16		0.29	0.27	0.32	

Table 8: Degrees of equivalence between pairs of institutes (Artifact set 2)
(With drift corrections)

7.3 The Coefficient E_n of each participating institute

The coefficients E_n of each participating institute by using the measurement result without drift correction were presented in Table 9 and Fig. 11.

Nominal	x ref	u(x ref)	U(x ref)	En			
				NIMT	VMI	SPRING	NMIJ
20	20.02	0.09	0.19	0.08	-0.41	0.48	-0.09
25	24.98	0.09	0.19	0.11	-0.06	0.28	-0.27
30	30.69	0.08	0.16	0.36	-0.59	0.43	0.22
35	35.77	0.08	0.17	0.02	-0.26	0.12	0.23
40	40.40	0.07	0.15	0.12	-0.63	0.09	0.53
45	45.00	0.07	0.15	0.02	-0.43	0.03	0.44
50	50.27	0.09	0.18	0.01	-0.22	0.05	0.19
55	55.73	0.09	0.17	-0.18	-0.02	-0.11	0.19
60	60.22	0.10	0.20	-0.20	0.07	-0.23	0.20

Table 9: The coefficient E_n of artifact set 2 (measured by participant's primary indenter) (Without drift correction)

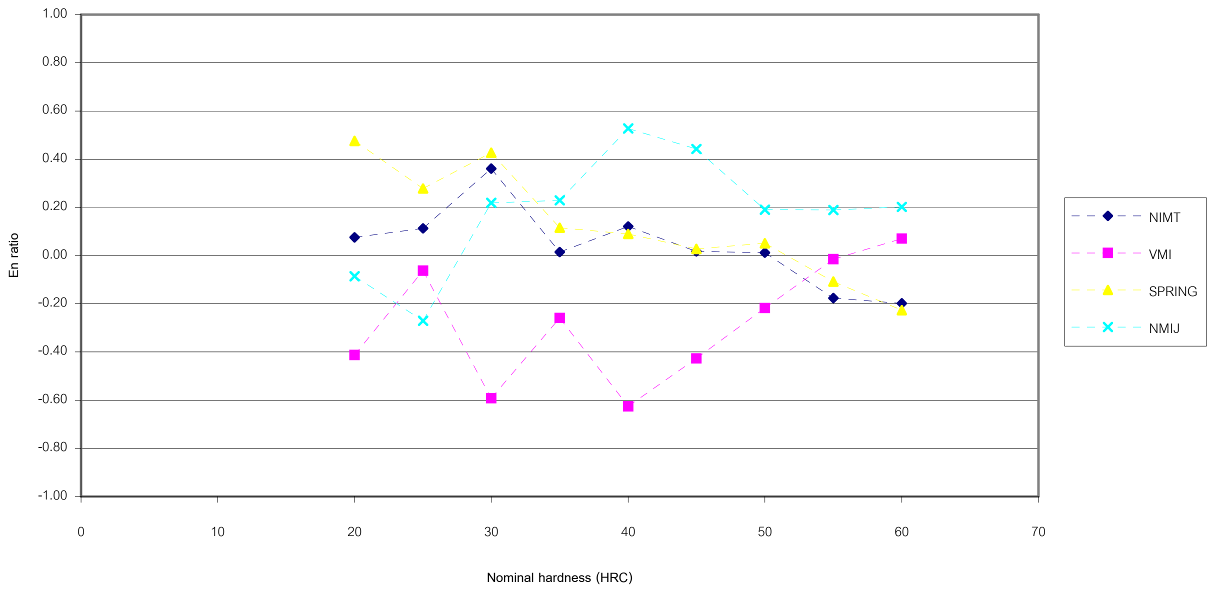


Fig.11: E_n coefficients of the participating institutes (Artifact Set2) (Without drift correction)

The coefficients E_n of each participating institute by using the measurement result with drift corrections were presented in Table 10 and Fig. 12.

Nominal	x ref	u(x ref)	U(x ref)	En			
				1	2	3	4
20	20.03	0.09	0.19	0.06	-0.42	0.48	-0.07
25	24.99	0.09	0.19	0.09	-0.08	0.28	-0.24
30	30.71	0.08	0.16	0.32	-0.63	0.44	0.30
35	35.76	0.08	0.17	0.03	-0.24	0.11	0.20
40	40.39	0.07	0.15	0.15	-0.59	0.08	0.48
45	44.99	0.07	0.15	0.04	-0.41	0.02	0.41
50	50.26	0.09	0.18	0.05	-0.18	0.05	0.13
55	55.70	0.09	0.17	-0.10	0.06	-0.12	0.07
60	60.18	0.10	0.20	-0.13	0.12	-0.22	0.12

Table 10: The coefficient E_n of artifact set 2 (measured by participant's primary indenter) (With drift corrections)

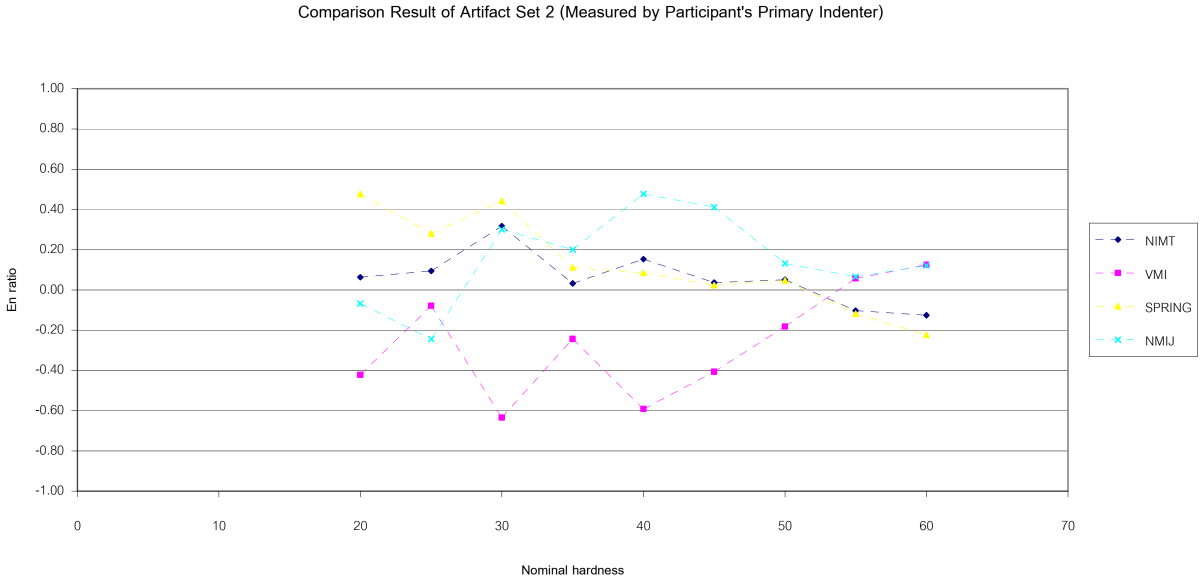


Fig.12: E_n coefficients of the participating institutes (Artifact Set2) (With drift corrections)

8. Experimental comparison

Not only the capability of national hardness standard was compared on this comparison but also the performance capability of participant's primary machine without the influence of the indenter was determined, as a study of scientific purposes.

8.1 The Degree of Equivalence of each participating institute

The measurement data and uncertainty of artifact set 1 reported by the participants are listed in Table11.

Nominal	Measurement data of each participant				Uncertainty (k=2) of each participant			
	NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
20	20.38	20.19	20.85	20.25	0.45	0.35	0.47	0.34
25	25.10	24.77	25.32	24.89	0.45	0.40	0.47	0.34
30	30.82	30.49	30.87	30.62	0.45	0.27	0.47	0.34
35	35.87	35.23	35.75	35.66	0.45	0.29	0.47	0.34
40	40.60	40.22	40.39	40.44	0.45	0.24	0.40	0.30
45	45.25	45.05	44.88	45.17	0.45	0.27	0.40	0.30
50	50.32	50.08	49.88	50.25	0.45	0.25	0.57	0.30
55	55.67	55.58	55.19	55.62	0.45	0.27	0.57	0.30
60	60.16	60.29	59.75	60.13	0.45	0.42	0.57	0.30

Table 11: Measurement data and Uncertainty of artifact set1 (measured by common indenter) (Without drift correction)

If the drifts of artifact in hardness value were significant, the application of corrections due to drift error was necessary. By using the drift corrections from Table 21, new measurement data of participant after application of the drift corrections was shown in Table 12.

Nominal	Measurement data of each participant				Uncertainty (k=2) of each participant			
	1	2	3	4	1	2	3	4
20	20.38	20.19	20.87	20.28	0.45	0.35	0.47	0.34
25	25.10	24.79	25.37	24.99	0.45	0.40	0.47	0.34
30	30.82	30.49	30.88	30.63	0.45	0.27	0.47	0.34
35	35.87	35.24	35.76	35.67	0.45	0.29	0.47	0.34
40	40.60	40.22	40.39	40.43	0.45	0.24	0.40	0.30
45	45.25	45.05	44.87	45.14	0.45	0.27	0.40	0.30
50	50.32	50.08	49.87	50.23	0.45	0.25	0.57	0.30
55	55.67	55.57	55.17	55.57	0.45	0.27	0.57	0.30
60	60.16	60.28	59.71	60.05	0.45	0.42	0.57	0.30

Table 12: Measurement data and Uncertainty of artifact set1 (measured by common indenter) (With drift corrections)

By using the measurement data without the drift correction (From Table 11), the key comparison reference value (*KCRV* or x_{ref}), the deviation from *KCRV* and the uncertainty of the deviation from *KCRV* of each participant were determined as shown in Table 13.

Nominal	X ref	U(x ref)	Deviation from KCRV				Uncertainty of the Deviation from KCRV (k=2)			
			NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
20	20.36	0.20	0.02	-0.17	0.49	-0.11	0.49	0.40	0.51	0.39
25	24.98	0.20	0.12	-0.21	0.34	-0.09	0.49	0.45	0.51	0.40
30	30.63	0.18	0.19	-0.14	0.24	-0.01	0.48	0.32	0.50	0.38
35	35.54	0.18	0.33	-0.31	0.21	0.12	0.49	0.34	0.50	0.39
40	40.36	0.16	0.24	-0.13	0.03	0.08	0.48	0.29	0.43	0.34
45	45.08	0.17	0.17	-0.03	-0.20	0.09	0.48	0.32	0.43	0.34
50	50.15	0.17	0.17	-0.07	-0.27	0.10	0.48	0.30	0.59	0.34
55	55.57	0.17	0.10	0.01	-0.38	0.05	0.48	0.32	0.60	0.35
60	60.12	0.20	0.04	0.16	-0.37	0.01	0.49	0.47	0.60	0.36

Table 13: Deviation from KCRV and the uncertainty of the deviation of artifact set 1 (measured by common indenter) (Without drift correction)

In case of drift corrections were applied to the results. By using the measurement data corrected by drift effect (From Table 12), the key comparison reference value (*KCRV* or x_{ref}), the deviation from *KCRV* and the uncertainty of the deviation from *KCRV* of each participant were determined as in Table 14.

Nominal	X ref	U(x ref)	Deviation from KCRV				Uncertainty of the Deviation from KCRV (k=2)			
			NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
20	20.37	0.20	0.01	-0.18	0.49	-0.09	0.49	0.40	0.51	0.39
25	25.03	0.20	0.07	-0.24	0.34	-0.04	0.49	0.45	0.51	0.40
30	30.64	0.18	0.18	-0.15	0.24	0.00	0.48	0.32	0.50	0.38
35	35.54	0.18	0.33	-0.31	0.21	0.13	0.49	0.34	0.50	0.39
40	40.35	0.16	0.25	-0.13	0.03	0.08	0.48	0.29	0.43	0.34
45	45.07	0.17	0.18	-0.03	-0.21	0.07	0.48	0.32	0.43	0.34
50	50.14	0.17	0.18	-0.06	-0.27	0.09	0.48	0.30	0.59	0.34
55	55.55	0.17	0.12	0.02	-0.38	0.03	0.48	0.32	0.60	0.35
60	60.08	0.20	0.08	0.19	-0.37	-0.03	0.49	0.47	0.60	0.36

Table 14: Deviation from KCRV and the uncertainty of the deviation of artifact set 1 (measured by common indenter) (With drift corrections)

The comparison results without drift correction of artifact set 1 are plotted in Fig. 13 and Fig. 15.Where as the comparison results with drift corrections of artifact set 2 are plotted in Fig. 14 and Fig. 16.

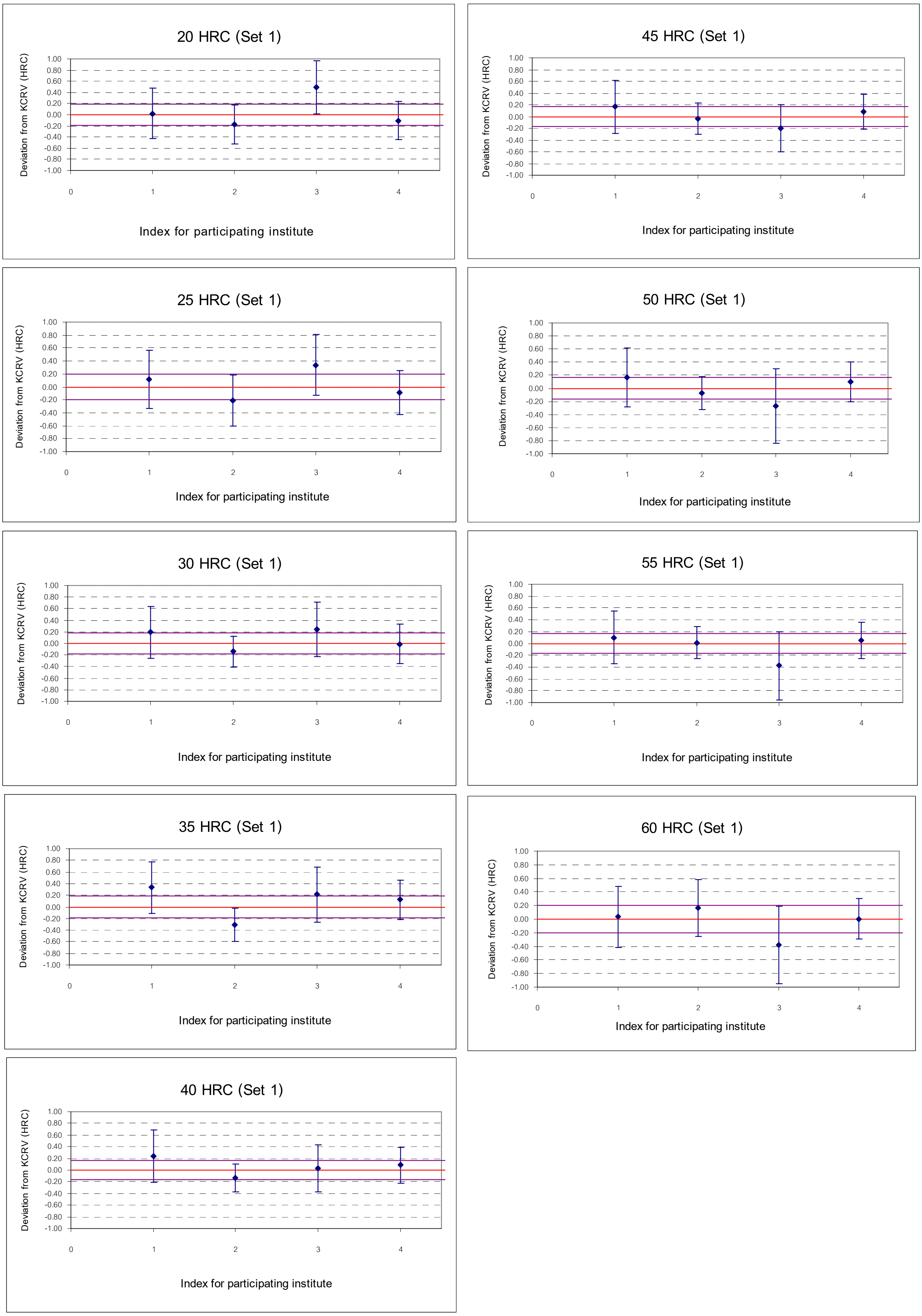


Fig. 13: Deviation from KCRV and the uncertainties of the deviation of artifact set1 (Without drift correction)

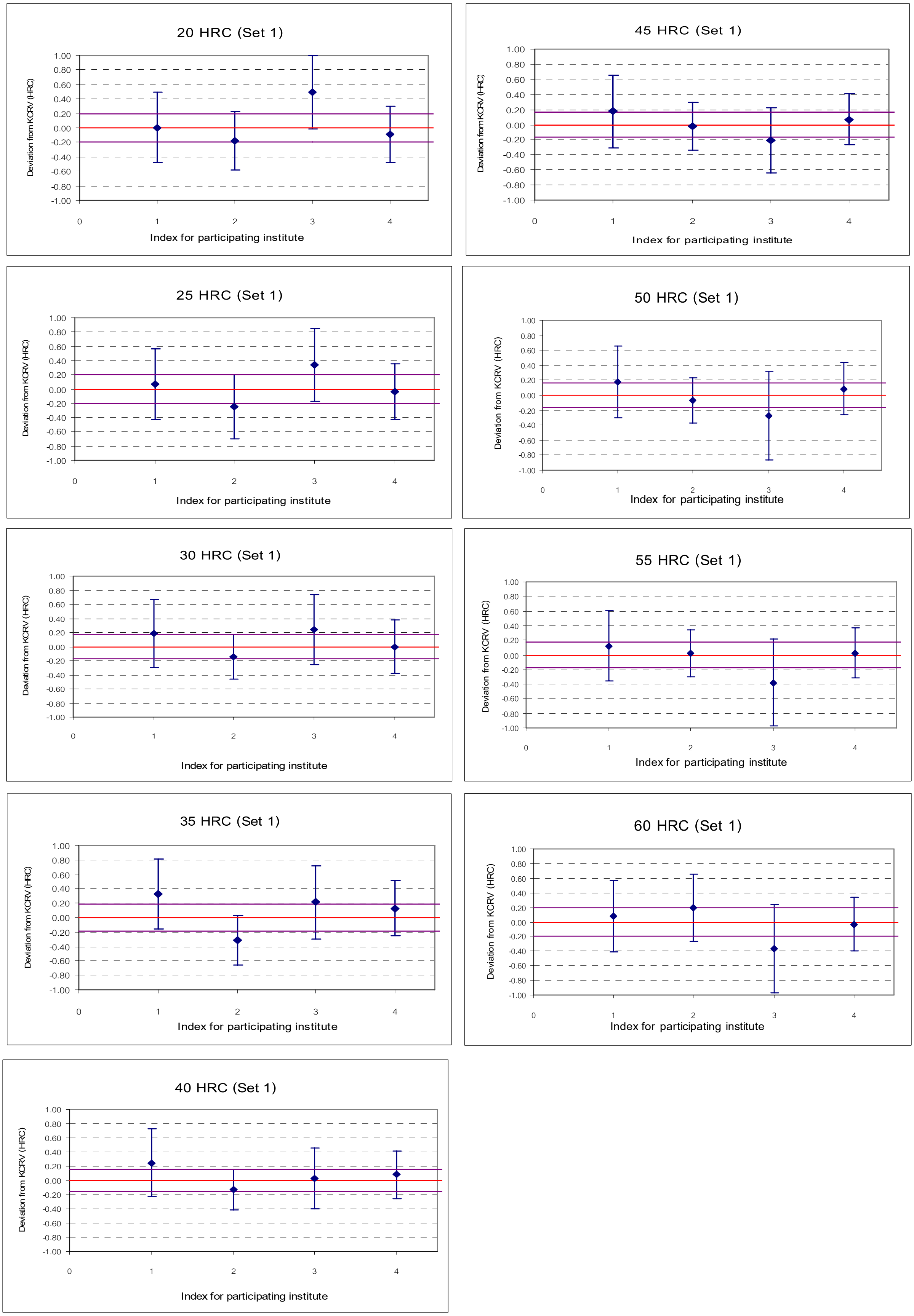


Fig. 14: Deviation from KCRV and the uncertainties of the deviation of artifact set1 (With drift corrections)

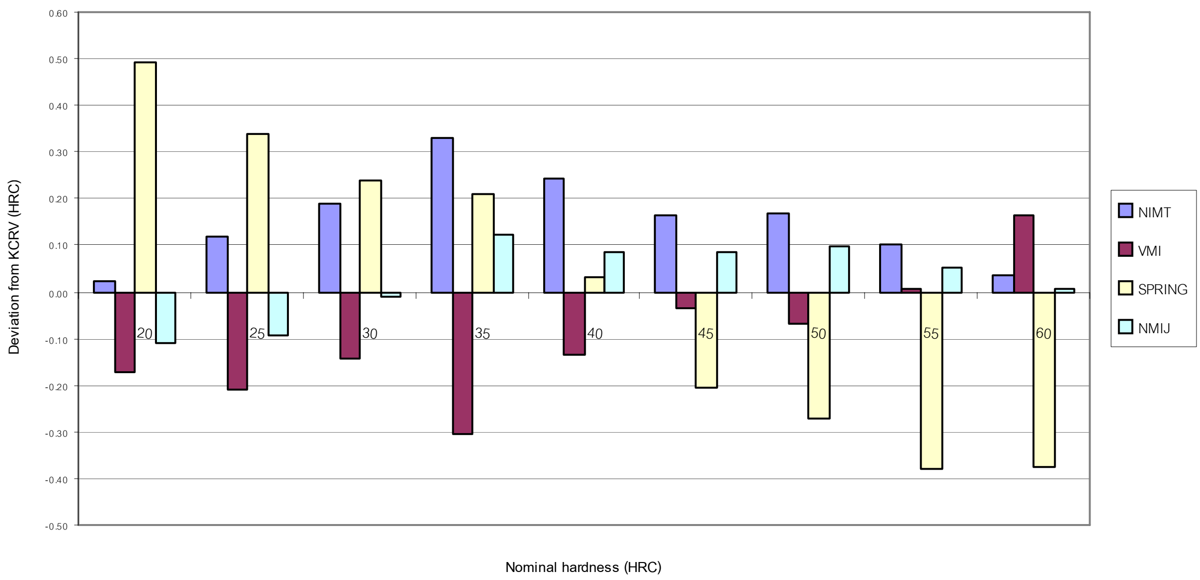


Fig. 15: Deviation from reference values (KCRV) of artifact set 1
(Without drift correction)

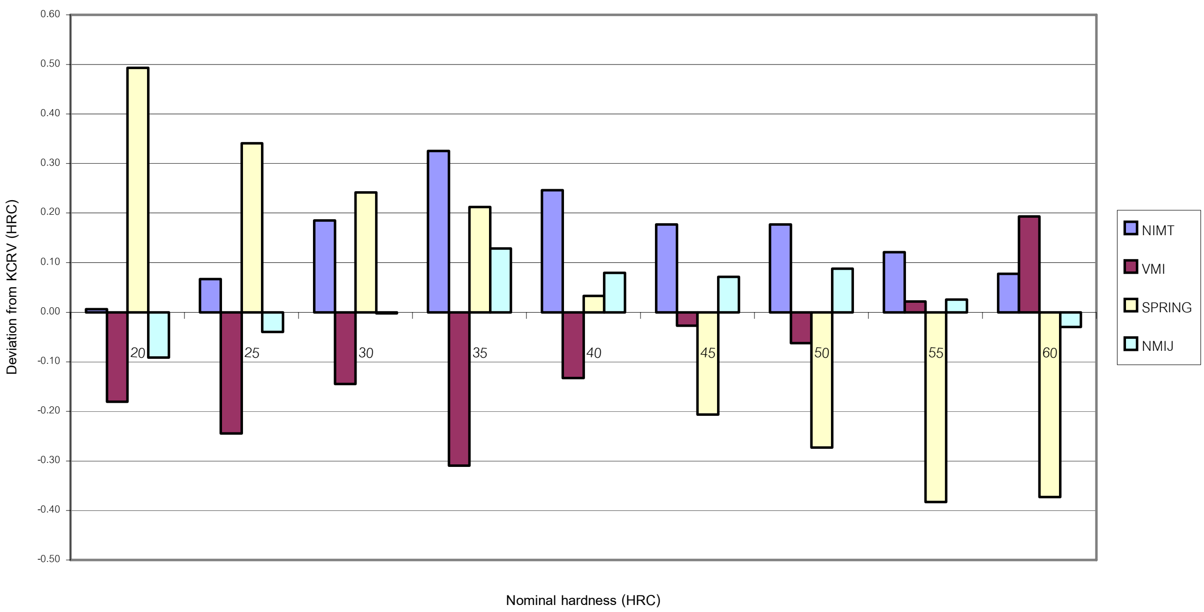


Fig. 16: Deviation from reference values (KCRV) of artifact set 1
(With drift corrections)

8.2 The Degree of Equivalence of between pairs of the institute

The degree of equivalence between pairs of participating institutes of artifact set 2 was expressed by the difference of their deviations from *KCRV* and the uncertainty of the difference at the 95% level of confidence. Table 15 and Table 16 presents the degree of equivalence between pairs of the participating institutes by using the measurement result without drift correction and with drift corrections, respectively.

Institute	Nominal	Difference between pairs				Uncertainties of the differences			
		NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
NIMT	20		0.19	-0.47	0.13		0.33	0.42	0.32
	25		0.33	-0.22	0.21		0.36	0.42	0.32
	30		0.33	-0.05	0.20		0.28	0.42	0.32
	35		0.64	0.12	0.21		0.29	0.42	0.32
	40		0.38	0.21	0.16		0.26	0.36	0.29
	45		0.20	0.37	0.08		0.28	0.36	0.29
	50		0.24	0.44	0.07		0.27	0.53	0.29
	55		0.09	0.48	0.05		0.28	0.53	0.29
	60		-0.13	0.41	0.03		0.38	0.53	0.29
VMI	20	-0.19		-0.66	-0.06	0.33		0.34	0.24
	25	-0.33		-0.55	-0.12	0.36		0.38	0.28
	30	-0.33		-0.38	-0.13	0.28		0.29	0.19
	35	-0.64		-0.52	-0.43	0.29		0.31	0.20
	40	-0.38		-0.17	-0.22	0.26		0.22	0.15
	45	-0.20		0.17	-0.12	0.28		0.23	0.16
	50	-0.24		0.20	-0.17	0.27		0.39	0.15
	55	-0.09		0.39	-0.04	0.28		0.40	0.16
	60	0.13		0.54	0.16	0.38		0.50	0.27
SPRING	20	0.47	0.66		0.60	0.42	0.34		0.34
	25	0.22	0.55		0.43	0.42	0.38		0.34
	30	0.05	0.38		0.25	0.42	0.29		0.34
	35	-0.12	0.52		0.09	0.42	0.31		0.34
	40	-0.21	0.17		-0.05	0.36	0.22		0.25
	45	-0.37	-0.17		-0.29	0.36	0.23		0.25
	50	-0.44	-0.20		-0.37	0.53	0.39		0.41
	55	-0.48	-0.39		-0.43	0.53	0.40		0.41
	60	-0.41	-0.54		-0.38	0.53	0.50		0.41
NMIJ	20	-0.13	0.06	-0.60		0.32	0.24	0.34	
	25	-0.21	0.12	-0.43		0.32	0.28	0.34	
	30	-0.20	0.13	-0.25		0.32	0.19	0.34	
	35	-0.21	0.43	-0.09		0.32	0.20	0.34	
	40	-0.16	0.22	0.05		0.29	0.15	0.25	
	45	-0.08	0.12	0.29		0.29	0.16	0.25	
	50	-0.07	0.17	0.37		0.29	0.15	0.41	
	55	-0.05	0.04	0.43		0.29	0.16	0.41	
	60	-0.03	-0.16	0.38		0.29	0.27	0.41	

Table 15: Degrees of equivalence between pairs of institutes (Artifact set 1)
(Without drift correction)

Institute	Nominal	Difference between pairs				Uncertainties of the differences			
		NIMT	VMI	SPRING	NMIJ	NIMT	VMI	SPRING	NMIJ
NIMT	20		0.19	-0.49	0.10		0.33	0.42	0.32
	25		0.31	-0.27	0.11		0.36	0.42	0.32
	30		0.33	-0.06	0.19		0.28	0.42	0.32
	35		0.63	0.11	0.20		0.29	0.42	0.32
	40		0.38	0.21	0.17		0.26	0.36	0.29
	45		0.20	0.38	0.11		0.28	0.36	0.29
	50		0.24	0.45	0.09		0.27	0.53	0.29
	55		0.10	0.50	0.10		0.28	0.53	0.29
	60		-0.12	0.45	0.11		0.38	0.53	0.29
VMI	20	-0.19		-0.67	-0.09	0.33		0.34	0.24
	25	-0.31		-0.59	-0.21	0.36		0.38	0.28
	30	-0.33		-0.39	-0.14	0.28		0.29	0.19
	35	-0.63		-0.52	-0.44	0.29		0.31	0.20
	40	-0.38		-0.17	-0.21	0.26		0.22	0.15
	45	-0.20		0.18	-0.10	0.28		0.23	0.16
	50	-0.24		0.21	-0.15	0.27		0.39	0.15
	55	-0.10		0.40	0.00	0.28		0.40	0.16
	60	0.12		0.57	0.22	0.38		0.50	0.27
SPRING	20	0.49	0.67		0.58	0.42	0.34		0.34
	25	0.27	0.59		0.38	0.42	0.38		0.34
	30	0.06	0.39		0.24	0.42	0.29		0.34
	35	-0.11	0.52		0.08	0.42	0.31		0.34
	40	-0.21	0.17		-0.05	0.36	0.22		0.25
	45	-0.38	-0.18		-0.28	0.36	0.23		0.25
	50	-0.45	-0.21		-0.36	0.53	0.39		0.41
	55	-0.50	-0.40		-0.41	0.53	0.40		0.41
	60	-0.45	-0.57		-0.34	0.53	0.50		0.41
NMIJ	20	-0.10	0.09	-0.58		0.32	0.24	0.34	
	25	-0.11	0.21	-0.38		0.32	0.28	0.34	
	30	-0.19	0.14	-0.24		0.32	0.19	0.34	
	35	-0.20	0.44	-0.08		0.32	0.20	0.34	
	40	-0.17	0.21	0.05		0.29	0.15	0.25	
	45	-0.11	0.10	0.28		0.29	0.16	0.25	
	50	-0.09	0.15	0.36		0.29	0.15	0.41	
	55	-0.10	0.00	0.41		0.29	0.16	0.41	
	60	-0.11	-0.22	0.34		0.29	0.27	0.41	

Table 16: Degrees of equivalence between pairs of institutes (Artifact set 1)
(With drift corrections)

8.3 The Coefficient E_n of each participating institute

The coefficients E_n of each participating institute by using the measurement result without drift correction were presented in Table 17 and Fig. 17.

Nominal	x ref	u(x ref)	U(x ref)	En			
				1	2	3	4
20	20.36	0.10	0.20	0.04	-0.43	0.97	-0.28
25	24.98	0.10	0.20	0.24	-0.47	0.66	-0.23
30	30.63	0.09	0.18	0.39	-0.44	0.48	-0.03
35	35.54	0.09	0.18	0.68	-0.89	0.42	0.31
40	40.36	0.08	0.16	0.51	-0.47	0.08	0.25
45	45.08	0.08	0.17	0.34	-0.11	-0.47	0.25
50	50.15	0.08	0.17	0.35	-0.23	-0.46	0.29
55	55.57	0.09	0.17	0.21	0.03	-0.64	0.15
60	60.12	0.10	0.20	0.07	0.35	-0.62	0.01

Table 17: E_n coefficients of artifact set 1 (measured by common indenter)
(Without drift correction)

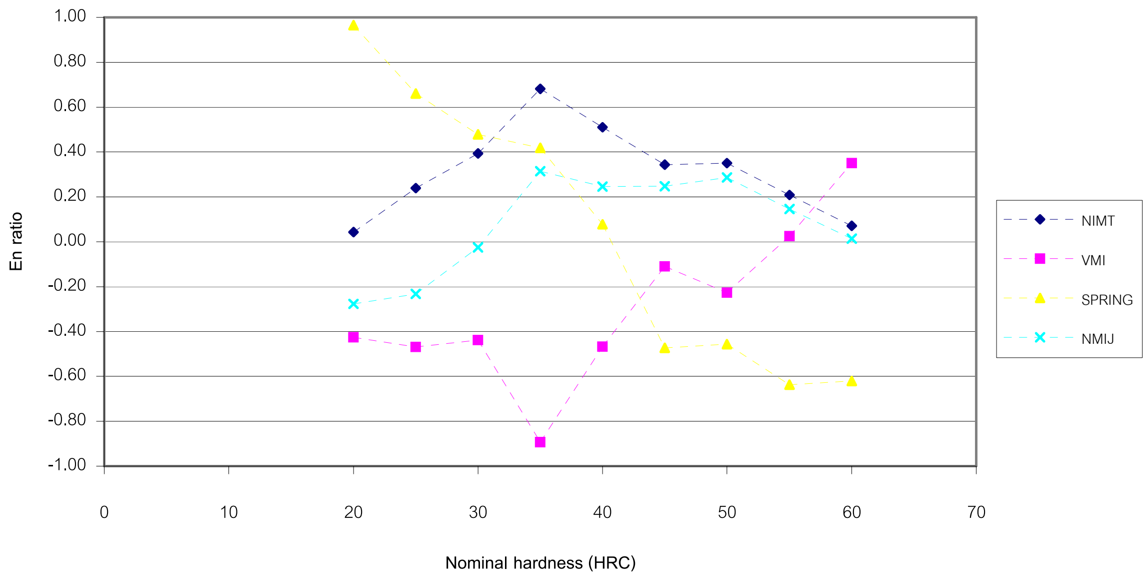


Fig.17: E_n coefficients of the participating institutes (Artifact Set1)
(Without drift correction)

The coefficients E_n of each participating institute by using the measurement result corrected by drift corrections were presented in Table 18 and Fig. 18.

Nominal	x ref	u(x ref)	U(x ref)	En			
				NIMT	VMI	SPRING	NMIJ
20	20.37	0.10	0.20	0.01	-0.45	0.97	-0.23
25	25.03	0.10	0.20	0.14	-0.55	0.67	-0.10
30	30.64	0.09	0.18	0.38	-0.45	0.48	-0.01
35	35.54	0.09	0.18	0.67	-0.90	0.42	0.33
40	40.35	0.08	0.16	0.52	-0.46	0.08	0.23
45	45.07	0.08	0.17	0.37	-0.09	-0.48	0.21
50	50.14	0.08	0.17	0.37	-0.21	-0.46	0.25
55	55.55	0.09	0.17	0.25	0.07	-0.64	0.07
60	60.08	0.10	0.20	0.16	0.42	-0.62	-0.08

Table 18: E_n coefficients of artifact set 1 (measured by common indenter) (With drift corrections)

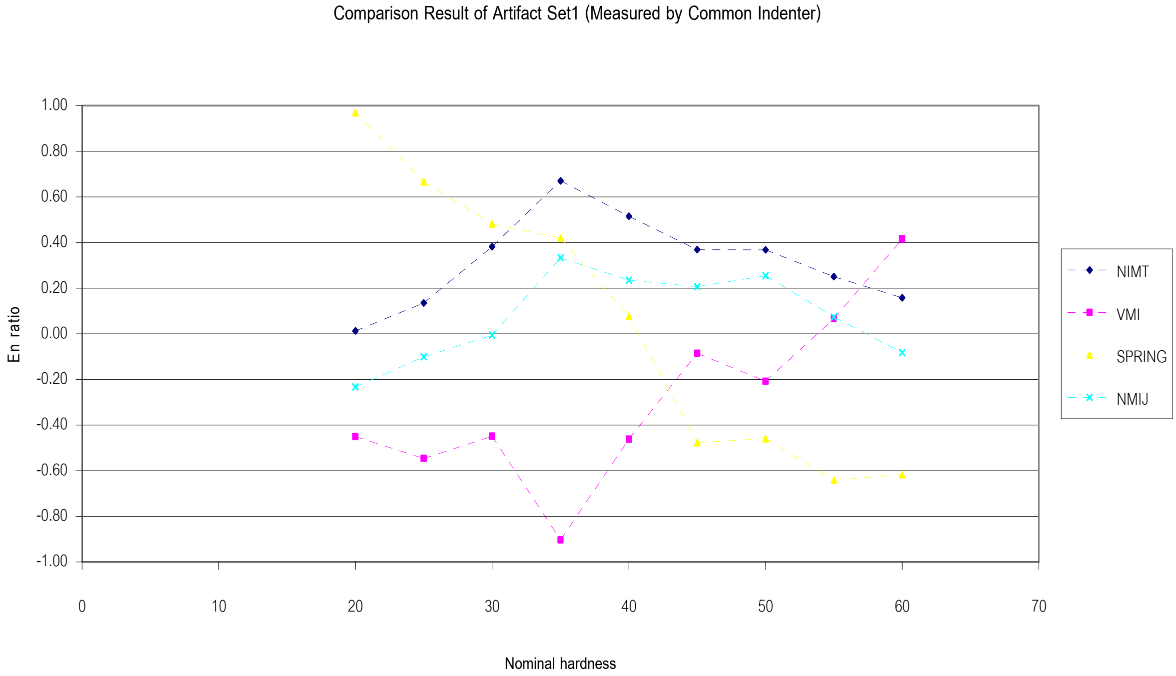


Fig.18: E_n coefficients of the participating institutes (Artifact Set1) (With drift corrections)

9. Stability of artifacts during transportation

In order to evaluate the stability of artifacts, the pilot institute made the measurements of the artifact at the beginning and the end of comparison. The drift in hardness block set 1 and set 2 were given in Table 19 and 20, and were plotted in Fig.19 and Fig. 20.

Nominal	1st measurement	2nd measurement	Drift in HRC
20	20.38	20.33	-0.05
25	25.10	24.94	-0.16
30	30.82	30.8	-0.02
35	35.87	35.85	-0.02
40	40.60	40.61	0.01
45	45.25	45.29	0.04
50	50.32	50.35	0.03
55	55.67	55.74	0.07
60	60.16	60.28	0.12

Table 19: The drift in hardness value of artifact set 1

Nominal	1st measurement	2nd measurement	Drift in HRC
20	20.06	20.04	-0.02
25	25.04	25.01	-0.03
30	30.86	30.78	-0.08
35	35.78	35.81	0.03
40	40.46	40.51	0.05
45	45.01	45.04	0.03
50	50.28	50.34	0.06
55	55.65	55.77	0.12
60	60.12	60.22	0.10

Table 20: The drift in hardness value of artifact set 2

From the Figures, drifts in hardness values of artifacts were small compared with the claimed uncertainty of pilot institute. In other words, the artifact blocks of both sets provided good stability for the comparison if compared with the claimed uncertainty of NIMT.

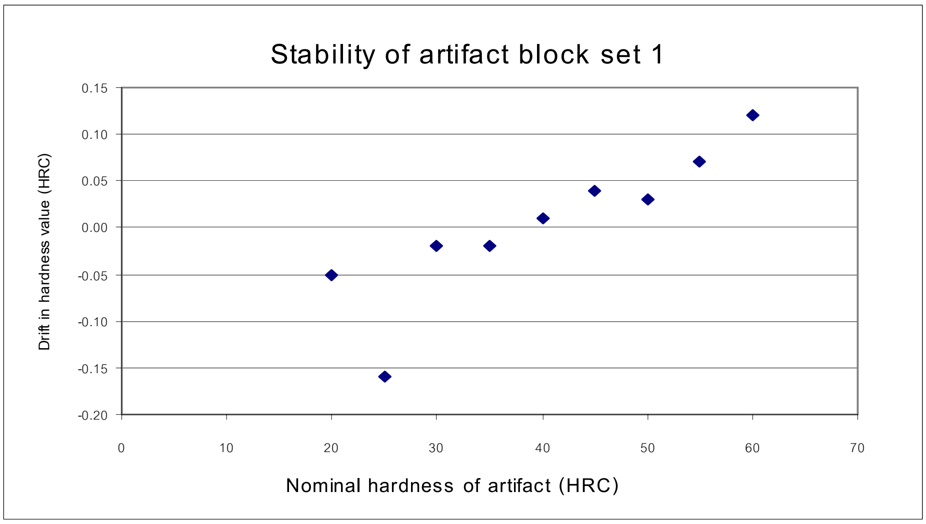


Fig. 19: The drift in hardness value of artifact block set 1

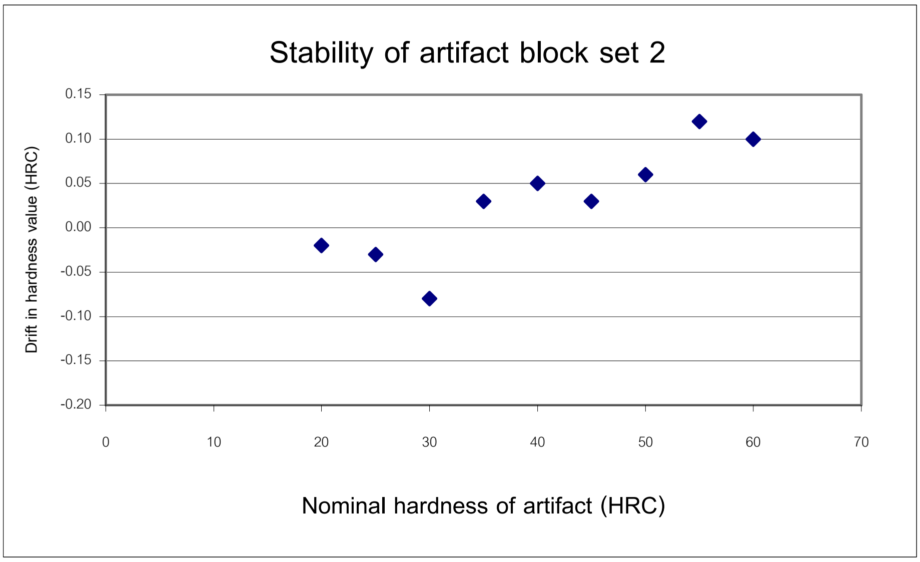


Fig. 20: The drift in hardness value of artifact block set 2

However, if we compared drifts with KCRV uncertainties, there was good stability of artifacts at low hardness levels. But the drifts in hardness were found to be significant at hardness level of 55 HRC and 60 HRC. Hence, according to this criterion, the application of drift corrections was needed. Table 21 and 22 showed the corrections due to drifts of artifact block set 1 and artifact block set 2, respectively.

Correction due to drift of artifact set 1				
Nominal	NIMT	VMI	SPRING	NMIJ
20	0.00	0.01	0.02	0.03
25	0.00	0.02	0.05	0.10
30	0.00	0.00	0.01	0.01
35	0.00	0.00	0.01	0.01
40	0.00	0.00	0.00	-0.01
45	0.00	0.00	-0.01	-0.03
50	0.00	0.00	-0.01	-0.02
55	0.00	-0.01	-0.02	-0.05
60	0.00	-0.01	-0.04	-0.08

Table 21: The corrections due to drift of artifact block set 1

Correction due to drift of artifact set 2				
Nominal	NIMT	VMI	SPRING	NMIJ
20	0.00	0.00	0.01	0.01
25	0.00	0.00	0.01	0.02
30	0.00	0.01	0.03	0.05
35	0.00	0.00	-0.01	-0.02
40	0.00	-0.01	-0.02	-0.03
45	0.00	0.00	-0.01	-0.02
50	0.00	-0.01	-0.02	-0.04
55	0.00	-0.01	-0.04	-0.08
60	0.00	-0.01	-0.03	-0.06

Table 22: The corrections due to drift of artifact block set 2

10. Discussions

The comparison was divided into 2 groups according to the different objectives. The first group was to compare the measurement result of Rockwell hardness scale C between participants, which is maintained as the hardness measurement standard of each NMI. Every NMI realizes that not only the primary hardness machine shall conform to ISO6508-3, but the testing cycle shall also harmonize with other NMIs. Furthermore, good indenters, which have geometric shapes conforming to ISO6508-3, are also needed. This comparison used the deviation from *KCRV* and the uncertainty of this deviation of a 95% level of confidence as the degree of equivalence. The E_n numbers were also calculated to express the equivalence between measurements of the participants.

The comparison result of artifact set 2 clearly reflected on the ability of maintaining the aforementioned factors of all participants. It was noted that VMI, SPRING and NMIJ applied the corrections for their own indenters to their measurement results. The range of the deviation from *KCRV* of each participating institute was between –0.19 HRC to +0.20 HRC with ±0.52 HRC of maximum uncertainty (k=2) of this deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.37 HRC to +0.37 HRC with ±0.43 HRC of maximum uncertainty (k=2) of this difference. The variation range of E_n numbers was between –0.63 to +0.53. It could be ascertained that the comparison result of Rockwell hardness measurement was correlated among the participants.

If we used the criteria that drift corrections were needed, the range of the deviation from *KCRV* of each participating institute was still between –0.19 HRC to +0.20 HRC with ±0.52 HRC of maximum uncertainty (k=2) of this deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.37 HRC to +0.37 HRC with ±0.43 HRC of maximum uncertainty (k=2) of this difference. The variation range of E_n numbers was between –0.63 to +0.48. It could be seen that, even the drift corrections were applied, the comparison result of Rockwell hardness measurement was also correlated among the participants.

The second group of comparison was the experimental comparison in order to determine the efficiency of hardness machine without the effect of indenter. The pilot institute prepared the common indenter to be used among participants eliminating the indenter effect. It is known that the indenter highly influences the measurement result compared with other influences. The artifact set 1 was used for determining the correspondence in measurement results obtained by using each NMI’s primary machine. According to certain publications, it was discovered that the comparison result using common indenter gave smaller deviation of the results than each participant’s indenter. But our comparison result gave the range of the deviation from *KCRV* of each participating institute between –0.38 HRC to +0.49 HRC and ±0.60 HRC of maximum uncertainty of this deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.66 HRC to +0.66 HRC with ±0.53 HRC of maximum uncertainty (k=2) of this difference. The range of degree of equivalence (E_n numbers) was between -0.89 to +0.97.

If we used the criteria that drift corrections were needed to result of artifact set 1, the corrected comparison result still gave the range of the deviation from *KCRV* of each participating institute between –0.38 HRC to +0.49 HRC and ±0.60 HRC of maximum uncertainty of this deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.67 HRC to +0.67 HRC with ±0.53 HRC of maximum uncertainty (k=2) of this difference. The range of degree of equivalence (E_n numbers) was between -0.90 to +0.97.

By comparing the comparison result of set 1 with the comparison result of set 2, it showed that the comparison using common indenter gave a larger deviation from *KCRV* and larger E_n numbers than using each participant's indenter. From Fig.13, it could be seen that the large deviation was mainly caused from SPRING's result. The possible explanation was the incompatibility of the common indenter with SPRING's machine. SPRING fitted their own indenter with the vertical draw screw whereas the common indenter was fitted with a spring load plunger. They corrected the results measured by common indenter with this incompatible effect. However, the deviation was still large. Participants observed that the compatibility and reproducibility between indenter and hardness machine is also an important factor (**Compatibility** represented a fitting ability of the common indenter to the participant's machine; **Reproducibility** represented the changeability of indenters used with the machine). From the ISO6508-2 and ISO6508-3 recommendations, the hardness calibration machine shall be used for verifying the indenter by comparing with the reference indenter. Therefore, in the future, there should be a study of compatibility and reproducibility between indenter and hardness machine to reduce the deviation of measurement result. This comparison also showed that not only the geometric shape of new reference indenter should be considered but also the compatibility between indenter and primary hardness machine.

There was no significant problem during the comparison. All the participating institutes carried out the measurement following the protocol and reported their results to the pilot institute. It was found that there was an anomaly from artifact set 1 of SPRING's reported results. The pilot institute informed this to SPRING. SPRING checked the results and informed that they did not correct their measurement result by indenter mounting correction. After receiving the corrected measurement result from SPRING, the pilot institute re-analyzed the comparison result and presented this report.

SPRING suggested that there is a systematic deviation in results obtained using side mounting on machine designed for top mounting. The pilot institute also obtained valuable comments of draft A report, issued following CIPM Guideline from NMIJ.

There were enthusiastic discussions concerning with the stability of artifacts. During the draft B report approving, WGH gave the comment to the pilot institute that the drift of the artifacts seemed to be significant at the high level of hardness. If concerning the KCRV uncertainty, at the level of 55 HRC (0.17 HRC) and 60 HRC (0.2 HRC), 0.1 HRC drift was significant. WGH suggested applying the correction due to drifts to the results or at least combining the drift effect to the uncertainty of KCRV.

After the pilot institute accepted and corrected the results by drift correction in draft B report, the revised draft B was sent to all participants to gather the comments and opinions again. NMIJ gave another point of view with this issue. Because of the stability of artifacts was evaluated from two measurements (before and after comparison) by NIMT, NMIJ introduced that the drift observed should be compared with the reproducibility of NIMT at the same hardness levels. In this case, the drift in artifacts was not significant to the results.

Refer to ISO GUM, any error should not be ignored from the measurement results, the result should be corrected by the correction. However, it is difficult to describe that the difference of NIMT's two measurements was generated only from the drift of the artifacts.

After the pilot institute compared the original comparison results and after drift-corrected comparison results, it was found that the drift-corrected results was not changed significantly.

According to the ambiguous of the significance of the drifts to the result and the participants would not like to use the drift correction, the pilot institute decided to use the measurement result without the application of the drift correction as the priority in the report. However, the further analysis and discussions of this interesting issue should be proposed in hardness community.

In this report, the Key Comparison Reference Value (*KCRV*), was calculated and the degrees of equivalence and E_n numbers were presented by using data originally submitted to pilot institute by the participants.

11. Conclusion

Four National Metrology Institutes participated in this ASEAN comparison in HRC from 20 to 60 HRC.

The stability of artifact blocks was determined using the measurement results of the pilot institute at the beginning and the end of the artifact circulation. Drifts in hardness values of artifacts were small compared with the claimed uncertainty of the pilot institute. By comparing in this way, the drifts in hardness were not significant to the measurement results.

However, it should be remarked that the drifts were significant if compared with the uncertainty of KCRV (at 55 HRC and 60 HRC) as the comment of WGH. The further analysis and discussions should be carried out in future.

Due to the indication of significance of the drifts to the results was still ambiguous, the drift corrections was not applied to the result in this report.

The degrees of equivalence of hardness scale measurement in the range 20 HRC to 60 HRC were expressed by two terms, deviations from the key comparison reference values and pair-wise differences of their deviations.

The priority of the comparison was the result of set 2 artifact whereas the result of set 1 artifact was for scientific purposes. As aforementioned, the comparison result was based on the result without the drift correction. For the set 2 artifact, the range of the deviation from *KCRV* of each participating institute was between –0.19 HRC to +0.20 HRC with ±0.52 HRC of maximum uncertainty (k=2) of this deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.37 HRC to +0.37 HRC with ±0.43 HRC of maximum uncertainty (k=2) of this difference. The variation range of E_n numbers was between –0.63 to +0.53.

The set 1 artifact experiment comparison gave the deviation from *KCRV* of each participant between –0.38 HRC to +0.49 HRC and ±0.60 HRC of maximum uncertainty (k=2) of the deviation. The range of the difference of deviations from *KCRV* between pairs of participating institutes was between –0.66 HRC to +0.66 HRC with ±0.53 HRC of maximum uncertainty (k=2) of this difference. The range of E_n numbers was between –0.89 to +0.97. This experimental comparison reflected on the effect of the compatibility between indenter and hardness machine. This effect directly influenced the indenter, which was verified according to ISO6508-2 and ISO6508-3. Therefore, the study of the effect of compatibility and reproducibility between indenter and machine should be carried out in the future.

The hardness scale measurement in the range 20 to 60 HRC of four participating national Metrology institutes (NIMT, NMIJ/AIST, VMI and SPRING) were found to be equivalent within their claimed uncertainties. The results of this ASEAN comparison were equivalent.

Annex I

Verification of Primary Rockwell Hardness Machines of Participants

NIMT primary Rockwell hardness machine verification

Metrology information	
Model of hardness machine	SHT-31
Serial number of hardness machine	310039
Manufacturer of hardness machine	Akashi Corporation
Hardness indication system	Laser Hologuage
Test force system	Lever-Type
Relative error of preliminary test force	0.02%(0.0019 kgf)
Relative uncertainty (2σ) of preliminary test force	0.08%(0.008 kgf)
Relative error of total test force	0.01%(0.0150 kgf)
Relative uncertainty (2σ) of total test force	0.02%(0.03 kgf)
Uncertainty of depth measuring device	0.12 μm
Serial number of the laboratory's indenter	NA50215
The tip radius of curvature of the laboratory's indenter	200 μm
The apex angle of cone of the laboratory's indenter	199° 58′

Testing condition

Velocity of the indenter when reading the surface	80.45 – 90.33 $\mu m / s$
Holding time of preliminary test force	2.74 – 3.20 s
Test force loading speed	32.66 – 33.45 $\mu m / s$
Total test force duration time	3.89 – 4.14 s
Time before reading permanent indentation depth	4 ± 0.5 s

Environment of comparison measurement

Measurement place	Hardness Laboratory, NIMT
Measurement date	13/10/04
Environment	Room Temperature: 23±2 °C Relative Humidity: 50±10% RH Atmospheric Pressure: 1003±10 mbar

Deformation of frame verification

	1	**2**	**3**
Deformation of frame (μm)	-0.18	-0.18	-0.18

VMI primary Rockwell hardness machine verification

Metrology information	
Model of hardness secondary machine	HNG - 250
Serial number of hardness secondary machine	030/78
Manufacturer of hardness secondary machine	VEB - Germany
Hardness indication system	Spiral microscope
Test force system	Dead weight
Relative error of preliminary test force	- 0,06 N
Relative uncertainty (2σ) of preliminary test force	0,02 %
Relative error of total test force	- 0,175 N
Relative uncertainty (2σ) of total test force	0,002 %
Uncertainty of depth measuring device	0,2 μm (0,1 HRC)
Serial number of the laboratory's indenter	7964
The tip radius of curvature of the laboratory's indenter	0,1975 mm
The apex angle of cone of the laboratory's indenter	120° 04'

Testing condition

Velocity of the indenter when reaching the surface	8 μm/s
Holding time of preliminary test force	12 s
Test force loading speed	30 ± 3 μm/s
Total test force duration time	4 s
Time before reading permanent indentation depth	12 s

Environment of comparison measurement

Measurement place	Force and Hardness Lab.
Measurement date	October, 21st-22nd 2004
Environment	23°C, 50 RH

Deformation of frame verification

	1	**2**	**3**
Deformation of frame (μm)	**0.1**	**0.1**	**0.1**

SPRING primary Rockwell hardness machine verification

Metrology information	
Model of hardness secondary machine	4150TK
Serial number of hardness secondary machine	941245
Manufacturer of hardness secondary machine	INDENTEC
Hardness indication system	Digital readout
Test force system	Lever-deadweight
Relative error of preliminary test force	-0.028 %
Relative uncertainty (2σ) of preliminary test force	0.031 %
Relative error of total test force	0.004 %
Relative uncertainty (2σ) of total test force	0.013 %
Uncertainty of depth measuring device (2σ)	0.2 μm
Serial number of the laboratory's indenter	IS3421
The tip radius of curvature of the laboratory's indenter	199.08 μm
The apex angle of cone of the laboratory's indenter	120.06°

Testing condition

Velocity of the indenter when reaching the surface	0.086 mm/s
Holding time of preliminary test force	2.44 s
Test force loading speed	Between 20 μm/s to 30 μm/s
Total test force duration time	4.03 s
Time before reading permanent indentation depth	3.63 s

Environment of comparison measurement

Measurement place	NMC's laboratory
Measurement date	2004-11-10 to 2004-11-12
Environment	Ambient temp.: 20 ± 2° C Relative Humidity: 50 ± 10 %rh

Deformation of frame verification

	1	**2**	**3**
Deformation of frame (μm)	0.46	0.48	0.48

NMIJ primary Rockwell hardness machine verification

Metrology information	
Model of hardness primary machine	Modified SHT-32
Serial number of hardness primary machine	240034
Manufacturer of hardness primary machine	AKASHI Co., Japan
Hardness indication system	digital (holographic gage)
Test force system	lever amplified dead weight
Relative error of preliminary test force	0.02% (0.018N) at maximum deviation
Relative uncertainty (*k*=2) of preliminary test force	0.05% (0.048N)
Relative error of total test force	0.01% (0.15N) at maximum deviation
Relative uncertainty (*k*=2) of total test force	0.02% (0.30N)
Uncertainty of depth measuring device(*k*=2)	0.09µm
Serial number of the laboratory’s indenter	DKM 13623
The tip radius of curvature of the laboratory’s indenter	201µm (mean radius)
The apex angle of cone of the laboratory’s indenter	119º54’

Testing condition

Velocity of the indenter when reaching the surface	100-130µm/s (20-60HRC)
Holding time of preliminary test force	3s (before first readings)
Test force loading velocity	40um/s for average velocity 30um/s for 80%-99% of the test force
Total test force duration time	5s
Time before reading permanent indentation depth	4s

Environment of comparison measurement

Measurement place	Hardness Lab.
Measurement date	8-9 December, 2004
Environment	21±1 ºC, 40±2%

Deformation of frame verification

	1	**2**	**3**
Deformation of frame (µm)	0.18	0.18	0.18

Annex II

Uncertainty Estimation of Participants

NIMT Uncertainty Estimation

Quantity Xi	Standard uncertainty $u(x_i)$		Probability Distribution	Sensitivity Coefficient (ci)	Uncertainty Contribution $u(y_i)$ / HRC
ΔFo	0.05	N	Rectangular	1.2E-01	0.006
Fo	0.06	N	Normal	1.2E-01	0.007
ΔF	0.35	N	Rectangular	-4.0E-02	-0.014
F	0.45	N	Normal	-4.0E-02	-0.018
h	0.10	µm	Normal	-5.0E-01	-0.05
Δh	0.03	µm	Rectangular	-5.0E-01	-0.01
V	1.00	µm/S	Normal	-2.0E-02	-0.020
δV_{res}	0.29	µm/S	Rectangular	-2.0E-02	-0.01
Δto	0.25	S	Normal	1.0E-02	0.003
Δt	0.25	S	Normal	-7.0E-02	-0.018
δH_{res}	0.003	HRC	Rectangular	1	0.003
frame	0.13	µm	Rectangular	0.5	0.06
u_c					0.09
U_e				k=2	0.18

Uncertainty of Primary Rockwell Hardness Machine

Where:

ΔF_0 = Error due to the deviation from the expected preliminary test force
F_0 = Preliminary test force
ΔF = Error due to the deviation from the expected total test force
F = Total test force
h = Indicated value of indentation depth
Δh = Systematic error of indentation depth
V = Calculated value of indentation velocity
δv_{res} = Resolution of indentation velocity
Δt_0 = Error due to the deviation from the expected preliminary force dwell time
Δt = Error due to the deviation from the expected total test force dwell time
δH_{res} = The resolution of hardness value
frame = Deformation of the frame

Quantity Xi	Standard uncertainty $u(x_i)$		Probability Distribution	Sensitivity Coefficient (ci)	Uncertainty Contribution $u(y_i)$ / HRC
RPM	0.09	HRC	Normal	1	0.09
RSI	0.18	HRC	Normal	1	0.18
$Block_{uni}$	0.09	HRC	Rectangular	1	0.09
u_c					0.21
U_e				k=2	0.43

Uncertainty Budget for Hardness Measurement of Block

Where:
RPM = Rockwell primary machine
RSI = Rockwell standard indenter
$Block_{uni}$ = Uniformity of reference block (1σ)

VMI Uncertainty Estimation

$$U = k \cdot \sqrt{\left(\frac{b}{2\sqrt{3}}\right)^2 + \left(\frac{U_{std}}{2}\right)^2} ,$$

$k = 2$;

b: uniformity (HRC);

U_{std}: uncertainty of standard (HRC):

≤ 25 HRC: U_{std} = 0,30 HRC;

≤ 55 HRC: U_{std} = 0,21 HRC;

> 55 HRC: U_{std} = 0,38 HRC.

SPRING Uncertainty Estimation

A. For the uncertainty budget using SPRING indenter

1. Since all the parameters were calibrated and conformed to ISO 6508-3 requirements, we would evaluate the type B uncertainty as given in 4.2.1.1 of EA-10/16.

x_i	a_i	$u^2(x_i) = \frac{a_i^2}{3}$	Sensitivity Coefficient at different hardness levels $c_i = \frac{\Delta H}{\Delta x_i}$			Contributions to $u^2(H)/HRC^2$ at different hardness scale $u^2(H) \approx \sum_{i=1}^{n} u_i^2(H) = \sum_{i-1}^{n} c_i^2 u^2(x_i)$		
			20 to 25	40 to 45	60 to 65	20 to 25	40 to 45	60 to 65
F_0 / N	0,2	1,3 • 10^-2^	1,2 • 10^-2^	7,0 • 10^-2^	5,0 • 10^-2^	1,9 • 10^-4^	6,4 • 10^-5^	3,3 • 10^-5^
F / N	1,5	7,5 • 10^-1^	4,0 • 10^-2^	-3,0 • 10^-2^	-2,0 • 10^-2^	1,2 • 10^-3^	6,8 • 10^-4^	3,0 • 10^-4^
$\alpha / ^\circ$	0,1	3,3 • 10^-3^	1,3 • 10^-0^	8,0 • 10^-1^	4,0 • 10^-1^	5,6 • 10^-3^	2,1 • 10^-3^	5,3 • 10^-4^
r / mm	0,005	8,3 • 10^-6^	1,5 • 10^+1^	3,0 • 10^+1^	5,0 • 10^+1^	1,9 • 10^-3^	7,5 • 10^-3^	2,1 • 10^-2^
$h / \mu m$	0,2	1,3 • 10^-2^	-5,0 • 10^-1^	-5,0 • 10^-1^	-5,0 • 10^-1^	3,3 • 10^-3^	3,3 • 10^-3^	3,3 • 10^-3^
$v / (\mu m / s$	10	3,3 • 10^+1^	-2,0 • 10^-2^	0,0 • 10^0^	3,0 • 10^-2^	1,3 • 10^-2^	0,0 • 10^0^	3,0 • 10^-2^
t_0 / s	1,5	7,5 • 10^-1^	1,0 • 10^-2^	5,0 • 10^-3^	4,0 • 10^-3^	7,5 • 10^-5^	1,9 • 10^-5^	1,2 • 10^-5^
t / s	2	1,3 • 10^0^	-7,0 • 10^-2^	-4,0 • 10^-2^	-3,0 • 10^-2^	6,4 • 10^-3^	2,1 • 10^-3^	1,2 • 10^-3^
TOTAL $u_d^2 / HRC^2 = \sum u_i^2 / HRC^2$						0,03	0,02	0,06
Standard uncertainty u_d / HRC						0,18	0,13	0,24
Expanded uncertainty $U / HRC = ku_d / HRC$						0,36	0,26	0,47

Where: x_i = Input quantity
a_i = Tolerance interval
F_0 = Preliminary test force
F = Total test force
α = Indenter angle
r = Indenter radius
h = Indentation depth
v = Indentation velocity
t_0 = Preliminary test force dwell time
t = Total test force dwell time

2. Note that the above parameter are taking tolerances from ISO 6508-3, except for *h*, is the uncertainty. The correction for each calibrated value was applied in the submitted results, hence the uncertainty has been considered in the above type B evaluation
3. For each calibrated value, we choose the larger closer type B certainty evaluated from 1. and combined with the type A uncertainty from the 9 measurement and reported in expanded uncertainty.

B. For the uncertainty budget using common indenter (S/N NA53655)

1. The type B uncertainty is same as the evaluation from A. above, u_d.
2. However, we using for reference hardness block to compared between the indenters of SPRING and Common fitted with linear regression and found that a maximum error occurred with **-** 0.14 HRC. As such for each calibrated value using the common indenter would have to correct using the fitted value with the assuming type B uncertainty $0.14/3^{0.5}$, u_f.
3. The uncertainty due to the non-uniformity of the reference hardness blocks are within 0.4 HRC, assuming with the rectangular distribution, the type B uncertainty $0.4/12^{0.5}$, u_{nu}..
4. Therefore the total type B uncertainty would be combined as together with type A, calculated from the 9 measured values as follows.

Uncertainty Component	20 HRC	25 HRC	30 HRC	35 HRC	40 HRC	45 HRC	50 HRC	55 HRC	60 HRC
u_d	0.18	0.18	0.18	0.18	0.13	0.13	0.24	0.24	0.24
u_f	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081
u_{nu}	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Type B Uncertainty	0.231	0.231	0.231	0.231	0.195	0.195	0.28	0.28	0.28
Type A uncertainty	0.038	0.039	0.036	0.034	0.015	0.021	0.019	0.029	0.029
Combined uncertainty	0.234	0.234	0.234	0.233	0.196	0.196	0.281	0.281	0.281
Expanded uncertainty*	0.47	0.47	0.47	0.47	0.40	0.40	0.57	0.57	0.57

*Note that the expanded uncertainty is based on k = 2 at approximately 95 % level of confidence.

NMIJ Uncertainty Estimation

Uncertainty budget of NMIJ (for participant's indenter)

x_i	$u(x_i)$			Sensitivity Coefficient at different hardness levels $c_i = \frac{\Delta H}{\Delta x_i}$			Contributions to at different hardness scale) $u^2(H)/HRC^2$		
	20 to 35	40 to 55	60 to 65	20 to 35	40 to 55	60 to 65	20 to 35	40 to 55	60 to 65
F_0 / N	4.8E-02			1.2E-01	7.0E-02	5.0E-02	3.32E-05	1.13E-05	5.76E-06
F / N	3.0E-01			-4.0E-02	-3.0E-02	-2.0E-02	1.44E-04	8.10E-05	3.60E-05
h / μ m	4.7E-02			-5.0E-01	-5.0E-01	-5.0E-01	5.62E-04	5.62E-04	5.62E-04
v / μ m/s	2.9E-01			-2.0E-02	0.0E+00	3.0E-02	3.34E-05	0.00E+00	7.51E-05
t_0 / s	2.9E-01			1.0E-02	5.0E-03	4.0E-03	8.35E-06	2.09E-06	1.34E-06
t / s	2.9E-01			-7.0E-02	-4.0E-02	-3.0E-02	4.09E-04	1.34E-04	7.51E-05
$u_{ind.}$ / HRC	1.5E-01	1.3E-01	1.3E-01	1.0E+00	1.0E+00	1.0E+00	2.25E-02	1.69E-02	1.69E-02
u_{block} / HRC	6.0E-02	6.0E-02	6.0E-02	1.0E+00	1.0E+00	1.0E+00	3.60E-03	3.60E-03	3.60E-03
TOTAL $u_d^2/HRC^2 = \sum u_i^2/HRC^2$							0.03	0.02	0.02
Standard uncertainty u_d/HRC							0.17	0.15	0.15
Expanded uncertainty $U/HRC = ku_d/HRC$							0.33	0.30	0.30

Where the $u_{ind.}$ is the uncertainty due to the correction value of the indenter used, and u_{block} is the standard uncertainty due to the non-uniformity of the blocks.

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