COOMET regional comparison of the national standards of air kerma for x-radiation qualities used for radiation protection and diagnostic radiology

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Abstract:

The results of the COOMET supplementary comparison of the national measurement standards of air kerma for x-radiation qualities used for radiation protection and diagnostic radiology are presented. Nine National Metrology Institutes from the COOMET organization and the International Atomic Energy Agency participated in this COOMET project no.641. The BelGIM acted as a pilot laboratory. The comparison reference value (CRV) was obtained as the mean result of the PTB and the VNIIM. One of the participants, the SMU (Slovakia) did not take part in the comparison due to staffing issues. Almost all participants obtained valid results which were consistent within the relative standard uncertainties of the comparison ranging from 0.28% to 2.6%. Some participants had unacceptable results.

1. Introduction

This report describes the COOMET regional comparison of the national measurement standards of air kerma for x-radiation qualities used for radiation protection and diagnostic radiology according to the CIPM Mutual Recognition Arrangement [1]. Results will be published in the Appendix B of the BIPM key comparison database (KCDB) using the identifier COOMET.RI(I)-S3. This is the first comparison of this kind within the COOMET region. Nine National Metrology Institutes (NMIs) and the International Atomic Energy Agency (IAEA), listed in Table 1, took part in the comparison.

Up to now only the national air kerma standards for gamma radiation qualities Cs-137 (protection level) and Co-60 (COOMET.RI(I)-S1 and –K1) have been compared among the member countries of COOMET. There were also two bilateral comparisons (COOMET.RI(I)-S2 and –S4) of air kerma standards for x-ray radiation qualities. Due to the fact that the majority of the member countries have not realized the so-called CCRI-low- and medium-energy x-ray qualities used for the key comparisons BIPM.RI(I)-K2 and –K3, it was decided at the COOMET TC 1.9 meeting in 2015 to exclude of the corresponding key comparisons within COOMET (projects 446/DE/08, 447/DE/08). However, for the time being it is more useful to compare the air kerma standards for x-radiation qualities used for radiation protection purposes

(ISO 4037 Narrow spectrum series [2]) and in diagnostic radiology (IEC 61267 RQR series [3]). These qualities are already established and used by several members of COOMET and need support for the CMC entries of those countries. Therefore, the main objective of the current project is the confirmation of traceability of measurements and calibrations for these x-radiation qualities according to the *Mutual Recognition Arrangement of national measurement standards and of calibration and measurement certificates issued by national metrology institutes* (CIPM-MRA, Paris, 14 October 1999).
All measurements were carried out before the introduction of the ICRU report 90 [4] (ICRU 90). The measurement result of each participant does not include ICRU 90 data. The results of comparisons will still be valid after the implementation of the data of the ICRU 90.

Table 1. Participants of the comparison COOMET.RI(I)-S3

Participant	Institute	Country	Contact person	E-mail of contact person
1	BelGIM	Belarus	Siarhei A. Saroka	tomminoker@tut.by
2	PTB	Germany	Ludwig Büermann	ludwig.bueermann@ptb.de
3	INM-MD	Moldova	Efimia Luchian	ionizante@inm.gov.md
4	IAEA	International	Paula Toroi	p.toroi@iaea.org
5	AzMI	Azerbaijan	Elmar Shahverdiyev	shahverdiyev@mail.ru
6	VNIIM	Russia	Alexandr V. Oborin	oav@vniim.ru
7	CPHR	Cuba	Gonzalo Walwyn Salas	gonzalo@cphr.edu.cu
8	GEOSTM	Georgia	Simon Sukhishvili	s.sukhishvili@gmail.com
9	NSC-“IM”	Ukraine	Andrey Orobinski	orobin61@gmail.com
10	NACEKS	Kazakhstan	Nassyr Mamyrbek	m.nassyr@mail.ru

2. Procedure

2.1 Object of comparison

The object of the comparison was the calibration of three ionization chambers of different types in terms of air kerma in the participants’ x-ray reference radiation fields under reference conditions as defined in 2.4.

2.2 Transfer chambers

Three ionization chambers with different volumes and wall thicknesses were provided by the BelGIM. The chambers were manufactured by Standard Imaging in Middleton, USA. The reference point of the chambers was in the centre of the spherical volume. The chambers were aligned in the beam with the mark on the stem facing the radiation source. The chambers had a Triax TNC Plug (M/F) with adapter to PTW-M type connector. The main technical data are shown in Table 2.

Table 2: Main technical data of the transfer chambers

Chamber model	Exradin A3	Exradin A4	Exradin A5
Serial number	XR143435	XP151681	XY150091
Collecting volume, cm^3	3.6	30	100
Applied polarising voltage, V	+300[(a)]	+400[(a)]	+400[(a)]
Shell wall thickness, mm	0.25	0.5	3.0
Outside diameter, mm	19.6	39.1	63.1
Nominal calibration coefficient, Gy/C	7.9E+6	7.9E+5	2.6E+5
Collector diameter, mm	2.1	4.1	6.5

[(a)] Positive polarity was applied to the outer electrode with respect to the collecting electrode.

2.3 Radiation qualities

The comparison was carried out by means of the calibration of three transfer ionization chambers in terms of air kerma under reference conditions at the following radiation qualities:
- N-40, N-60, N-80, N-100, N-120, N-150, N-200, N-250, N-300 for the transfer chambers A4 and A5;
- RQR2, RQR3, RQR5, RQR7, RQR9, RQR10 for the transfer chambers A3 and A4.

Preferentially, the participants had to calibrate the transfer chambers for all these qualities. If this was not possible, it was mandatory to calibrate the chambers at least for five selected qualities of the suggested set from the N-series [2] and for three selected qualities of the suggested set from the RQR series [3]. If possible, it was preferable to choose the calibration qualities N-40, N-60, N-120, N-300, RQR2, RQR5 and RQR10. If participants did not have RQR series realized in their laboratory they were allowed to participate only with the N-series.

2.4 Reference conditions, measurement procedure and report of results

The recommended source-to-chamber distance (from the focus of the x-ray tube to the reference point of the chamber) was detween 100 cm and 200 cm. The recommended air kerma rate was between 10 mGy/min and 120 mGy/min for RQR qualities and between 3 mGy/h and 120 mGy/h for N-series qualities. The beam cross section at the reference plane should fully cover the spherical volume of the chamber.

The transfer chambers were placed in the laboratory at least 12 hours before the measurements started in order to let them adjust to the climatic conditions. The measurements were started not earlier than 1 hour after the high voltage application to the chamber. The ionization currents of the transfer were measured with and without the radiation beam. The signal-to-noice ratios of the currents were not less than 1000. The background current was subtracted from the signal current. A complete measurement consisted of at least 10 repeated single measurements and the mean value was taken as the result. The calibration coefficients of the transfer chambers were measured at one polarity (see table 1) and were given in terms of air kerma per unit charge in Gy/C referring to the standard conditions of air temperature, pressure and relative humidity of $T = 293.15$ K, $P = 101.325$ kPa and $h = 50$ %. The relative air humidity was between 20 % and 80 % during the calibrations, otherwise a correction to $h = 50$ % was applied. Participants did not apply any corrections for the incomplete charge collection.

A form for the results reporting was distributed together with the technical protocol. The uncertainties were given in accordance with the ISO Guide to the expression of uncertainties in measurements (GUM) [5].

2.5 Course of comparison

Three transfer chambers were circulated star-shaped between the BelGIM and the participants. After each participant's calibration the BelGIM performed the chambers' constancy checks. With a few exceptions, the chambers stayed at the participant's site for no longer than 3 weeks. The results were reported to the coordinator within about 2 weeks after the calibration.

2.6 Time schedule

The comparison started in April 2016 with the BelGIM measurements and was completed in January 2019 with the last stability measurements at the BelGIM. The time schedule is shown in Table 3.

Table 3. Time schedule of the comparison

Participant	Date of calibration at the participant's site	Constancy measurements at the BelGIM
BelGIM, Belarus	Apr - 2016	
PTB, Germany	Jun - 2016	Jul - 2016
INM-MD, Moldova	Aug - 2016	Sep - 2016
IAEA, International	Jan - 2017	Mar - 2017
AzMI, Azerbaijan	May - 2017	Jun - 2017
VNIIM, Russia	Jun - 2017	Jul - 2017
CPHR, Cuba	Jan - 2018	Mar - 2018
GEOSTM, Georgia	Jun - 2018	Jul - 2018
NSC-"IM", Ukraine	Aug - 2018	Oct - 2018
NACEKS, Kazakhstan	Dec - 2018	Jan - 2019

2.7 Procedure for handling the results of the pilot laboratory

The pilot laboratory participated in the comparison. The BelGIM determined its values of the calibration coefficients in April 2016. The report on these measurements was sent to the COOMET TC 1.9 Chairman and to the Secretary of the CCRI before the first participant had submitted the report to the pilot laboratory. For the purpose of the constancy check, the pilot laboratory made measurements of the air kerma rate of Cs-137 source at the same distance after each participant's measurements. All of the results were corrected to the date of the first measurement and were normalized to the mean value.

3. Results

3.1 Constancy of the transfer chambers

The constancy of the transfer chambers was checked by repeated measurements of Cs-137 air kerma rate. The first stability check measurements were performed in April 2016 and were then repeated each time when the chambers returned to the BelGIM after the participant's measurements. The last stability check measurements were carried out in January 2019. For each transfer chamber the mean value (corrected to standard pressure and temperature), decay corrected to the date of the first measurement, was calculated and then was used for the single values normalization. The mean values and the standard deviations of the normalized values are summarized in Table 4. The single values are shown in Figure 1. None of the single values deviates by more than 0.5 % from the mean value. For all chambers the maximum standard deviation of the mean normalized value was close to 0.0030. From these values a relative standard uncertainty due to possible long-term instabilities of the transfer chambers of 0.30 % was taken into account (see 3.4).

Table 4. Mean values and standard deviations of the normalized air kerma rates

	Cs-137	
Chamber	Mean	Sdev
A3 s/n XR143435	1.0000	0.0030
A4 s/n XP151681	1.0000	0.0016
A5 s/n XY150091	1.0000	0.0022

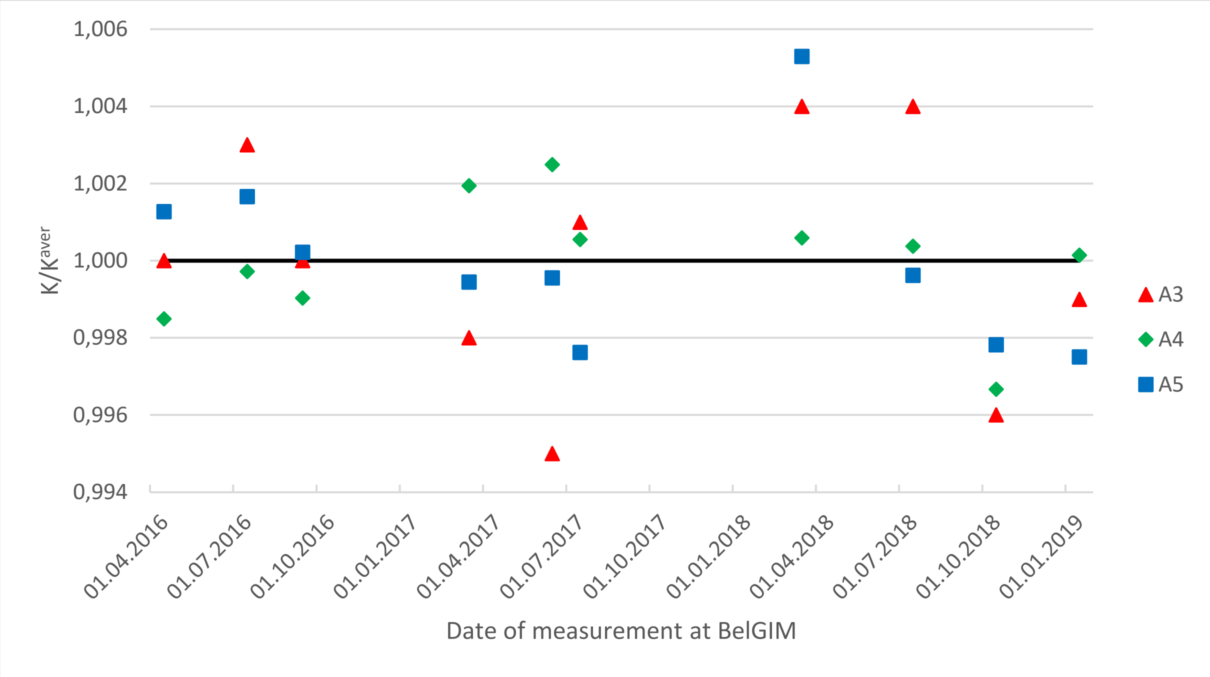

Figure 1. Cs-137 air kerma rates for three transfer chambers normalized to their mean values obtained from the constancy check measurements at the BelGIM

3.2 Summary of the reported results

Tables 5 and 6.1 to 6.4 summarize the reported irradiation conditions, calibration coefficients and uncertainties. The distance between the source and the reference point was from 100 cm to 200 cm. The air kerma rates ranged between 3 mGy/h and 120 mGy/h for N-series and between 10 mGy/min and 115 mGy/min for RQR qualities. The relative uncertainties of the calibration coefficients ranged between 0.30 % and 2.8 %. The comparatively high relative standard uncertainties of more than 1 % reported by three participants were due to the uncertainties in the air kerma rate measurements with the national standards (see Tables 6.1 to 6.4).

Table 5. Irradiation conditions at the participants' sites

	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
Standard	FK	K10-100/ [K70-300	A3 32002	A3 32002	A3, A4 32002	Radcal 10X5-6, NE2575	32002, 23361	M77334 34035	A3 32002	A3 LS01
Traceability	primary	primary	VNIIM	IAEA	IAEA	PTB/IAEA	IAEA	IAEA	IAEA	PTB
Distance, cm RQR/N	100/100	100/100	100/150	100/100	100/100	100/200	100/200	200/200	100/100	100/200
Diameter, cm RQR/N	10/15	10/10	8.3/22.5	40/40	10/10	8.4/26.8	7/7	33.5/33.5	16/16	10/26
RQR Rate, mGy/min	10-20	60-100	20-100	50	20-115	10-100	50	13-52	12-112	50
N Rate, mGy/h	19.8	70-100	15-25	35	12-120	3-25	9.0	13-77	8-66	12

Table 6.1. Calibration coefficients (/10^6 Gy/C) and their relative standard uncertainties for A3 chamber and RQR qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACEKS	IAEA
RQR2	7.972	7.986	7.988	-	-	7.943	-	-	8.117	-
RQR3	7.947	7.951	7.952	-	8.028	7.958	7.620	7.919	8.112	7.951
RQR5	7.913	7.888	7.934	-	7.967	7.939	7.860	7.917	8.083	7.914
RQR7	7.913	7.889	7.900	-	7.955	7.925	7.490	8.045	8.060	7.919
RQR9	7.921	7.895	7.909	-	7.944	7.936	7.830	8.107	8.076	7.918
RQR10	7.927	7.909	7.910	-	7.977	7.935	7.460	8.203	8.095	7.939
$u(K_a)$ / %	0.27	0.26	0.86	-	0.80	0.61	1.55	2.55	1.24	0.48
u_{other} / %	0.22	0.15	0.53	-	0.24	0.10	0.41	0.43	0.42	0.23
u_{total} / %	0.35	0.30	1.01	-	0.83	0.62	1.61	2.58	1.32	0.53

Table 6.2. Calibration coefficients (/10^6 Gy/C) and their relative standard uncertainties for A4 chamber and RQR qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
RQR2	1.045	1.044	1.052	-	-	1.044	-	-	1.096	-
RQR3	1.036	1.035	1.038	1.033	1.034	1.040	0.990	1.036	1.074	1.039
RQR5	1.021	1.018	1.025	1.023	1.022	1.026	1.020	1.032	1.070	1.025
RQR7	1.016	1.012	1.018	1.017	1.016	1.020	1.010	1.049	1.086	1.019
RQR9	1.012	1.009	1.015	1.014	1.009	1.018	1.010	1.052	1.069	1.013
RQR10	1.010	1.008	1.013	1.012	1.008	1.015	0.990	1.064	1.073	1.012
$u(K_a)$ / %	0.27	0.26	0.86	1.48	0.80	0.61	1.55	2.55	1.24	0.48
u_{other} / %	0.22	0.15	0.53	1.33	0.24	0.10	0.41	0.43	0.42	0.23
u_{total} / %	0.35	0.30	1.01	1.87	0.83	0.62	1.61	2.58	1.32	0.53

Table 6.3. Calibration coefficients (/10^6 Gy/C) and their relative standard uncertainties for A4 chamber and Narrow spectrum qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
N-40	1.014	1.014	0.996	0.999	1.006	-	0.861	0.960	0.928	1.019
N-60	1.001	1.002	0.995	0.993	1.002	-	0.844	0.944	0.922	1.009
N-80	1.008	1.005	1.000	0.994	1.008	1.012	0.844	0.966	0.933	1.015
N-100	1.008	1.010	1.001	1.021	1.005	1.010	0.838	0.973	0.929	1.015
N-120	1.007	1.011	1.001	1.011	1.005	1.003	0.840	0.976	0.934	1.014
N-150	1.010	1.013	1.001	1.010	1.002	1.006	0.858	0.972	0.932	1.015
N-200	1.009	1.011	1.002	1.011	1.005	-	-	0.997	0.941	1.019
N-250	1.013	1.013	1.000	-	-	-	-	-	-	1.021
N-300	1.017	1.017	0.996	-	-	-	-	-	-	1.025
$u(K_a)$ / %	0.27	0.26	0.86	1.12	0.78	0.83	0.72	2.67	1.27	0.52
u_{other} / %	0.22	0.15	0.57	0.92	0.17	0.10	0.41	0.82	0.49	0.32
u_{total} / %	0.35	0.30	1.03	1.45	0.80	0.84	0.83	2.79	1.36	0.61

Table 6.4. Calibration coefficients (/10^5 Gy/C) and their relative standard uncertainties for A5 chamber and Narrow spectrum qualities

Quality	PTB	VNIIM	BelGIM	INM	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
N-40	3.139	3.146	3.120	3.163	3.126	-	2.640	2.879	3.070	3.150
N-60	2.942	2.943	2.940	2.955	2.942	-	2.470	2.828	3.049	2.950
N-80	2.937	2.923	2.890	2.960	2.927	2.921	2.440	2.857	3.080	2.940
N-100	2.944	2.946	2.930	2.958	2.933	2.920	2.430	2.885	3.072	2.950
N-120	2.963	2.964	2.960	2.972	2.945	2.935	2.450	2.900	3.087	2.970
N-150	2.979	2.977	2.980	2.984	2.959	2.952	2.530	2.894	3.084	2.980
N-200	2.995	3.010	3.020	3.010	2.987	-	-	2.981	3.111	3.010
N-250	3.016	3.019	2.990	-	-	-	-	-	-	3.030
N-300	3.033	3.037	2.960	-	-	-	-	-	-	3.040
$u(K_a)$ / %	0.27	0.26	0.86	1.12	0.78	0.83	0.72	2.67	1.27	0.52
u_{other} / %	0.22	0.15	0.57	0.92	0.17	0.10	0.41	0.82	0.49	0.32
u_{total} / %	0.35	0.30	1.03	1.45	0.80	0.84	0.83	2.79	1.36	0.61

3.3 Comparison reference value

The PTB and the VNIIM took part in the key comparisons BIPM.RI(I)-K2 [6] and BIPM.RI(I)-K3 [7]. The results for the ratio $R_{\mathrm{NMI}} = N_{K,\mathrm{NMI}}/N_{K,\mathrm{BIPM}}$ and the evaluated indirect ratios of the calibration factors of PTB and VNIIM are shown in table 7. These data agree reasonably well with the direct comparison value between 0.9950 and 1.0048 obtained in this work, with average value 1.0003. This result gives confidence in the measurements of both laboratories.

Table 7. Results of the comparisons BIPM.RI(I)-K2 [6, 8] and BIPM.RI(I)-K3 [7, 9]

High voltage, kV	HVL	R_{PTB}	R_{VNIIM}	R_{PTB}/R_{VNIIM}
50a	2.262 mm Al	0.9994	0.9993	1.0001
50b	1.017 mm Al	0.9989	0.9987	1.0002
100	4.030 mm Al	1.0027	1.0014	1.0013
135	0.489 mm Cu	1.0045	1.0018	1.0027
180	0.977 mm Cu	1.0049	1.0026	1.0023
250	2.484 mm Cu	1.0055	1.0026	1.0029

For each quality, the comparison reference value (CRV) $N_{K,\mathrm{CRV}}$ was calculated as the mean of the PTB and the VNIIM calibration coefficients. The relative standard uncertainty u_{CRV} of $N_{K,\mathrm{CRV}}$ was estimated as 0.21 % which takes into account the correlation in the type B uncertainties associated with the physical constants (0,15 %). The following results were obtained:

Table 8. Comparison reference value (CRV)

	A3	**A4**
RQR2	7.979×10^6 Gy/C	1.045×10^6 Gy/C
RQR3	7.949×10^6 Gy/C	1.036×10^6 Gy/C
RQR5	7.901×10^6 Gy/C	1.020×10^6 Gy/C
RQR7	7.901×10^6 Gy/C	1.014×10^6 Gy/C
RQR9	7.908×10^6 Gy/C	1.010×10^6 Gy/C
RQR10	7.918×10^6 Gy/C	1.009×10^6 Gy/C
	A4	**A5**
N-40	1.014×10^6 Gy/C	3.143×10^5 Gy/C
N-60	1.002×10^6 Gy/C	2.943×10^5 Gy/C
N-80	1.007×10^6 Gy/C	2.930×10^5 Gy/C
N-100	1.009×10^6 Gy/C	2.945×10^5 Gy/C
N-120	1.009×10^6 Gy/C	2.964×10^5 Gy/C
N-150	1.012×10^6 Gy/C	2.978×10^5 Gy/C
N-200	1.010×10^6 Gy/C	3.003×10^5 Gy/C
N-250	1.013×10^6 Gy/C	3.018×10^5 Gy/C
N-300	1.017×10^6 Gy/C	3.035×10^5 Gy/C

3.4 Comparison results

The ratio $R_{K,i}$ of the participant's calibration factor $N_{K,i}$ and the CRV $N_{K,\mathrm{CRV}}$ was calculated according to

$$R_{K,i} = \frac{N_{K,i}}{N_{K,CRV}}, \tag{1}$$

The uncertainty $u_{R,i}$ of $R_{K,\mathrm{i}}$ was calculated according to the following equation

$$u_{R,i}^2 = u_i^2 + u_{CRV}^2 + u_{stab}^2 - \sum_k \left(f_k u_i(k)\right)^2 - \sum_k (f_k u_{CRV}(k))^2, \tag{2}$$

u_i is the relative standard uncertainty of the transfer chamber calibration coefficient reported by NMI i, u_{CRV} is the relative standard uncertainty associated with the CRV, u_{stab} is the relative standard uncertainty due to the long term stability of the transfer chambers, $u_i(k)$ is a particular (correlated) uncertainty component k, $u_{CRV}(k)$ is the uncertainty of the same component k. The last two terms account for any correlated quantities between the NMI and the CRV, where the factor f_k

is the correlation coefficient. u_{stab} was estimated to be 0.3 % from the relative standard deviation of the air kerma rates obtained from the repeated measurements at the BelGIM as described in 3.1. The results for $R_{K,i}$ obtained for each of the transfer chambers and its mean values are listed in Tables 9.1 to 9.6 and shown in Figures 2.1 to 2.6.

In general, the only correlation taken into account was the uncertainties of the physical constants, which were used for the primary standards which are the same for all participants because all are traceable to a primary standard at least. The uncertainty of the physical constants for X-ray cavity chamber standards at that time was 0.15 %. Therefore, this uncertainty was subtracted from the total uncertainties given by the participants. Due to the very small relative uncertainty contribution (only 0.15 %) it did not change the total uncertainties very much. Due to the direct traceability of BelGIM to VNIIM and also CPHR and IAEA to PTB uncertainties of the primary lab (excluding uncertainties of the physical constants) were subtracted from the total uncertainties of BelGIM, CPHR and IAEA.

The mean value of the ratios $R_{K,i}$ for the same quality of the different chambers were taken as the results of the comparison. The maximum of the uncertainties calculated according to (2) was taken as the uncertainty of the results.

Table 9.1. Ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for A3 chamber and RQR qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
RQR2	0.9991	1.0009	1.0011	-	-	0.9955	-	-	1.0173	-
RQR3	0.9997	1.0003	1.0004	-	1.0099	1.0011	0.9586	0.9962	1.0205	1.0003
RQR5	1.0016	0.9984	1.0042	-	1.0084	1.0048	0.9949	1.0021	1.0231	1.0017
RQR7	1.0015	0.9985	0.9999	-	1.0068	1.0031	0.9480	1.0182	1.0201	1.0023
RQR9	1.0016	0.9984	1.0001	-	1.0046	1.0035	0.9901	1.0252	1.0212	1.0013
RQR10	1.0011	0.9989	0.9990	-	1.0075	1.0021	0.9422	1.0360	1.0224	1.0027
u / %	0.36	0.36	1.04	-	0.89	0.67	1.64	2.60	1.36	0.58

Table 9.2. Ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for A4 chamber and RQR qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
RQR2	1.0005	0.9995	1.0072	-	-	1.0000	-	-	1.0493	-
RQR3	1.0005	0.9995	1.0024	0.9976	0.9986	1.0044	0.9561	1.0005	1.0372	1.0034
RQR5	1.0015	0.9985	1.0054	1.0034	1.0025	1.0063	1.0005	1.0123	1.0495	1.0054
RQR7	1.0020	0.9980	1.0039	1.0030	1.0020	1.0058	0.9961	1.0345	1.0710	1.0049
RQR9	1.0015	0.9985	1.0045	1.0035	0.9985	1.0077	0.9995	1.0411	1.0579	1.0025
RQR10	1.0010	0.9990	1.0040	1.0030	0.9990	1.0057	0.9812	1.0545	1.0634	1.0030
u / %	0.36	0.36	1.04	1.90	0.89	0.67	1.64	2.60	1.36	0.58

Table 9.3. Ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for A4 chamber and Narrow spectrum qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
N-40	1.0000	1.0000	0.9822	0.9849	0.9921	-	0.8491	0.9467	0.9152	1.0049
N-60	0.9995	1.0005	0.9935	0.9916	1.0005	-	0.8427	0.9430	0.9202	1.0075
N-80	1.0015	0.9985	0.9935	0.9875	1.0015	1.0057	0.8385	0.9598	0.9267	1.0084
N-100	0.9990	1.0010	0.9921	1.0119	0.9960	1.0011	0.8305	0.9645	0.9205	1.0059
N-120	0.9985	1.0015	0.9916	1.0015	0.9955	0.9937	0.8321	0.9666	0.9250	1.0045
N-150	0.9985	1.0015	0.9896	0.9985	0.9906	0.9949	0.8482	0.9609	0.9218	1.0035
N-200	0.9990	1.0010	0.9921	1.0013	0.9950	-	-	0.9868	0.9312	1.0089
N-250	1.0000	1.0000	0.9872	-	-	-	-	-	-	1.0079
N-300	1.0000	1.0000	0.9794	-	-	-	-	-	-	1.0079
u / %	0.36	0.36	1.06	1.49	0.87	0.90	0.89	2.81	1.40	0.66

Table 9.4. Ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for A5 chamber and Narrow spectrum qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
N-40	0.9989	1.0011	0.9928	1.0065	0.9947	-	0.8401	0.9161	0.9769	1.0024
N-60	0.9998	1.0002	0.9992	1.0042	0.9998	-	0.8394	0.9611	1.0362	1.0025
N-80	1.0024	0.9976	0.9863	1.0102	0.9990	0.9970	0.8328	0.9751	1.0512	1.0034
N-100	0.9997	1.0003	0.9949	1.0044	0.9959	0.9915	0.8251	0.9796	1.0431	1.0017
N-120	0.9998	1.0002	0.9988	1.0029	0.9938	0.9904	0.8267	0.9786	1.0417	1.0022
N-150	1.0003	0.9997	1.0007	1.0020	0.9936	0.9913	0.8496	0.9718	1.0356	1.0007
N-200	0.9975	1.0025	1.0058	1.0025	0.9948	-	-	0.9928	1.0361	1.0025
N-250	0.9995	1.0005	0.9909	-	-	-	-	-	-	1.0041
N-300	0.9993	1.0007	0.9753	-	-	-	-	-	-	1.0016
u / %	0.36	0.36	1.06	1.49	0.87	0.90	0.89	2.81	1.40	0.66

Table 9.5. Mean $R_{K,\mathrm{i}}$ of the ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for RQR qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
RQR2	0.9998	1.0002	1.0042	-	-	0.9978	-	-	1.0333	-
RQR3	1.0001	0.9999	1.0014	0.9976	1.0043	1.0028	0.9574	0.9984	1.0289	1.0019
RQR5	1.0016	0.9985	1.0048	1.0034	1.0055	1.0056	0.9977	1.0072	1.0363	1.0036
RQR7	1.0018	0.9983	1.0019	1.0030	1.0044	1.0045	0.9721	1.0264	1.0456	1.0036
RQR9	1.0016	0.9985	1.0023	1.0035	1.0016	1.0056	0.9948	1.0332	1.0396	1.0019
RQR10	1.0011	0.9990	1.0015	1.0030	1.0033	1.0039	0.9617	1.0453	1.0429	1.0029
u / %	0.36	0.36	1.04	1.90	0.89	0.67	1.64	2.60	1.36	0.58

Table 9.6. Mean $R_{K,\mathrm{i}}$ of the ratios $R_{K,\mathrm{i}}$ and their relative standard uncertainties for Narrow spectrum qualities

Quality	PTB	VNIIM	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
N-40	0.9994	1.0006	0.9875	0.9957	0.9934	-	0.8446	0.9314	0.9461	1.0037
N-60	0.9997	1.0003	0.9964	0.9979	1.0002	-	0.8411	0.9520	0.9782	1.0050
N-80	1.0019	0.9981	0.9899	0.9989	1.0002	1.0013	0.8357	0.9674	0.9889	1.0059
N-100	0.9993	1.0007	0.9935	1.0082	0.9960	0.9963	0.8278	0.9721	0.9818	1.0038
N-120	0.9992	1.0008	0.9952	1.0022	0.9946	0.9920	0.8294	0.9726	0.9833	1.0034
N-150	0.9994	1.0006	0.9952	1.0003	0.9921	0.9931	0.8489	0.9664	0.9787	1.0021
N-200	0.9983	1.0017	0.9990	1.0019	0.9949	-	-	0.9898	0.9837	1.0057
N-250	0.9998	1.0002	0.9891	-	-	-	-	-	-	1.0060
N-300	0.9997	1.0003	0.9774	-	-	-	-	-	-	1.0048
u / %	0.36	0.36	1.06	1.49	0.66	0.90	0.89	2.81	1.40	0.66

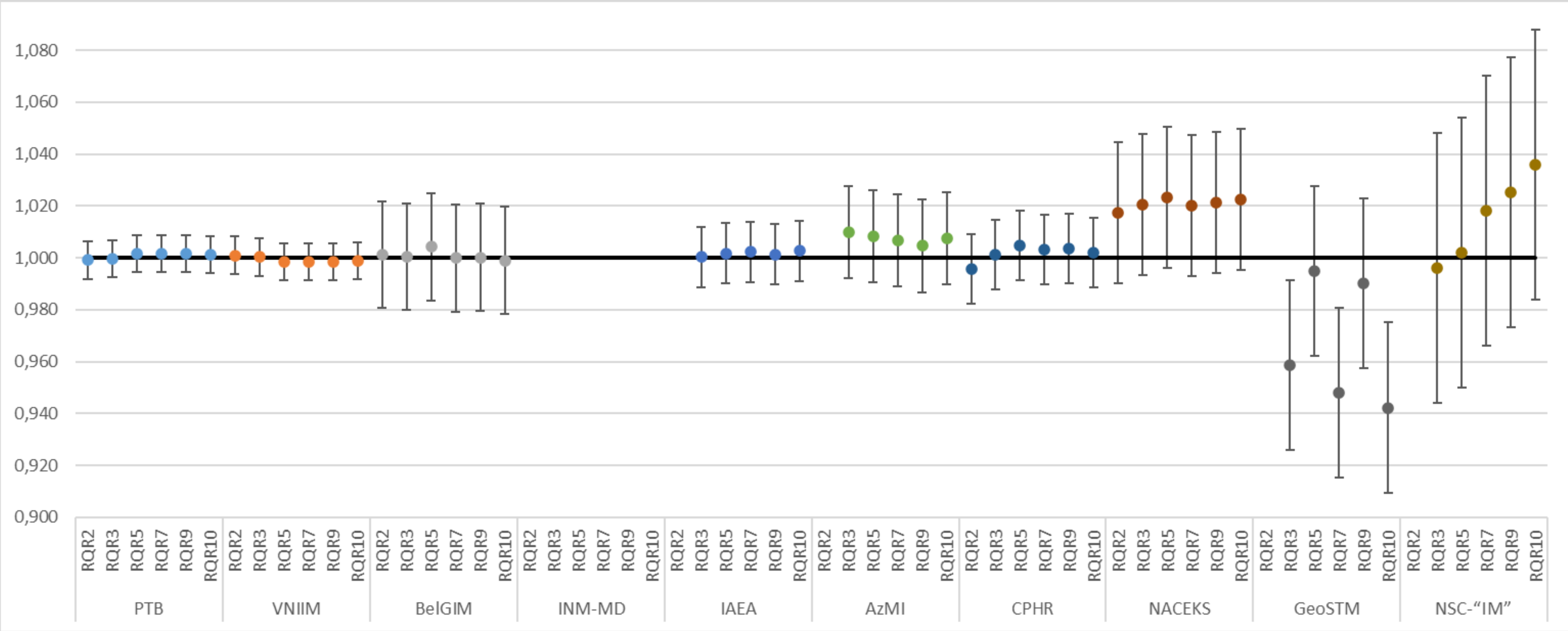

Figure 2.1. Ratios $R_{K,\mathrm{i}}$ and their expanded uncertainties $2{*}u_{R,i}$ for A3 chamber for RQR qualities.

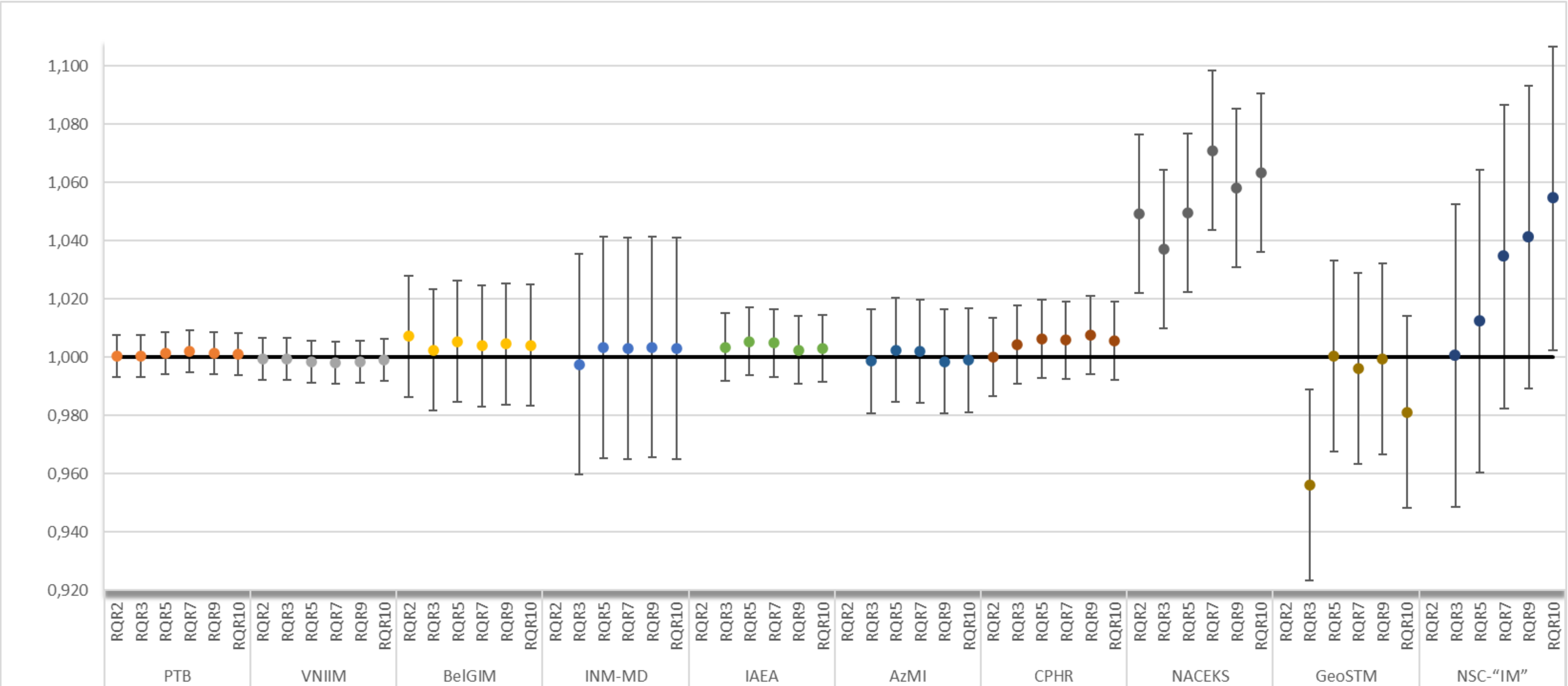

Figure 2.2. Ratios $R_{K,i}$ and their expanded uncertainties $2*u_{R,i}$ for A4 chamber for RQR qualities.

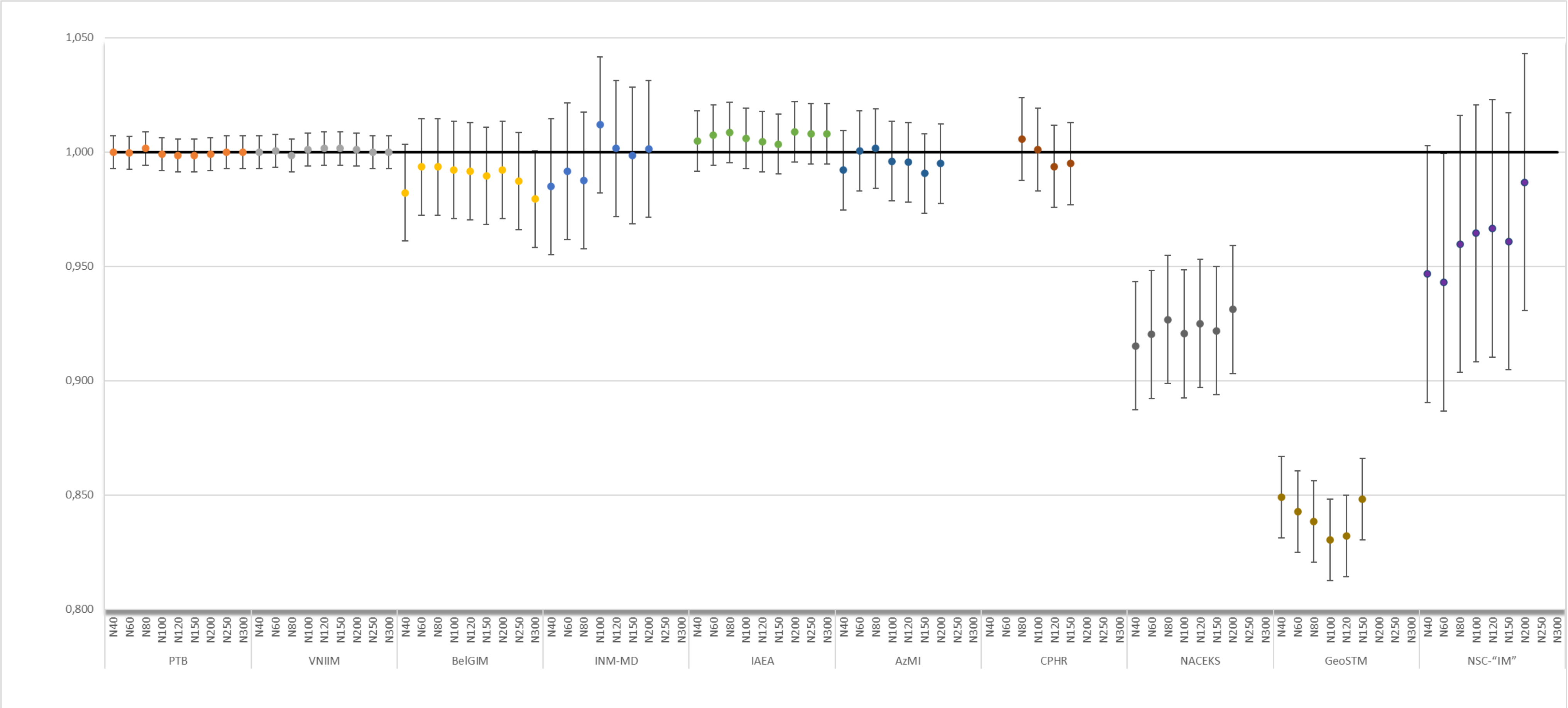

Figure 2.3. Ratios $R_{K,i}$ and their expanded uncertainties $2*u_{R,i}$ for A4 chamber for Narrow spectrum qualities.

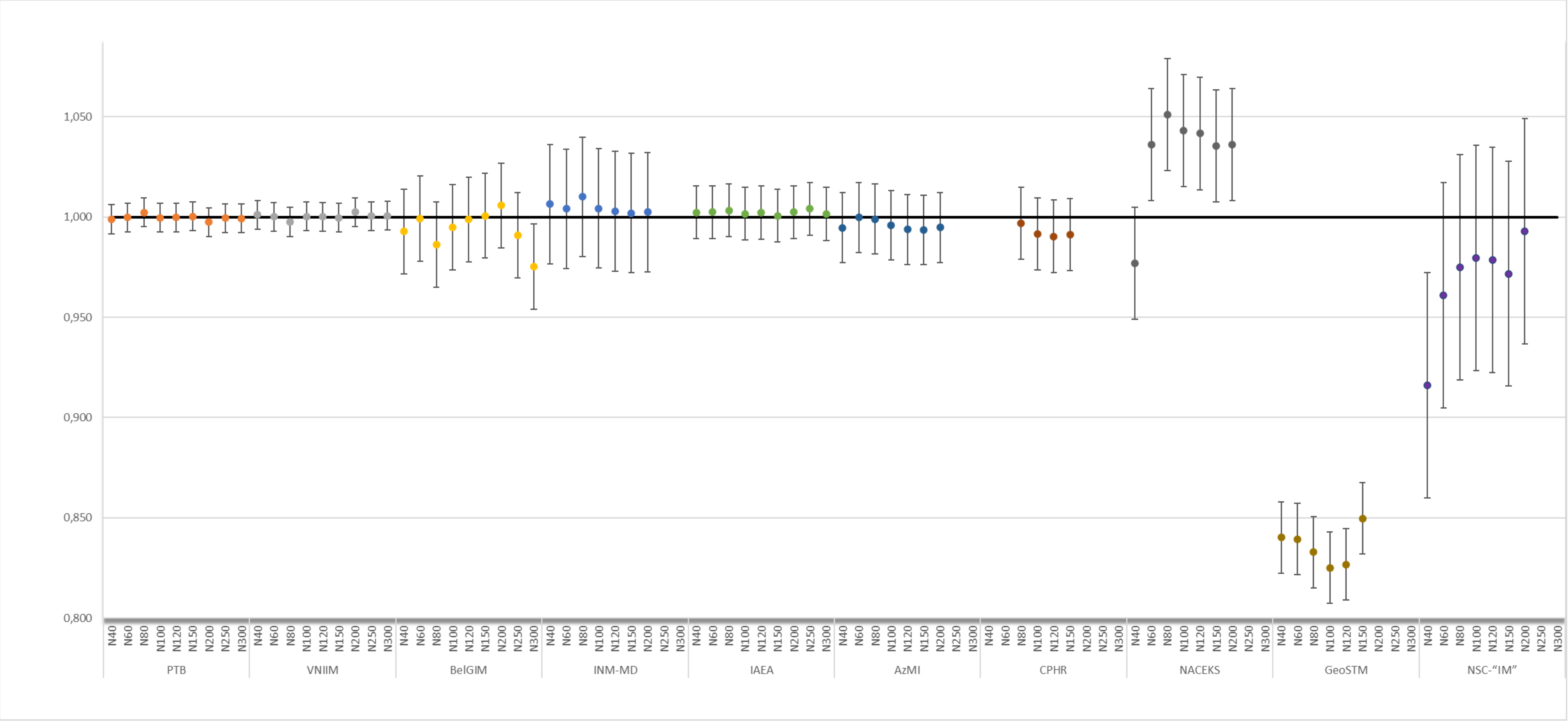

Figure 2.4. Ratios $R_{K,i}$ and their expanded uncertainties $2*u_{R,i}$ for A5 chamber for Narrow spectrum qualities.

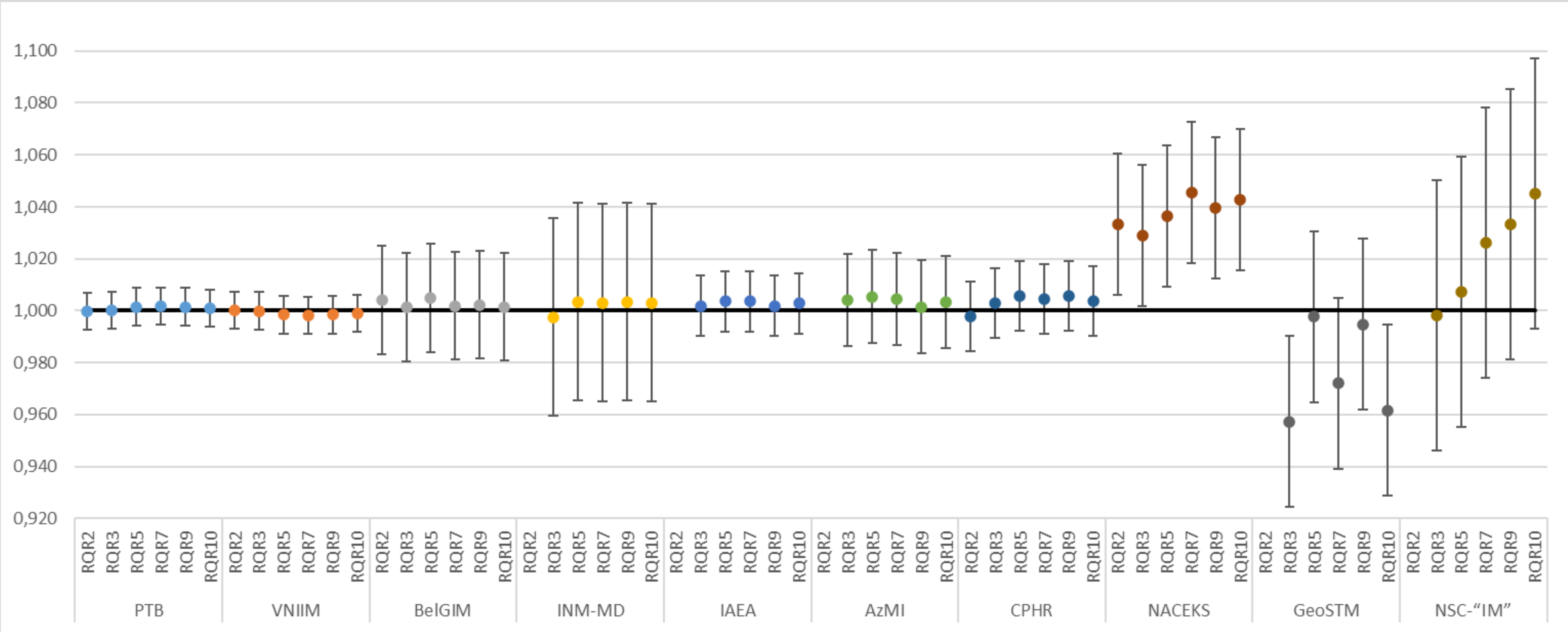

Figure 2.5. Mean $R_{K,\mathrm{i\ mean}}$ of the ratios $R_{K,\mathrm{i}}$ and their expanded uncertainties 2* $u_{R,i\ mean}$ for RQR qualities.

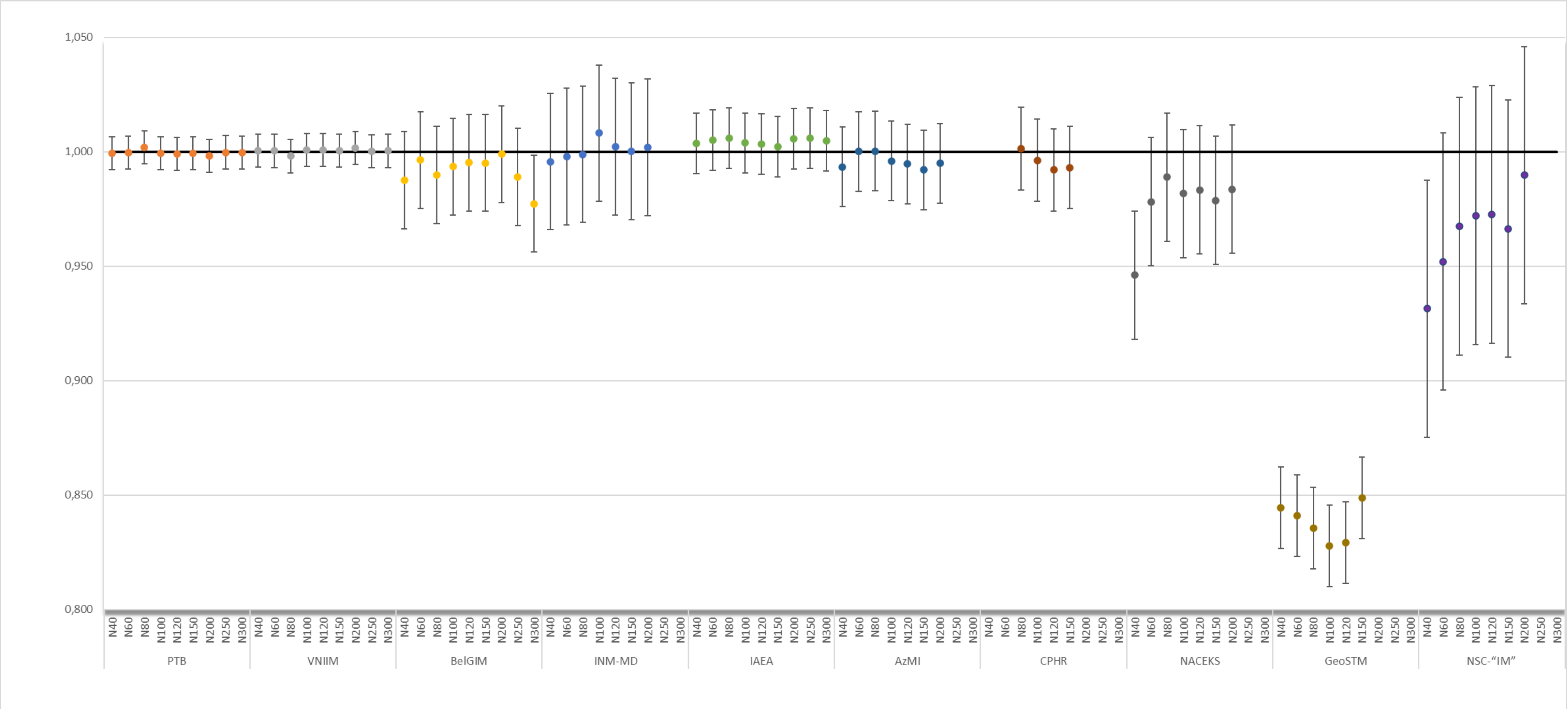

Figure 2.6. Mean $R_{K,\text{i mean}}$ of the ratios $R_{K,\text{i}}$ and their expanded uncertainties $2{*}u_{R,i\ mean}$ for Narrow spectrum qualities.

From Figures 2.1 to 2.6 it can be concluded that, except for three NMIs, all other values generally deviate from the CRV by less than their expanded uncertainties. Results for all N-series, RQR3 and RQR10 qualities of the GEOSTM, for all RQR and N-40 qualities of the NACEKS, for N-40 quality of the NSC-"IM" and for N-300 quality of the BelGIM deviate significantly by more than their expanded uncertainty from the CRV. All other participants obtained consistent results for all three transfer chambers. It can be concluded that, except for the GEOSTM and the NACEKS, the reproducibility of the measurements of the calibration coefficients is much better than the estimated total uncertainty. There are no results of the INM-MD for the A3 chamber at RQR qualities due to a large leakage current which was observed for this chamber. When the chamber was returned to the BelGIM, it was dried and the connector was cleaned. These measures resolved all the leakage issues and the transfer chamber could be used for the remaining comparisons.

4. Evaluation of the degree of equivalence with the CRV

The degree of equivalence of laboratory *i* with respect to the CRV is effectively given by the difference $D_i = R_{K,i,\mathrm{mean}} - 1$ and its expanded uncertainty U_i. The results for D_i and U_i, expressed in mGy/Gy, are shown in Tables 10.1 and 10.2. These data form the basis of the results entered into the BIPM key comparison database for comparison COOMET.RI(I)-S3.
Note that no values are listed in Tables 10.1 and 10.2 for the PTB and the VNIIM because their results were used to define the CRV (see section 3.3). The degree of equivalence between these two primary standards laboratories is still given by the result obtained in the key comparisons BIPM.RI(I)-K2 and -K3.

Table 10.1. The degrees of equivalence, D_i, of each NMI's measurement standard with respect to the CRV for RQR qualities

Quality	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
				mGy/Gy				
RQR2	4.2	-	-	-2.2	-	-	33.3	-
RQR3	1.4	-2.4	4.3	2.8	-42.7	-1.7	28.8	1.9
RQR5	4.8	3.4	5.4	5.5	-2.3	7.2	36.3	3.6
RQR7	1.9	3.0	4.4	4.5	-28.0	26.3	45.6	3.6
RQR9	2.3	3.5	1.5	5.6	-5.2	33.2	39.6	1.9
RQR10	1.5	3.0	3.2	3.9	-38.3	45.3	42.9	2.9
U_i	20.7	37.9	17.7	13.4	32.9	49.8	26.0	11.6

Table 10.2. The degrees of equivalence, D_i, of each NMI's measurement standard with respect to the CRV for Narrow spectrum qualities

Quality	BelGIM	INM-MD	AzMI	CPHR	GEO STM	NSC-„IM“	NACE KS	IAEA
				mGy/Gy				
N-40	-12.5	-4.3	-6.6	-	-155.4	-68.6	-53.9	3.6
N-60	-3.6	-2.1	0.2	-	-159.0	-48.0	-21.8	5.0
N-80	-10.1	-1.1	0.3	1.3	-164.4	-32.6	-11.1	5.9
N-100	-6.5	8.2	-4.1	-3.7	-172.2	-27.9	-18.2	3.8
N-120	-4.8	2.2	-5.3	-8.0	-170.6	-27.4	-16.6	3.3
N-150	-4.9	0.3	-7.9	-6.9	-151.1	-33.7	-21.3	2.1
N-200	-1.1	1.9	-5.1	-	-	-10.2	-16.4	5.7
N-250	-11.0	-	-	-	-	-	-	6.0
N-300	-22.7	-	-	-	-	-	-	4.8
U_i	21.4	29.8	17.5	18.1	21.0	57.8	28.5	13.1

5. Conclusions

The comparison results presented in Tables 9.5 and 9.6 and Figures 2.5 and 2.6 show agreement between the SSDLs and CRV at the level of the standard (k =1) and expanded (k = 2) uncertainties of the comparison, respectively. The supplementary comparison COOMET.RI(I)-S3 for the determination of air kerma for x-radiation qualities used for radiation protection and diagnostic radiology shows the standards of the BelGIM, the INM-MD, the IAEA, the AzMI, the CPHR, the NACEKS, the GEOSTM and the NSC-"IM" to be in general agreement at the level of the standard uncertainty of the comparison, except for Narrow spectrum series and RQR3, RQR10 qualities of the GEOSTM, for N-40 and all RQR qualities of the NACEKS, for N-40 quality of the NSC-"IM" and for N-300 quality of the BelGIM. Tables of degrees of equivalence are presented.

6. References

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