Comparison of national air kerma standards for ISO 4037 narrow spectrum series in the range 30 kV to 300 kV

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Abstract

For the first time results are presented of an indirect comparison of ten national standards for air kerma for ten radiation qualities of the ISO 4037 narrow spectrum series in the range from 30 kV to 300 kV. Nine of the ten participants maintain primary air kerma standards, one is traceable to PTB. The comparison was conducted in the time period from February 2004 until October 2005. For each radiation quality, the results are analysed in terms of the degrees of equivalence of each national standard with respect to the comparison reference value. These data form the basis of the results in the BIPM key comparison database for comparison EUROMET.RI(I)-S3. In addition, results are presented of differences in the results due to different realizations of beam qualities at the participants sites and of the influence of different transfer chamber sizes on the variance of the comparison results.

1 Introduction

Existing key comparisons between national air kerma standards for x-radiation are those for low- and medium-energy x-rays designated as BIPM.RI(I)-K2 [1] and -K3 [2]. The range of x-radiation qualities are from 10 kV to 50 kV and 100 kV to 250 kV characterized by half-value layers in the range from 0.037 mm Al to 2.262 mm Al and 0.15 mm Cu to 2.5 mm Cu, respectively. The air kerma rates in use are 1 mGy/s and 0.5 mGy/s. The ISO 4037 [3] narrow spectrum series x-ray qualities used for the comparison described in this work cover the range from 30 kV to 300 kV and are characterized by half-value layers from about 0.04 mm Cu to 6 mm Cu. Due to the heavier filtration the usual air kerma rates are in the much lower range from about 10 µGy/s to 20 µGy/s. Consequently, this supplementary comparison differs from the two existing key comparisons in the dose rate range being lower by about a factor of 100 and extends the radiation qualities from half-value layers of 2,5 mm Cu to about 6 mm Cu.

The ISO 4037 qualities are mainly used for the calibration of radiation protection detectors. It is sometimes necessary, to calibrate detectors of very large dimensions and consequently large field sizes are needed. However, the reference value of the air kerma rate is usually measured with free-air chambers which have apertures of the dimension of only a few centimetres. In order to examine the influence of different field sizes on the calibration coefficient it was decided to use transfer ionization chambers of different measuring volumes for the calibration of which field sizes of about 5 cm, 20 cm and 30 cm are needed. Radiation qualities of identical series but realized in different laboratories will usually be slightly different. In order to obtain some information about that, one of the transfer chambers was calibrated with and without an additional Cu layer of thickness 0.1mm in front of the chamber.

2. Procedure

2.1 Object of comparison

Three spherical ionization chambers of different volumes (30 cm^3, 1000 cm^3, 10000 cm^3) were calibrated in terms of air kerma. One of the chambers (30 cm^3) was also calibrated behind a Cu sheet of thickness 0.1 mm. With the first three chambers the influence of field size effects (like homogeneity and filter produced scattered radiation) on the comparison results was to be examined. The chamber/Cu-sheet combination was to serve as an indicator in the case of not matching radiation qualities between the participants.

2.2 Transfer chambers

The main technical data of the three spherical chambers used as transfer standards for the comparison are listed in Table 1. All chambers were manufactured by the Austrian Research Center Seibersdorf. They are otherwise in use as secondary standards at the PTB since more than 15 years. The wall material of all chambers consist of DELRIN^{R}500 of thickness 3 mm. The reference point of the chambers is the centre of the sphere. The chambers were aligned in the beams with the white point marked on the wall facing the radiation source. The signal connection of the chambers was a BNC plug and the chamber high voltage was connected with a banana plug. The TK30 was circulated together with a 0.1 mm thick Cu sheet in a frame holder construction which could optionally be fixed on the chamber stem in a unique way. Pictures of the transfer chambers are shown in Appendix A.

Table 1. Main technical data of the transfer chambers

Type	Serial Number	Sensitive volume (nominal)	Outside diameter	Diameter of inner electrode	Chamber high voltage	Saturation loss
TK30	113	30 cm^3	44 mm	3 mm	- 300 V	<0.5% up to 4 Gy/h
LS 01	111	1000 cm^3	140 mm	50 mm	- 400 V	<0.5% up to 0.3 Gy/h
LS 10	113	10 000 cm^3	275 mm	80 mm	-1000 V	<0.2% up to 10 mGy/h

2.3 Radiation qualities and reference conditions

The radiation qualities used for the comparison were the narrow-spectrum series defined in ISO 4037-1 [3] for tube potentials between 30 kV and 300 kV. Characteristics of the narrow-spectrum series are shown in Table 2. The calibration coefficients for the transfer chambers were given in terms of air kerma per unit charge in units of Gy/C and referred to standard conditions of air temperature, pressure and relative humidity of T = 293.15 K, P = 1013.25 hPa and h = 50 %, respectively.

Table 2. Characteristics of ISO 4037 narrow-spectrum series

Mean energy E / keV	Tube Potential kV	Additional Filtration / mm				1st HVL mm Cu	2nd HVL mm Cu
		Pb	Sn	Cu	Al		
24	30				4.0	1.15 Al	1.30 Al
33	40			0.21		0.084	0.091
48	60			0.6		0.24	0.26
65	80			2.0		0.58	0.62
83	100			5.0		1.11	1.17
100	120		1.0	5.0		1.71	1.77
118	150		2.5			2.36	2.47
164	200	1.0	3.0	2.0		3.99	4.05
208	250	3.0	2.0			5.19	5.23
250	300	5.0	3.0			6.12	6.15

2.4 Participants and course of comparison

Ten participants, listed in Table 3, were included in the comparison. PTB was the pilot laboratory.

Table 3. Participating Institutes

Participant	Institute	Country
OMH*	National Office of Measures	Hungary
NMi	NMi Van Swinden Laboratoriumi	The Netherlands
BEV	Bundesamt für Eich- und Vermessungswesen	Austria
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency	Australia
NPL	National Physical Laboratory	United Kingdom
NIST	National Institute of Standards and Technology	United States
STUK	Radiation and Nuclear Safety Authority	Finland
NMIJ/AIST	National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology	Japan
INER	National Radiation Standard Laboratory, Institute of Nuclear Energy Research	Taiwan
PTB	Physikalisch-Technische Bundesanstalt	Germany

*) OMH has changed its name and is now called MKEH, Magyar Kereskedelmi Engédeyezési Hivatal.

A star-shaped circulation of the chambers between PTB and the other participants was realized. After each participant's calibration the PTB performed chamber constancy checks. The chambers stayed at the participants site for no longer than 3 weeks. The results were reported to the coordinator within 6 weeks after the calibration. An MS-Excel sheet was provided by the coordinator in which information about the radiation qualities and primary standards used at the participants site and the calibration results were filled in. The uncertainties were given in accordance with the ISO Guide to the expression of uncertainties in measurements [4]. The comparison was conducted from February 2004 until October 2005, as shown in Table 4.

Table 4. Date of calibration at the participants site and constancy check measurements at PTB

Participant	Date of calibration	Constancy checks
PTB	February 2004	
OMH	February 2004	February 2004
NMi	April 2004	April 2004
BEV	May/June 2004	June 2004
ARPANSA	August 2004	August2004
NPL	October 2004	November 2004
NIST	December 2004	February 2005
STUK	March 2005	April 2005
NMIJ/AIST	June/July 2005	August 2005
INER	September 2005	October 2005

3 Results

3.1 Energy dependence of the response of the transfer chambers

The correction factor for the radiation quality, k_{Q,Q_0}, is defined as the ratio of the calibration coefficients at the radiation quality Q and Q_0 being ^{137}Cs gamma radiation. The dependence of k_{Q,Q_0} as a function of the mean energy of the radiation quality measured at PTB is shown in Figure 1.

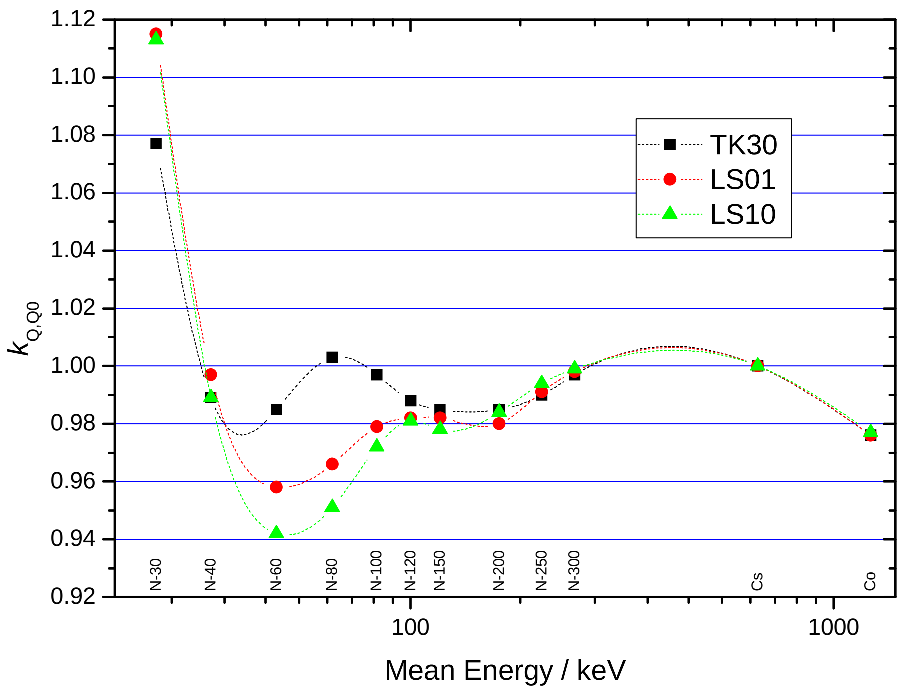


Figure 1. Correction factor for the radiation quality, k_{Q,Q_0}, as a function of the mean energy of the radiation quality. The lines connecting the points serve to guide the eyes. k_{Q,Q_0} varies only moderately down to N-40 but increases strongly between N-40 and N-30.

3.2 Stability measurements

Stability measurements were performed at the PTB after each participant's measurements. In order to obtain maximum information all transfer chambers were calibrated each time for the ISO 4037 N-20 to N-300 and in addition for ^{137}Cs and ^{60}Co γ radiation at comparable air kerma rates of the order of some μGy/h. Measurements were performed in February, April, June, August and November in 2004 and in February, April, August and October in 2005. The mean values and relative standard deviations of the samples are shown in Table 5.

Table 5. Mean values and relative standard deviations of the samples of the calibration coefficients measured at the PTB during the star shaped comparison

	TK30		TK30 + Cu		LS01		LS10	
	Mean N_K 10^6 Gy/C	S-Dev %	Mean N_K 10^6 Gy/C	S-Dev %	Mean N_K 10^4 Gy/C	S-Dev %	Mean N_K 10^3 Gy/C	S-Dev %
N-20	1.6571	0.10	-		4.3518	0.14	5.2753	0.19
N-25	1.2820	0.10	-		3.2943	0.13	3.9455	0.19
N-30	1.1254	0.14	6.3883	0.22	2.8353	0.32	3.3506	0.31
N-40	1.0333	0.11	2.2467	0.16	2.5353	0.19	2.9785	0.20
N-60	1.0297	0.21	1.3675	0.15	2.4359	0.39	2.8349	0.40
N-80	1.0485	0.17	1.1633	0.16	2.4571	0.26	2.8635	0.35
N-100	1.0422	0.12	1.0932	0.20	2.4892	0.26	2.9258	0.33
N-120	1.0324	0.16	1.0607	0.22	2.4977	0.26	2.9537	0.34
N-150	1.0294	0.22	1.0470	0.28	2.4978	0.34	2.9449	0.20
N-200	1.0290	0.14	1.0353	0.14	2.4904	0.32	2.9634	0.22
N-250	1.0348	0.14	1.0387	0.22	2.5196	0.20	2.9917	0.31
N-300	1.0420	0.16	1.0444	0.18	2.5385	0.20	3.0090	0.19
S-Cs	1.0452	0.13	-		2.5423	0.10	3.0110	0.12
S-Co	1.0206	0.12	-		2.4807	0.17	2.9409	0.13

The normalized air kerma responses of the transfer chambers measured during the comparison period are shown in Figs. 2 to 5. From the results obtained at Cs and Co gamma radiation it can be concluded that the chambers behaved sufficiently constantly during the comparison. It is important to note that for the x-radiations the TK30 was calibrated at 1m distance from the focal spot directly against the free-air chamber. The LS01 chamber was subsequently calibrated at 2 m distance against the TK30 and the LS10 at 3 m distance against the LS01. This procedure avoids problems due to low current signals of the free-air chamber at larger distances from the focal spot. For the TK30 chamber the variances of the calibration coefficients for the x-radiations are comparable to those for the gamma radiations. This is not true for the larger LS01 and LS10 chamber which reflected significantly higher variances for the x-radiations. This finding can neither be explained by type A uncertainties in the current measurements, which were always less than 0.1%, nor by differences in the set-up, which caused much lower uncertainties. It is assumed that the higher variances are due to effects of the larger radiation fields which might reflect slightly different dose rate profiles on different days.

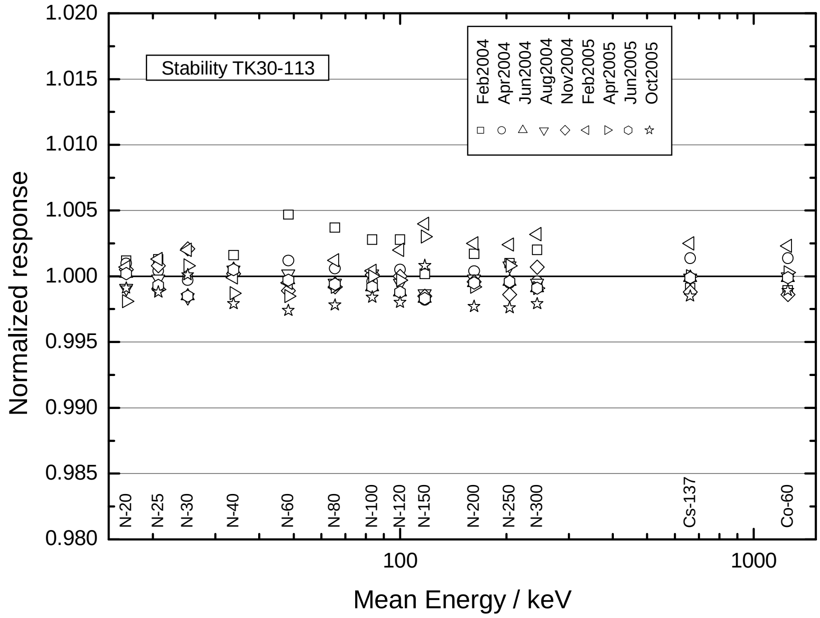


Figure 2. Measured air kerma response of the transfer chamber TK30-113 during the comparison normalized to the mean value as a function of the mean energy of the radiation qualities.

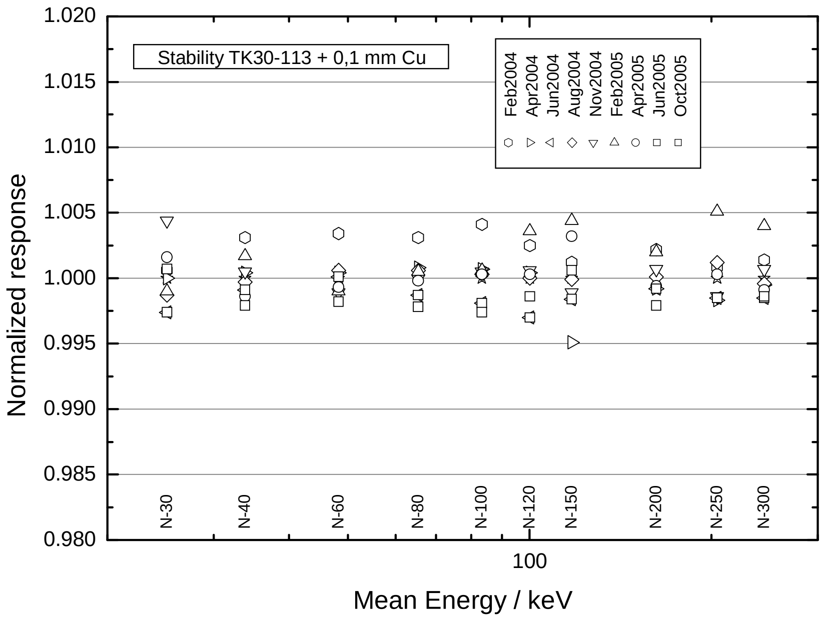


Figure 3. Measured air kerma response of the transfer chamber TK30-113/Cu during the comparison normalized to the mean value as a function of the mean energy of the radiation qualities.

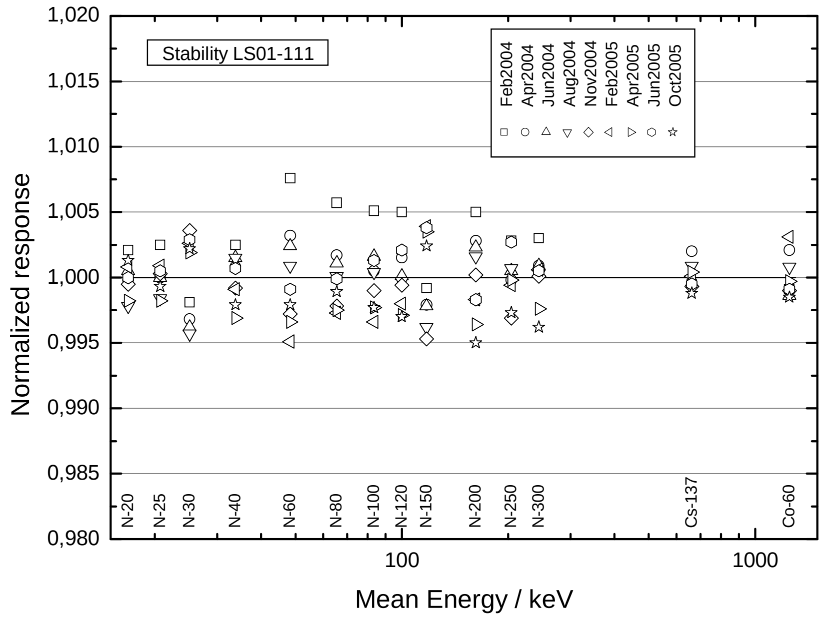


Figure 4. Measured air kerma response of the transfer chamber LS01-111 during the comparison normalized to the mean value as a function of the mean energy of the radiation qualities.

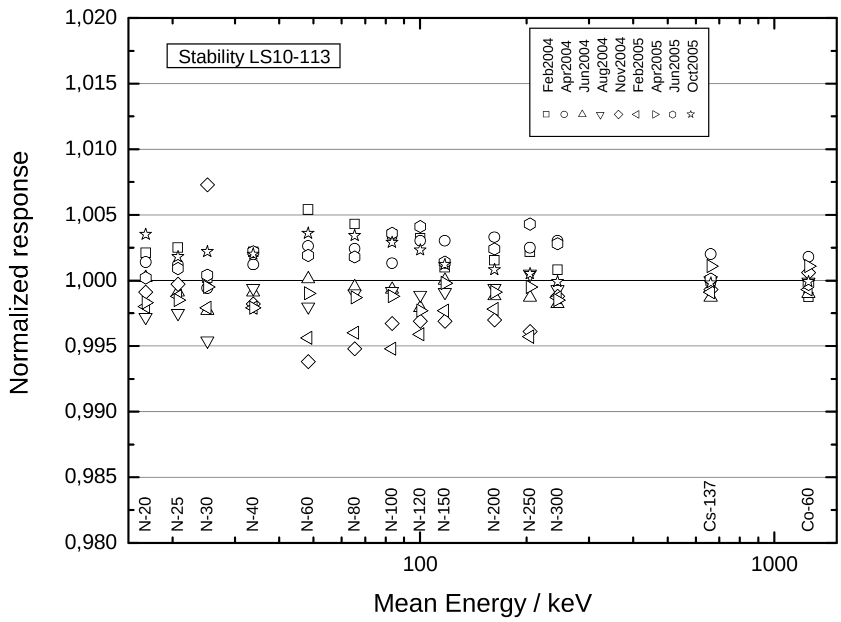


Figure 5. Measured air kerma response of the transfer chamber LS10-113 during the comparison normalized to the mean value as a function of the mean energy of the radiation qualities.

3.3 National air kerma standards and calibration conditions at the participant's sites

The essential technical data of the national air kerma standards of the participants and the essential parameters characterizing the calibration conditions at the participants sites are summarized in Table 6. The STUK does not maintain its own primary standard but uses the secondary standard ionization chamber of type NE2575 manufactured by "Saint-Gobain Crystals and Detectors UK Ltd." which is traceable to the PTB. The OMH, NPL, NIST and INER used different free air chambers for the low- and medium-energy x-ray qualities. The PTB and INER used cylindrical and all other participants plane parallel type free air chambers. The aperture diameters vary between 0.4 cm and 2.5 cm. The measuring volumes of the free air chambers used for the comparison are quite different ranging from 0.88 cm^3 up to 90.3 cm^3.

The calibration conditions were not exactly prescribed in the technical protocol in order to leave some degrees of freedom to the participants who could use their routine procedures for such kind of calibrations. Therefore the conditions were not the same at the participants sites. Different focal distances, beam sizes and air kerma rates were used as shown in Table 6. Most of the participants calibrated the TK30 directly against their primary standards at distances between 1000 mm and 1500 mm. The NPL and STUK used secondary standards for this purpose. The NPL and STUK calibrated all three transfer chambers at the same (large) distances of 2900 mm and 3000 mm, respectively. Due to time constraints, NPL was obliged to calibrate all of the chambers at the same time. To accommodate the size of the LS10 chamber, the calibrations were performed at 2900 mm focal distance instead of the 2000 mm used routinely. Except NIST, who calibrated the larger chambers directly against their primary standard, all other participants used secondary standards for this purpose. The LS01 chamber was calibrated at focal distances between 1000 mm and 4235 mm, the LS10 at distances between 2000 mm and 5360 mm.

It is useful to know the signal currents of the national standards and the transfer chambers during the measurements at the participant's sites. Therefore the approximate currents were calculated from the given air kerma rates at N-30 and/or N-100 and the known measuring volumes of the ionization chambers. The values are also listed in Table 6. The signal currents of the national standards in Table 6 correspond to the air kerma rates used by the participants for the calibration of the TK30. Signal currents between 0.4 pA at ARPANSA and 37.5 pA at STUK were obtained. Depending on the leakage these signal currents caused more or less type A uncertainties in the determination of the conventional true value of the air kerma rates (see Table 9 in chapter 3.5). The signal currents of the transfer chambers were generally much larger than their expected leakage currents and therefore did not cause any considerable type A uncertainties in the majority of the measurements at any site.

The half value layers of the ISO 4037 narrow spectrum series realized at the participant's sites are listed in Table 7a together with the values given in the standard itself. The normalized values in Table 7b show that all values agree with those of the standard within ± 5 %.

Table 6. Essential technical data of the national air kerma standards and parameters characterizing the calibration conditions at the participant's site. Abbreviations: cyl: cylindric, pp: plane parallel, n: nominal, P: Primary Standard, S: Secondary Standard, SSD: Source detector distance

National air kerma Standards	PTB	OMH	OMH	NMi	BEV	AR-PANSA	NPL	NPL	NIST	NIST	STUK	NMIJ/ AIST	INER	INER
FAC Type	cyl	pp	pp	pp	pp	pp	pp	Pp	pp	pp	NE2575	pp	cyl	cyl
Used at kV	30-300	30	40-300	30-300	30-300	30-300	30	40-300	30-60	80-300	30-300	30-300	30-40	60-300
Aperture diameter / cm	2.0009	0.49995	0.9827	1.0061	1.96	0.80476	0.80014	1.0014	1.00017	0.9999		2.5009	0.4000	1.0005
Collecting length / cm	20.001	4.094	29.647	10.04	30.0	10.0849	1.9714	9.9948	7.003	10.08		9.99	7.0000	29.3129
Electrode separation / cm	40	6.00	32.0	60	32.6	20	6.25	26.4(n)	9.0	20.0		24.00	8.0000	30.0000
Collector width / cm				34	31.9	30	7.3 (n)	35(n)	9.0	26.8		23.55	15.5130	53.9500
Measuring volume / cm^3	62.892	0.80369	22.675	7.9795	90.3	5.1297	1.0048	7.8963	5.502	7.92	600	49.073	0.8801	23.0458
Polarizing voltage / V	3000	1600	6000	6000	6000	5000	-1500	-3000	-5000	-5000	250	-4000	2000	3500

Calibration conditions	PTB	OMH	OMH	NMi	BEV	AR-PANSA	NPL	NPL	NIST	NIST	STUK	NMIJ/ AIST	INER	INER
TK30 calibrated against	P	P	P	P	P	P	S	S	P	P	S	P	P	P
LS01 calibrated against	S	S	S	S	S	S	S	S	P	P	S	S	S	S
LS10 calibrated against	S	S	S	S	S	S	S	S	P	P	S	S	S	S
TK30: SDD / mm	1000	1000	1000	1000	1350	1331	2000	2900	1000	1000	3000	1520	1000	1500
LS01: SDD / mm	2000	2500	2500	3000	2500	4235	2000	2900	1000	1000	3000	3020	2000	3000
LS10: SDD / mm	3000		5000	3000	5000	5360		2900	2000	2000	3000	5020	4000	4800
TK30: beam diam. / mm	100	110	113	100.3	170	110	275	350	100	60	430	210	120	100
LS01: beam diam. / mm	200	275	283	301	310	350	275	350	150	210	430	400	240	200
LS10: beam diam. / mm	450		565	301	610	443		350	300	300	430	660	480	320
Air kerma rates / µGy/s	N-100	N-30	N-100	N-100	N-100	N-100	N-30	N-100	N-30	N-100	N-100	N-100	N-30	N-100
Calibration of TK30	9.6	101.1	9.7	7.8	7.3	2.4	6.25	0.74	50.3	4.4	1.76	1.68	102.9	2.22
Calibration of LS01	2.3	2.58	1.63	0.79	2.1	0.23	6.25	0.74	50.3	4.9	0.56	0.21	24.63	0.51
Calibration of LS10	1		0.2	0.79	0.49	0.14		0.74	3.21	0.6	0.56	0.14	5.54	0.19
National Standard: I / pA	21.4	2.9	7.8	2.2	23.4	0.4	2.2	2.6	9.8	1.2	37.5	2.9	3.2	1.8
TK30: I / pA	10.2	107.7	10.3	8.3	7.8	2.6	6.7	0.8	53.6	4.7	1.9	1.8	109.6	2.4
LS01: I / pA	81.7	91.6	57.9	28.0	74.6	8.2	221.9	26.3	1785.7	174.0	19.9	7.5	874.4	18.1
LS10: I / pA	355.0		71.0	280.5	174.0	49.7		262.7	1139.6	213.0	198.8	49.7	1966.7	67.5

Table 7a. First half value layers of the ISO narrow spectrum qualities at the participant's sites given in mm Al for N-30 and mm Cu for the other qualities.

Quality	ISO 4037	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	1.15	1.182	1.16	1.19	1.15	1.14	1.21	1.154	1.15	1.15	1.155
N-40	0.084	0.088	0.08	0.086	0.084	0.083	0.085	0.082	0.084	0.0831	0.087
N-60	0.24	0.243	0.24	0.23	0.22	0.24	0.234	0.241	0.24	0.2405	0.24
N-80	0.58	0.588	0.57	0.57	0.58	0.59	0.581	0.59	0.58	0.58	0.59
N-100	1.11	1.111	1.12	1.08	1.09	1.14	1.12	1.14	1.11	1.11	1.14
N-120	1.71	1.692	1.74	1.67	1.70	1.69	1.73	1.76	1.71	1.711	1.75
N-150	2.36	2.336	2.36	2.30	2.48	2.34	2.42	2.41	2.36	2.36	2.41
N-200	3.99	3.904	4.01	3.80	4.00	4.04	4.10	4.09	4.00	3.99	4.09
N-250	5.19	5.093	5.24	5.10	5.19	5.25	5.33	5.34	5.20	5.19	5.24
N-300	6.12	5.983	6.15	6.02	6.03	6.09	6.26	6.17	6.12	6.12	6.11

Table 7b. First half value layers of the ISO 4037 narrow spectrum qualities at the participant's sites normalized to those given in the standard.

Quality	ISO 4037	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	1	1.03	1.01	1.03	1.00	0.99	1.05	1.00	1.00	1.00	1.00
N-40	1	1.05	0.95	1.02	1.00	0.99	1.01	0.98	1.00	0.99	1.04
N-60	1	1.01	1.00	0.96	0.92	1.00	0.98	1.00	1.00	1.00	0.99
N-80	1	1.01	0.98	0.98	1.00	1.02	1.00	1.02	1.00	1.00	1.01
N-100	1	1.00	1.01	0.97	0.98	1.03	1.01	1.03	1.00	1.00	1.03
N-120	1	0.99	1.02	0.98	0.99	0.99	1.01	1.03	1.00	1.00	1.02
N-150	1	0.99	1.00	0.97	1.05	0.99	1.03	1.02	1.00	1.00	1.02
N-200	1	0.98	1.01	0.95	1.00	1.01	1.03	1.03	1.00	1.00	1.02
N-250	1	0.98	1.01	0.98	1.00	1.01	1.03	1.03	1.00	1.00	1.01
N-300	1	0.98	1.00	0.98	0.99	1.00	1.02	1.01	1.00	1.00	1.00

3.4 Calibration coefficients of the participants

The calibration coefficients and uncertainties obtained by the participants are listed in the Tables B1 to B4 and are also shown in the figures B1 to B4 of Appendix B. In order to present the results for each transfer chamber in a way that the relative variation of the data can easily be recognized they were normalized for each radiation quality to their mean values and plotted against the tube voltage as shown in Figures 6 to 9. If these graphs are compared with those in Figures 2 to 5 it becomes clear that the repeated constancy check measurements of the transfer chambers at PTB reflected sufficiently lower variation compared to those of the comparison results. This is shown quantitatively by the numbers presented in Table 8 where the standard deviations of the distributions of the results, those of the stability measurements and their ratios are listed. It appears that the ratios were mostly greater by more than a factor of 3 and this is sufficiently large if one takes into account that the stability measurements include not only the real stability of the transfer chambers but also the reproducibility of the whole calibration procedure at one laboratory.

Table 8. Comparison of the standard deviations of the distributions of the calibration coefficients obtained by the participants and those of the stability check measurements at PTB

	TK30			LS01			LS10		
Quality	Results s / %	Stability s / %	Ratio	Results s / %	Stability s / %	Ratio	Results s / %	Stability s / %	Ratio
N-30	0.74	0.14	5.3	1.11	0.32	3.4	1.57	0.31	5.0
N-40	0.77	0.11	7.1	1.23	0.19	6.7	1.24	0.20	6.1
N-60	1.00	0.21	4.8	1.14	0.39	2.9	1.16	0.40	2.9
N-80	0.55	0.17	3.3	0.92	0.26	3.5	1.16	0.35	3.3
N-100	0.65	0.12	5.3	1.12	0.26	4.4	1.09	0.33	3.3
N-120	1.19	0.16	7.6	0.84	0.26	3.3	0.64	0.34	1.9
N-150	0.60	0.22	2.7	0.62	0.34	1.8	0.69	0.20	3.5
N-200	0.86	0.14	6.1	0.76	0.32	2.3	1.08	0.22	4.9
N-250	0.76	0.14	5.4	0.82	0.20	4.0	0.82	0.31	2.7
N-300	1.58	0.16	9.6	1.27	0.20	6.4	2.24	0.19	11.5

Compared to the results obtained from key comparisons between national air kerma standards for low- and medium -energy x-rays, designated as BIPM.RI(I)-K2 [1] and K3 [2], the data of the present work reflect significantly larger differences. One of the objects of this work was to analyze in more detail which influence quantities are responsible for the larger variation of the data even though in most cases the same primary standard free-air ionization chambers are used.

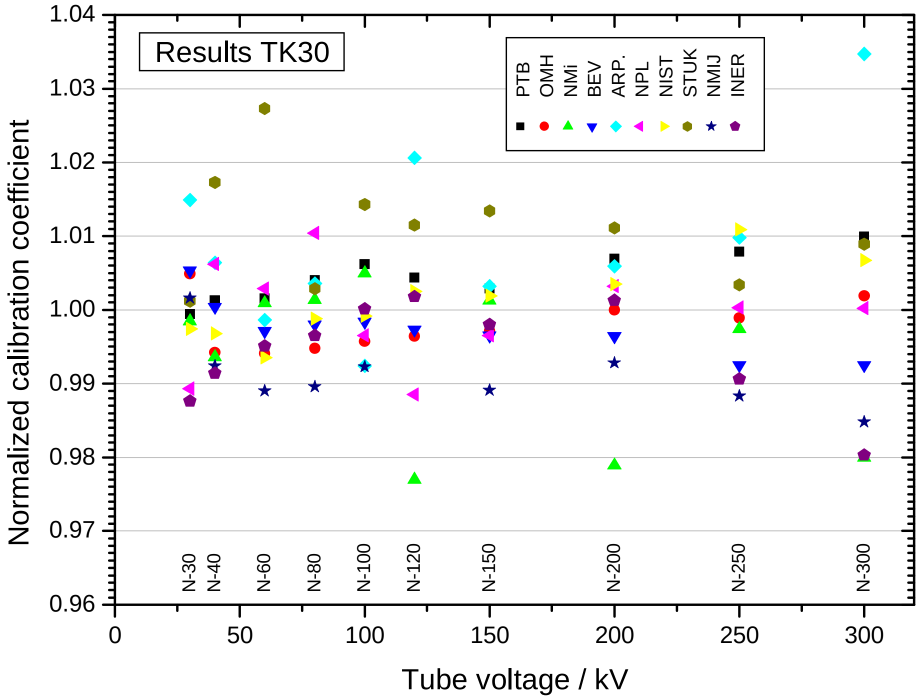


Figure 6. Calibration coefficients of the transfer chamber TK30-113 normalized to the mean value of all participants as a function of the tube voltage.

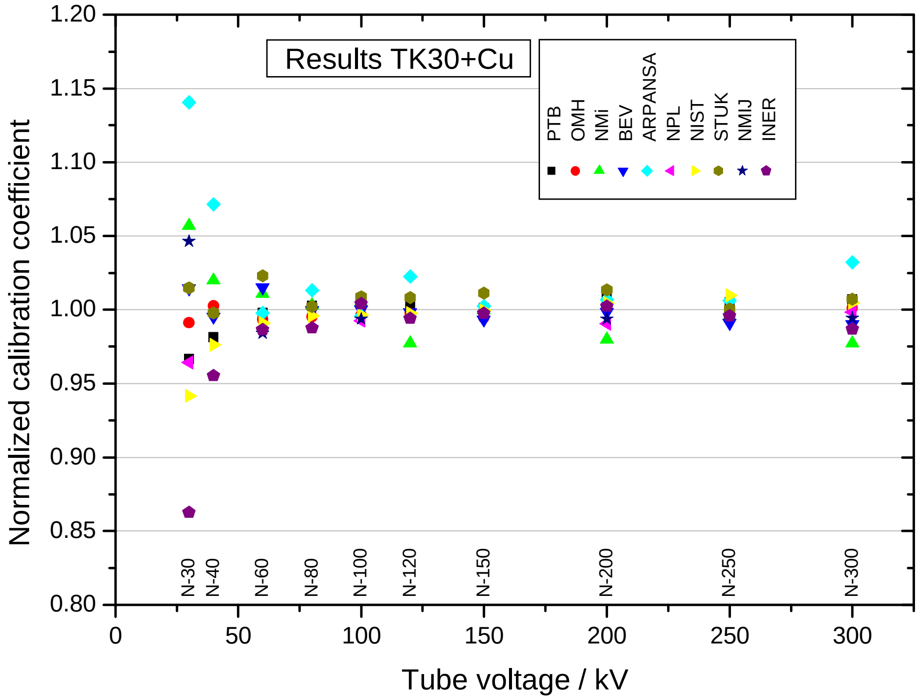


Figure 7. Calibration coefficients of the transfer chamber TK30-113+0.1mmCu normalized to the mean value of all participants as a function of the tube voltage.

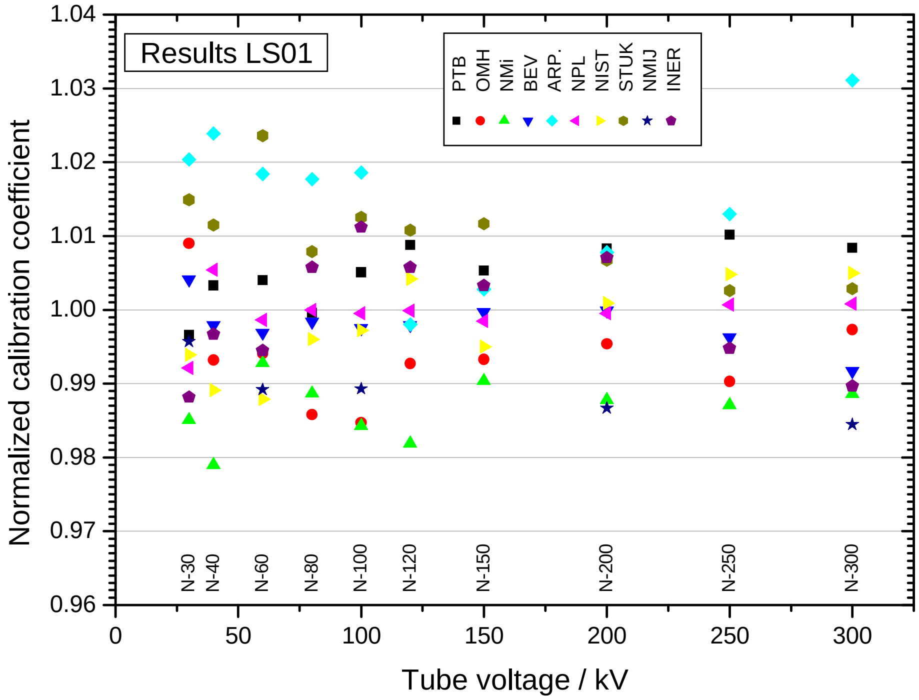


Figure 8. Calibration coefficients of the transfer chamber LS01-111 normalized to the mean value of all participants as a function of the tube voltage.

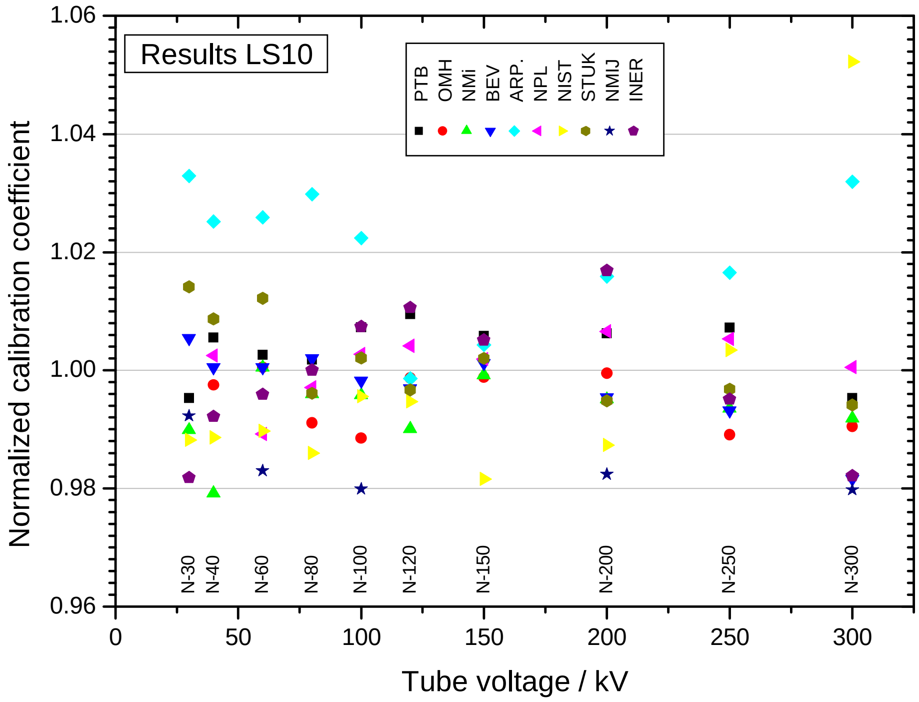


Figure 9. Calibration coefficients of the transfer chamber LS10-113 normalized to the mean value of all participants as a function of the tube voltage.

3.5 Uncertainties of the calibration coefficients

From the tables in appendix B it can be seen that the relative uncertainties of the calibration coefficients given by the participants for a specific chamber and radiation quality are significantly different by up to a factor of four. In order to analyze the differences, the main uncertainty components of the participant's results given for the TK30 are compared in Table 9 for the beam qualities N-30, N-100 and N-300. It can be read from the table that the majority of the relative standard uncertainties are in the range between about 0.3 % and 0.5 %. Participants claiming uncertainties in this range obtained their dominant contributions from the type B uncertainty of the conventional true value of the air kerma rate which is measured with free-air ionization chambers. Larger uncertainties above 0.5 % were given by NMi, NPL, ARPANSA and STUK due to different sources.

The NPL obtained larger uncertainties of about 0.78 % mainly caused by an additional component, called $R_{50/300}$, which was about 0.46 % independent of the beam quality. The NPL used two different x-ray facilities one for the low- (up to 50 kV) and the other for the medium-energy (up to 300 kV) x-ray range. The radiation quality N-40 can be generated at both facilities. When the secondary standards were calibrated at N-40 at both facilities a larger random variability was observed than for repeated measurements at any given quality at the same facility. This problem is still not resolved satisfactorily and therefore $R_{50/300}$ was introduced to account for this kind of uncertainty. In addition, NPL estimates 0.23 % uncertainty contribution from the non-uniformity of the beam, which is more than the values taken by the other participants.

The NMi submitted uncertainties of about 0.7 % for N-30 to N-200 and 1.3 % for N-250 and N-300. The increased uncertainty for N-30 to N-200 is mainly caused by the type A uncertainty in the charge measurement with the NMi free-air chamber, which was 0.5 % at all qualities. At N-250 and N-300 two additional components contribute significantly to the increased uncertainty, which are the uncertainties in the front face penetration and in the correction factor for electron loss which were estimated at 1.0 % and 0.5 %, respectively.

The ARPANSA estimated larger uncertainties between 1.1 % and 1.6 % because of type A uncertainties of their free air chamber MEFAC of up to 1.5 % at N-100. The MEFAC is designed for therapy-level beams, and has a very small signal for the ISO Narrow Series. From Table 6 it can be read that the signal current of the MEFAC was only about 0.4 pA at the radiation quality N-100.

The STUK claimed larger uncertainties of up to 1.5 % in their uncertainty budget which is due to the fact that this is a secondary standard laboratory and the main uncertainty component is the type B uncertainty of the air kerma measurements.

Table 9. Summary of the main uncertainty components given by the participants for the calibration coefficients of the transfer chamber TK30 at N-30, N-100 and N-300

N-30: Component	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
air kerma (Type B)	0.27	0.50	0.69	0.41	0.31	0.51	0.31	1.36	0.25	0.37
air kerma (Type A)	0.10			0.23	0.70	0.10	0.33	0.30		
charge/current (TK30)	0.05	0.09	0.10	0.10	0.10	0.08	0.21		0.06	0.21
monitor	0.05					0.01		0.10		
distance	0.10	0.02	0.20	0.04	0.15	0.01	0.01		0.05	0.01
beam nonuniformity	0.15	0.10			0.21	0.23			0.10	
air density correction	0.04	0.08	0.04	0.07	0.10	0.10	0.08		0.06	0.05
scattered radiation			0.10		0.90				0.20	
humidity						0.06	0.07		0.05	0.10
$R_{50/300}$						0.46				
Angular						0.12				
Set-up								0.54	0.05	
Quadratic sum	0.35	0.53	0.73	0.49	1.22	0.75	0.51	1.50	0.36	0.44

N-100: Component	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
air kerma (Type B)	0.27	0.35	0.65	0.30	0.31	0.54	0.31	1.08	0.29	0.23
air kerma (Type A)	0.10			0.23	1.50	0.10	0.33	0.20		
charge/current (TK30)	0.05	0.15	0.10	0.10	0.10	0.08	0.21		0.07	0.53
monitor	0.05					0.01		0.10		
distance	0.10	0.02	0.20	0.04	0.15	0.01	0.01		0.05	0.01
beam nonuniformity	0.15	0.10			0.21	0.23			0.10	
air density correction	0.04	0.08	0.04	0.07	0.10	0.10	0.08		0.06	0.02
scattered radiation			0.10		0.20				0.20	
humidity						0.06	0.07		0.05	0.03
$R_{50/300}$						0.46				
Angular						0.12				
Set-up								0.54	0.01	
Quadratic sum	0.35	0.40	0.70	0.40	1.57	0.78	0.51	1.23	0.39	0.58

N-300: Component	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
air kerma (Type B)	0.27	0.35	1.27	0.30	0.31	0.54	0.31	1.08	0.35	0.23
air kerma (Type A)	0.10			0.35	1.00	0.10	0.33	0.20		
charge/current (TK30)	0.05	0.29	0.10	0.10	0.10	0.08	0.21		0.07	0.13
monitor	0.05					0.01		0.10		
distance	0.10	0.02	0.20	0.04	0.15	0.01	0.01		0.05	0.01
beam nonuniformity	0.15	0.10			0.21	0.23			0.10	
air density correction	0.04	0.08	0.04	0.07	0.10	0.10	0.08		0.06	0.02
scattered radiation			0.10		0.20				0.20	
humidity						0.06	0.07		0.05	0.03
$R_{50/300}$						0.46				
Angular						0.12				
Set-up								0.54	0.01	
Quadratic sum	0.35	0.47	1.29	0.48	1.11	0.78	0.51	1.23	0.43	0.27

The uncertainties given for the three transfer chambers of different sizes are compared in Table 10 for the selected radiation qualities N-30, N-100 and N-300. The PTB, OMH, BEV, NMIJ/AIST and the INER estimated essentially increasing uncertainties with increasing size of the chambers. It was already stated that NIST calibrated the larger chambers LS01 and LS10 directly against their free-air chambers. This causes slightly larger type A uncertainties in the free-air chamber current measurements due to the lower dose rates at larger distances. The other participants invoked secondary standard chambers for the calibration at larger distances and this lead to slightly increased relative uncertainties. The NMi, NPL and STUK estimated about the same uncertainties for all three transfer chambers independent on the chamber size. The NPL calibrated all the three transfer chambers at the same distance, which might be an explanation for the nearly unchanged uncertainties. The ARPANSA's uncertainties are clearly dominated by the type A uncertainties of their free-air chamber MEFAC as already stated in 3.5 and hence no correlation to the transfer chamber size is observed.

Table 10. Comparison of the relative uncertainties of the calibration coefficients given for the different chambers at selected radiation qualities

	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30										
TK30	0.35	0.52	0.74	0.50	1.22	0.75	0.38	1.50	0.36	0.44
LS01	0.45	0.56	0.77	0.75	1.4	0.8	0.37	1.50	0.40	0.56
LS10	0.53		0.77	0.9	1.4		0.40	1.50	0.41	0.61
N-100										
TK30	0.35	0.40	0.70	0.40	1.57	1.0	0.40	1.23	0.39	0.58
LS01	0.45	0.41	0.72	0.75	1.2	0.9	0.37	1.23	0.51	0.46
LS10	0.53	0.46	0.72	0.9	1.1	0.9	0.49	1,23	0.51	0.47
N-300										
TK30	0.35	0.48	1.29	0.50	1.11	1.0	0.38	1.23	0.43	0.27
LS01	0.45	0.47	1.31	0.75	1.3	0.9	0.39	1.23	0.49	0.31
LS10	0.53	0.53	1.31	0.9	1.3	0.9	0.43	1.23	0.49	0.33

4. Evaluation

The comparison was evaluated based on the results shown in Tables B1-B4. According to the objects of the comparison (i) indirect comparison of the air kerma standards for the ISO 4037 narrow-spectrum series in the range 30 kV to 300 kV and (ii) comparison of the calibration coefficients for these qualities of three different sized chambers with diameters 4.4 cm (TK30), 14 cm (LS01) and 27.5 cm (LS 10) different results were extracted for (i) and (ii). The evaluation of the indirect comparison of the air kerma standards (i) was based on the results obtained with the TK30, because the diameter of this chamber is closer to the aperture diameters of the primary standards in use and hence field size dependent effects are minimized. The data was evaluated following the proposed guidelines for the evaluation of key comparison data [5]. The results in terms of the "Supplementary Comparison Reference Values" (SCRV) and of the degrees of equivalences (DoE) between the participants and the SCRV are presented in chapter 4.1. The influence of possible differences due to beam quality realizations are presented and discussed in chapter 4.2. The evaluation of the comparison results based on the other transfer chambers LS01 and LS10 and the differences obtained between the results of the three transfer chambers are presented in chapter 4.3.

4.1 Degrees of equivalence for the supplementary comparison EUROMET.RI(I)-S3 between national air kerma standards for the ISO-narrow spectrum series

The DoE of a national measurement standard is expressed quantitatively by two terms: its deviation, D, from the comparison reference value and the uncertainty, U, of this deviation (at a 95 % level of confidence). If x_i denotes the comparison result of participant i and x_r the SCRV, the deviations can be expressed as $D_i = (x_\mathrm{i} - x_\mathrm{r})$. The comparison results x_i and their uncertainties u_i associated with the data obtained from the calibration coefficients and their uncertainties of the TK30 transfer chamber were evaluated following the procedures described in reference [5]. The comparison reference values x_r were calculated from the data x_i and u_i of all participants except STUK which does not maintain a primary standard but is traceable to PTB. However, the data of STUK is included in the evaluation of the DoE. It turned out that the evaluation of the data with x_r calculated as the weighted mean of the data of the participants (procedure A in [5]) did not pass the consistency check at the qualities N-250 and N-300. This can be explained by the significantly large differences between some of the participants results of up to 5 % which is more than about 8 times the relative standard uncertainties given by the corresponding participants. However, it is not justified to exclude some of the results as "outliers" because all of them were obtained invoking primary standard free air chambers. Therefore procedure B of reference [5] was applied which calculates x_r based on the median. The uncertainties of the reference values, u_r, the deviations D_i and the expanded uncertainties of these, U_i, were evaluated with a statistical estimation based on Monte Carlo sampling as described in [5]; 10^6 samples were used in this calculation following the recommendation in [5]. The obtained values x_r and u_r are shown in Table 11. The uncertainties of the values at N-250 and N-300 are significantly larger than those of the others. The reason is again the significant scatter of some of the participants calibration coefficients by more than several times of the corresponding standard uncertainties. The ratios of the calibration coefficients of the participants, x_i, and the SCRV x_r, are given in Table 12. The DoEs were expressed as differences in the ratios with respect to the SCRV, $D_i = (x_\mathrm{i} - x_\mathrm{r}) / x_\mathrm{r}$ and the expanded uncertainties U_i of these differences. The results expressed in parts of 10^3 are summarized in Table 13. These data are also shown in the Figures C1 to C10 of Appendix C. From the figures and Table 13 it appears that the comparison data are mostly (90 out of 99) consistent within the expanded uncertainties except for the results of

NMi at N-120 and N-200, ARPANSA at N-300, NIST at N-250, STUK at N-60, NMIJ at N-150 and N-300, and INER at N-30 and N-300. Possible reasons for the discrepancies should be investigated by the corresponding participants.

Table 11. Comparison reference values, x_r, and relative uncertainties, $u(x_r)$, of each quality, which is the median of the participant's calibration coefficients in units of Gy/C

Qual.	SCRV x_r	$u(x_r)$ / %
N-30	1.1259E+06	0.24
N-40	1.0305E+06	0.24
N-60	1.0292E+06	0.22
N-80	1.0470E+06	0.24
N-100	1.0374E+06	0.26
N-120	1.0300E+06	0.24
N-150	1.0255E+06	0.21
N-200	1.0240E+06	0.24
N-250	1.0266E+06	0.39
N-300	1.0321E+06	0.44

Table 12. Ratios x_i/x_r at each of the radiation qualities.

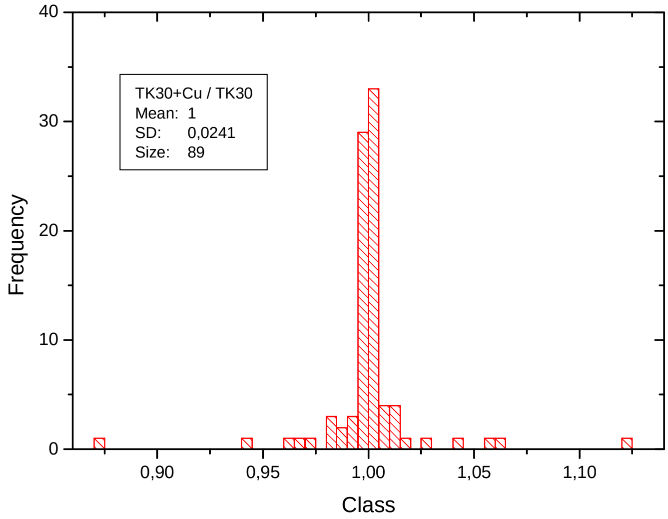
Qual.	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	0.9994	1.0049	0.9985	1.0053	1.0149	0.9893	0.9974	1.0012	1.0016	0.9876
N-40	1.0043	0.9972	0.9966	1.0034	1.0094	1.0092	0.9997	1.0203	0.9953	0.9944
N-60	1.0051	0.9977	1.0046	1.0008	1.0022	1.0066	0.9971	1.0311	0.9926	0.9988
N-80	1.0051	0.9959	1.0024	0.9991	1.0047	1.0115	0.9999	1.0040	0.9907	0.9976
N-100	1.0075	0.9970	1.0063	0.9997	0.9937	0.9977	1.0005	1.0156	0.9935	1.0014
N-120	1.0051	0.9972	0.9778	0.9981	1.0214	0.9893	1.0033	1.0123		1.0026
N-150	1.0040	0.9981	1.0024	0.9976	1.0043	0.9976	1.0030	1.0145	0.9901	0.9991
N-200	1.0066	0.9997	0.9787	0.9961	1.0056	1.0029	1.0032	1.0109	0.9926	1.0010
N-250	1.0089	0.9999	0.9984	0.9935	1.0108	1.0013	1.0120	1.0044	0.9893	0.9916
N-300	1.0115	1.0035	0.9816	0.9941	1.0363	1.0018	1.0083	1.0105	0.9864	0.9819

Table 13. Differences D_i and their expanded (k = 2) uncertainties U_i expressed in parts of 10^3, and the ratio D_i / U_i of each participant. Ratios D_i / U_i > 1 characterize discrepancies and are printed in bold letters. Some 9 out of 99 results are inconsistent.

Qual.		PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	D_i	-0.5	5.0	-1.4	5.4	15.0	-10.5	-2.5	1.2	1.7	-12.3
	U_i	6.9	10.6	13.7	10.3	23.4	15.9	7.7	30.4	7.2	9.7
	D_i/U_i	0.1	0.5	0.1	0.5	0.6	0.7	0.3	0.0	0.2	**1.3**
N-40	D_i	4.2	-2.9	-3.4	3.4	9.4	9.2	-0.3	20.3	-4.7	-5.7
	U_i	7.8	8.2	13.2	9.0	22.2	19.7	7.3	30.4	8.6	9.2
	D_i/U_i	0.5	0.3	0.3	0.4	0.4	0.5	0.0	0.7	0.5	0.6
N-60	D_i	5.2	-2.2	4.6	0.8	2.2	6.6	-2.8	31.1	-7.4	-1.2
	U_i	7.9	7.7	13.6	8.6	16.1	19.5	7.8	25.0	8.4	6.7
	D_i/U_i	0.7	0.3	0.3	0.1	0.1	0.3	0.4	**1.2**	0.9	0.2
N-80	D_i	5.2	-4.0	2.5	-0.9	4.8	11.6	0.0	4.0	-9.3	-2.4
	U_i	8.1	8.6	13.3	7.8	21.2	20.0	7.8	25.1	8.8	8.8
	D_i/U_i	0.6	0.5	0.2	0.1	0.2	0.6	0.0	0.2	1.0	0.3
N-100	D_i	7.5	-3.0	6.4	-0.3	-6.2	-2.2	0.5	15.6	-6.3	1.5
	U_i	8.6	8.5	14.0	8.0	36.5	19.0	8.1	25.1	9.0	11.1
	D_i/U_i	0.9	0.3	0.5	0.0	0.2	0.1	0.1	0.6	0.7	0.1
N-120	D_i	5.1	-2.9	-22.3	-2.0	21.4	-10.8	3.2	12.3		2.5
	U_i	7.8	8.3	14.5	7.5	28.4	19.2	8.0	25.1		9.8
	D_i/U_i	0.6	0.3	**1.5**	0.3	0.8	0.6	0.4	0.5		0.3
N-150	D_i	4.1	-1.8	2.5	-2.4	4.3	-2.4	3.1	14.5	-9.8	-0.8
	U_i	7.5	7.9	13.3	7.9	10.6	18.9	7.6	25.0	8.8	5.4
	D_i/U_i	0.5	0.2	0.2	0.3	0.4	0.1	0.4	0.6	**1.1**	0.2
N-200	D_i	6.6	-0.3	-21.3	-3.9	5.6	2.9	3.2	10.9	-7.5	1.0
	U_i	8.2	7.4	14.5	8.4	11.7	18.8	7.8	25.1	9.3	7.4
	D_i/U_i	0.8	0.0	**1.5**	0.5	0.5	0.2	0.4	0.4	0.8	0.1
N-250	D_i	9.0	-0.1	-1.6	-6.4	10.8	1.4	12.0	4.4	-10.7	-8.4
	U_i	10.3	9.1	23.2	10.5	16.9	17.8	11.0	25.8	11.5	9.3
	D_i/U_i	0.9	0.0	0.1	0.6	0.6	0.1	**1.1**	0.2	0.9	0.9
N-300	D_i	11.5	3.5	-18.4	-5.9	36.3	1.9	8.3	10.5	-13.7	-18.1
	U_i	11.2	10.4	25.6	11.6	14.0	15.9	11.3	26.1	12.2	10.2
	D_i/U_i	1.0	0.3	0.7	0.5	**2.6**	0.1	0.7	0.4	**1.1**	**1.8**

4.2 Influence of different realizations of the radiation qualities

The calibration coefficients obtained with the special combination of TK30 + 0.1 mm Cu filter were normalized to those obtained with the TK30 without the filter. This normalization eliminates the differences in the absolute calibration coefficients and the resulting numbers are assumed to reflect mainly the dependence of the results on differences in the realizations of the radiation qualities. These ratios of all qualities and of all participants are shown as frequency distributions in Figure 10. In the upper part all qualities are included whereas in the lower part the data of the N-30 and N-40 qualities were omitted. It was found that 62 out of 89 data points agree within ± 0.5 %, 79 out of 89 within ± 2 %. The most significant differences were found at N-30 and N-40 at some participants sites (see Figure 7). It can be concluded that at some participants sites there are large differences in the radiation qualities N-30 and N-40, but for the other qualities there is a sufficiently good agreement. It is recommended that the participants concerned check their corresponding qualities.



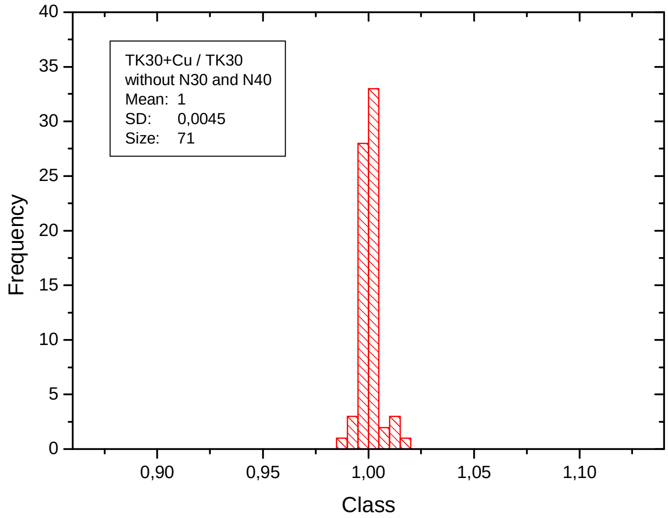


Figure 10. Frequency distributions of the ratio of the calibration coefficients obtained with the TK30 and TK30 + 0.1mm Cu filter by all participants. The upper diagram includes all radiation qualities, the qualities N-30 and N-40 are omitted in the lower one.

4.3 Influence of the chamber size on the comparison results

SCRV and DoE with the SCRV were calculated based on the results obtained with the transfer chambers LS01 and LS10 in order to examine the influence of the transfer chamber size on the comparison results. The applied evaluation procedure was exactly the same as that one used for the TK30 described in chapter 4.1. The results are summarized in Appendix D and graphs of the DoE with the SCRV of each radiation quality obtained with the TK30, LS01 and LS10 are shown in Appendix E.
The differences in the values D_i between the data obtained with the TK30 and the LS01, TK30 and LS10 and LS01 and LS10 were calculated for each radiation quality and participant, to eliminate to a certain extent the influence on the results caused by differences in the national air kerma standards. Frequency distributions of the the values D_i and of the differences in these values obtained by the three transfer chambers were evaluated and are shown in the Figures 11 and 12.

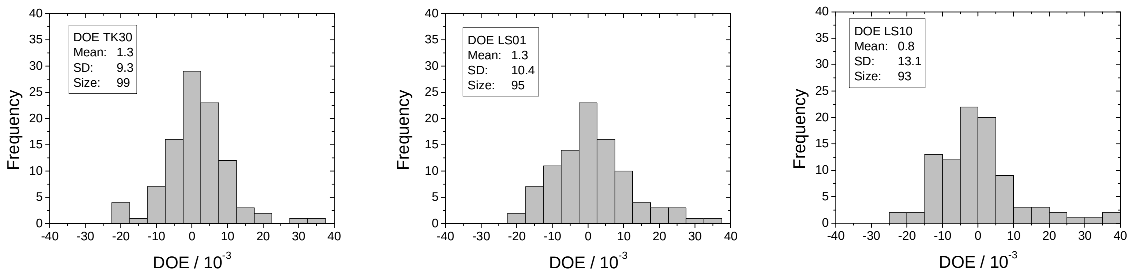


Figure 11. Frequency distributions of the differences D_i (denoted as DOE in the diagrams) of all qualities obtained by all participants based on the results obtained with the transfer standards TK30 (left), LS01 (centre) and LS10 (right) are used.

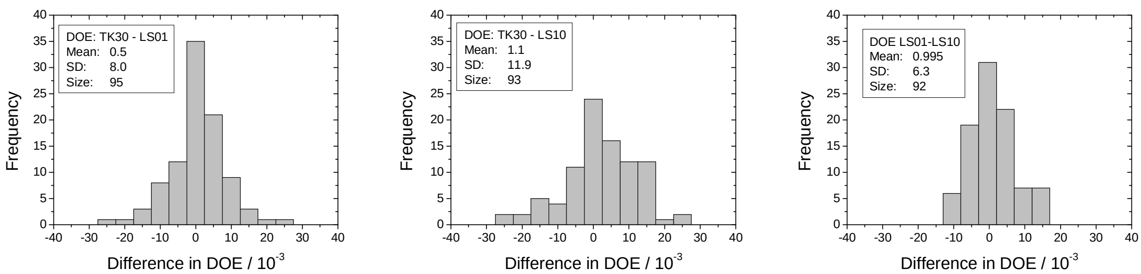


Figure 12. Frequency distributions of the differences in the values D_i between TK30 and LS01 (left), TK30 and LS10 (centre) and LS01 and LS10 (right) calculated for all radiation qualities and participants.

From Figure 11 it can be read that the standard deviations of the frequency distributions of the values D_i obtained with the transfer chambers TK30, LS01 and LS10 increase as 9.3x10^{-3}, 10.4x10^{-3} and 13.1x10^{-3}, respectively. From this trend it is concluded that in general the results have a larger spread as the size of the transfer chamber increases. What are the possible reasons for this result? The frequency distributions of the differences in the D_i data of the transfer chambers shown in Figure 12 do not contain the variation in the data due to differences in the national air kerma standards and one would expect that these distributions have significantly reduced standard deviations. However, the standard deviations of the distributions of the differences between the TK30 and the two larger chambers LS01 and LS10 are 8x10^{-3} and 11.9x10^{-3}, respectively, and thus are of the same magnitude as those of the DoE distributions. Only the distribution of the differences between the data of the two larger chambers LS01 and LS10 has a significantly reduced value of the standard deviation of 6.3×10^{-3}.

To understand these results it is helpful to look in some more detail. Figures 13, 14 and 15 show the differences in the D_i values between the different transfer chambers as a function of the participants. It can be seen that the variation of the data is significantly different between the participants in the Figures 13 and 14 but much closer in the Figure 15. To quantify this observation the standard deviations of the distributions of the data shown in the three Figures were calculated for each participant and are plotted together in one graph shown in Figure 16.

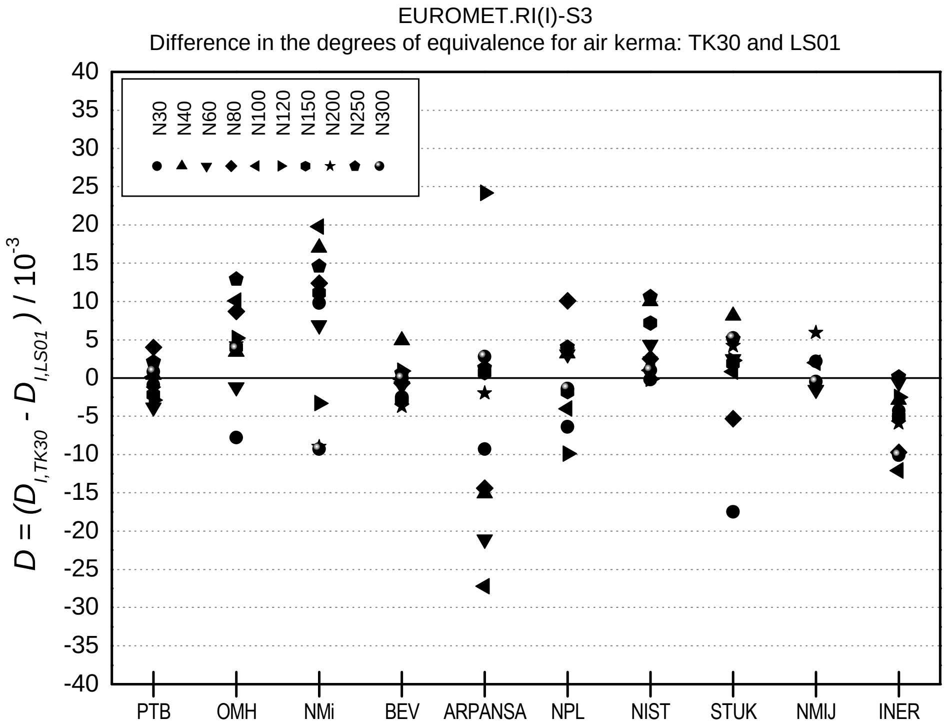


Figure 13. Differences in the values D_i obtained with the TK30 transfer chamber to those obtained with the LS01 chamber.

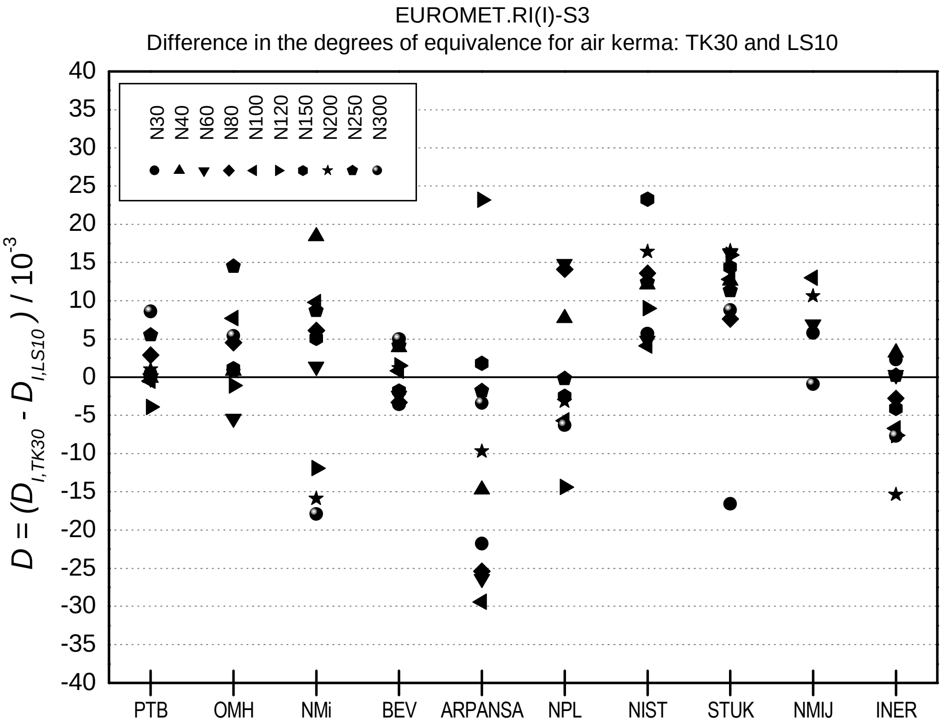


Figure 14. Differences in the values D_i obtained with the TK30 transfer chamber to those obtained with the LS10 chamber.

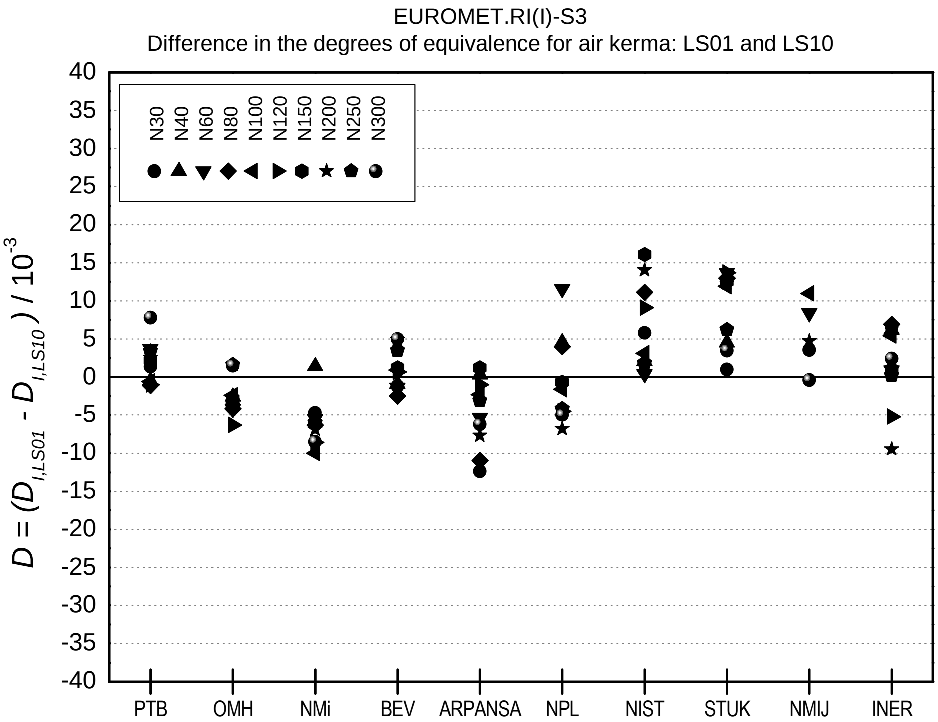


Figure 15. Differences in the values D_i obtained with the LS01 transfer chamber to those obtained with the LS10 chamber.

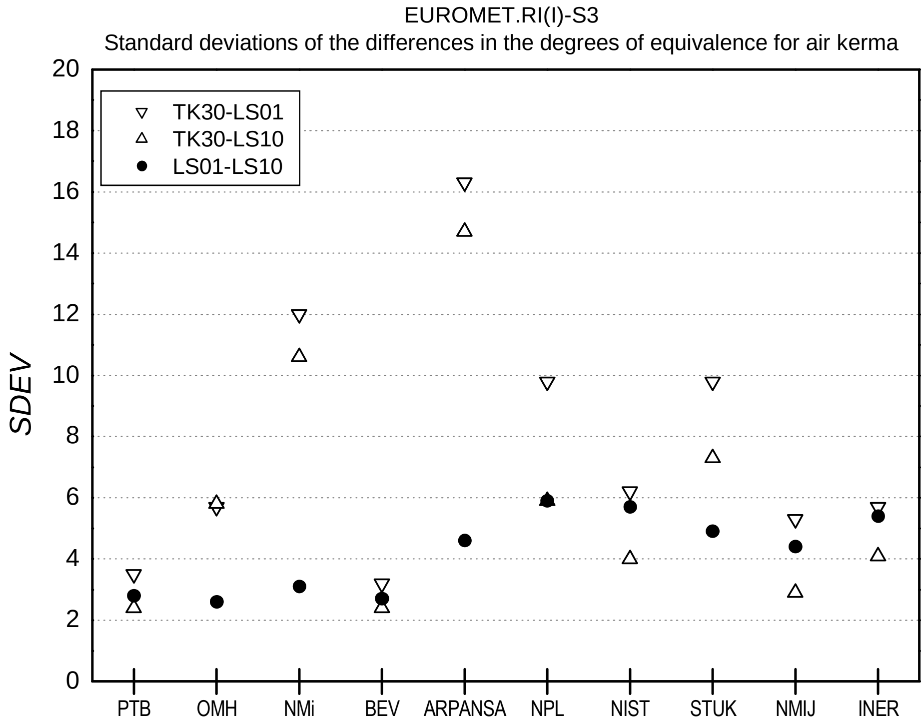


Figure 16. Standard deviations of the distributions of the differences in values D_i shown in Figures 13, 14 and 15.

From Figure 16 it can be seen that the variation of the differences in the values D_i between the different chambers is of comparable size for the participants PTB, BEV, NIST, NMIJ/AIST and INER. In contrast, the standard deviations of OMH, NMi, ARPANSA, NPL and STUK show significant differences with the general trend that the value of the standard deviation of the samples of the differences between the two larger chambers is much lower than that between the TK30 and the two larger chambers. For some of the participants this observation can in part be explained by the calibration procedure. Whereas the TK30 was calibrated directly against the primary standard the LS01 and LS10 were calibrated against the same secondary standard. If the primary standard has significant type A uncertainties due to low signal currents such variations will enter into the calibration coefficients of secondary standards. If the calibration against the primary standard of the TK30 and the secondary standard to be used subsequently for the calibration of the LS01 and LS10 at larger distances are based on two different measurements with the primary standard they will reflect these differences due to the type A uncertainties. Therefore the differences in the values D_i between the TK30 and the two larger chambers will reflect these differences but not those between the two larger chambers because they were calibrated against the same secondary standard which by itself has negligible type A uncertainties. This explanation is clearly the dominating effect for the results obtained by NMi and ARPANSA which can already be seen from the above Figures. However, even if the described effects and the differences in the national air kerma standards are eliminated as reflected by the data shown in the Figure 15 there still remain non-negligible data variations between the results of transfer chambers of different sizes. Possibly these effects are due to non-homogenous radiation fields which should be considered more carefully in the uncertainty budgets.

From the analyses of the comparison results a preferred procedure can be recommended in order to achieve low uncertainties for the calibration of large detectors in low air kerma rate radiation fields. In a first step a suitable secondary standard should be calibrated against the primary chamber at short focal distances to keep type A uncertainties of the primary standard as low as possible. In a second step the large detector should be calibrated against the secondary standard at the necessary focal distance. If the secondary standard calibrated in the first step is still not suitable for the lower air kerma rates at very large focal distances a further secondary standard of bigger size than the first one should be calibrated at an intermediate focal distance and subsequently be used for the calibration of very large detectors. In general the additional uncertainties introduced by this step by step procedure using secondary standards are lower than those obtained by type A uncertainties due to low signals of the free air chamber at large focal distances. However, one should be aware of any additional type B uncertainty introduced by each step.

5. Summary and conclusions

Within the framework of the EUROMET project no. 545 a comparison of 10 national air kerma standards for 10 radiation qualities of the ISO 4037 narrow spectrum series in the range from 30 kV to 300 kV was conducted. The comparison was performed using three spherical ionization chambers of types TK30, LS01 and LS10, characterized by different outer diameters of 44 mm, 140 mm and 275 mm, respectively. The smallest chamber, type TK30, was circulated together with a Cu sheet of 0.1 mm thickness. The star shaped comparison was performed in the period from February 2004 until October 2005. During this period, nine repeated constancy check measurements were done at the pilot laboratory PTB. It turned out that the transfer chambers behaved sufficiently constantly during the course of the comparison. All participants were in time and successful with their measurements. The following results were obtained:

(i) The supplementary comparison reference values (SCRV) and the degrees of equivalence (DoE) of the participants results with the comparison reference values of each quality were evaluated from the calibration coefficients obtained with the TK30 chamber. These data form the basis of the results in the BIPM key comparison database for comparison EUROMET.RI(I)-S3. The majority of the resulting data points (90 out of 99) were consistent with the SCRV within the expanded uncertainties.

(ii) Most of the relative standard uncertainties given for the TK30 calibration coefficients were in the range between about 0.3 % and 0.5 %. The dominant contribution came from the uncertainties of the air kerma rates measured with the free-air ionization chambers. Some participants estimated significantly larger uncertainties. It is recommended, that these participants improve their calibration procedures.

(iii) Differences in the beam quality realizations at the participant's sites were analyzed by the ratio of the TK30 calibration coefficients obtained without and with the 0.1 mm Cu sheet placed in front of the chamber. It appeared that the majority of these ratios, 62 out of 89, agreed within ± 0.5 % and 79 out of 89 within ± 2 %. Significant differences were only found at N-30 and N-40 at some participant's sites.

(iv) Influences on the results were analyzed if ionization chambers of significantly different sizes were used. The variation of the data points were analyzed from the evaluated DoE with the SCRV obtained with the three transfer chambers for all participant's results. It turned out that the relative standard deviations of the distributions of the differences to the comparison reference values increased with the chamber size indicating that the results become less reliable (10 out of 95 and 15 out of 93 results obtained with the LS01 and LS10, respectively, were inconsistent). A detailed analysis of the differences in the DoE data obtained with the three transfer chambers led to the conclusion that the main effects are caused by the use of non optimized calibration procedures for large detectors in radiation fields characterized by low air kerma rates and by an underestimation of the corresponding uncertainties.

In general it can be concluded, that there is a satisfying degree of equivalence between the participant's results if one takes into account that the ISO narrow qualities are mainly used for calibration of dosimeters used in radiation protection where the demand on the magnitude of the uncertainties are usually not as high as in diagnostic radiology or radiotherapy. Nevertheless, some participants should think about improvements in their primary air kerma standards, especially at N-250 and N-300. In view of the increasing scatter of the comparison results with the size of the chambers, which were not strongly correlated with the differences in the national air kerma standards, the uncertainty budgets should be checked to identify whether all components have really been included. All the participants have published CMC lines covering a wide air kerma range of ISO X-ray beam qualities. Further, published CMCs of radiation protection quantities (H^*; H_p; H') are also based on the air kerma using conversion coefficients. The uncertainties of these CMC claims are not fully consistent with the uncertainty associated with the degree of equivalence in the Tables 13, D3 and D6, so these published uncertainty values need re-evaluation by the participants. A recommended procedure for the calibration of large sized detectors at low air kerma rates is to use secondary standard chambers of larger measuring volumes as transfer standards to be used at larger focal distances. The additional uncertainties introduced by this procedure are usually less than those connected with the low signal currents of the free-air chambers. However, not only the different calibration techniques of the participants but some hidden feature of the X-ray beams and setups (time and dose rate dependence of radial non-uniformity of the beam, ageing effect of the tubes) could be the reason of different values in the Tables 13, D3, and D6. Finally, some of the participants should check their realizations of the ISO narrow qualities especially at N-30 and N-40. It is recommended to repeat this type of comparison after a period of 10 years.

References

[1] Burns D.T., *Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays*, Metrologia, 2003, **40**, Tech. Suppl., 06031

[2] Burns D.T., *Degrees of equivalence for the key comparison BIPM.RI(I)-K3 between national primary standards for medium-energy x-rays*, Metrologia, 2003, **40**, Tech. Suppl., 06036

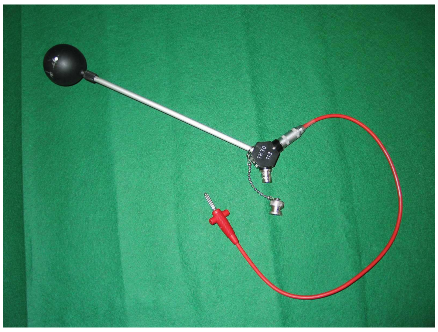
[3] ISO International Organisation for Standardisation (1996). "*X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy – Part 1: Radiation characteristics and production methods.*" ISO 4037-1:1996(E).

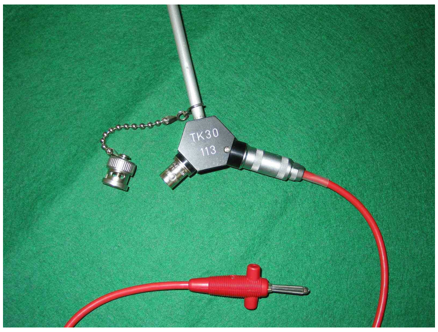
[4] ISO International Organisation for Standardisation (1993). *Guide to the Expression of Uncertainty in Measurement*. Geneva, ISBN 92-67-10188-9.

[5] Cox M. G., *The evaluation of key comparison data*, Metrologia, 2002, **39**, 589-595

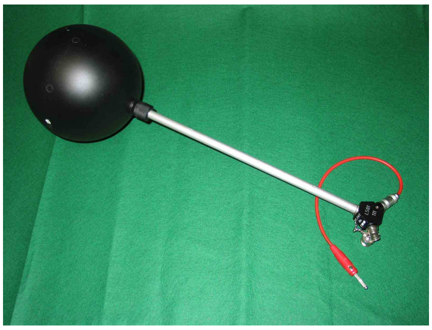
APPENDIX A: Pictures of the transfer chambers

1. TK30, Serial number 113



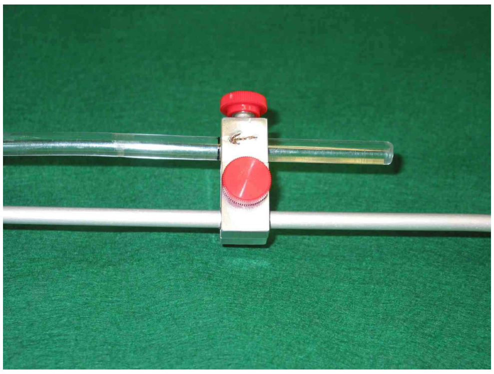


2. LS01, Serial number 111



3. LS10, Serial number 113

4 TK30 - 113 with additional Cu-sheet



APPENDIX B: Tables of the participants results

Table B1. Calibration coefficients in units of 10^6 Gy/C and relative standard uncertainties given by the participants for the transfer chamber TK30-113.

TK30-113: Calibration coeffients in units of 10^6 Gy/C										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	1.1253	1.1315	1.124	1.132	1.143	1.114	1.123	1.13	1.128	1.1120
N-40	1.0349	1.0276	1.027	1.034	1.040	1.040	1.030	1.05	1.026	1.0247
N-60	1.0345	1.0269	1.034	1.030	1.032	1.036	1.026	1.06	1.022	1.0280
N-80	1.0523	1.0427	1.050	1.046	1.052	1.059	1.047	1.05	1.037	1.0444
N-100	1.0451	1.0342	1.044	1.037	1.031	1.035	1.038	1.05	1.031	1.0388
N-120	1.0353	1.0271	1.007	1.028	1.052	1.019	1.033	1.04		1.0327
N-150	1.0296	1.0236	1.028	1.023	1.030	1.023	1.029	1.04	1.015	1.0246
N-200	1.0308	1.0237	1.002	1.020	1.030	1.027	1.027	1.04	1.016	1.0251
N-250	1.0358	1.0265	1.025	1.020	1.038	1.028	1.039	1.03	1.016	1.0180
N-300	1.0440	1.0357	1.013	1.026	1.070	1.034	1.041	1.04	1.018	1.0134
TK30-113: Relative standard uncertainty of the calibration coeffients in %										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	0.35	0.52	0.74	0.50	1.2	0.8	0.38	1.50	0.36	0.44
N-40	0.35	0.41	0.70	0.45	1.1	1.0	0.38	1.50	0.40	0.44
N-60	0.35	0.38	0.70	0.45	0.9	1.0	0.38	1.23	0.37	0.33
N-80	0.35	0.41	0.70	0.40	1.1	1.0	0.40	1.23	0.38	0.44
N-100	0.35	0.40	0.70	0.40	1.9	1.0	0.40	1.23	0.39	0.58
N-120	0.35	0.44	0.70	0.40	1.4	1.0	0.40	1.23		0.54
N-150	0.35	0.41	0.70	0.40	0.5	1.0	0.37	1.23	0.40	0.25
N-200	0.35	0.39	0.70	0.40	0.6	1.0	0.38	1.23	0.42	0.38
N-250	0.35	0.44	1.29	0.40	0.8	1.0	0.39	1.23	0.44	0.27
N-300	0.35	0.48	1.29	0.50	0.5	1.0	0.38	1.23	0.43	0.27

Table B2. Calibration coefficients in units of 10^6 Gy/C and relative standard uncertainties given by the participants for the transfer chamber TK30-113+0.1 mm Cu.

TK30-113+0.1 mm Cu: Calibration coeffients in units of 10^6 Gy/C										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	6.392	6.556	6.989	6.708	7.541	6.376	6.226	6.71	6.919	5.7040
N-40	2.2546	2.3037	2.343	2.286	2.462		2.243	2.29		2.1947
N-60	1.3727	1.3667	1.391	1.396	1.372		1.363	1.41	1.354	1.3571
N-80	1.1674	1.1591	1.168	1.164	1.180		1.160	1.17		1.1501
N-100	1.0983	1.0869	1.097	1.091	1.087	1.083	1.087	1.10	1.084	1.0955
N-120	1.0637	1.0574	1.036	1.058	1.084		1.057	1.07		1.0537
N-150	1.0485	1.0416	1.047	1.040	1.050		1.047	1.06		1.0444
N-200	1.0379	1.0318	1.009	1.028	1.037	1.020	1.034	1.04	1.023	1.0324
N-250	1.0397	1.0302	1.030	1.025	1.041		1.045	1.04		1.0304
N-300	1.0460	1.0401	1.015	1.028	1.072	1.037	1.044	1.05	1.033	1.0251
TK30-113+Cu: Relative standard uncertainty of the calibration coeffients in %										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	0.35	0.56	0.74	0.41	1.2	0.8	0.38	1.50	0.36	0.47
N-40	0.35	0.40	0.70	0.35	1.2		0.38	1.50		0.47
N-60	0.35	0.38	0.70	0.35	0.9		0.38	1.23	0.37	0.66
N-80	0.35	0.41	0.70	0.30	1.1		0.38	1.23		0.40
N-100	0.35	0.41	0.70	0.30	1.9	1.0	0.39	1.23	0.39	1.02
N-120	0.35	0.49	0.70	0.30	1.4		0.39	1.23		0.77
N-150	0.35	0.44	0.70	0.30	0.5		0.37	1.23		0.25
N-200	0.35	0.41	0.70	0.30	0.6	1.0	0.38	1.23	0.42	0.28
N-250	0.35	0.44	1.29	0.30	0.8		0.39	1.23		0.32
N-300	0.35	0.47	1.29	0.30	0.6	1.0	0.38	1.23	0.43	0.39

Table B3. Calibration coefficients and relative standard uncertainties given by the participants for the transfer chamber LS01-111.

LS01-111: Calibration coeffients in units of 10^4 Gy/C										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	2.830	2.865	2.797	2.851	2.897	2.817	2.822	2.88	2.827	2.8060
N-40	2.542	2.516	2.480	2.528	2.594	2.547	2.506	2.56		2.5250
N-60	2.454	2.430	2.427	2.437	2.489	2.441	2.415	2.50	2.418	2.4311
N-80	2.471	2.437	2.444	2.468	2.516	2.472	2.462	2.49		2.4864
N-100	2.502	2.451	2.450	2.483	2.535	2.488	2.482	2.52	2.463	2.5172
N-120	2.510	2.470	2.443	2.483	2.483	2.488	2.499	2.51		2.5026
N-150	2.496	2.466	2.459	2.482	2.490	2.479	2.470	2.51		2.4910
N-200	2.503	2.471	2.452	2.482	2.502	2.481	2.485	2.50	2.449	2.4999
N-250	2.527	2.477	2.469	2.492	2.534	2.503	2.513	2.51		2.4882
N-300	2.546	2.518	2.496	2.504	2.603	2.527	2.537	2.53	2.486	2.4988
LS01-111: Relative standard uncertainty of the calibration coeffients in %										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	0.45	0.56	0.77	0.75	1.4	0.8	0.37	1.50	0.40	0.56
N-40	0.45	0.40	0.72	0.75	1.8	0.9	0.38	1.50		0.56
N-60	0.45	0.38	0.72	0.75	1.2	0.9	0.38	1.23	0.41	0.33
N-80	0.45	0.41	0.72	0.75	0.9	0.9	0.38	1.23		0.30
N-100	0.45	0.41	0.72	0.75	1.2	0.9	0.37	1.23	0.51	0.46
N-120	0.45	0.49	0.72	0.75	1.7	0.9	0.40	1.23		0.40
N-150	0.45	0.44	0.72	0.75	0.7	0.9	0.38	1.23		0.29
N-200	0.45	0.41	0.72	0.75	0.8	0.9	0.38	1.23	0.43	0.29
N-250	0.45	0.44	1.31	0.75	1.0	0.9	0.38	1.23		0.27
N-300	0.45	0.47	1.31	0.75	1.3	0.9	0.39	1.23	0.49	0.31

Table B4. Calibration coefficients and relative standard uncertainties given by the participants for the transfer chamber LS10-113.

LS10-113: Calibration coeffients in units of 10^3 Gy/C										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	3.346	*	3.328	3.38	3.473	-	3.322	3.41	3.336	3.301
N-40	2.975	2.951	2.897	2.96	3.033	2.966	2.925	2.98		2.935
N-60	2.836	2.830	2.830	2.83	2.902	2.798	2.799	2.86	2.781	2.817
N-80	2.860	2.829	2.843	2.86	2.939	2.846	2.814	2.84		2.854
N-100	2.916	2.862	2.883	2.89	2.960	2.903	2.883	2.90	2.837	2.917
N-120	2.947	2.915	2.890	2.91	2.915	2.931	2.904	2.91		2.950
N-150	2.933	2.913	2.914	2.92	2.929	2.922	2.863	2.92		2.931
N-200	2.952	2.932	2.919	2.92	2.980	2.953	2.896	2.92	2.882	2.983
N-250	2.982	2.928	2.941	2.94	3.009	2.976	2.970	2.95		2.9463
N-300	2.991	2.977	2.981	2.95	3.101	3.007	3.162	2.99	2.945	2.952
LS10-113: Relative standard uncertainty of the calibration coeffients in %										
	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ/AIST	INER
N-30	0.53		0.77	0.9	1.4		0.40	1.50	0.41	0.61
N-40	0.53	0.46	0.72	0.9	1.8	0.9	0.39	1.50		0.61
N-60	0.53	0.44	0.72	0.9	1.2	0.9	0.40	1.23	0.41	0.44
N-80	0.53	0.43	0.72	0.9	0.8	0.9	0.43	1.23		0.31
N-100	0.53	0.46	0.72	0.9	1.1	0.9	0.49	1.23	0.51	0.47
N-120	0.53	0.46	0.72	0.9	1.7	0.9	0.47	1.23		0.29
N-150	0.53	0.44	0.72	0.9	0.7	0.9	0.40	1.23		0.31
N-200	0.53	0.45	0.72	0.9	0.7	0.9	0.46	1.23	0.44	0.37
N-250	0.53	0.46	1.31	0.9	1.0	0.9	0.42	1.23		0.30
N-300	0.53	0.53	1.31	0.9	1.3	0.9	0.43	1.23	0.49	0.33

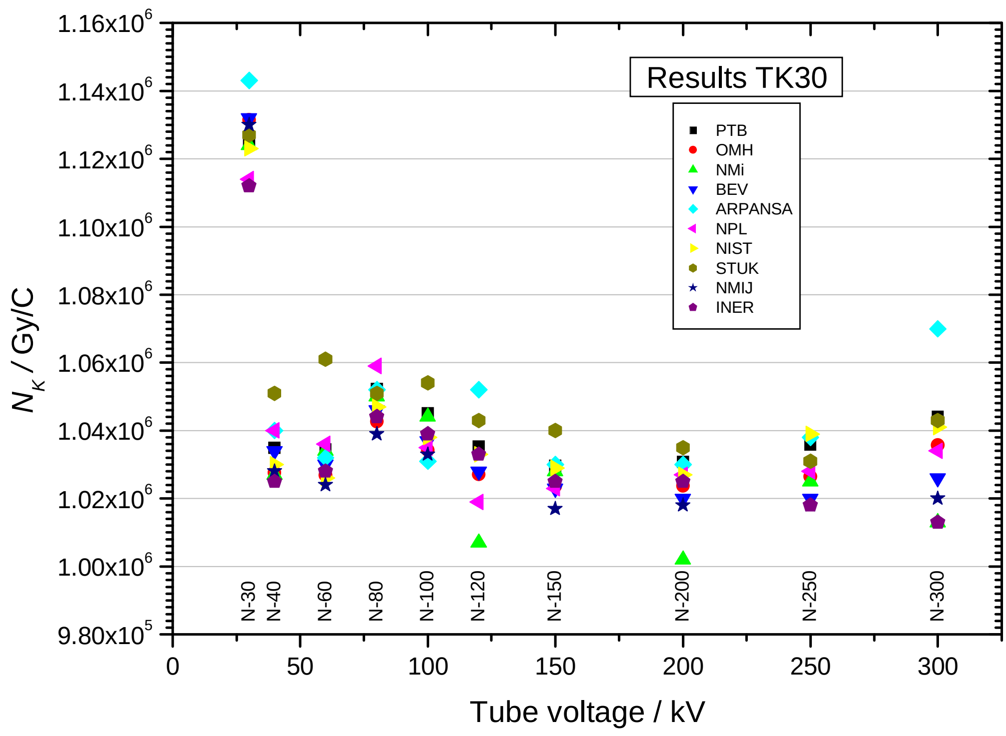


Figure B1. TK30 calibration coefficients of all participants as a function of the tube voltage.

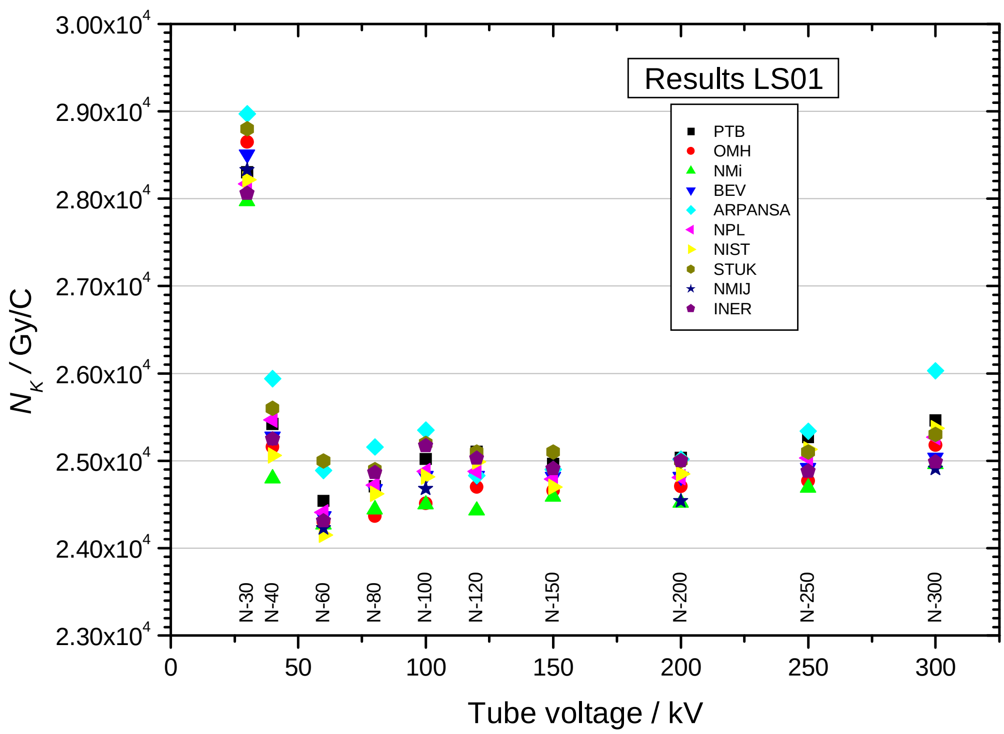


Figure B2. LS01 calibration coefficients of all participants as a function of the tube voltage.

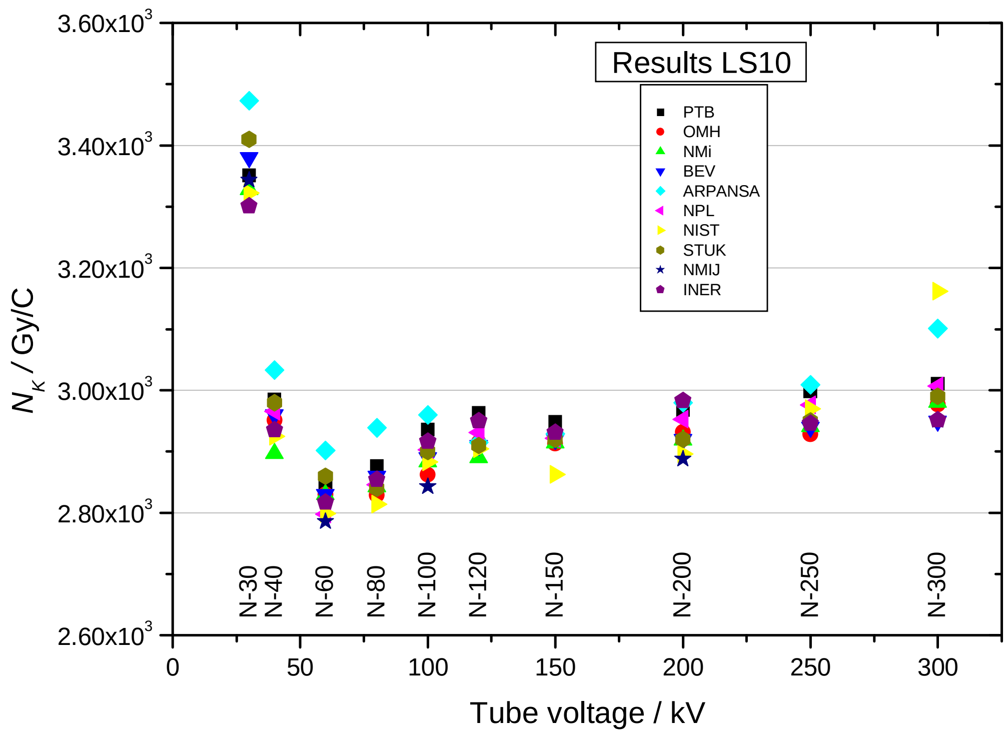


Figure B3. LS10 calibration coefficients of all participants as a function of the tube voltage.

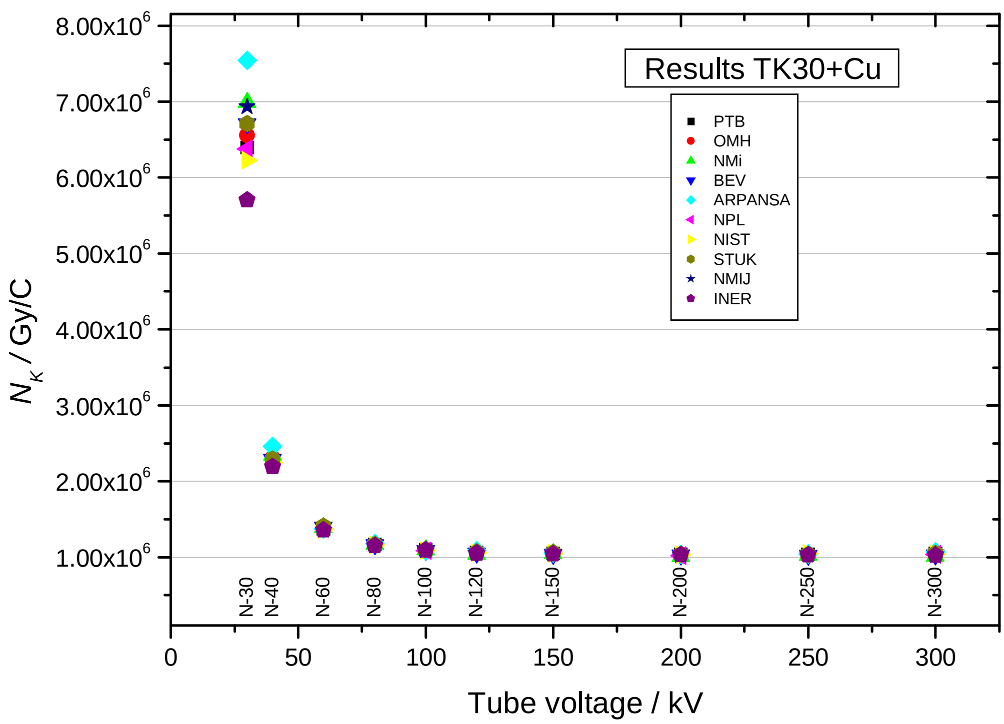
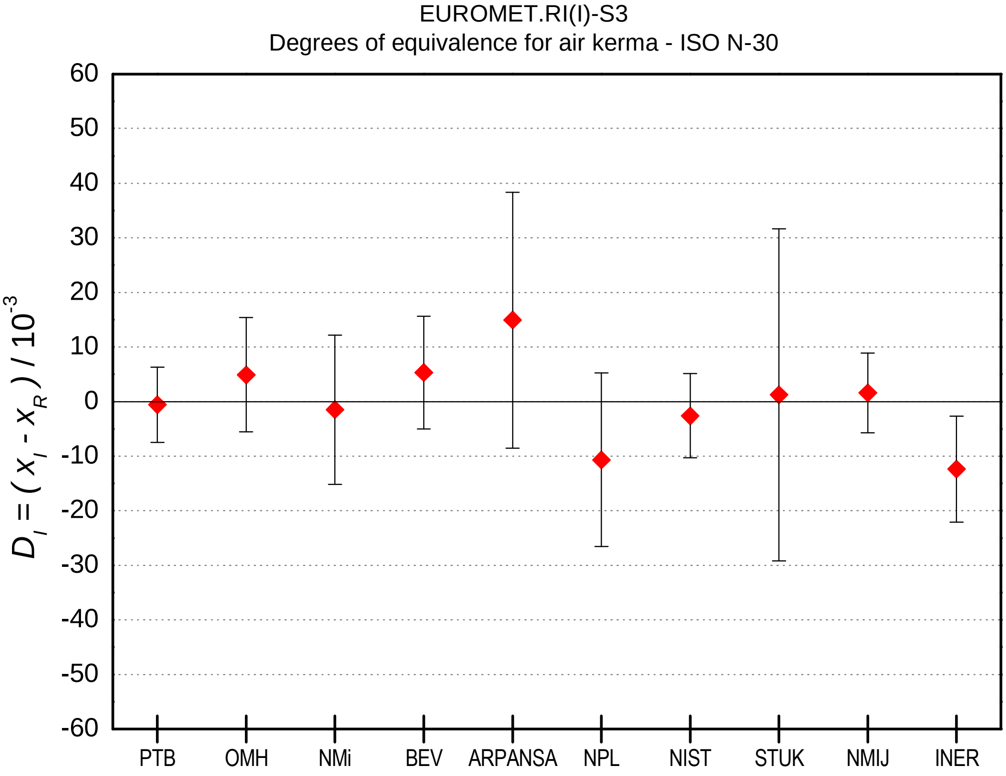
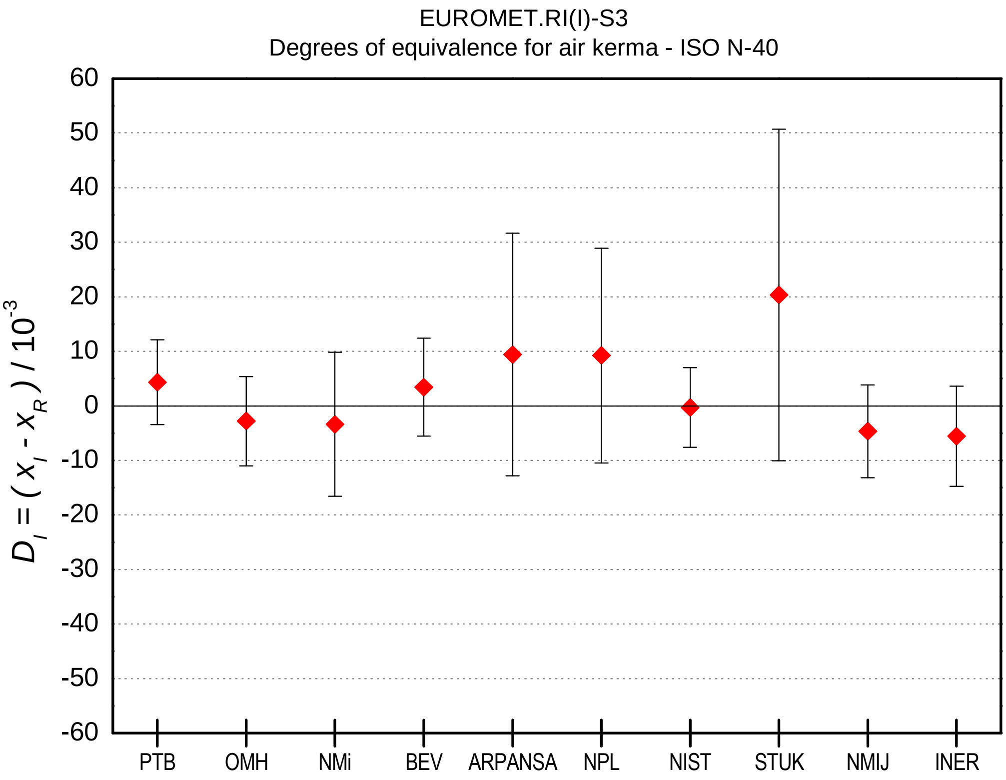
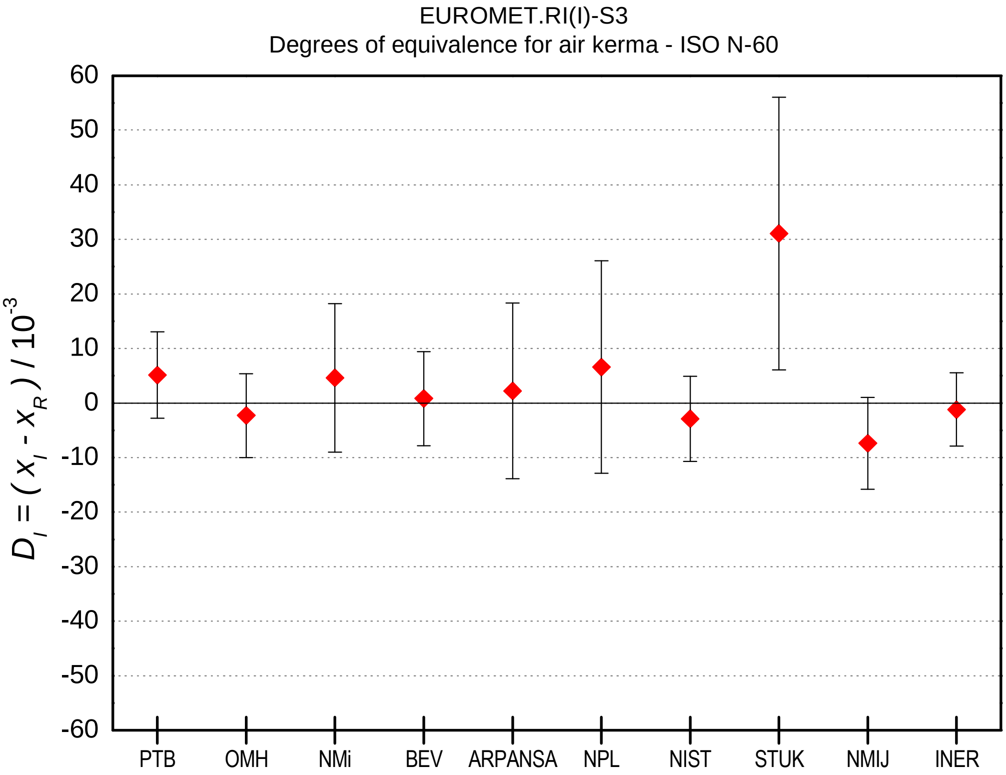


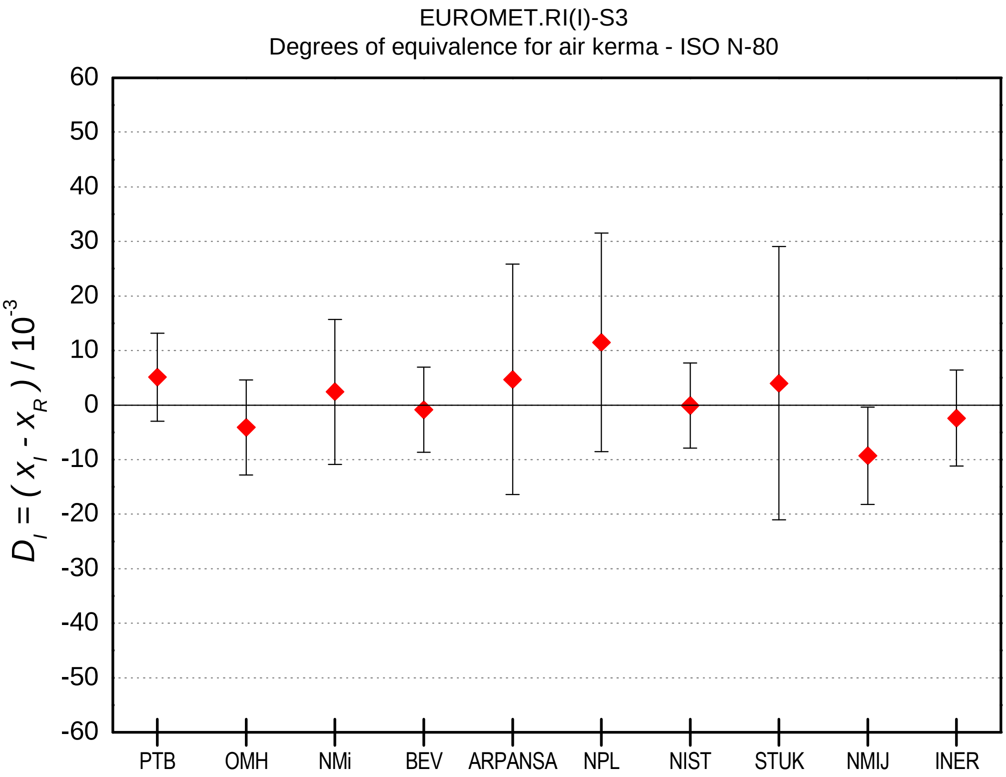
Figure B4. TK30/Cu calibration coefficients of all participants as a function of the tube voltage.

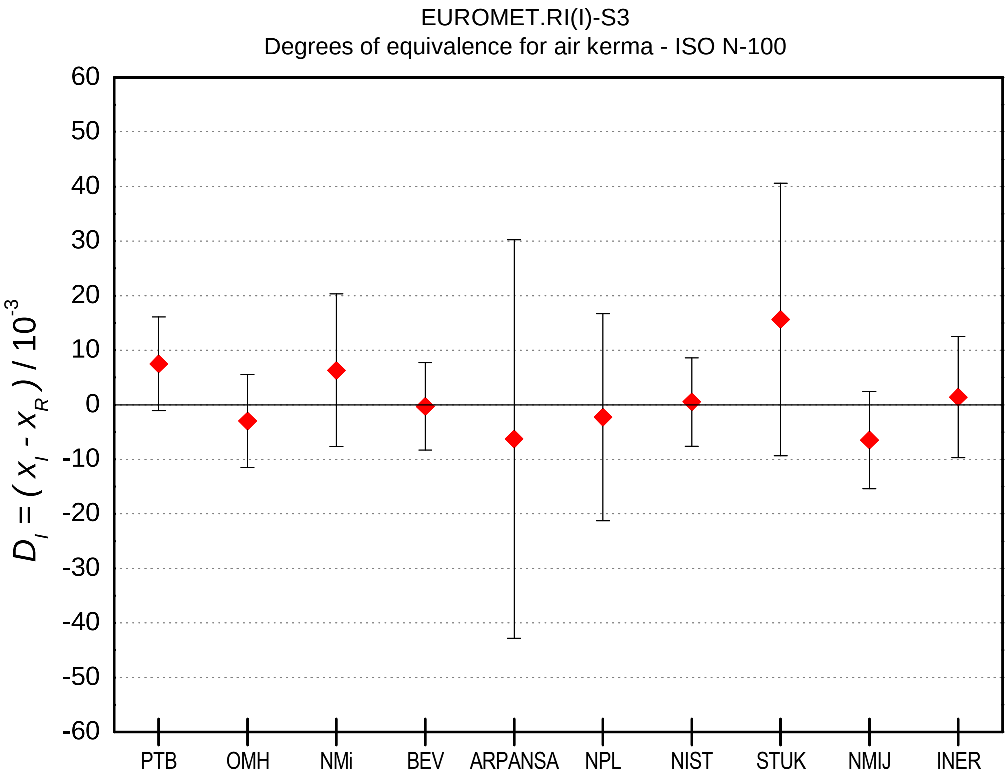
APPENDIX C: Graphs of the degree of equivalence with SCRV

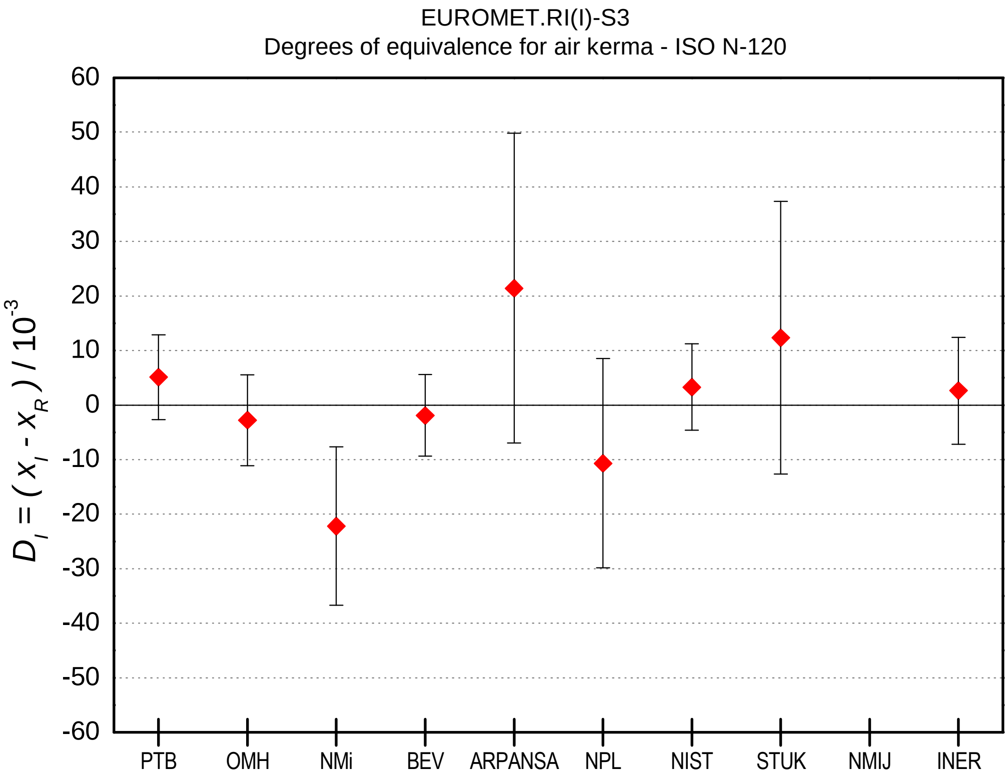


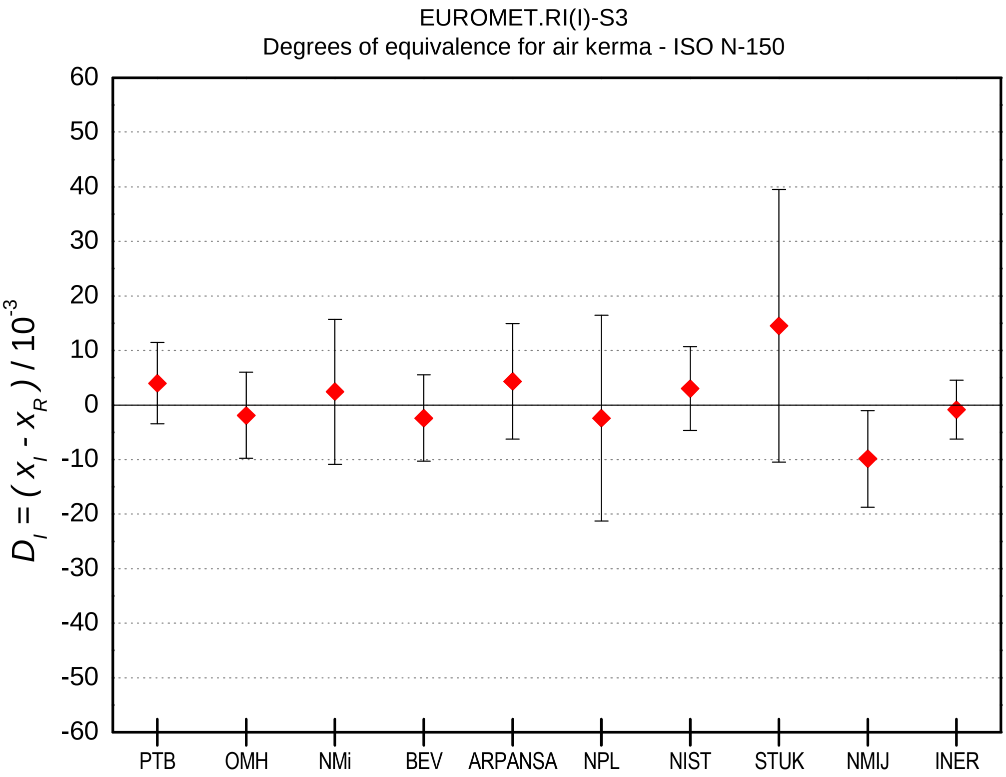


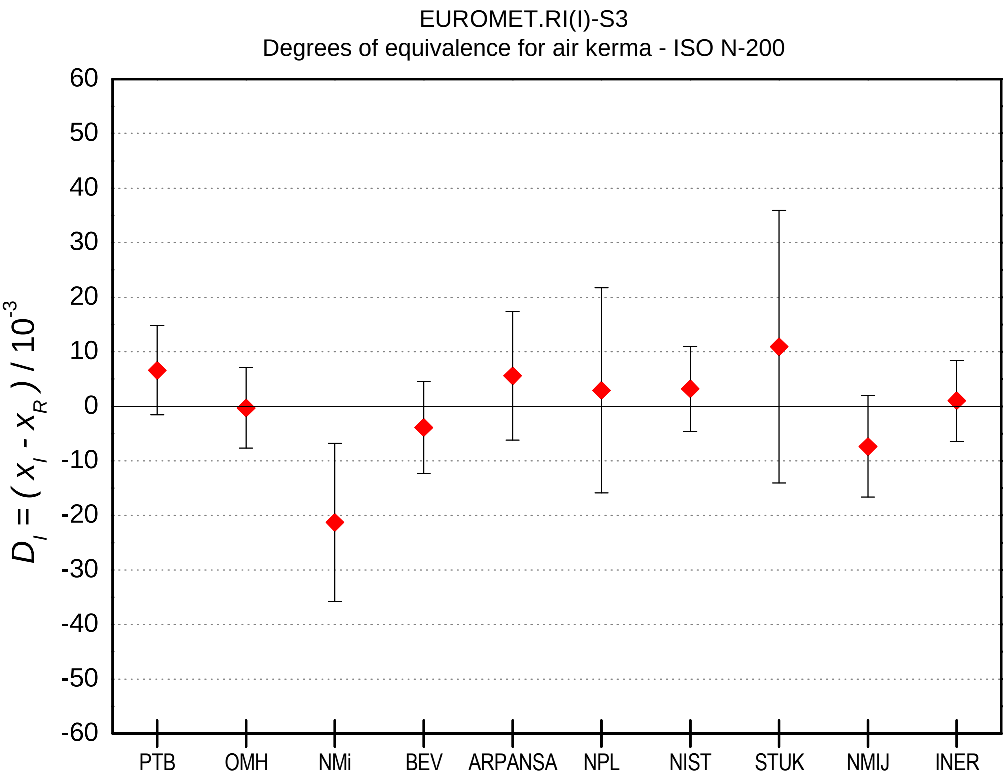

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-60
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER

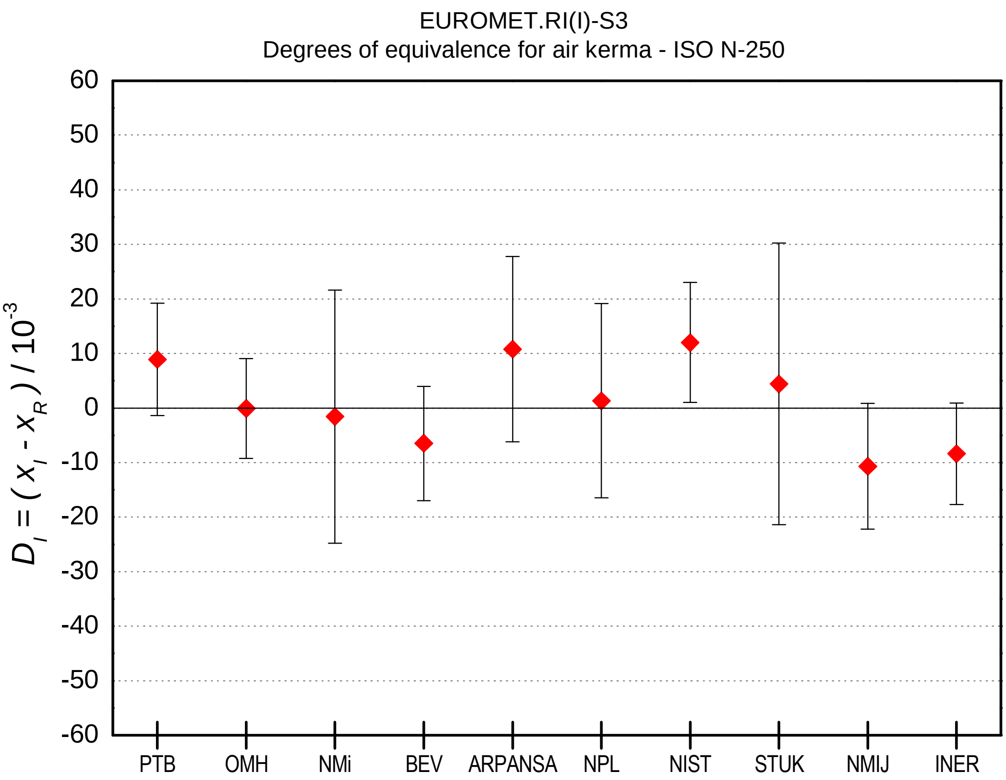

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-80
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER

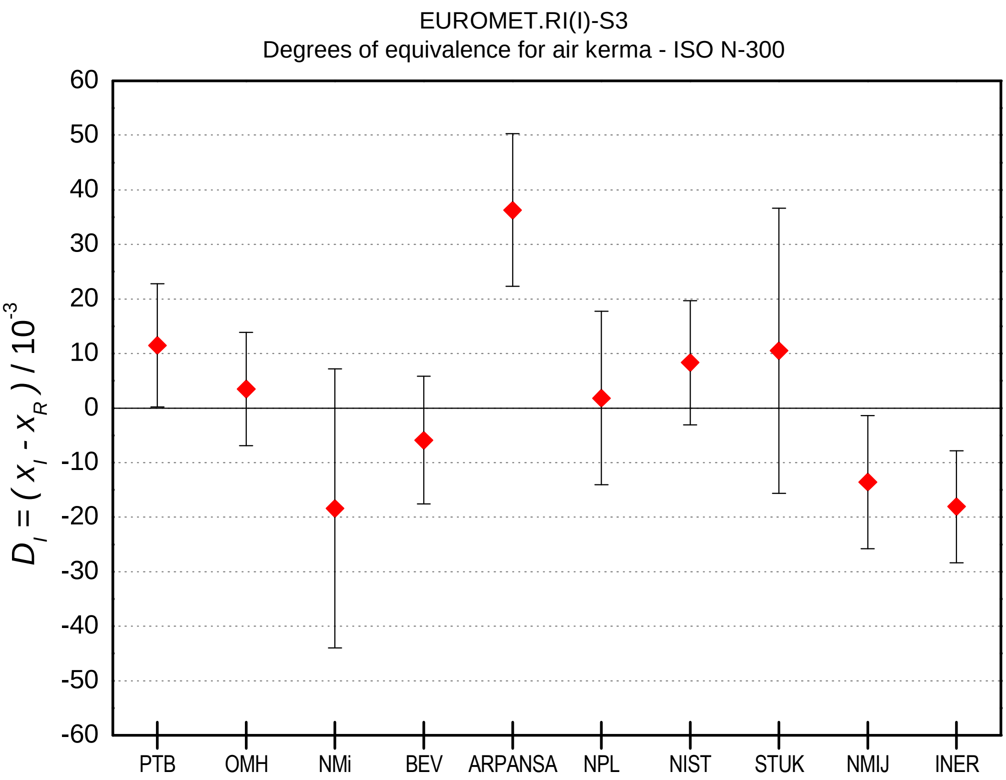

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-100
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-120
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-150
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-200
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-250
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-300
$D_I = (x_I - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER

APPENDIX D: Tables of the SCRV and the degrees of equivalence with SCRV based on the results obtained with the LS01 and LS10 tranfer chamber

Table D1. Comparison reference values, x_r, and relative uncertainties, $u(x_r)$, of each quality, which is the median of the participant's calibration coefficients in units of Gy/C, based on the results obtained with the LS01 chamber

Qual.	SCRV x_r	$u(x_r)$ / %
N-30	2.8286E+04	0.26
N-40	2.5318E+04	0.36
N-60	2.4326E+04	0.26
N-80	2.4685E+04	0.31
N-100	2.4836E+04	0.35
N-120	2.4900E+04	0.38
N-150	2.4805E+04	0.31
N-200	2.4825E+04	0.31
N-250	2.5096E+04	0.35
N-300	2.5189E+04	0.38

Table D2. Ratios x_i/x_r at each of the radiation qualities based on the results obtained with the LS01 chamber

Qual.	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	1.0004	1.0129	0.9888	1.0079	1.0243	0.9959	0.9977	1.0188	0.9995	0.9920
N-40	1.0039	0.9938	0.9795	0.9985	1.0245	1.0060	0.9897	1.0121		0.9973
N-60	1.0090	0.9989	0.9977	1.0018	1.0233	1.0034	0.9927	1.0286	0.9941	0.9994
N-80	1.0011	0.9872	0.9901	0.9998	1.0191	1.0014	0.9974	1.0094		1.0073
N-100	1.0074	0.9869	0.9865	0.9998	1.0208	1.0018	0.9995	1.0147	0.9916	1.0135
N-120	1.0081	0.9920	0.9811	0.9972	0.9972	0.9992	1.0034	1.0100		1.0051
N-150	1.0062	0.9941	0.9913	1.0006	1.0037	0.9994	0.9958	1.0126		1.0042
N-200	1.0082	0.9954	0.9877	0.9998	1.0077	0.9994	1.0008	1.0066	0.9866	1.0070
N-250	1.0068	0.9870	0.9838	0.9930	1.0096	0.9974	1.0014	0.9992		0.9915
N-300	1.0108	0.9996	0.9909	0.9941	1.0335	1.0032	1.0073	1.0053	0.9869	0.9920

Table D3. Differences D_i and their expanded (k = 2) uncertainties U_i expressed in parts of 10^3, and the ratio D_i / U_i of each participant. Ratios D_i / U_i > 1 characterize discrepancies and are printed in bold letters. Results obtained if the LS01 chamber is used as transfer standard. Some 10 out of 95 results are inconsistent.

Qual.		PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	D_i	0.4	12.9	-11.2	7.9	24.3	-4.1	-2.3	18.8	-0.5	-8.0
	U_i	8.4	12.3	15.5	15.0	28.3	14.9	7.8	30.4	7.7	11.7
	D_i/U_i	0.0	1.0	0.7	0.5	0.9	0.3	0.3	0.6	0.1	0.7
N-40	D_i	3.9	-6.2	-20.5	-1.5	24.5	6.0	-10.3	12.1		-2.7
	U_i	9.3	9.7	15.8	12.4	36.2	16.3	10.3	30.9		13.3
	D_i/U_i	0.4	0.6	**1.3**	0.1	0.7	0.4	1.0	0.4		0.2
N-60	D_i	9.0	-1.1	-2.3	1.8	23.3	3.4	-7.2	28.6	-5.9	-0.6
	U_i	10.2	7.6	13.4	14.0	25.5	17.1	8.8	25.1	9.2	6.9
	D_i/U_i	0.9	0.1	0.2	0.1	0.9	0.2	0.8	**1.1**	0.6	0.1
N-80	D_i	1.1	-12.8	-9.9	-0.2	19.1	1.4	-2.6	9.4		7.3
	U_i	8.6	10.2	14.6	13.1	18.7	16.0	8.2	25.4		8.6
	D_i/U_i	0.1	**1.2**	0.7	0.0	1.0	0.1	0.3	0.4		0.8
N-100	D_i	7.4	-13.1	-13.5	-0.2	20.9	1.8	-0.5	14.7	-8.5	13.5
	U_i	10.8	10.7	15.4	13.1	24.0	16.1	8.0	25.6	11.7	11.6
	D_i/U_i	0.7	**1.2**	0.9	0.0	0.9	0.1	0.1	0.6	0.7	**1.2**
N-120	D_i	8.1	-8.0	-18.9	-2.8	-2.8	-0.8	3.4	10.0		5.0
	U_i	11.2	11.5	15.9	13.5	30.9	15.8	9.5	25.7		11.1
	D_i/U_i	0.7	0.7	**1.2**	0.2	0.1	0.1	0.4	0.4		0.5
N-150	D_i	6.2	-5.9	-8.7	0.6	3.7	-0.6	-4.2	12.6		4.2
	U_i	10.0	9.8	14.4	13.4	13.6	16.1	8.7	25.4		8.5
	D_i/U_i	0.6	0.6	0.6	0.0	0.3	0.0	0.5	0.5		0.5
N-200	D_i	8.2	-4.6	-12.3	-0.2	7.7	-0.6	0.8	6.6	-13.3	7.0
	U_i	10.6	9.1	15.1	13.5	15.2	16.3	7.8	25.4	10.4	8.3
	D_i/U_i	0.8	0.5	0.8	0.0	0.5	0.0	0.1	0.3	**1.3**	0.8
N-250	D_i	6.8	-13.0	-16.2	-7.0	9.5	-2.6	1.4	-0.8		-8.5
	U_i	10.5	10.9	25.2	14.3	18.9	15.4	8.2	25.6		8.8
	D_i/U_i	0.7	**1.2**	0.6	0.5	0.5	0.2	0.2	0.0		1.0
N-300	D_i	10.8	-0.4	-9.1	-5.9	33.5	3.2	7.3	5.3	-13.1	-8.0
	U_i	11.7	9.1	24.4	14.5	28.5	16.3	10.4	26.7	12.2	9.6
	D_i/U_i	0.9	0.0	0.4	0.4	**1.2**	0.2	0.7	0.2	**1.1**	0.8

Table D4. Comparison reference values, x_r, and relative uncertainties, $u(x_r)$, of each quality, which is the median of the participant's calibration coefficients in units of Gy/C, based on the results obtained with the LS10 chamber

Qual.	SCRV x_r	$u(x_r)$ / %
N-30	3.3496E+03	0.42
N-40	2.9617E+03	0.39
N-60	2.8211E+03	0.31
N-80	2.8534E+03	0.38
N-100	2.8932E+03	0.38
N-120	2.9202E+03	0.37
N-150	2.9217E+03	0.33
N-200	2.9349E+03	0.37
N-250	2.9714E+03	0.35
N-300	2.9827E+03	0.42

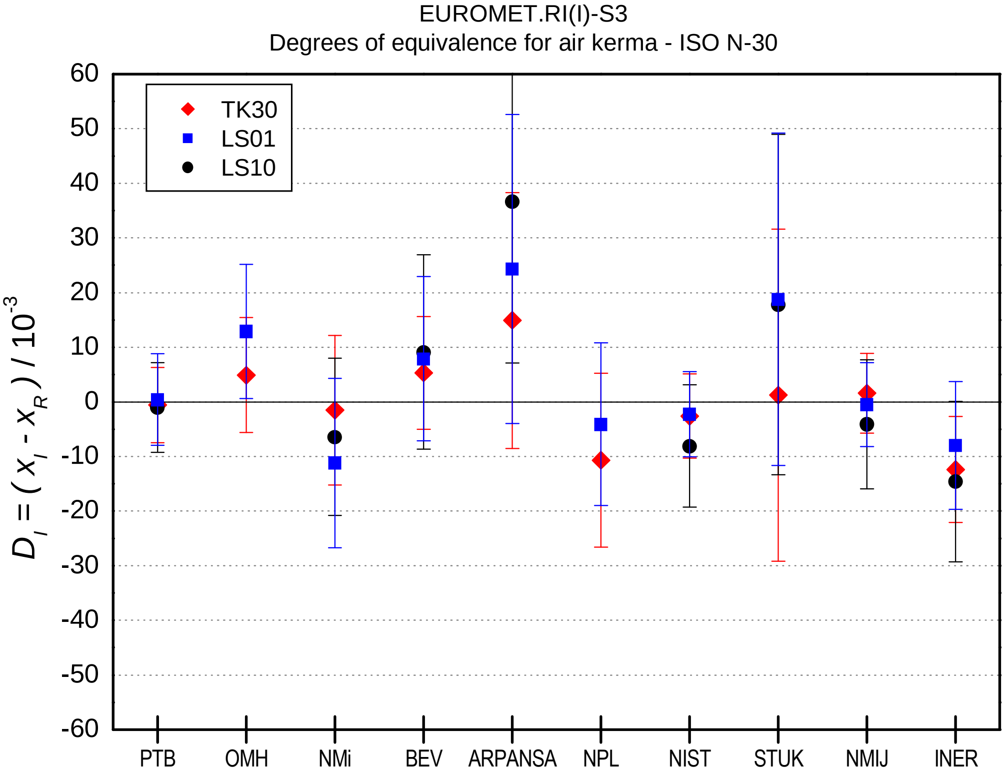
Table D5. Ratios x_i/x_r at each of the radiation qualities based on the results obtained with the LS10 chamber

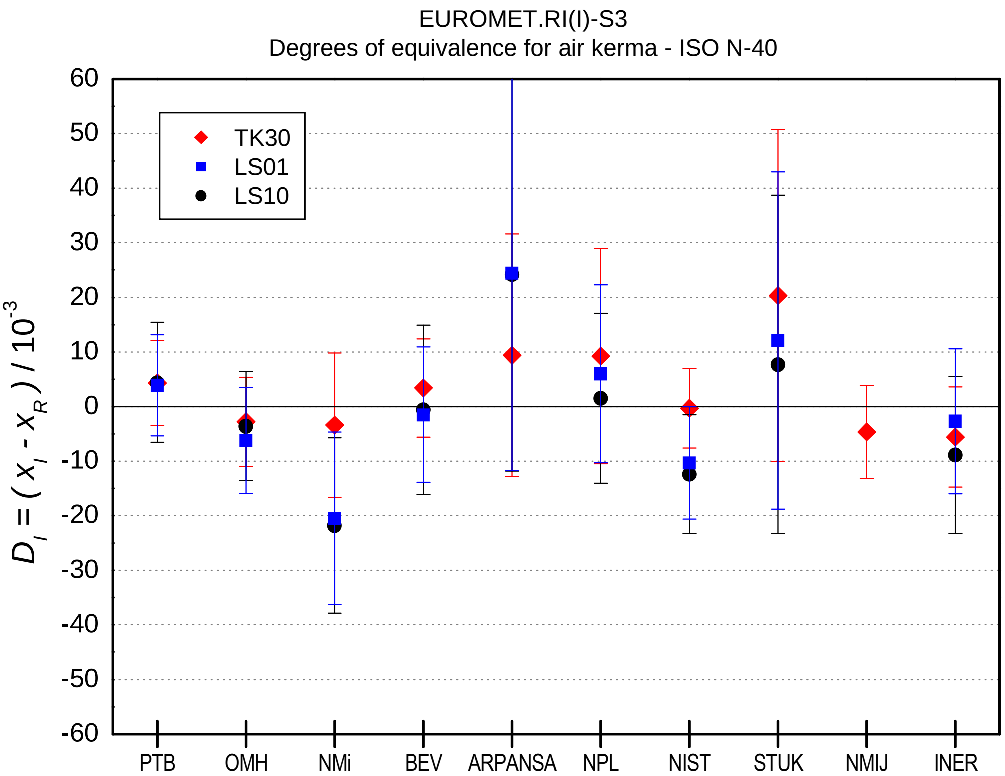
Qual.	PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	0.9990		0.9936	1.0091	1.0367		0.9919	1.0178	0.9959	0.9854
N-40	1.0044	0.9964	0.9782	0.9994	1.0242	1.0015	0.9876	1.0077		0.9911
N-60	1.0052	1.0032	1.0032	1.0032	1.0286	0.9918	0.9923	1.0149	0.9857	0.9985
N-80	1.0021	0.9915	0.9964	1.0023	1.0301	0.9974	0.9863	0.9964		1.0003
N-100	1.0080	0.9892	0.9965	0.9989	1.0231	1.0034	0.9963	1.0028	0.9806	1.0081
N-120	1.0091	0.9982	0.9897	0.9965	0.9982	1.0037	0.9943	0.9963		1.0102
N-150	1.0040	0.9970	0.9974	0.9994	1.0025	1.0001	0.9798	1.0001		1.0032
N-200	1.0057	0.9990	0.9946	0.9949	1.0154	1.0062	0.9868	0.9943	0.9819	1.0165
N-250	1.0034	0.9854	0.9898	0.9894	1.0126	1.0015	0.9996	0.9930		0.9913
N-300	1.0029	0.9981	0.9994	0.9891	1.0397	1.0082	1.0603	1.0017	0.9873	0.9896

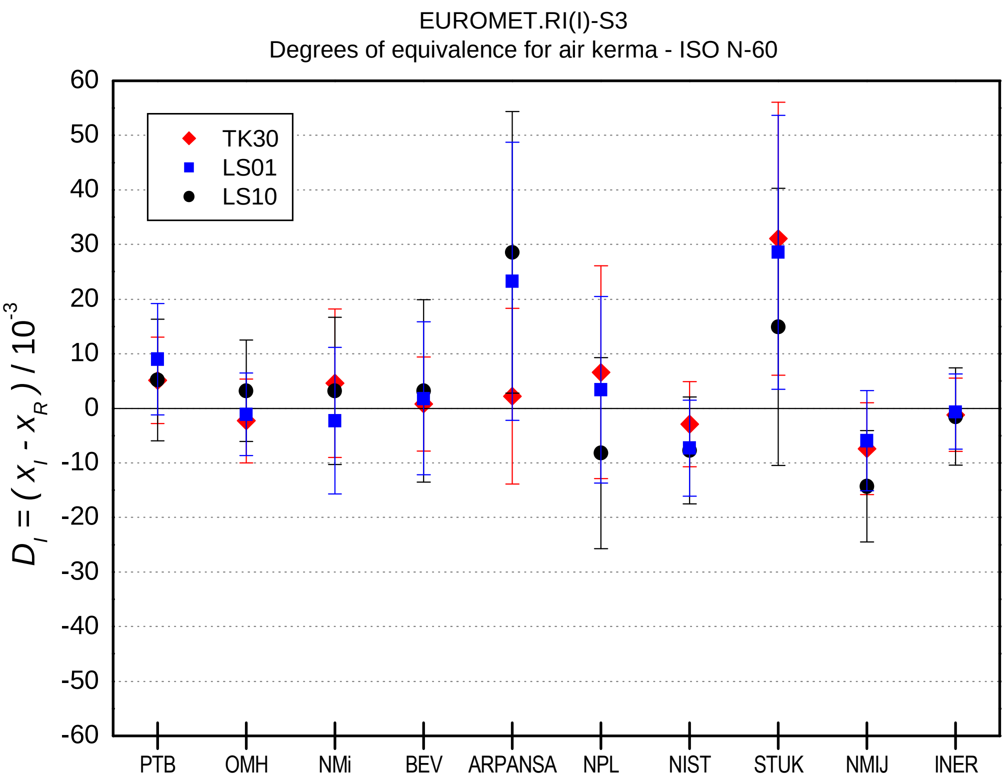
Table D6. Differences D_i and their expanded (k = 2) uncertainties U_i expressed in parts of 10^3, and the ratio D_i / U_i of each participant. Ratios D_i / U_i > 1 characterize discrepancies and are printed in bold letters. Results obtained if the LS10 chamber is used as transfer standard. Some 15 out of 93 results are inconsistent.

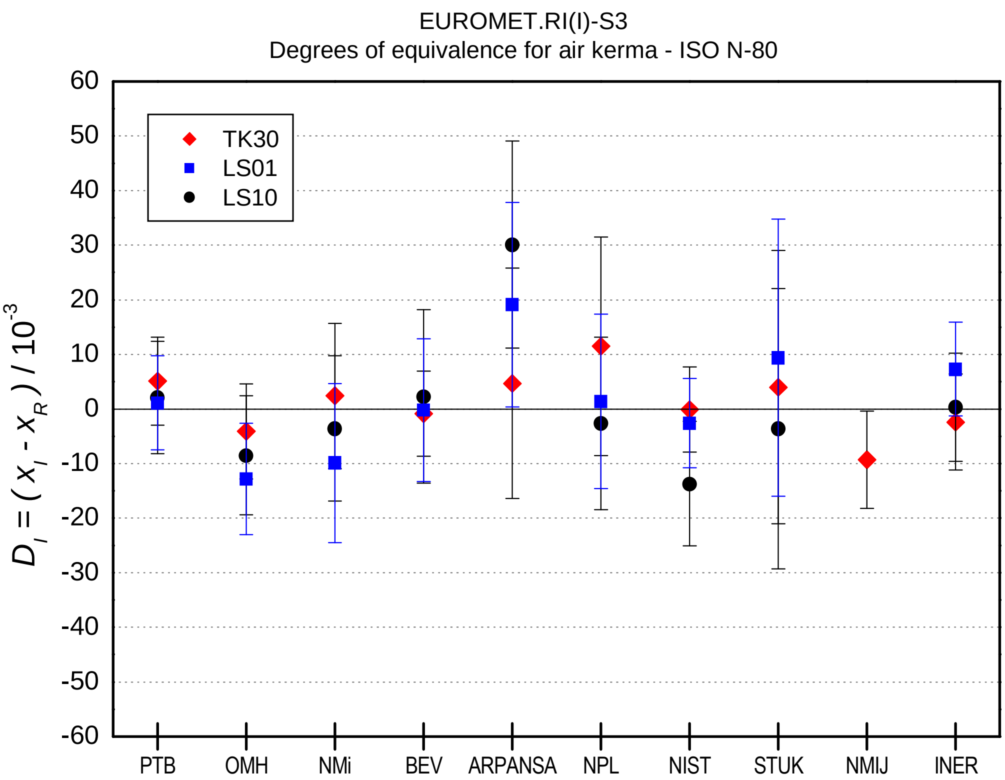
Qual.		PTB	OMH	NMi	BEV	AR-PANSA	NPL	NIST	STUK	NMIJ /AIST	INER
N-30	D_i	-1.0		-6.4	9.1	36.7		-8.1	17.8	-4.1	-14.6
	U_i	8.2		14.4	17.8	29.6		11.2	31.2	11.8	14.7
	D_i/U_i	0.1		0.4	0.5	**1.2**		0.7	0.6	0.3	1.0
N-40	D_i	4.4	-3.6	-21.8	-0.6	24.2	1.5	-12.4	7.7		-8.9
	U_i	11.0	10.0	16.1	15.5	36.0	15.6	10.9	31.0		14.4
	D_i/U_i	0.4	0.4	**1.4**	0.0	0.7	0.1	**1.1**	0.2		0.6
N-60	D_i	5.2	3.2	3.2	3.2	28.6	-8.2	-7.7	14.9	-14.3	-1.5
	U_i	11.1	9.3	13.5	16.7	25.8	17.5	9.8	25.4	10.2	8.9
	D_i/U_i	0.5	0.3	0.2	0.2	**1.1**	0.5	0.8	0.6	**1.4**	0.2
N-80	D_i	2.1	-8.5	-3.6	2.3	30.1	-2.6	-13.7	-3.6		0.4
	U_i	10.3	10.9	13.3	15.9	19.0	15.8	11.4	25.7		9.9
	D_i/U_i	0.2	0.8	0.3	0.1	1.6	0.2	**1.2**	0.1		0.0
N-100	D_i	8.0	-10.8	-3.5	-1.1	23.1	3.4	-3.7	2.8	-19.4	8.1
	U_i	12.4	11.6	13.6	16.0	24.0	16.6	10.5	25.7	12.6	11.6
	D_i/U_i	0.6	0.9	0.3	0.1	1.0	0.2	0.3	0.1	**1.5**	0.7
N-120	D_i	9.1	-1.8	-10.3	-3.5	-1.8	3.7	-5.7	-3.7		10.2
	U_i	12.2	9.7	15.1	16.4	30.8	16.6	10.7	25.7		9.5
	D_i/U_i	0.7	0.2	0.7	0.2	0.1	0.2	0.5	0.1		**1.1**
N-150	D_i	4.0	-3.0	-2.6	-0.6	2.5	0.1	-20.2	0.1		3.2
	U_i	10.8	9.3	13.4	16.5	13.6	16.4	10.1	25.5		9.0
	D_i/U_i	0.4	0.3	0.2	0.0	0.2	0.0	**2.0**	0.0		0.4
N-200	D_i	5.7	-1.0	-5.4	-5.1	15.4	6.2	-13.2	-5.7	-18.1	16.5
	U_i	11.5	8.8	13.9	16.5	16.4	17.1	11.6	25.7	11.4	10.6
	D_i/U_i	0.5	0.1	0.4	0.3	0.9	0.4	**1.1**	0.2	**1.6**	**1.6**
N-250	D_i	3.4	-14.6	-10.2	-10.6	12.6	1.5	-0.4	-7.0		-8.7
	U_i	10.5	11.5	24.5	17.7	19.4	15.7	8.7	25.6		9.3
	D_i/U_i	0.3	**1.3**	0.4	0.6	0.7	0.1	0.0	0.3		0.9
N-300	D_i	2.9	-1.9	-0.6	-10.9	39.7	8.2	60.3	1.7	-12.7	-10.4
	U_i	10.9	10.5	23.4	18.3	28.6	17.8	12.3	26.0	12.6	10.5
	D_i/U_i	0.3	1.0	0.0	0.6	**1.4**	0.5	**4.9**	0.1	1.0	1.0

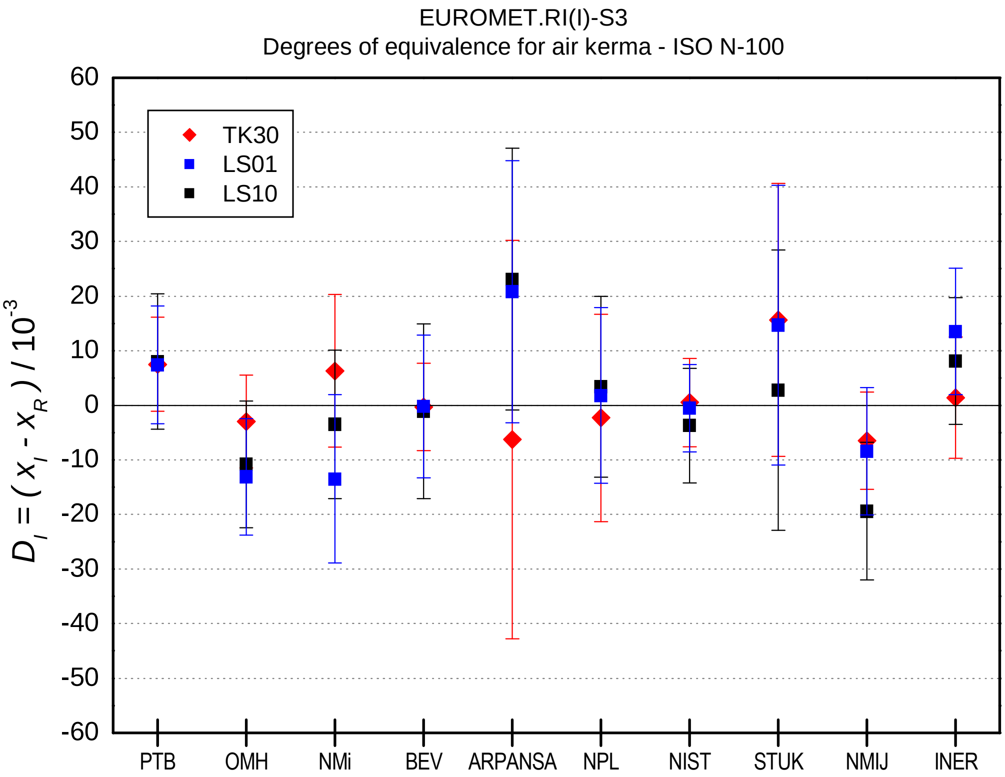
APPENDIX E: Graphs of the DoE with SCRV based on TK30, LS01 and LS10

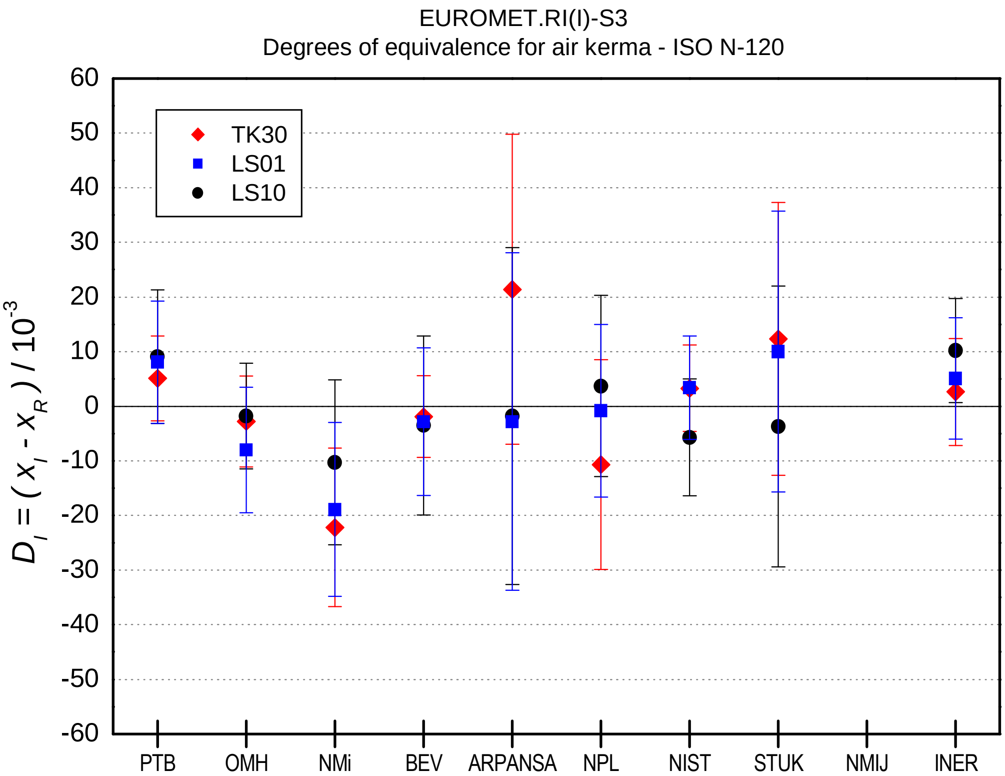


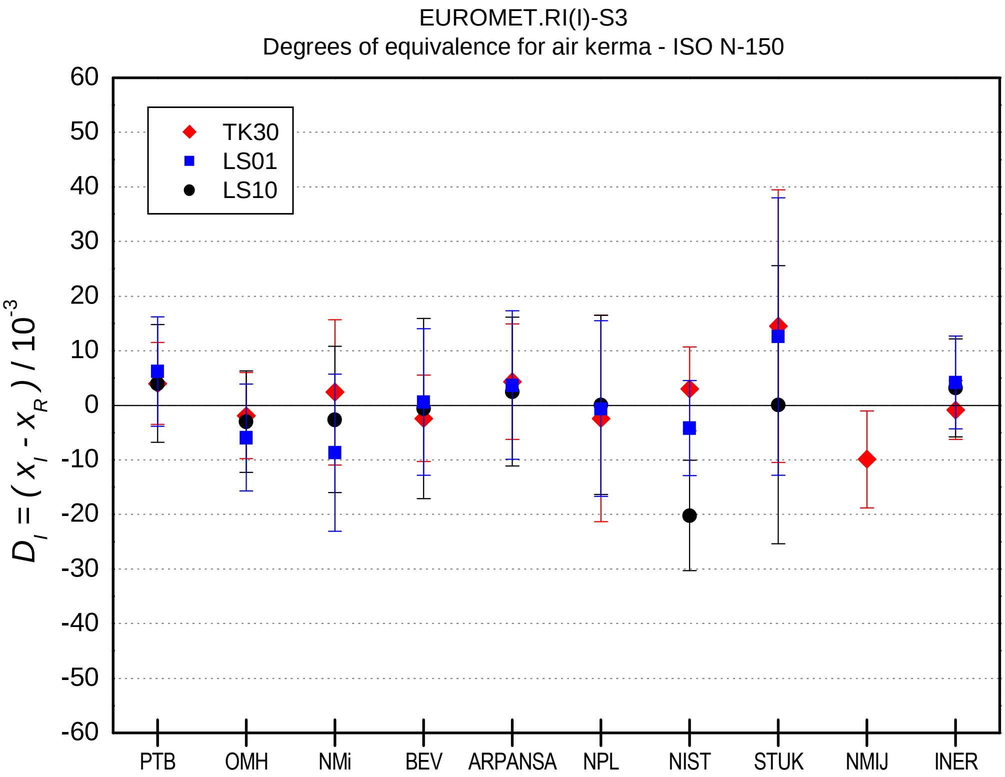


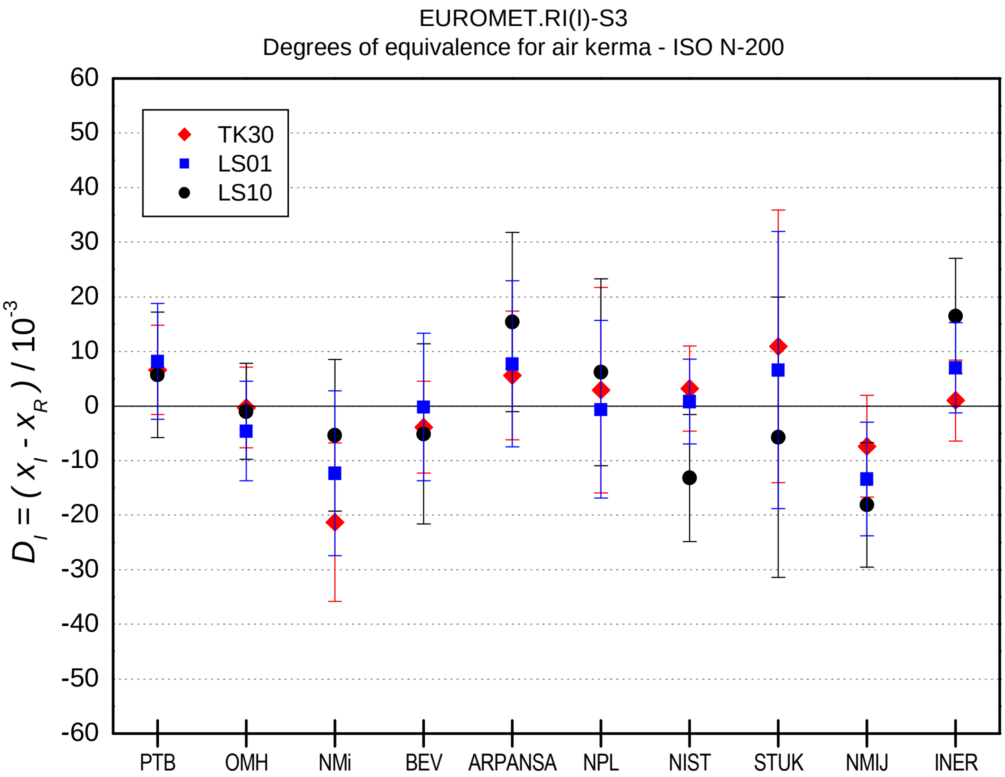

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-60
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER

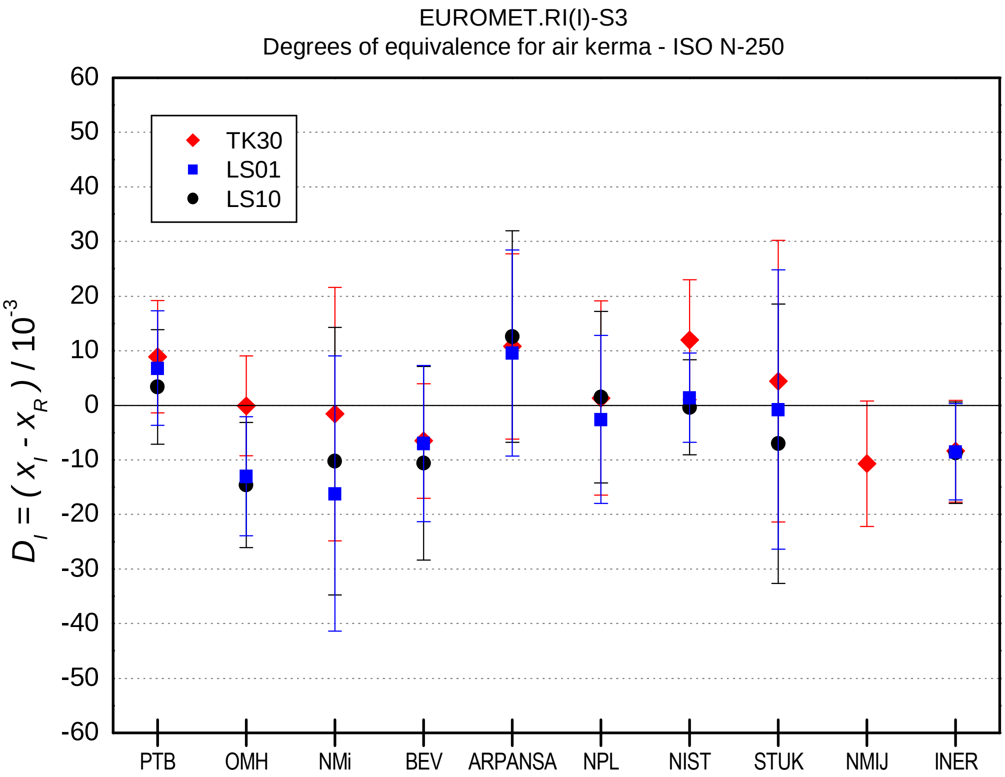

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-80
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER

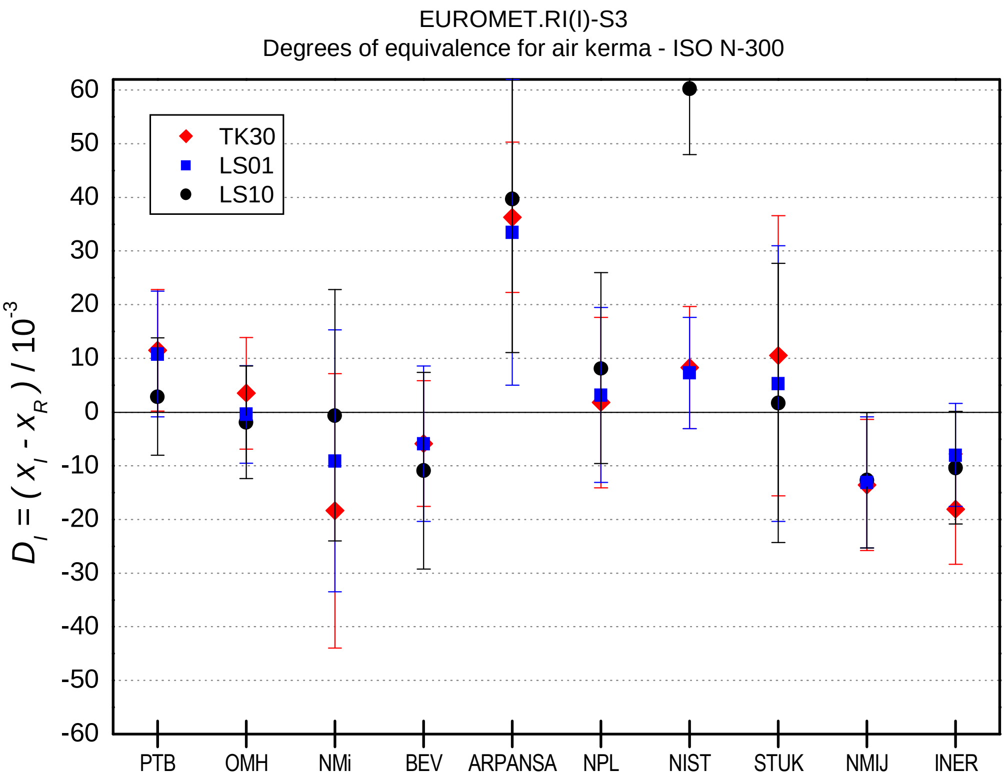

EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-100
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-120
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-150
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-200
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-250
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER


EUROMET.RI(I)-S3
Degrees of equivalence for air kerma - ISO N-300
TK30
LS01
LS10
$D_i = (x_i - x_R) / 10^{-3}$
PTB
OMH
NMi
BEV
ARPANSA
NPL
NIST
STUK
NMIJ
INER