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Comparison of air kerma and absorbed dose to water measurements of ^{60}Co radiation beams for radiotherapy

Report on EUROMET project no. 813, identifiers in the BIPM key comparison database (KCDB) are EUROMET.RI(I)-K1 and EUROMET.RI(I)-K4

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Abstract

The results of an unprecedented international effort involving 26 countries are reported. The EUROMET.RI(I)-K1 and EUROMET.RI(I)-K4 key comparisons were conducted with the goal of supporting the relevant calibration and measurement capabilities (CMC) planned for publication by the participant laboratories. The measured quantities were the air kerma (K_{air}) and the absorbed dose to water (D_{w}) in ^{60}Co radiotherapy beams. The comparison was conducted by the pilot laboratory MKEH (Hungary), in a star-shaped arrangement from January 2005 to December 2008. The calibration coefficients of four transfer ionization chambers were measured using two electrometers. The largest deviation between any two calibration coefficients for the four chambers in terms of air kerma and absorbed dose to water was 2.7% and 3.3% respectively. An analysis of the participant uncertainty budgets enabled the calculation of degrees of equivalence (DoE), in terms of the deviations of the results and their associated uncertainties. As a result of this EUROMET project 813 comparison, the BIPM key comparison database (KCDB) will include eleven new K_{air} and fourteen new D_{w} DoE values of European secondary standard dosimetry laboratories (SSDLs), and the KCDB will be updated with the new DoE values of the other participant laboratories. The pair-wise degrees of equivalence of participants were also calculated. In addition to assessing calibration techniques and uncertainty calculations of the participants, these comparisons enabled the experimental determinations of $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios in the ^{60}Co gamma radiation beam for the four radiotherapy transfer chambers.

1 Introduction

In October 1999, National Metrology Institutes (NMI) worldwide signed the Mutual Recognition Arrangement (*'Arrangement on the mutual recognition of the equivalence of national standards and of calibration certificates issued by national metrology institutes'*) established by the International Committee of Weights and Measures (CIPM) and known as the CIPM MRA [1] with the aim of establishing a basis for the mutual recognition of calibration and measurement capabilities (CMCs). In Appendix C of the CIPM MRA, a part of the key comparison database (KCDB), the BIPM has been publishing lists of these (CMCs) provided by the NMIs that have signed the CIPM MRA. Calibration services can, however, only be included in this database if a quality management system according to the ISO standard 17025 has been established. Quality assurance and confidence in the capabilities of other laboratories is usually ensured by the participation in comparisons in which the degrees of equivalences with other National Metrology Institutes or designated calibration laboratories have been determined.

The laboratories having primary standards regularly take part in the ongoing BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparisons, but these are comparisons only of primary standards and not of secondary standards that are used for the dissemination of the quantities. The degrees of equivalence of national standards of air kerma and absorbed dose to water have already been published in the KCDB of the CIPM MRA. http://kcdb.bipm.org/appendixB

2 Procedure

2.1 Object of the comparisons

The results of this comparison are used by both primary and secondary laboratories to support their relevant CMC claims. For this reason, the instruments that were chosen to conduct this comparison were a representation of what the participating facilities receive routinely as part of their calibration service. A total of four chambers and two electrometers were shipped to each participating facility. In these two regional key comparisons, the air kerma and absorbed dose to water calibration coefficients, $N_{K\mathrm{air}}$ and $N_{D\mathrm{w}}$, of the transfer chambers were determined. Furthermore, these measurements enabled the determination of the degrees of equivalence for each participant to be established. The reference class chambers used were of high quality which resulted in low measurement uncertainties. Such high quality measurements allow the calibration capabilities and the realization of the air kerma and absorbed dose to water quantities to be assessed appropriately at each participating facility.

An additional benefit from this comparison was the fact that one of the electrometers, the PAM 2001[1], contained an internal temperature and pressure transducer calibrated at the MKEH. This enabled each participant to check their own instruments for measuring temperature, pressure and electrical current against the values obtained with the UNIDOS and PAM 2001 electrometers supplied. The ratio of the absorbed dose to water and the air kerma calibration coefficient, $N_{D\mathrm{w}} / N_{K\mathrm{air}}$, and its corresponding uncertainty, could be determined for each chamber by all 26 participating countries. This information is of great value for hospitals that use ^{60}Co radiotherapy beams under the same reference conditions that are used in this work.

2.2 Transfer instruments

The main technical data of the transfer chambers are listed in Table 1. These chambers are recognized by the medical community for their high stability [2]. Each chamber has its own build-up cap for calibration in terms of air kerma. Two of the chambers, the NE 2561 and the PTW 30001, required the use of a 1mm wall PMMA[2]

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[1] Certain commercial equipment, instruments, and materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by any NMI, nor does it imply that the materials and/or equipment are the best available for the purpose.

[2] Polymethyl-methacrylate

sleeve for immersing the chambers in water for the absorbed dose to water calibrations. The PMMA sleeve fits tightly around the chamber. The other two chambers, (Wellhöffer FC-65 G and ND 1006) were waterproof. Adaptors and extension cables were provided for the chambers and electrometers' signal and high voltage connections. The reference points of the chambers are the geometrical centre of the sensitive volumes. Each chamber was aligned in the ^{60}Co beam established according to the ISO 4037 standard [3] with the black cross (marking the middle of the sensitive volume length) facing the radiation source.

The measurement of the ionization current for each chamber was made using two electrometers. One was the *PTW UNIDOS* (model 2.30 and serial number 20381) and the other was a Hungarian reference class *PAM* (model 2001, serial number 2306). Both electrometers were interfaced to a notebook computer and operated remotely using their associated data acquisition software (DAS). The DAS used with both electrometers generated text files containing relevant measurement parameters such as the direct measured ionization currents from the chambers, the temperature and pressure near the chambers and the exposure time. The readings of temperature and pressure recorded by the DAS of the PAM 2001 electrometer were obtained from the internal barometer and from the external waterproof PT 200 temperature probe that is attached to the electrometer. The PTW UNIDOS electrometer did not measure temperature and pressure internally. However, the data acquisition software, supplied by the pilot laboratory, allowed manual entry of the values of temperature and pressure obtained from an external meter. The values of temperature and pressure used by each participant was obtained from the standard thermometer and barometer used at each facility when the UNIDOS electrometer was used. Both electrometers included internal power supplies that were used to supply the high voltage applied to the chambers. All four chambers were calibrated using both the UNIDOS and PAM electrometers. The text files generated by the DAS for each electrometer were stored on the hard disk of the notebook (NEC Model Versa AXK6-2, SN R316900059) that was supplied during the comparison. These text files were visible to the participants. Additional hidden files containing all the measurement details were also stored on the hard disk. The hidden files were only accessible to the pilot laboratory (MKEH) for validation and quality control purposes. Photographs showing the electrometers and chambers with the appropriate attachments (build-up cap, sleeve and adaptor) are shown in *Appendix D*.

Table 1. Main technical data of the transfer chambers

Type serial number	Nom. NDw / (Gy/µC)	Nom. volume /cm3	Collecting potential[a] /V	Wall material	Wall thickness /(g/cm^2)	Head diam. /mm	Stem diam./length /mm	Water-proof
NE 2561 # 084	101	0.33	+ 200	Graphite	0.090	8.4	12.6/180	No
PTW 30001 #2118	54	0.60	+ 400	PMMA	0.045	7.0	12.6/130	No
Wellhöffer FC-65 G #518	45	0.65	+ 300	Graphite	0.068	7.0	8.6/80	Yes
ND 1006 #8503	120	0.28	+ 250	Delrin	0.07	8.0	10.0/300	Yes

[a] the central electrode is positive

2.3 Participants and operation of the comparisons

The status and technical details of the comparison project described in this work, entitled EUROMET project 813, were discussed and finalized at the EUROMET IR TC Contact Persons meeting in September 2004. At this meeting it was proposed to combine two key dosimetry comparisons in parallel as part of the EUROMET project 813. The two key comparisons are entitled EUROMET.RI(I)-K1 and EUROMET.RI(I)-K4 and encompass the comparison among all participating laboratories of the radiation quantities air kerma and absorbed dose to water respectively. This was facilitated in part by the fact that both key comparisons have similarities in the way the measurements are performed and therefore can be described by a common protocol.

National Metrology Institutes around the world are grouped into five geographical regions, each group being recognized as a Regional Metrology Organization (RMO). The RMOs include the Asia-Pacific Metrology Program (APMP), the Euro-Asian Cooperation of National Metrological Institutes (COOMET), the European Collaboration on Measurement Standards (EUROMET)[3], the Inter-American Metrology System (SIM), while the Middle East - North African Cooperation in Metrology (MENAMET) and the South African Development Community Cooperation in Measurement Traceability (SADCMET) are part of the

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[3] Now known as the European Association of National Metrology Institutes (EURAMET)

expanded Intra-Africa Metrology System AFRIMET . Representatives from the SIM, APMP and the COOMET were invited and encouraged to participate in the EUROMET project 813 comparison. In addition to the member countries of the EUROMET organization, Argentina, Brazil, Canada and United Sates participated from the SIM organization, Russia from the COOMET and Australia from the APMP. The successor of EUROMET from 2007 is the European Association of National Metrology Institutes, EURAMET:.

The schedule of participation gave priority to European secondary standard laboratories to support their relevant CMC claims that have already been published or submitted for publication. The EUROMET project 813 comparison was conducted following a star-shaped circulation pattern for the shipment of the instruments between the pilot laboratory, MKEH, and the participant laboratories. István Csete, from the pilot laboratory at the MKEH, was the coordinator of the EUROMET Project 813 comparison and responsible for calibrating the chambers over a period of four years that started in January of the year 2005. During the four year period, the chambers were calibrated every time the chambers were returned from each one of the participant laboratories to the MKEH, and prior to shipping them to the next participant. Ronaldo Minniti from the NIST assisted in this effort during the second part of the year 2007 by coordinating the comparison among the SIM participants within the American continent. After the instruments were received at the NIST from the MKEH, they were shipped between the NIST and SIM participants (Canada and Brazil only) in a star shape pattern. Similarly to the process followed by the MKEH among the EURAMET participants, the NIST calibrated the chambers each time they were returned form these two SIM participants. Although Argentina was originally planned to be part of the star shaped pattern coordinated by the NIST, they had to postpone their participation to a later time. Once the participation of all the SIM participants was completed, the instruments were shipped from the NIST back to the MKEH. The MKEH then continued shipping the instruments following a star shape pattern among the remaining participants until the comparison was completed in December of 2008, Argentina being the final participant.

Each of the 26 participants was allotted no longer than 3 weeks to perform all the measurements. Each facility had to perform a total of 16 air kerma measurements as a result of repeating twice the calibration of each of the four chambers with the two electrometers supplied by the pilot laboratory. In addition, each facility had to perform a total of 8 absorbed dose to water measurements resulting from repeating twice the calibration of each of the four chambers with only one of the supplied electrometers. For the absorbed dose to water measurements, the chambers PTW 30001 and Wellhöffer FC65-G were calibrated with the UNIDOS electrometer, while the NE 2561 and OMH ND 1006 chambers were calibrated using the PAM 2001 electrometer.

The averages of four N_{Kair} *and two* N_{Dw} *calibration coefficients for each of the four chambers were the accepted comparison results.* The results of each participant were reported to the MKEH within four weeks of the calibrations. To facilitate the reporting of the calibration results, two spreadsheets were prepared by the pilot laboratory (MKEH). Additional spreadsheets were provided to the participants to collect information about the national standards, including traceability and uncertainty of the measurements performed. *The technical protocol, including the schedule of measurements, was prepared on the basis of the EUROMET and CIPM Guidelines* [4,5]. *and approved by the CCRI(I) in December 2004* The list of the actual participants and the dates of measurements are listed in Table 2. The NPL performed the measurements in April 2007 according to the original schedule but was not able to deliver the results within the required schedule. By August 2008 a delay of six months had been accumulated relative to the originally planned schedule of this international comparison. The main reasons for the six month delay were the difficulties encountered with the customs agencies during the shipments from and to Brazil and Argentina. The LNE-LNHB, as a primary dosimetry laboratory, was accepted in 2005 by the participants to be the reserve linking laboratory, if necessary following technical or data evaluation difficulties. Consequently, the LNE-LNHB, repeated the calibrations of the transfer chambers as a closure of the comparison program.

Table 2. List of the 26 participants and dates of measurements

Contact person	**Country**	**Institute**	**Measurement date (day/month/year)**
István Csete	Hungary	OMH (MKEH)[a]	08/02/2005-11/12/2008
Frank Delaunay	France	LNE-LNHB[b]	09/03/2005-24/03/2005 16/04/2008-30/04/2008
Anna G. Leiton	Spain	LMRI-CIEMAT	18/04/2005-06/05/2005
Vladimir Sochor	Czech Republic	CMI	07/06/2005-18/06/2005
Antons Lapenas	Latvia	LNMC-RMTC	20/07/2005-24/07/2005
Jan-Erik Grindborg	Sweden	SSM (SSI)	06/09/2005-09/09/2005
Ilkka Jokelainen	Finland	STUK	12/10/2005-20/10/2005
Hans Bjerke	Norway	NRPA	18/11/2005-27/11/2005
Josef Dobrovodsky	Slovakia	SMU	09/01/2006-13/01/2006
Ahmed Meghzifene	International org.	IAEA	03/02/2006-24/02/2006
Hourdakis J. Costas	Greece	HAEC-HIRCL	05/04/2006-12/04/2006
Juliana Mintcheva Rosen Ivanov	Bulgaria	BIM (NCM)[c]	09/05/2006-19/05/2006
Branko Vekic	Croatia	IRB	05/06/2006-22/06/2006
Jerzy Kokocinski	Poland	GUM[c]	31/07/2006-11/08/2006
Joao Cardoso,	Portugal	ITN-LMRIR	02/10/2006-06/10/2006
Ludwig Buermann	Germany	PTB	23/10/2006-02/11/2006
Wilhelm Tiefenboeck	Austria	BEV	26/11/2006-06/12/2006
Gerhard Stucki	Switzerland	METAS	11/01/2007-26/01/2007
Eduard van Dijk	Netherlands	VSL(NMi)	16/03/2007-23/03/2007
Maria Pia Toni	Italy	ENEA	24/05/2007-04/06/2007
Ronaldo Minniti	USA	NIST[d]	01/08/2007-13/08/2007
John P. McCaffrey	Canada	NRC	05/09/2007-14/09/2007
Cosme N. M. da Silva	Brazil	LNMRI-IRD	09/11/2007-28/11/2007
Igor Kharitonov	Russia	VNIIM[c]	21/03/2008-24/03/2008
David Webb	Australia	ARPANSA	30/05/2008-20/06/2008
Margarita Saraví	Argentina	CNEA-CAE	22/08/2008-19/09/2008

Notes:
[a] Pilot and linking laboratory to the BIPM Key Comparisons Reference Values
[b] Reserve linking laboratory
[c] Participate in air kerma comparison only
[d] Pilot lab for SIM participants

2.4 Calibration conditions at participating laboratories

Each chamber was positioned with its reference point, at the depth of 5 g/cm^2 in a water phantom or, free in air at the reference distance in the ^{60}Co beam, where the conventional true values of reference absorbed dose to water rate, $\dot{D}_w$, or air kerma rate, $\dot{K}_{air}$ respectively, had been established by the national standard. The calibration coefficients are $N_{D\mathrm{w}} = \dot{D}_w / I_{\mathrm{corr}}$ and $N_{K\mathrm{air}} = \dot{K}_{air} / I_{\mathrm{corr}}$ where I_{corr} is the measured ionization current corrected for influence quantities, corresponding to the reference conditions for the calibration.

The collimated ^{60}Co radiation beam dose rates used by all participants ranged from 0.18 mGy/s to 34.8 mGy/s. The dose rates, along with the published CMC uncertainty and linking traceability, are listed in Table 3. The beam field size at the reference distance, for which the maximum intensity at the beam centre drops to 50% of its value, is 100 cm^2. The source detector reference distance (SDD) to the reference point of each chamber from the center of the ^{60}Co source was 100 cm at all participating laboratories except at the RMTC, CMI and the CNEA-CAE where the SDD for the air kerma measurements was 80 cm. At the STUK and the CMI, the absorbed dose to water measurements were made at SDDs of 105 cm and 129 cm respectively. Each participating laboratory used their own ISO standard 30 dm^3 cubic phantom for the absorbed dose to water measurements. The phantom consists of a cubic shaped tank filled with water and with walls made of PMMA [2]. The calibration coefficients of the transfer chambers were given in terms of absorbed dose to water or air kerma per charge, in units of Gy/μC, normalized to the standard conditions of air temperature, pressure and relative humidity of $T = 293.15$ K, $P = 101.325$ kPa and $h = 50$ % respectively. The dose rates used in this comparison resulted in negligible differences for incomplete charge collection (so no collection efficiency correction was applied) for the small volume chambers used. Furthermore, each laboratory maintained a relative air humidity between 20 % and 80 % resulting in negligible air humidity corrections.

Table 3. The uncertainty values, traceability information, and dose rates published as the CMC for each participant.

Participant	CMC uncertainty (k = 2)		Traceability		Applied dose rate (mGy/s)	
	K_a	D_w	K_a	D_w	K_a	D_w
MKEH	0.8	1.0	MKEH	MKEH	9.45	9.31
LNE-LNHB	0.9	1.3	LNHB	LNHB	10.1	10.2
CIEMAT	0.8	1.1	BIPM	BIPM	5.44	5.43
CMI	2.0	3.5	BEV	BIPM	4	5.9/2.04
RMTC	1.6	2.0	BIPM	BIPM	10.7	10.5
SSM	0.8	1.0	BIPM	BIPM	6.8	6.78
STUK	1.0	1.2	BIPM	BIPM	3.7	3.35
NRPA	0.9	1.0	BIPM	BIPM	2.56	2.57
SMU	1.3	2.4	SMU	PTB	5.43	5.55
IAEA	0.8	1.0	BIPM	BIPM	4.91	4.93
HAEC-HIRCL	-------	-------	BIPM	BIPM	3.72	3.71
BIM	1.0		BIM	-------	0.18	------
IRB	-------	-------	PTB	PTB	1.85	1.82
GUM	1.0		GUM	------	0.46	------
ITN-LMRIR	0.9	1.7	LMRIR	BIPM	2.6	2.58
PTB	0.6	0.5	PTB	PTB	15.96	15.66
BEV	0.8	0.9	BEV	BEV	4.76	4.71
METAS	0.9	1.0	BIPM	METAS	14.4	14.4
VSL	1.0	0.9	VSL	VSL	7.25	34.8
ENEA	1.4	1.4	ENEA	ENEA	9.58	9.6
NIST	1.4	1.2	NIST	NIST	2.91	2.99
NRC	1.0	1.0	NRC	NRC	10.7	9.5
LNMRI-IRD	1.4	1.5	BIPM	BIPM	3.4	3.1
VNIIM	1.5		VNIIM	-----	6.5	-----
ARPANSA	0.8	0.7	ARPANSA	ARPANSA	1.2	1
CNEA-CAE	-------	-------	BIPM	BIPM	2.55	2.58

3 Results

3.1 Stability of the transfer instruments

Stability measurements were performed at the MKEH after each participant's measurements. The first was performed on 17 April 2005 the last was on 25 November 2008. Twenty-seven recalibration series were made during these 42 months for each chamber in terms of air kerma, and fourteen recalibration series in terms of absorbed dose to water, using both electrometers. The two series of air kerma recalibrations, performed at the NIST were normalized with the MKEH/NIST ratio for each chamber. The 178 $N_{K\mathrm{air}}$ and 88 $N_{D\mathrm{w}}$ calibration coefficients for the four transfer chambers were normalized to their averages and can be seen in Figure 1.

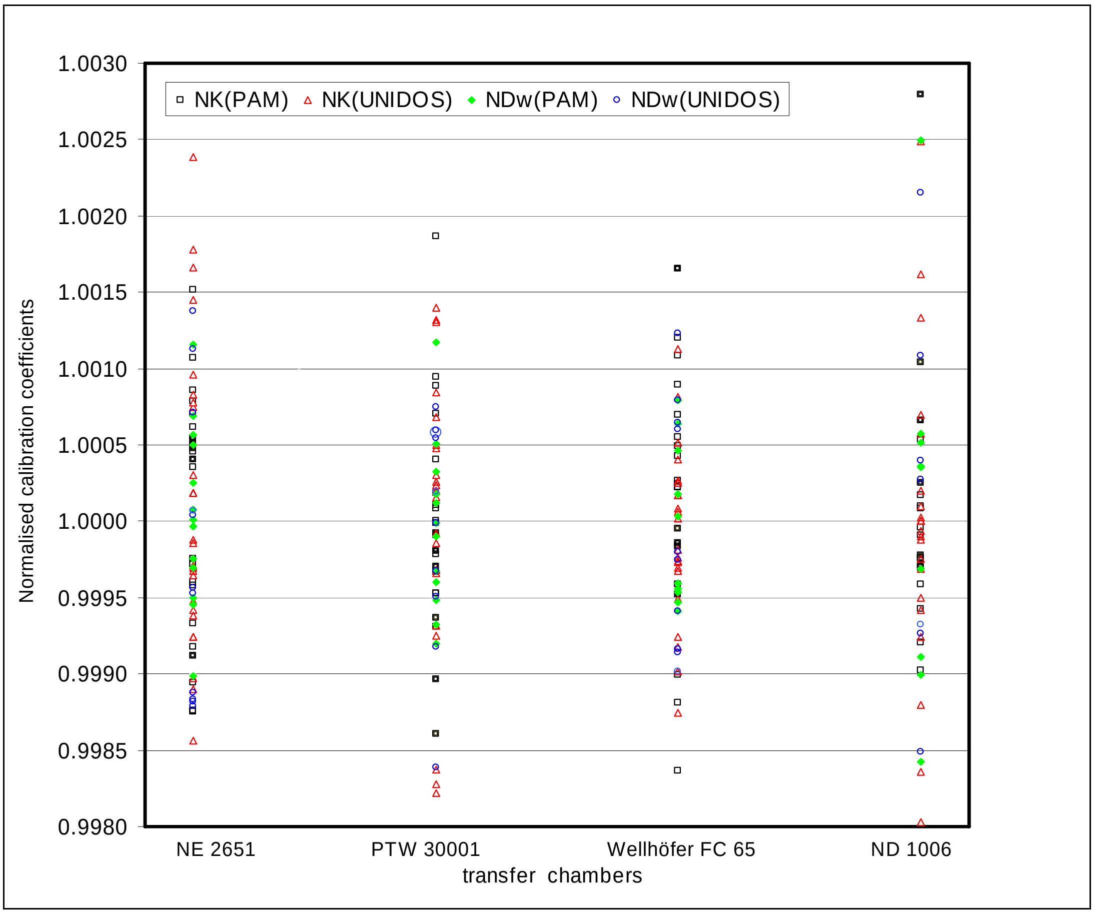

Figure 1. Results of the stability measurements of the four transfer chambers using the PAM and UNIDOS electrometers in terms of air kerma and absorbed dose to water

The frequency distribution of the normalized calibration coefficients to the average in terms of air kerma and absorbed dose to water are shown in Figure 2 and Figure 3 respectively.

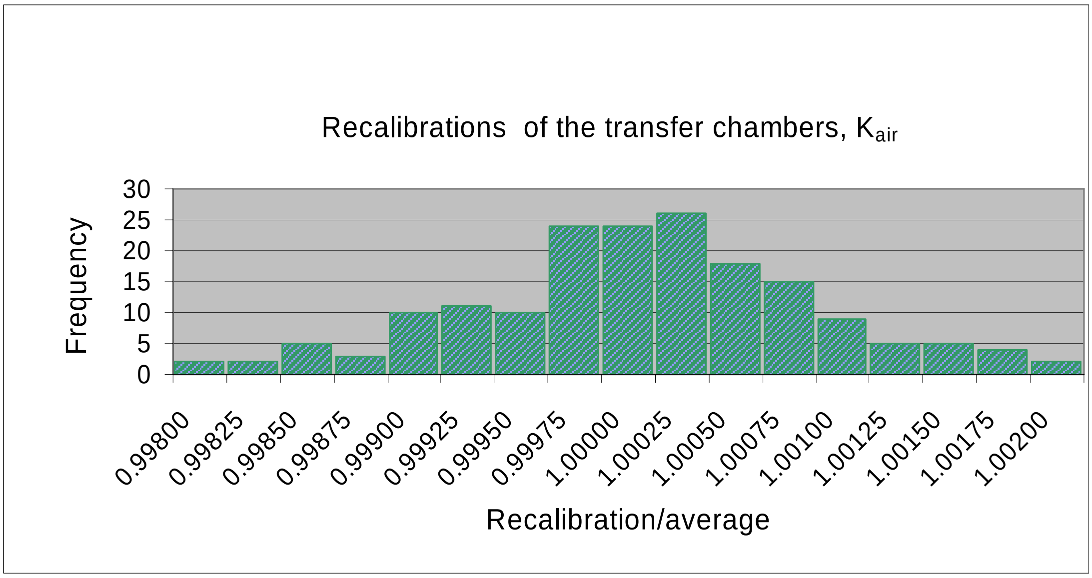

Figure 2. Frequency distribution of air kerma recalibrations at the MKEH

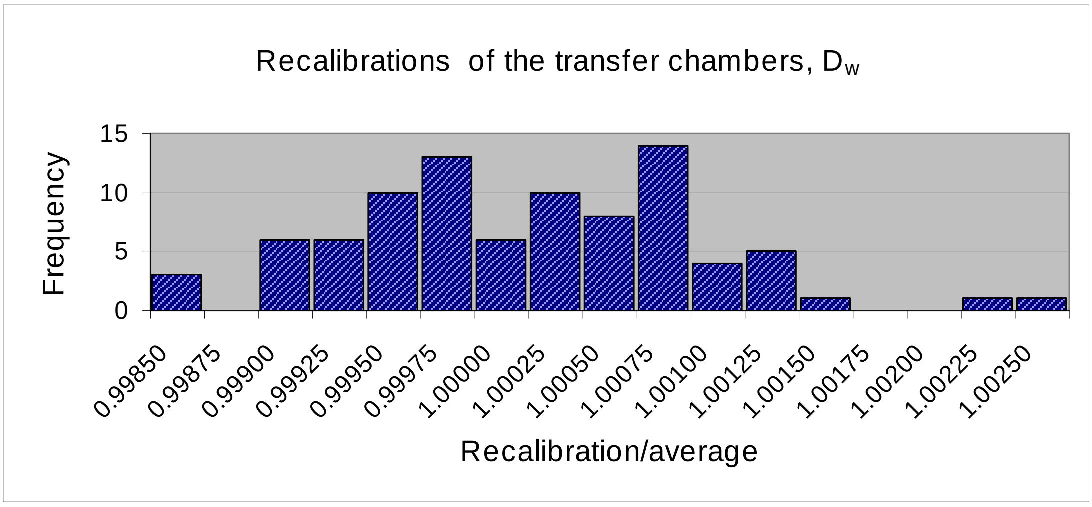

Figure 3. Frequency distribution of absorbed dose to water recalibrations at the MKEH

The average relative standard deviation of the stability measurements is ~ 0.08 % for both quantities. Details are in Table 4. The average relative standard deviations of the recalibrations involving both quantities and electrometers are 0.070 %, 0.075 %, 0.086 %, and 0.10 % for the chambers Wellhöffer FG-65 C, PTW 30001, NE 2561, and ND 1006 respectively. Another result of the stability measurements is that the calibrations performed by the PAM electrometer produced a smaller standard deviation than the calibration using the UNIDOS 2.3 electrometer. The average ratio of the calibration coefficients for the four chambers measured by the UNIDOS and PAM current measurement systems was 0.9993 for both quantities. This ratio changed from 0.9974 to 1.0009 during the 42 months of the comparison program.

Table 4. Standard deviations of the normalized repeat calibrations performed at the MKEH

Chamber/Electrometer	Standard Deviation $N_{K\mathrm{air}}$	Standard Deviation $N_{D\mathrm{w}}$
NE 2561/Unidos	0.001 09	0.000 97
NE 2561/PAM	0.000 79	0.000 59
PTW 30001/Unidos	0.001 02	0.000 74
PTW 30001/PAM	0.000 70	0.000 55
Wellhöffer FC-65 G/Unidos	0.000 58	0.000 76
Wellhöffer FC-65 G/PAM	0.000 89	0.000 55
ND 1006/Unidos	0.001 04	0.001 17
ND 1006/PAM	0.000 84	0.001 19
Average	**0.000 87**	**0.000 82**

The standard uncertainties of the stability of the transfer instruments (u_{K_stab}, $u_{D\mathrm{w}\_\mathrm{stab}}$) are calculated according to [6] using the data in Table 4, considering the 4 chambers and the two electrometers as eight independent transfer instruments. Both determinations recommended in [6] $\frac{1}{u_{stab}^2} = \sum_{i=1}^{8} \frac{1}{u_{stab\_i}^2}$; $u_{stab} = \frac{average\_u_{stab}}{\sqrt{8}}$ deliver the same values within 2×10^{-5} for both quantities so the average values in the Table 4 divided by $\sqrt{8}$ are used to establish $u_{K\_\mathrm{stab}} = 0.000\,31$ and $u_{D\mathrm{w}\_\mathrm{stab}} = 0.000\,29$. These values include not only the transfer chamber stability, but the uncertainty of reproducibility of the whole calibration procedure at the MKEH including the statistical uncertainties of the normalized ionization current measurements and the setup procedure.

Unfortunately, the waterproof ND 1006 chamber leaked when remaining underwater in a water phantom on two occasions. At first in March of 2007, the drying procedure at the MKEH was successful without any change of sensitivity. However, in February of 2008, the drying procedure was unsuccessful, resulting in an erratic chamber response and a continual exponential decrease in the calibration coefficient. The measured $N_{K\mathrm{air}}$ and $N_{D\mathrm{w}}$ values by the VNIIM, LNE-LNHB, ARPANSA and the CNEA-CAE were corrected to ensure coherent data evaluation to account for the change in the sensitivity. These correction factors in the range from 0.4 % to 1.5 % were interpolated in terms of the measurement date using a curve fitting program based on the twelve repeated calibrations at the MKEH. The additional uncertainty from these correction factors is negligible.

An additional stability check of current measurements made by the UNIDOS and PAM 2001 electrometers consisted of three comparison measurements to the MKEH current measurement system featuring the following equipment: a Keithley 263 current generator, a Keithley 616 electrometer using external feedback capacitor and a Keithley 642 electrometer. The deviations from ten reference current values in the range from 10 pA to 250 pA were less than ± 0.07 % and ± 0.15 % for the PAM 2001 and the UNIDOS electrometers, respectively. However, the UNIDOS electrometer has shown a fluctuation of leakage current, ≤ 50 fA, at some laboratories, perhaps caused by instability of the initial internal temperature and stress in the insulator material of the signal cable connection.

The pressure and temperature probes of the PAM electrometer were calibrated at the MKEH against the appropriate national standard before the project started and their stabilities were re-checked before each recalibration of the ionization chambers. Both probes have shown excellent stabilities, well within the stated uncertainties. In summary, the stability investigation of the transfer instruments indicates reliable stability during the course of the comparison.

3.2 Results of participants

As described previously a total of four $N_{K\mathrm{air}}$ and two $N_{D\mathrm{w}}$ calibration coefficients were determined for each chamber. Recall for example that for the air kerma calibrations each chamber was calibrated twice with a given electrometer and both electrometers were used for each chamber. These four values of $N_{K\mathrm{air}}$ were used to determine the average air kerma calibration coefficient shown in Table 5 for each chamber. Similarly, the two values of $N_{D\mathrm{w}}$ obtained for each chamber were used to determine the average absorbed dose to water calibration coefficient shown in Table 6. The MKEH results are the initial calibration results measured in February 2005 and deposited with the TC chair and the CCRI(I) Secretary. As mentioned previously, no corrections were applied for collection efficiency, polarity or the use of the sleeve for the non waterproof chambers. The uncertainty of the calibration reported by each participant is listed in the last column of Table 5 and Table 6. In these tables, the ratio of the calibration coefficients obtained with the UNIDOS and PAM electrometers are also listed (denoted as UNIDOS/PAM) by averaging all the available data from the participants.

Table 5 Average measured air kerma calibration coefficients of the participants

Average N_{Kair} values in units of Gy/μC measured by the UNIDOS and PAM electrometers						
participant	NE 2561 #084	PTW 30001 #2118	Wellhöffer FG-65 C #518	ND 1006 #8503	UNIDOS/PAM (on average)	$u_c(N_K)$ (%)
Ref. Value [a]	**93.786**	**49.825**	**43.828**	**112.983**		
Traceable to the BIPM						
CIEMAT	93.623	49.637	43.816	113.097	0.9980	0.24
LNMC-RMTC	93.791	49.605	43.836	112.595	0.9976	0.50
SSM	93.828	49.739	43.959	113.348	0.9945	0.40
STUK	93.672	49.528	43.790	112.780	0.9967	0.39
NRPA	94.308	49.959	44.069	113.836	0.9984	0.38
IAEA	93.662	49.759	43.888	113.380	0.9953	0.40
HAEC-HIRCL	94.127	49.841	44.061	114.215	1.0004	0.61
BIM	93.502	49.365	43.805	111.753	0.9910	0.67
GUM	92.905	49.047	43.272	111.236	0.9964	0.88
ITN-LMRIR	93.792	49.785	43.833	112.696	----	0.33
METAS	93.576	49.783	43.783	112.972	1.0010	0.27
LNMRI-IRD	94.001	49.974	43.960	112.979	0.9970	0.70
CNEA-CAE[b]	93.867	49.698	43.979	114.082	0.9998	0.52
average	**93.743**	**49.671**	**43.850**	**112.998**		
standard dev	**0.34**	**0.25**	**0.20**	**0.85**		
avr./ref. value	**0.9995**	**0.9969**	**1.0005**	**1.0001**		
Traceable to other primary standard						
LNE-LNHB_1[c]	93.668	49.649	43.783	112.427	0.9972	0.40
CMI	93.589	49.323	43.702	111.035	0.9981	0.78
SMU	94.039	50.012	44.151	114.110	0.9996	0.35
IRB	94.221	49.886	44.061	113.506	0.9986	0.38
PTB	94.502	50.253	44.195	114.121	0.9999	0.20
BEV[c]	94.289	50.065	44.046	113.916	0.9992	0.42
VSL[c]	93.361	49.703	43.657	112.654	0.9975	0.47
ENEA[c]	93.739	49.752	43.816	112.679	0.9970	0.40
NIST	94.200	49.970	43.982	113.092	0.9989	0.36
NRC[c]	94.096	50.065	44.020	113.541	0.9969	0.27
VNIIM[b]	93.695	49.809	43.804	112.807	0.9997	0.23
LNE-LNHB_2[b,c]	93.680	49.847	43.691	112.480	0.9994	0.40
ARPANSA[b,c]	93.689	49.776	43.786	112.877	0.9974	0.52
MKEH	94.263	50.014	44.028	113.602	1.0000	0.23
MKEH[c,d]	94.271	49.993	44.025	113.506	0.9993	0.23
average	**93.931**	**49.866**	**43.909**	**113.081**	0.9979	
standard dev	**0.34**	**0.23**	**0.18**	**0.83**		
avr./ref. value	**1.0015**	**1.0008**	**1.0018**	**1.0007**		

[a] Reference value is defined in section 3.3

[b] Interpolated value for ND 1006 chamber see section 3.1

[c] Linking laboratories, see section 3.3

[d] Average values measured over the 4 years recalibrations

Table 6. Average measured absorbed dose to water calibration coefficients of the participants

Average N_{Dw} values in units of Gy/µC measured by the UNIDOS and PAM electrometers						
participant	PTW 30001 #2118	Wellhöffer FG-65 C #518	NE 2561 #084	ND 1006 #8503	UNIDOS/PAM (on average)	$u_c(N_D)$ (%)
ref. value[a]	**54.267**	**47.874**	**101.928**	**122.444**		
Traceable to the BIPM						
CIEMAT	53.883	47.675	101.575	122.389		0.37
CMI	54.158	48.044	100.095	120.375	0.9984	1.18
LNMC-RMTC	53.808	47.761		121.994	0.9977	0.60
SSM	53.965	47.893	102.068	122.894		0.50
STUK	53.934	47.706	101.810	122.193		0.43
NRPA	54.372	48.032	102.298	123.480		0.44
IAEA	54.170	47.947	101.707	122.700	0.9949	0.50
HAEC-HIRCL	54.392	48.024	102.307	122.932		0.62
ITN-LMRIR	54.057	47.459	101.189	120.518		0.65
LNMRI-IRD	54.298	47.824	102.257	123.446		0.75
CNEA_CAE[b]	54.614	48.685	103.856	122.044	1.0013	0.81
average	**54.150**	**47.914**	**101.916**	**122.270**		
standard dev	**0.25**	**0.31**	**0.96**	**1.03**		
avr./ref. value	**0.9979**	**1.0008**	**0.9999**	**0.9986**		
Traceable to other primary standard						
LNHB_1[c]	53.985	47.742	101.517	121.334	0.9970	0.47
SMU	54.000	47.731	100.994	122.488		1.20
IRB	53.767	47.544	101.777	121.804		0.97
PTB[c]	54.064	47.633	101.746	122.358		0.22
BEV[c]	54.118	47.804	101.763	122.792		0.45
METAS[c]	54.265	47.866	102.055	122.880		0.44
VSL[c]	54.086	47.599	101.940			0.44
ENEA[c]	54.243	47.895	101.540	121.829	0.9976	0.38
NIST	54.382	47.779		121.441	0.9985	0.47
NRC[c]	54.191	47.771	101.696	122.314		0.43
****LNE-LNHB_2**[b,c]	53.969	47.646	101.449	121.180	1.0003	0.47
ARPANSA[b]	54.436	48.023	101.927	122.511	0.9986	0.40
MKEH	54.144	47.791	101.543	122.054	1.0000	0.49
MKEH[c,d]	54.118	47.780	101.506	122.047	0.9993	0.49
average	**54.127**	**47.756**	**101.662**	**122.082**		
standard dev	**0.18**	**0.13**	**0.28**	**0.57**		
avr./ref. value	**0.9973**	**0.9981**	**0.9959**	**0.9968**		

[a] Reference value is defined in section 3.3

[b] Interpolated value for ND 1006 chamber see section 3.1

[c] Linking laboratories, see section 3.3

[d] Average values measured over the 4 years recalibrations

As shown in Tables 5 and 6, the average UNIDOS/PAM ratios are less than one. This ratio provides a measure of the possible differences between the measurement systems used. The calibration coefficients were obtained with two different measuring systems as mentioned previously. One system made use of the PAM electrometer and its internal barometer and thermometer. The other measurement system made use of the reference thermometer and barometers used at each participant's facility. Ideally, if the UNIDOS/PAM ratios shown in Tables 5 and 6 would be equal to unity, it would imply that there are no differences between the two measurements systems. Furthermore, this would reflect that the thermometer and barometer used at a given participants' facility would measure identically to the ones provided with the calibrated PAM system, if the UNIDOS measured the same current as the PAM electrometer at each participant's facility. During the recalibrations at the MKEH a small systematic deviation from unity of the UNIDOS/PAM ratio was observed similar to the ones measured by the participants. So, in addition to the stability measurements mentioned in section 3.1, some PSDL participants were also asked to check the UNIDOS current measurement system separately. Unfortunately, these additional check measurements with current sources did not reveal any stable systematic deviation between the two electrometers. Finally no corrections were applied to account for the response of the UNIDOS system, particularly because the transfer chamber and electrometer together were considered to be a compact therapy dosimeter.

3.3 Reference value determinations

The CCRI(I) took the decision at its meeting in 1999 to use the BIPM determination of air kerma and absorbed dose to water as the basis of the key comparison reference values (KCRV) [7]. The formalism to calculate the degree of equivalence in terms of the two components, the difference of the result from the KCRV and its associated uncertainty, (D_i, $\underline{U_i}$), for dosimetry comparisons was agreed at the meeting of the Key Comparison Working Group of CCRI(I) in April 2008 and published [8] . The D_i is defined as the relative difference between the air kerma or absorbed dose to water measured by a National Metrology Institute (NMI), and the appropriate KCRV, K_{BIPM} or $D_{\mathrm{w,BIPM}}$, divided by the KCRV in units of milligray per gray (mGy/Gy). Thus,

$$D_{K,\mathrm{NMI}} = (K_{\mathrm{NMI}} - K_{\mathrm{BIPM}})/K_{\mathrm{BIPM}} = K_{\mathrm{NMI}}/K_{\mathrm{BIPM}} - 1 = R'_K - 1 \qquad (1)$$

$$D_{D\mathrm{w,NMI}} = (D_{\mathrm{wNMI}} - D_{\mathrm{w,BIPM}})/D_{\mathrm{w,BIPM}} = D_{\mathrm{w,NMI}}/D_{\mathrm{w,BIPM}} - 1 = R'_D - 1\ . \qquad (2)$$

The R'_K and R'_D ratios represent the key comparison results for NMIs having primary standards. These ratios are known and are accessible from the BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparison reports published in the KCDB (http://kcdb.bipm.org/appendixB). An NMI that holds primary standards that participated in this EUROMET project 813 comparison and also has compared directly in the past with the BIPM, can act as so-called linking laboratory. A linking laboratory enables the link or comparison of the result of a NMI with that of the BIPM. The R'_K and R'_D ratios will hereafter be referred to as the R'_{link} values for the case of NMIs that qualified as linking laboratories during this comparison. Furthermore, the calibration coefficients from these specific laboratories are referred throughout the text as N_{link}. Several laboratories qualified as linking laboratories in this comparison and will be discussed later in the text. The corresponding calibration coefficients N_{link} for these labs are listed in Tables 5 and 6.

As a first step in evaluating the results from each participant, the R_{NMI} values were determined using the following expression: $R_{\text{NMI}} = R'_{\text{link}} \times N_{\text{NMI}}/N_{\text{link}}$ where N can be the calibration coefficient of a transfer chamber in either air kerma or absorbed dose to water [6]. The $N_{\text{link}}/R'_{\text{link}}$ values will hereafter be referred to as *reference calibration coefficients* (N_{ref}) for each transfer chamber, thus $R_{\text{NMI}} = N_{\text{NMI}}/N_{\text{ref}}$.

As a first approach to establish the reference calibration coefficient N_{ref} consider MKEH, the pilot laboratory, to be the linking laboratory. For this, the N_{ref} values should be taken for each transfer chamber as the average value of the calibration coefficients, ($N_{K\text{air,MKEH}}$ and $N_{D\text{w,MKEH}}$), measured at the pilot linking laboratory (listed in Table 5 and Table 6) then divided by the published linking ratios $R'_{\text{MKEH}} = K_{\text{MKEH}}/K_{\text{BIPM}} = 1.0109$ and $D_{\text{wMKEH}}/\text{D}_{\text{wBIPM}} = 0.9983$. These key comparison results were measured in 2006 and 2002 for air kerma and absorbed dose to water respectively [9,10]. However, the K_{BIPM} reference value for ^{60}Co radiation increased by 1.0054 in November 2007 after the CCRI approval of the re-evaluation of the BIPM standard, hence the new $K_{\text{MKEH}}/K_{\text{BIPM}}$ ratio is 1.0055; more details can be found in references [11] and [12]. The associated relative combined standard uncertainties of $N_{K\text{air,MKEH}}$ and $N_{D\text{w,MKEH}}$ are 0.23 % (from Table 5) and 0.49 % (from Table 6) respectively. These values differ by only a negligible amount for the different transfer chambers. The $N_{\text{ref,MKEH}}$ value acquired through the use of a MKEH secondary standard chamber, NE 2561 has previous traceability to the BIPM [10]. The average value of the calibration coefficients of the NE 2561 #084 chamber resulting from the repeat calibrations at MKEH (over the 4 year period) divided by the R'_{MKEH} ratios, give practically the same values as measured at the BIPM in 2002 for both quantities, when the BIPM air kerma reference was revised as indicated above;

($N_{K\text{a,MKEH}}/R'_{K\text{a,MKEH}}/N_{K\text{a,BIPM}} = 1.00004$; and $N_{D\text{,MKEH}}/R'_{D\text{,MKEH}}/N_{D\text{,BIPM}} = 1.0005$) validating the calibration techniques of the NE 2561 chamber in terms of both quantities at the MKEH. The $N_{\mathrm{ref,MKEH}}$ values for the transfer chambers are shown in Table 7. However, using the approach of $N_{\mathrm{ref}} = N_{\mathrm{ref,MKEH}}$ some systematic calibration procedure errors for a single link laboratory could be uncovered.

The second approach to establish the N_{ref} values could be to use only the average $N_{K\mathrm{air,LNHB}}$ and $N_{D\mathrm{w,LNHB}}$ values of the two series measured in 2005 and 2008 by LNE-LNHB, initially chosen as a reserve link laboratory. LNE-LNHB is one, out of the several participants listed in Table 7, that qualify as a reserve linking laboratory. The values of $R'_{K,\mathrm{link}} = 0.9981$ and $R'_{D,\mathrm{link}} = 0.9970$ are from the key comparison results measured in 2003 [13, 14]. The $N_{\mathrm{ref,LNHB}}/N_{\mathrm{ref,MKEH}}$ values are in Table 7. In the ideal case these ratios should be unity. In practice, the average values for the four transfer chambers, 1.0006 and 0.9985 for air kerma and absorbed dose to water respectively, are well within the standard uncertainties, hence the calibration measurements at the MKEH and LNE-LNHB are consistent. The average of the $N_{\mathrm{ref,MKEH}}$ and $N_{\mathrm{ref,LNHB}}$ values could also be used to establish the N_{ref} values. However, the chamber to chamber variation of these MKEH/LNHB ratios falls in a relatively large range, of approximately 0.5 %. Such variation can result perhaps from some set-up differences between the two laboratories, particularly in the case of the ND 1006 chamber measured in water. Note that this chamber produced the lowest stability value during the repeat calibrations at the MKEH and its calibration coefficients, as measured by all the participants. This ND 1006 chamber also had the largest variation amongst the four chambers. Considering the various approaches for the establishment of the most reliable reference values, N_{ref}, for each chamber and for the identification of appropriate weighting factors required for the calculation of mean values for the four chambers, the evaluation technique of 'round-robin' type of comparison is considered to be optimal, even though a star-shaped comparison program was performed.

This 'round-robin' approach uses all the available $N_{K\mathrm{a}}$ and $N_{D\mathrm{w}}$ values of the participating NMIs having primary standards. Furthermore their results in this comparison are coherent with their previous published key comparison results found in references [12] and the BIPM.RI(I)-K4. In this way the N_{ref} values can be established for each chamber as $N_{ref} = \frac{\sum_{i=1}^{n} N_{ref,link,i}}{n}$, the un-weighted mean of , $N_{\mathrm{ref,link}}$, where n is the number of linking laboratories. Weighting factors could be the variances of the key comparison results, but both methods give practically the same mean values since the BIPM key comparison uncertainties of all candidate NMIs are very similar. To judge the coherence of the candidate participants to act as link laboratories two criteria were established to contribute to the $N_{\text{ref,}}$ value calculation:

1. *The measured N_{Ka} and N_{Dw} values for the four chambers should be within the standard uncertainty stated by the NMI.*
2. *The standard uncertainties of the key comparison result, $u_c(R^{'})$ and the present comparison result, $u_c(\bar{R}_{\text{NMI}})$ calculated with the $N_{ref,MKEH}$ values should overlap.*

The list of NMI's meeting the two requirements for both quantities are listed in the first column of Table 7. The calculated final $N_{\text{K,ref}}$ and $N_{\text{D,ref}}$ values are shown in Table 7 in units of Gy/µC. The final $N_{\text{K,ref}}$ values results from the average of the 7 linking laboratories listed in the first part of Table 7, while the final $N_{\text{D,ref}}$ values results from the average of the 9 linking laboratories listed in the second part of Table 7. As observed in Table 7, these $N_{\text{,ref}}$ values are slightly different than the $N_{\text{,ref,MKEH}}$ values. To further analyse the linking laboratories results and to check the first and second approaches for the calculation of N_{ref}, the $N_{\text{ref,link}}$ / $N_{\text{ref,,MKEH}}$ ratios of the linking laboratories were calculated for each chamber and are also given in Table 7. From the discussion in the paragraphs above, the average values of $N_{\text{ref,link}}$ / $N_{\text{ref,,MKEH}}$ for the NE 2561 chamber for air kerma and absorbed dose to water are expected to be 1.0000 and 1.0005 respectively. However, as shown in the row labelled 'average' in Table 7, these ratios for the NE 2561 chamber are 1.0003 and 1.0024 for air kerma and absorbed dose to water respectively. This represents an excellent agreement for the value of the air kerma reference calibration coefficient $N_{\text{K,ref}}$. However, not quite such a good agreement is obtained for the value of the absorbed dose to water reference calibration coefficient $N_{\text{D,ref,}}$. In general for all four chambers the N_{ref} values are higher than the $N_{\text{ref,,MKEH}}$ values. The average differences for all chambers between the N_{ref} and $N_{\text{ref,MKEH}}$ values, derived from the last column of Table 7, are 0.11% and 0.13% for air kerma and absorbed dose to water respectively. The (N_{ref} – $N_{\text{ref,MKEH}}$) differences are higher than the standard deviations of the $N_{\text{ref,}}$ values for air kerma for the PTW 30001 chamber and for absorbed dose to water for the NE 2561 chamber.

Similary, a comparison can be made between the final N_{ref} and $N_{\text{ref,LNHB}}$ values. For this case also the final N_{ref} values are higher than the $N_{\text{ref,LNHB}}$ values listed in Table 7. The average differences for all chambers between the final N_{ref} and $N_{\text{ref,LNHB}}$ values, derived from the last column of Table 7, are 0.05% and 0.28% for air kerma and absorbed dose to water respectively. Further investigation of the calibration techniques of each participant may explain the similar differences evaluated in Table 7.

Although, the unweighted mean value $N_{ref} = \frac{\sum_{i=1}^{n} N_{ref,link,i}}{n}$ *was used to establish the reference calibration coefficient of each transfer chamber, a weighted mean value of the transfer chambers was used for determining the comparison ratio* $\overline{R}_{\mathrm{NMI}}$*. The standard deviations of the* $N_{link}/N_{MK\mathrm{EH}}$ *ratios shown in Table 7 as a measure of stability of the transfer chambers were used as the weighting factors in the calculation of the weighted mean values ,*$\overline{R}_{\mathrm{NMI}}$*. The mean comparison ratios* $\overline{R}_{\mathrm{NMI}}$ *calculated in this way, constitute the final comparison ratios for each NMI for the both quantities, air kerma and absorbed dose to water.*

Table 7. Selected linking laboratories and their $N_{\text{ref,link}} / N_{\text{ref,MKEH}}$ ratios for the transfer chambers for both quantities. Also shown are the standard deviations of the ratios. The $N_{\text{ref,MKEH}}$ and N_{ref} calibration coefficients are in Gy/μC.

	$N_{K,\text{ ref,link}} / N_{K,\text{ref,MKEH}}$ ratios for the transfer chambers for air kerma					
	linking laboratory	**NE 2561 #084**	**PTW 30001 #2118**	**Wellhöffer FG-65 C #518**	**ND 1006 #8503**	**average for the chambers**
1	MKEH	1.0000	1.0000	1.0000	1.0000	1.0000
2	LNE-LNHB	1.0010	1.0025	1.0008	0.9981	1.0006
3	ENEA	1.0001	1.0009	1.0010	0.9985	1.0001
4	ARPANSA	1.0019	1.0037	1.0026	1.0025	1.0027
5	NRC	1.0011	1.0044	1.0029	1.0033	1.0029
6	BEV	1.0002	1.0014	1.0005	1.0036	1.0014
7	VSL	0.9979	1.0018	0.9992	1.0000	0.9997
	average $N_{K,\text{ref,link}} / N_{K,\text{ MKEH}}$	**1.0003**	**1.0021**	**1.0010**	**1.0009**	**1.0011**
	standard dev. $N_{K,\text{ref,link}} / N_{K,\text{ MKEH}}$	0.0013	0.0016	0.0013	0.0023	
	$N_{K,\text{MKEH}}$ [a]	93.755	49.720	43.784	112.886	
	$N_{K,\text{ref}}$ [a]	**93.786**	**49.825**	**43.828**	**112.983**	
	$N_{D,,\text{link}} / N_{D,\text{ ,MKEH}}$ ratios for the transfer chambers for absorbed dose to water					
	linking laboratory	**NE 2561 #084**	**PTW 30001 #2118**	**Wellhöffer FG-65 C #518**	**ND 1006 #8503**	**average for the chambers**
1	MKEH	1.0000	1.0000	1.0000	1.0000	1.0000
2	LNHB	1.0011	0.9987	0.9995	0.9948	0.9985
3	PTB	1.0046	1.0012	0.9991	1.0048	1.0024
4	ENEA	1.0017	1.0037	1.0038	0.9996	1.0022
5	ARPANSA	1.0000	1.0017	1.0010	0.9997	1.0006
6	NRC	1.0026	1.0020	1.0005	1.0029	1.0020
7	BEV	1.0018	0.9993	0.9998	1.0054	1.0016
8	METAS	1.0038	1.0011	1.0002	1.0052	1.0026
9	VSL	1.0064	1.0015	0.9983		1.0021
	average $N_{D,\text{ref,link}} / N_{D,\text{ MKEH}}$	**1.0024**	**1.0010**	**1.0002**	**1.0016**	**1.0013**
	standard dev $N_{D,\text{ref,link}} / N_{D,\text{ MKEH}}$	0.0021	0.0015	0.0015	0.0037	
	$N_{D,\text{ref,MKEH}}$ [a]	101.679	54.211	47.862	122.254	
	$N_{D,\text{ref}}$ [a]	**101.928**	**54.267**	**47.874**	**122.444**	
[a] calibration coefficients in unit of Gy/μC						

For the final $\overline{R}_{\text{NMI}}$ comparison ratios for each participant , the $R_{\text{NMI}} = N_{\text{NMI}}/N_{\text{ref}}$ ratios were evaluated using the data from Table 5, Table 6 (for the N_{NMI} values) and Table 7 (for the N_{ref} values). As mentioned previously, the standard deviations of the $N_{link}/N_{MK\text{EH}}$ values listed in Table 7 were used as weighting factors in the final comparison rations $\overline{R}_{\text{NMI}}$. However a comparison was made of this chosen approach with a second approach using the $1/u^2_{\mathrm{stab}}$ values for each chamber as weighting factors. In what follows a summary of these two approaches is discussed. The u_{stab} values are pure statistical uncertainties that result from calculating the standard deviation of the repeat calibration performed at the pilot linking laboratory summarized in Table 4. Since the results from more than one linking laboratory were used to establish the reference values for each chamber, the standard deviation of the $N_{K,\mathrm{ref,link}}/N_{K,\mathrm{ref,MKEH}}$ values in Table 7 provides an alternative measuring parameter of the stability of the transfer chamber. If this latter parameter is used instead to quantify the stability of the ND 1006 chamber, then this chamber would contribute less to the calculation of the weighted mean $\overline{R}_{\mathrm{NMI}}$. As a result this would suppress the advantage of the fact that the pilot laboratory uses regularly the ND 1006 chamber. However, a smaller weighting factor is consistent with the fact that this particular chamber is different from the others since it has a perpendicular stem. Therefore, the use of the non-statistical uncertainty seems more realistic. A comparison evaluation of both approaches shows that the differences between the two $\overline{R}_{\mathrm{NMI}}$ values using the data in Table 4 or in Table 7 for u^2_{stab} value are in the range of 0.01 % to 0.05 % for both quantities depending on the deviation of the NMIs' results for the ND 1006 chamber from its reference calibration coefficients.

The R_{NMI} and $\overline{R}_{\mathrm{NMI}}$ values can be seen in Figure 4 and in Figure 5. The uncertainty bars of the average values are the relative standard uncertainties of the laboratories as they were reported. *The detailed uncertainty budgets of each laboratory for both quantities are calculated according to the GUM* [15] *and given in Appendix E*

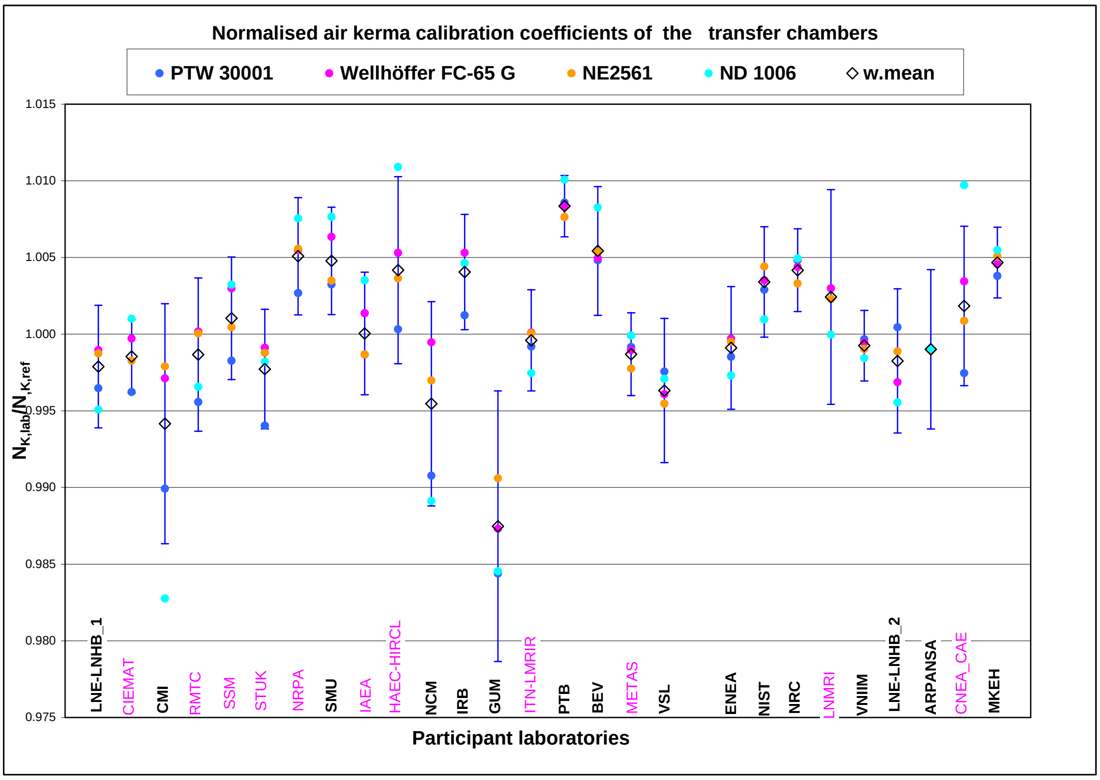

Figure 4. Graph of the normalized average air kerma calibration coefficients of the transfer chambers, and the weighted mean, $\overline{R}_{\mathrm{NMI}}$, values of participants. (The bold-text participants are traceable to primary standard other than the BIPM standard.)

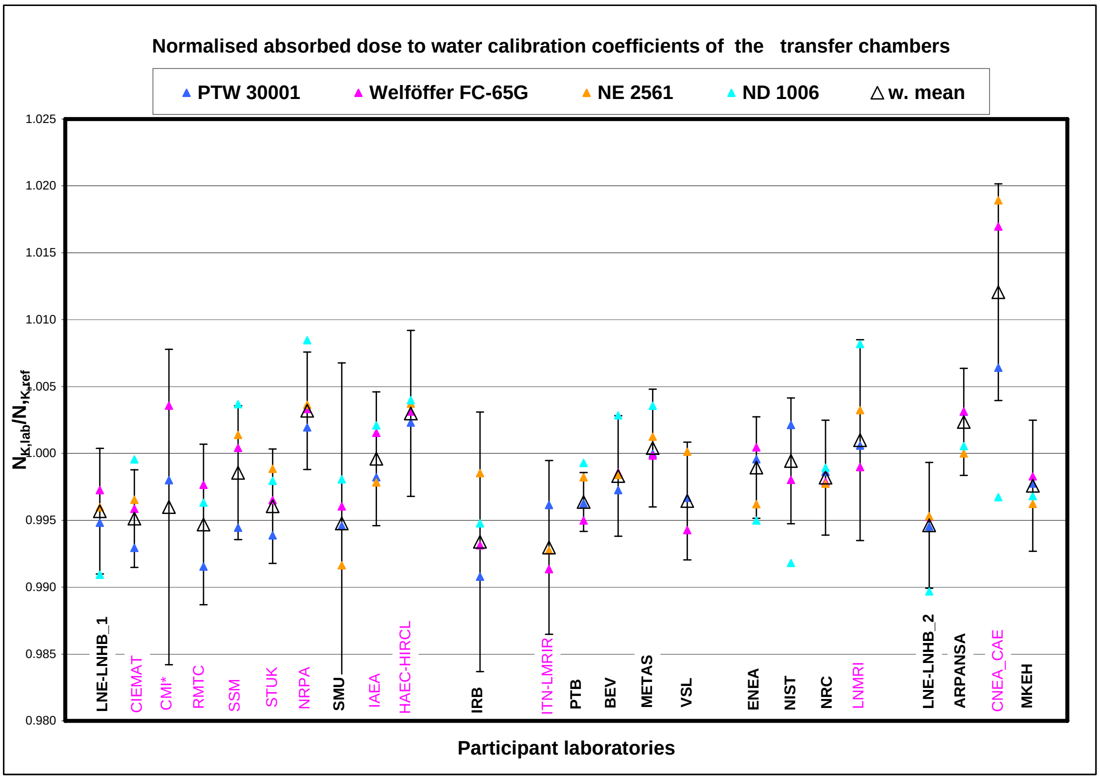

Figure 5. Graph of the normalized average absorbed dose to water calibration coefficients of the transfer chambers, and the weighted mean, $\overline{R}_{\mathrm{NMI}}$, values of participants. (The bold-text participants are traceable to primary standard other than the BIPM standard.)

The spread of the normalized calibration coefficients around the weighted mean, in Figure 4 and Figure 5 indicates the calibration capability of each laboratory. The calibration coefficients are considered to be independent calibrations of the four chambers, therefore these relative values would be expected to lie within the standard uncertainty stated by each participant, especially as these are the averages of the four air kerma and two absorbed dose calibrations performed by each participant for each chamber. The seven $N_{K\mathrm{a}}$ and eight $N_{D\mathrm{w}}$ outlying results for the ND 1006 chamber could be explained as a result of the challenge in positioning the probe at these facilities. This was due to the chamber having a long perpendicular stem.

3.4 $N_{\mathrm{Dw}}/N_{\mathrm{Ka}}$ ratios of the transfer chambers

The $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ values of these therapy chambers have been already published in many scientific journals and the values are also available in national and IAEA dosimetry codes of practice. However, these ratios depend on the national and international reference standards. The BIPM air kerma KCRV and many national standards have changed in recent years which results in new experimental values for these therapy chambers and these new $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios can provide useful information for the medical physics community.

The measured $N_{D\mathrm{w}}$ and $N_{K\mathrm{a}}$ values of participants having secondary standards calibrated at the BIPM can be used without any further correction. In the case of other participants having a degree of equivalence based on the BIPM.RI(I)-K4 and BIPM.RI(I)-K1 key comparisons or traceable to any of these, their measured values should be divided by the appropriate key comparison ratios ‚*R*', values to obtain consistent $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios.

The $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios for the transfer chambers measured by 23 independent laboratories, their weighted mean values and the standard deviation are listed in Table 8. The weighting factors are the $1/u^2_{\mathrm{c}}(N)$ values of the participants in Table 5 and Table 6.

Table 8. $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios of the transfer chambers

$N_{\mathrm{Dw}}/N_{\mathrm{Ka}}$	PTW 30001	Wellhöffer FC-65 G	NE 2561	ND 1006
LNE-LNHB-1	1.0861	1.0892	1.0826	1.0780
CIEMAT	1.0855	1.0881	1.0849	1.0822
CMI	1.0980	1.0994	1.0695	1.0841
RMTC	1.0847	1.0895	---	1.0835
SSM	1.0850	1.0895	1.0878	1.0842
STUK	1.0890	1.0894	1.0869	1.0835
NRPA	1.0883	1.0899	1.0847	1.0847
SMU	1.0817	1.0830	1.0759	1.0754
IAEA	1.0886	1.0925	1.0859	1.0822

HAEC-HIRCL	1.0913	1.0899	1.0869	1.0763
IRB	1.0869	1.0882	1.0893	1.0822
ITN-LMRIR	1.0858	1.0827	1.0789	1.0694
PTB	1.0849	1.0869	1.0857	1.0812
BEV	1.0880	1.0924	1.0863	1.0849
METAS	1.0901	1.0934	1.0907	1.0878
VSL	1.0900	1.0922	1.0938	---
ENEA	1.0933	1.0962	1.0863	1.0842
NIST	1.0934	1.0914	---	1.0789
NRC	1.0877	1.0905	1.0861	1.0826
LNMRI-IRD	1.0865	1.0879	1.0878	1.0926
LNHB_2	1.0815	1.0893	1.0817	1.0768
ARPANSA	1.0882	1.0913	1.0825	1.0806
CNEA-CAE	1.0989	1.1070	1.1064	1.0787
MKEH	1.0903	1.0931	1.0845	1.0830
weighted mean	**1.0878**	**1.0903**	**1.0860**	**1.0819**
st.dev.	0.0009	0.0010	0.0015	0.0009

These mean values are not recommended as replacements for measured $N_{D\mathrm{w}}$ calibration coefficients in therapy practice, since the variation of the $N_{D\mathrm{w}}/N_{K\mathrm{a}}$ ratios of series of these chambers has been reported to be significantly higher [4] than the standard deviation for a single chamber of each type as in Table 8.

3.5 Proposal for the degrees of equivalence

The degree of equivalence for each participant NMI, D_{NMI}, with respect to the reference value is expressed as a difference and the uncertainty of that difference (see section 3.3). The differences are

$$D_{K,\mathrm{NMI}} = \overline{R}_{K,\mathrm{NMI}} - 1 \tag{3a}$$

$$D_{D,\mathrm{NMI}} = \overline{R}_{D,\mathrm{NMI}} - 1 \tag{3b}$$

for air kerma ,(1a), and absorbed dose to water (3b),

where $\overline{R}_{K,\mathrm{NMI}}$ is the weighted mean of the

$$R_{K,\mathrm{NMI}}=(\boldsymbol{N}_{K,\mathrm{NMI}}/\boldsymbol{N}_{K,\mathrm{ref}}) \tag{4a}$$

ratios measured for the four transfer chambers

and $\overline{R}_{D,\mathrm{NMI}}$ is the weighted mean of the

$$R_{D,\mathrm{NMI}}=(\boldsymbol{N}_{D,\mathrm{NMI}}/\ \boldsymbol{N}_{D,\mathrm{ref}}) \tag{4b}$$

ratios measured for the four transfer chambers.

The expanded uncertainties ($k = 2$) for the degrees of equivalence are

$$U_{K,\mathrm{NMI}} = 2u\,\overline{R}_{K,\mathrm{NMI}} \tag{5a}$$

$$U_{D,\mathrm{NMI}} = 2u\,\overline{R}_{D,\mathrm{NMI}} \tag{5b}$$

for air kerma ,(5a), and absorbed dose to water (5b).

The variance of the average ratio, $\overline{R}_{K,\mathrm{NMI}}$ is:

$$u^2_{\overline{\mathrm{R}}\mathrm{K,NMI}} = \left(u^2(N_{Kair})_{NMI} + u^2(\dot{K}_{air})_{BIPM} + u^2(N_{Kair})_{link} + u^2(N_{Kair})_{stab} - \sum_{i=1} f_i^{\,2}\left(u^2{}_i(K_{air})_{NMI} + u^2{}_i(K_{air})_{BIPM}\right)\right) \tag{6a}$$

and the variance of the average ratio, $\overline{\mathrm{R}}_{\mathrm{D,NMI}}$ is:

$$u^2_{\overline{\mathrm{R}}\mathrm{D,NMI}} = \left(u^2(N_{Dw})_{NMI} + u^2(D_w)_{BIPM} + u^2(N_{Dw})_{link} + u^2(N_{Dw})_{stab} - \sum_{i=1}^{2} f_i^{\,2}\left(u^2{}_i(D_w)_{NMI} + u^2{}_i(D_w)_{BIPM}\right)\right) \tag{6b}$$

where the five components in (6a) are:

1. $u(N_{K\mathrm{air}})_{\mathrm{NMI}}$ values are in the last column of Table 5.

2. $u(\dot{K}_{\mathrm{air}})_{\mathrm{BIPM}} = 0.15$ %. [11]

3. $u(N_{\mathrm{Kair}})_{\mathrm{link}}$ is determined as $\dfrac{u_j(N_{Kair})_{link,mean}}{\sqrt{n}}$ where $n =$ number of the linking laboratories, $u_j(N_{Kair})_{link,mean}$ the average $u_j(N_{Kair})$ values of the linking laboratories , and $u_j(N_{Kair})$ comprises on the following components:

a) Statistical uncertainty of the air kerma determinations at the linking laboratory *j*.

b) Statistical uncertainty of the air kerma determination of the linking laboratory *j* at the BIPM.

c) Statistical uncertainty of the transfer instrument calibrations at the linking laboratory *j*.

d) The non statistical uncertainties of current measurements at the linking laboratory *j*.

The above mentioned uncertainty components of $u_j(N_{K\mathrm{air}})$ were obtained from the BIPM reports on the key comparisons of the seven link laboratories and the reported uncertainty budget of this comparison program. The calculated value of $u(N_{K\mathrm{air}})_{\mathrm{link}} = 0.041$ %

4. The average standard deviation of the recalibrations of the four transfer chambers performed at MKEH, $u(N_{Kair})_{stab} = 0.031$ % (see section 2.4).

5. The $u_i(K_{air})_{NMI}$ and $u_i(K_{air})_{BIPM}$ terms denote the correlated uncertainty components. Five uncertainties are fully correlated ($f_i = 1$) [ρ_{air}; $(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$; $s_{\mathrm{c,a}}$,& W/e; g; k_{h}] in the air kerma determination between the BIPM and each participant. The summation of these for the BIPM standard is 0.0012^2. The same value was used for all participants except for LNHB, VSL, BEV and GUM for which 0.0028^2, 0.0026^2, 0.34^2 % and 0.34^2 % were used respectively. Regarding the uncertainty of the cavity chamber wall correction (k_{wall}), a value of $f_i = 0.8$ recommended by the CCRI(I) is used. This is due to the fact that the wall correction is calculated by all primary laboratories using similar Monte Carlo methods. For the case of NMIs that are traceable to the BIPM, the non statistical uncertainty components used for determining the air kerma the BIPM, are considered to be correlated with $f_{\mathrm{i}} = 1$, so the summation is 2×0.0015^2.

In the equation (4b) the $u(N_{Dw})_{NMI}$ values are in the last column of Table 6, and the $u(D_w)_{BIPM}$=0.0029 [11]. The $u(N_{Dw})_{link}$ calculation is similar to the $u(N_{Kair})_{link}$ calculation being based on the nine linking laboratories and its value is given by $u(N_{Dw})_{link}$=0.05%. For the calculation of the four (a. to d.) components for $u_j(N_{Dw})$ values, the primary standard calorimeters, having higher statistical uncertainty components, were supposed to establish the reference absorbed dose to water. The $u(N_{Dw})_{stab} = 0.029$%. (see section 2.4).

The correlated uncertainty components $u_i(D_w)$ between the participants having a graphite calorimeter, and the BIPM having graphite cavity chamber, are the $u(1+\varepsilon)_{\mathrm{w,c}}$ and $u(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$ with correlation coefficients taken as ($f_i = 0.7$) and ($f_i = 0.95$), respectively [11]. For the rest of the participants there are no further correlated components for the absorbed dose to water determination. For an NMI traceable to the BIPM, all of the non-statistical uncertainty components of absorbed dose to water determinations at the BIPM are correlated with $f_i = 1$, so the summation is 2×0.0021^2

The calculated degrees of equivalence using equations 3a, 4a, 5a, 6a for air kerma are in Table 9 and illustrated in Figure 6. The calculated degrees of equivalence using equations 3b, 4b, 5b, 6b for absorbed dose to water are in Table 10 and illustrated in Figure 7.

Table 9. Degrees of equivalence, in terms of the difference D_i, with respect to the key comparison reference value and its associated expanded ($k = 2$) uncertainty, $U(D_i)$, for air kerma. (The bold-text participants are traceable to a primary standard other than the BIPM standard.)

Participants	*Di* (mGy/Gy)	*U*(*Di*) (mGy/Gy
[a]**LNE-LNHB**	-1.9	4.8
CIEMAT	-1.5	3.9
CMI	-5.8	14.1
RMTC	-1.3	9.6
SSM	1.0	7.5
STUK	-2.3	7.3
NRPA	5.1	7.1
SMU	5.2	6.5
IAEA	0.0	7.5
HAEC-HIRCL	4.2	11.9
BIM	-4.5	13.0
IRB	4.1	7.2
GUM	-12.5	17.4
ITN-LMRIR	-0.4	6.0
PTB	8.3	3.4
BEV	5.4	5.0
METAS	-1.3	4.6
VSL	-3.7	7.8
ENEA	-0.9	7.6
NIST	3.4	6.4
NRC	4.2	4.8
LNMRI-IRD	2.4	13.7
VNIIM	-0.8	4.0
ARPANSA	-1.0	10.6
CNEA-CAE	1.8	10.0
[b]**MKEH**	4.7	4.0

[a] Average of the two sets of measurements

[b] Based on the first measurement performed on February 2005

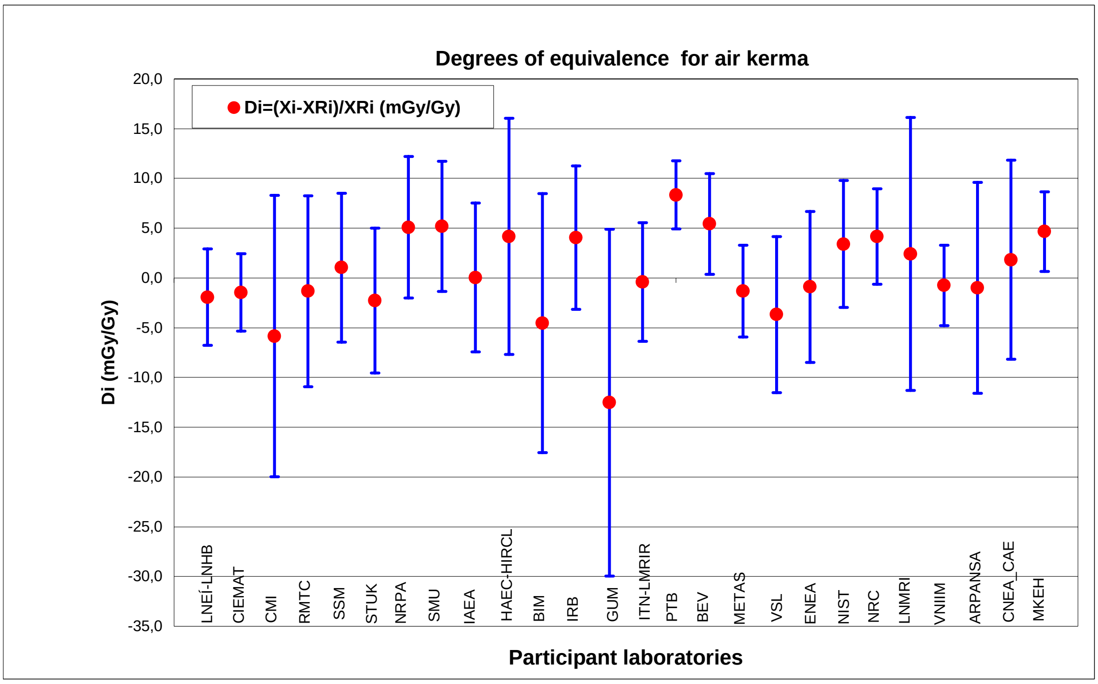

Figure 6. Degrees of equivalence for air kerma

Table 10. Degrees of equivalence in terms of the difference *Di*, with respect to the key comparison reference value and its expanded ($k = 2$) uncertainty, *U*(*Di*), for absorbed dose to water. (The bold-text participants are traceable to a primary standard other than the BIPM standard.)

Participants	*Di* (mGy/Gy)	*U*(*Di*) (mGy/Gy)
[a]**LNE-LNHB**	-4.8	10.3
CIEMAT	-4.9	7.3
CMI	-4.0	23.6
RMTC	-5.3	12.0
SSM	-1.4	10.0
STUK	-3.9	8.5
NRPA	3.2	8.8
SMU	-4.7	24.7
IAEA	-0.4	10.0
HAEC-HIRCL	3.0	12.4
IRB	-6.6	20.3
ITN-LMRIR	-7.1	13.0
PTB	-3.6	7.4
BEV	-1.7	10.1
METAS	0.4	10.6
VSL	-3.4	8.5
ENEA	-1.1	8.3
NIST	-0.6	11.1
NRC	-1.8	10.4
LNMRI-IRD	1.0	15.0
ARPANSA	2.4	9.1
CNEA-CAE	12.0	17.9
[b]**MKEH**	-2.4	9.6

[a] Average of the two series of measurements

[b] Based on the first measurement performed on February 2005

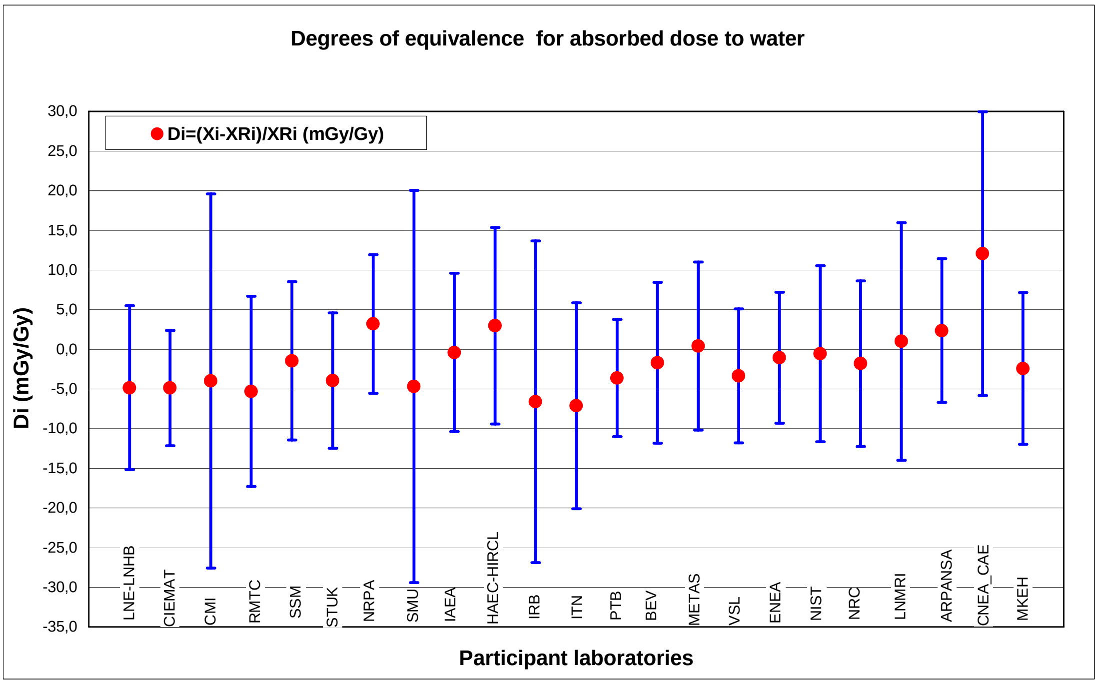

Figure 7. Degrees of equivalence for absorbed dose to water

The degrees of equivalence shown in Tables 9 and Table 10 and illustrated in Figures 6 and 7 indicate the level of agreement of each NMI with the BIPM KCRV. The previous sections described the choice of participants that acted as linking labs (shown in Table 7) and also how the comparison results for each NMI (given by $\overline{R}_{\text{NMI}}$) were linked with the BIPM KCRV.

The relative differences Di between each laboratory's result and the KCRV and its expanded uncertainty $U(Di)$ are shown in Fig. 6 and 7. The ideal case would be for the differences Di to be equal to zero. As seen in Fig. 6, the relative differences Di for air kerma show agreement between most of the NMIs results and the reference value within the expanded uncertainty $U(Di)$ (i.e. the uncertainty bars cross the horizontal axis at $Di=0$) . However, the deviations from the reference value for BEV, MKEH and the PTB are not within their expanded uncertainties $U(Di)$ (the uncertainty bars do not cross the horizontal axis at $Di=0$). Similar deviations from the reference value can also be observed in the BIPM.RI(I)-K1 comparison. It must be noted that the results of primary standard laboratories that have 1cm^3 volume so called "CCO1" type cylindrical graphite cavity chamber (SMU, MKEH, BEV, PTB, BIM, ZMDM and ITN,) have a systematic positive deviation from the KCRV (see Appendix A). These chambers have particularly large k_{wall} correction that may be influencing the results. Further study of the BIPM parallel-plate cavity chamber and the CCO1 type of cavity chambers could be interesting.

As seen in Table 10, for absorbed dose to water the deviations from the reference value fall within the calculated expanded uncertainty $U(Di)$ for each NMI.

An interesting point is that the Di values for all European SSDLs, except for HAEC-HIRCL (Greece) and NRPA (Norway), have negative values between -1.5 mGy/Gy and -7.2 mGy/Gy. All these SSDLs are traceable directly to the BIPM.

It is interesting to compare the results reported here with previously published BIPM and the available RMO key comparison results BIPM.RI(I)-K4, [12,16]. For this purpose, the available RMO air kerma and absorbed dose to water key comparisons are shown in Fig. 8 and Fig. 9 (Appendix A). Note that these values are indicative only, as the accepted degrees of equivalence are those published in the KCDB, (the COOMET results are under publication) being one result per NMI. The laboratories that participated in BIPM key comparisons are indicated in Fig. 8 and Fig. 9 by adding the word "key" next to the name of the NMI. The data for all the other laboratories shown in the Fig. 8 and Fig. 9 result from RMO key comparisons. While comparing the results shown in Fig.8 and Fig. 9 one should keep in mind that the reference value determination of an RMO key comparison involves one or more linking laboratories and transfer instruments. As a result, larger uncertainties values $U(Di)$ are expected for RMO key comparison relative to the BIPM key comparisons.

3.6 Proposal for the degrees of equivalence between pairs of participants

For the air kerma standard for each pair of NMIs i and j, $D_{i,j} = \overline{R}_{K,i} - \overline{R}_{K,j}$ and its variance is

$$u_{i,j}^2 = \left(u^2(N_{Kair})_i + u^2(N_{Kair})_j - \sum_{k=1}^{6} (f_k^2 u_{i.k}^2(K) + f_k^2 u_{j.k}^2(K)) + 2u^2(N_{Kair})_{stab} \right) \quad (7a)$$

when the participants, i and j are traceable to different primary standards.

The $u_k(K)$ means the uncertainties of the fully ($f_k = 1$) correlated constants for the air kerma determination [ρ_{air}; $(\mu_{en}/\rho)_{a,c}$; $s_{c,a}$, and W/e; g; k_h] between the participants i and j. and $u(k_{wall})$correction with $f_6 = 0.8$ if both i and j participant used Monte Carlo methods for its calculation.

When both i and j are traceable to the same laboratory, e.g. the BIPM,

$$u_{i,j}^2 = \left(u^2(N_{Kair})_i + u^2(N_{Kair})_j - 2u^2(\dot{K}_{air})_{BIPM} + 2u^2(N_{Kair})_{stab} \right) \quad (7b)$$

For the absorbed dose to water standard for each pair i and j, $D_{i,j} = \overline{R}_{D,i} - \overline{R}_{D,j}$ and its variance is

$$u_{i,j}^2 = \left(u^2(N_{D_w})_i + u^2(N_{D_w})_j + 2u^2(N_{Dw})_{stab} \right) \quad (8a)$$

when one participant is traceable to a water calorimeter and the other is traceable to the BIPM graphite cavity standard or to a graphite calorimeter.

When one participant is traceable to a graphite calorimeter and the other is traceable to the BIPM graphite cavity standard the variance is

$$u_{i,j}^2 = \left(u^2(N_{D_w})_i + u^2(N_{D_w})_j - \sum_{k=1}^{2}(f_k u_k(D_w))_i^2 - \sum_{k=1}^{2}(f_k u_k(D_w))_j^2 + 2u^2(N_{Dw})_{stab} \right) \quad (8b)$$

where f_1=0.95; u_1=$u((\mu_{en}/\rho)_{w,c}$ and f_2=0.7; u_2=$u(1+\varepsilon)_{w,c}$

When both i and j participants have the same water or graphite calorimeter the variance is

$$u_{i,j}^2 = \left(u^2(N_{D_w})_i + u^2(N_{D_w})_j - \sum_{k}(f_k u_k(D_w))_i^2 - \sum_{k}(f_k u_k(D_w))_j^2 + 2u^2(N_{Dw})_{stab} \right) \quad (8c)$$

where the $(f_k u_k)_i$ and $(f_k u_k)_j$ values are published in the Final report for BIPM.RI-K4 [17]

When both *i* and *j* are traceable to the same laboratory e.g. the BIPM, the variance is

$$u_{i,j}^2 = \left(u^2(N_{D_w})_i + u^2(N_{D_w})_j - 2u^2(\dot{D}_w)_{BIPM} + 2u^2(N_{Dw})_{stab} \right) \quad (8d)$$

The correlated uncertainty components between NMIs, being traceable to the BIPM in equations (7b) and (8d) can be estimated with the $u(\dot{K}_{air})_{BIPM}$ and $u(\dot{D}_w)_{BIPM}$ terms since only the uncertainties of the current measurements are uncorrelated, but these are normally negligible. The calculated pair-wise degrees of equivalence, (D_{ij}) and its expanded uncertainties, (U_{ij}), using equations 7a, 7b and 8a-8d for air kerma and absorbed dose to water, are in the Appendices B and C.

4 Summary and conclusion

An unprecedented international comparison involving 26 countries was conducted for the purpose of linking the measurement standards for air kerma and absorbed dose to water to each other. High stability transfer instruments were used for this work which enabled each participant to establish the degrees of equivalence, DoE, of their national standards for air kerma and absorbed dose to water. This international effort allowed participating SSDLs to obtain for the first time their degrees of equivalence to be included in the BIPM KCDB. A total of 11 new air kerma and 14 new absorbed dose to water degrees of equivalence values will be added to the KCDB. Furthermore, these new values can be used to support the relevant CMC claims of each of these participants. The average calibration coefficient values, used for the calculations made in this work, indicated that the deviations from the key comparison reference values are within the calculated expanded uncertainty $U(Di)$ ($k = 2$) for each participant for both quantities except for the BEV, PTB and the MKEH only in terms of air kerma, similar to their BIPM.RI(I)- K1 results.

This work was beneficial for all the participants. One of the benefits was that they could validate their calibration techniques. This was achieved by having to calibrate four high quality transfer instruments at each facility using two independent current measuring devices. Furthermore, each participant had to review their uncertainty analysis and this will have a direct impact on the uncertainties stated in every participants' CMC claims.

This regional key comparison was the first to make use of a complete dosemeter system (chamber, electrometer and data acquisition system) that was shipped to all participants. Considering the resulting values of degrees of equivalence, the robustness of the EURAMET.RI(I)-K1 and EURAMET.RI(I)-K4 key comparisons are comparable with the respective BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparisons.

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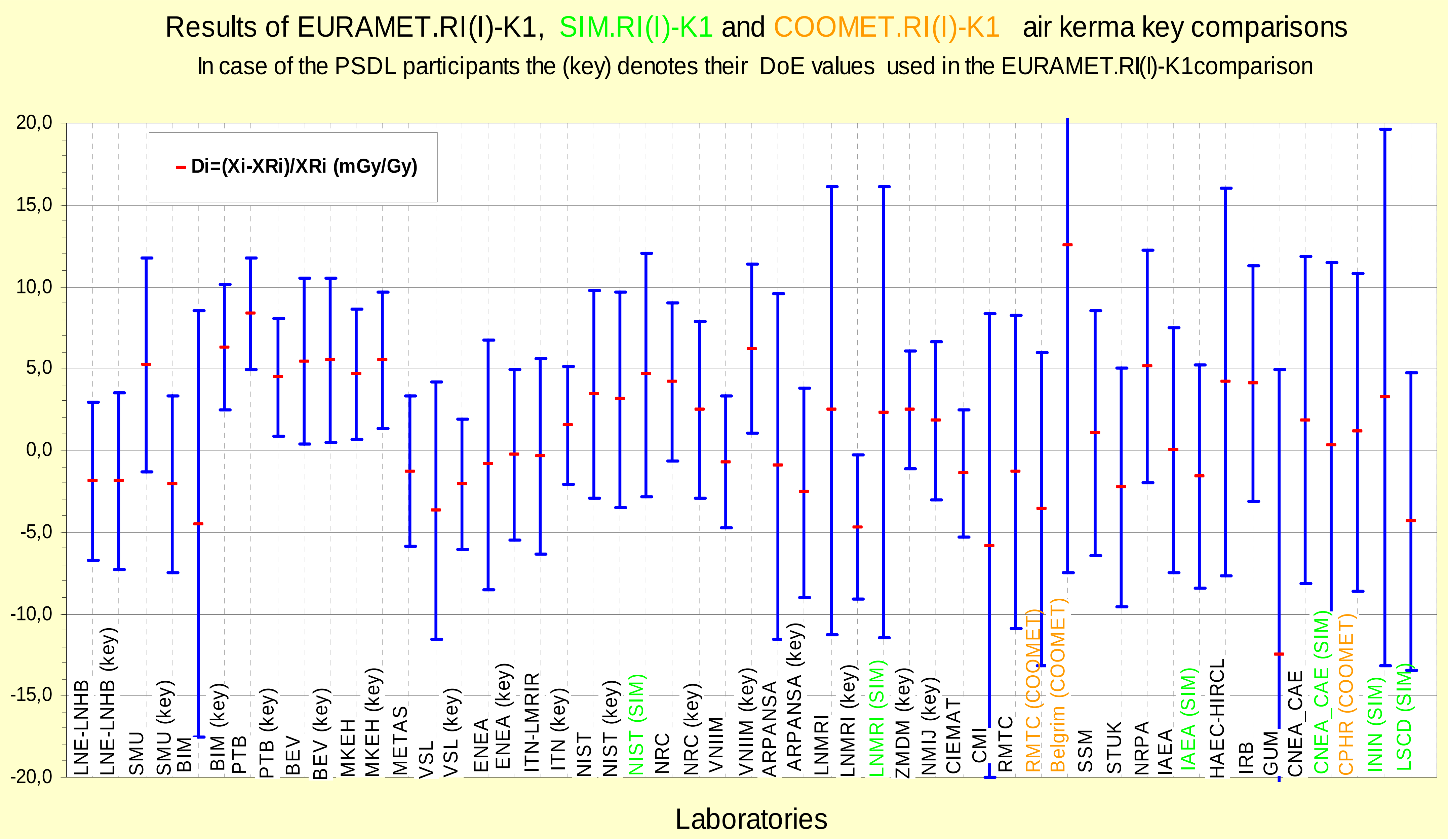


Figure 8. Results of EURAMET.RI(I)-K1, SIM.RI(I)-K1 and COOMET.RI(I)-K1 air kerma key comparisons.
The (key) denotes the DoE values of PSDL participants used in the EURAMET.RI(I)-K1comparison

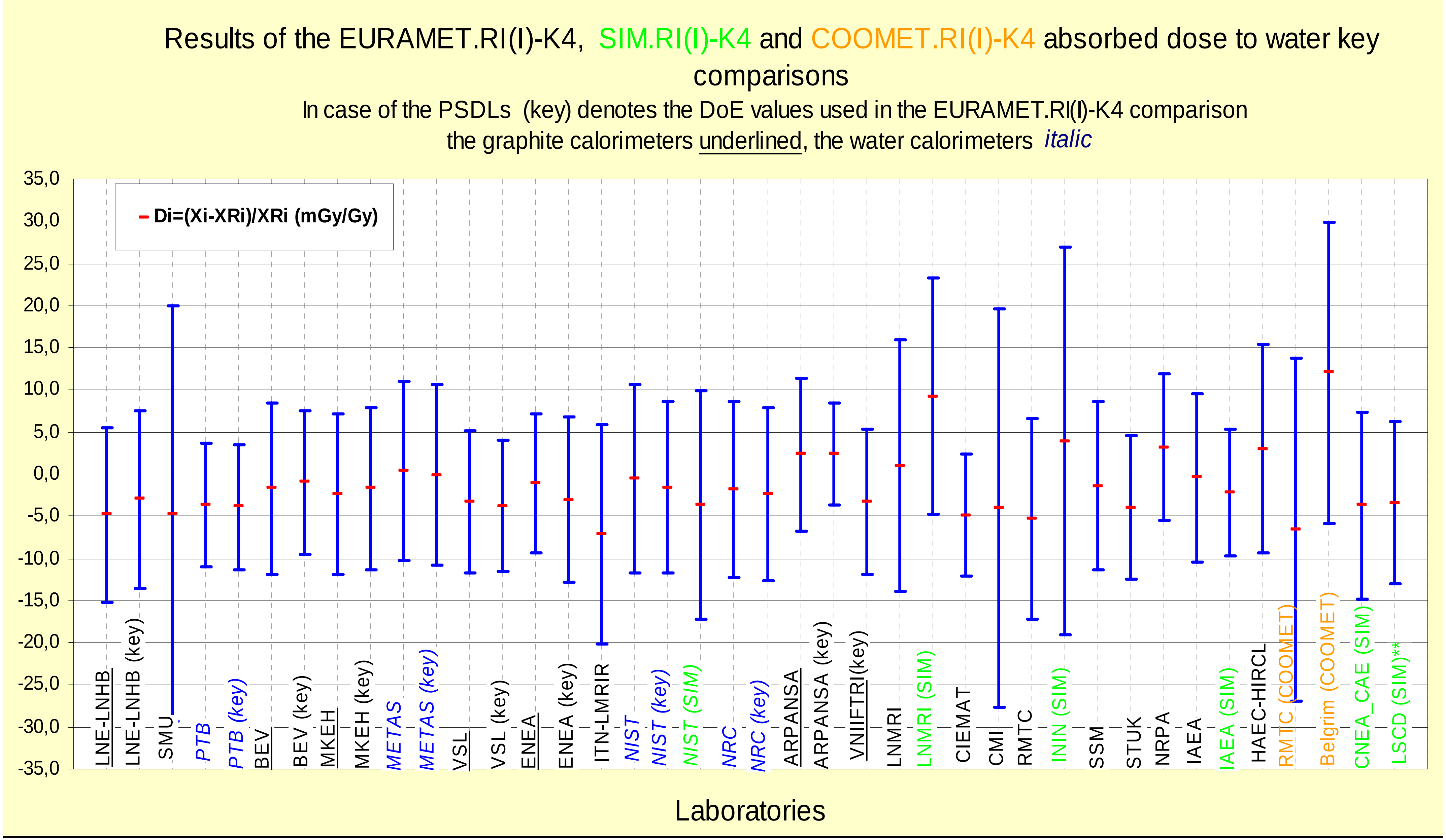


Figure 9. Results of EURAMET.RI(I)-K4, SIM.RI(I)-K4 and COOMET.RI(I)-K4 absorbed dose to water key comparisons.
The (key) denotes the DoE values of PSDL participants used in the EURAMET.RI(I)-K4 comparison

Appendix B Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$ for air kerma standards

lab i	**lab j**		**LNE-LNHB**		CIEMAT		**CMI**		**LNMC-RMTC**		SSM		STUK		NRPA	
air kerma	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-1.9**	**4.8**	---	---	-0.48	6.10	3.91	14.81	-0.60	10.68	-2.97	8.84	0.35	8.66	-7.02	8.52
CIEMAT	**-1.5**	**3.9**	0.48	6.10	---	---	4.39	14.62	-0.13	10.41	-2.49	8.51	0.82	8.32	-6.54	8.18
CMI	**-5.8**	**14.1**	-3.91	14.81	-4.39	14.62	---	---	-4.51	17.05	-6.88	15.96	-3.56	15.86	-10.93	15.78
LNMC-RMTC	**-1.3**	**9.6**	0.60	10.68	0.13	10.41	4.51	17.05	---	---	-2.37	12.22	0.95	12.09	-6.41	12.00
SSM	**1.0**	**7.5**	2.97	8.84	2.49	8.51	6.88	15.96	2.37	12.22	---	---	3.32	10.50	-4.05	10.39
STUK	**-2.3**	**7.3**	-0.35	8.66	-0.82	8.32	3.56	15.86	-0.95	12.09	-3.32	10.50	---	---	-7.36	10.24
NRPA	**5.1**	**7.1**	7.02	8.52	6.54	8.18	10.93	15.78	6.41	12.00	4.05	10.39	7.36	10.24	---	---
SMU	**5.2**	**6.5**	7.11	7.89	6.64	7.52	11.02	15.45	6.51	11.55	4.15	9.87	7.46	9.71	0.10	9.59
IAEA	**0.0**	**7.5**	1.97	8.84	1.50	8.51	5.88	15.96	1.37	12.22	-0.99	10.65	2.32	10.50	-5.04	10.39
HAEC-HIRCL	**4.2**	**11.9**	6.11	12.77	5.63	12.54	10.02	18.42	5.50	15.31	3.14	14.08	6.45	13.97	-0.91	13.88
BIM	**-4.5**	**13.0**	-2.61	13.84	-3.08	13.64	1.30	19.19	-3.21	16.22	-5.58	15.07	-2.26	14.96	-9.62	14.88
IRB	**4.1**	**7.2**	5.98	8.45	5.51	8.11	9.90	15.75	5.38	11.95	3.02	10.33	6.33	10.18	-1.03	10.06
GUM	**-12.5**	**17.4**	-10.60	18.04	-11.07	17.88	-6.69	22.40	-11.20	19.92	-13.56	18.99	-10.25	18.91	-17.61	18.85
ITN-LMRIR	**-0.4**	**6.0**	1.52	7.59	1.05	7.21	5.43	15.30	0.92	11.36	-1.44	9.64	1.87	9.48	-5.49	9.35
PTB	**8.3**	**3.4**	10.28	5.58	9.80	5.04	14.19	14.41	9.68	10.12	7.31	8.15	10.63	7.95	3.26	7.81
BEV	**5.4**	**5.0**	7.36	6.70	6.88	6.26	11.27	14.88	6.76	10.78	4.39	8.96	7.70	8.78	0.34	8.64
METAS	**-1.3**	**4.6**	0.62	6.58	0.15	6.13	4.53	14.82	0.02	10.70	-2.34	8.86	0.97	8.68	-6.39	8.55
VSL	**-3.7**	**7.8**	-1.75	9.00	-2.22	8.68	2.16	16.05	-2.35	12.34	-4.71	10.79	-1.40	10.64	-8.76	10.53
ENEA	**-0.9**	**7.6**	1.03	8.79	0.56	8.46	4.94	15.93	0.43	12.19	-1.93	10.61	1.38	10.46	-5.98	10.34
NIST	**3.4**	**6.4**	5.34	7.76	4.86	7.38	9.25	15.38	4.74	11.47	2.37	9.77	5.69	9.61	-1.68	9.49
NRC	**4.2**	**4.8**	6.10	6.51	5.63	6.06	10.01	14.79	5.50	10.66	3.13	8.81	6.45	8.63	-0.91	8.50
LNMRI	**2.4**	**13.7**	4.35	14.50	3.88	14.30	8.26	19.66	3.75	16.78	1.39	15.67	4.70	15.56	-2.66	15.49
VNIIM	**-0.8**	**4.0**	1.18	5.97	0.70	5.48	5.09	14.56	0.58	10.34	-1.79	8.42	1.53	8.23	-5.84	8.09
ARPANSA	**-1.0**	**10.6**	0.94	11.63	0.46	10.95	4.85	17.36	0.34	14.03	-2.03	12.68	1.29	12.56	-6.08	12.46
CNEA_CAE	**1.8**	**10.0**	3.77	11.06	3.30	10.80	7.68	17.28	3.17	13.91	0.80	12.55	4.12	12.43	-3.24	12.33
MKEH	**4.7**	**4.0**	6.60	5.97	6.12	5.48	10.51	14.56	6.00	10.34	3.63	8.42	6.95	8.23	-0.42	8.09

The bolded NMIs are traceable to other primary standard than the BIPM

Appendix B Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$ for air kerma standards

lab i	lab j		SMU		IAEA		HAEC-HIRCL		BIM		IRB		GUM		ITN-LMRIR	
air kerma	Di (mGy/Gy)	U(Di) (mGy/Gy)	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	-1.9	4.8	-7.11	7.89	-1.97	8.84	-6.11	12.77	2.61	13.84	-5.98	8.45	10.60	18.04	-1.52	7.59
CIEMAT	-1.5	3.9	-6.64	7.52	-1.50	8.51	-5.63	12.54	3.08	13.64	-5.51	8.11	11.07	17.88	-1.05	7.21
CMI	-5.8	14.1	-11.02	15.45	-5.88	15.96	-10.02	18.42	-1.30	19.19	-9.90	15.75	6.69	22.40	-5.43	15.30
LNMC-RMTC	-1.3	9.6	-6.51	11.55	-1.37	12.22	-5.50	15.31	3.21	16.22	-5.38	11.95	11.20	19.92	-0.92	11.36
SSM	1.0	7.5	-4.15	9.87	0.99	10.65	-3.14	14.08	5.58	15.07	-3.02	10.33	13.56	18.99	1.44	9.64
STUK	-2.3	7.3	-7.46	9.71	-2.32	10.50	-6.45	13.97	2.26	14.96	-6.33	10.18	10.25	18.91	-1.87	9.48
NRPA	5.1	7.1	-0.10	9.59	5.04	10.39	0.91	13.88	9.62	14.88	1.03	10.06	17.61	18.85	5.49	9.35
SMU	5.2	6.5	---	---	5.14	9.87	1.01	13.50	9.72	14.53	1.13	9.53	17.71	18.57	5.59	8.78
IAEA	0.0	7.5	-5.14	9.87	---	---	-4.13	14.08	4.58	15.07	-4.01	10.33	12.57	18.99	0.45	9.64
HAEC-HIRCL	4.2	11.9	-1.01	13.50	4.13	14.08	---	---	8.71	17.66	0.12	13.84	16.70	21.11	4.58	13.33
BIM	-4.5	13.0	-9.72	14.53	-4.58	15.07	-8.71	17.66	---	---	-8.59	14.84	7.99	21.78	-4.13	14.37
IRB	4.1	7.2	-1.13	9.53	4.01	10.33	-0.12	13.84	8.59	14.84	---	---	16.58	18.82	4.46	9.29
GUM	-12.5	17.4	-17.71	18.57	-12.57	18.99	-16.70	21.11	-7.99	21.78	-16.58	18.82	---	---	-12.12	18.45
ITN-LMRIR	-0.4	6.0	-5.59	8.78	-0.45	9.64	-4.58	13.33	4.13	14.37	-4.46	9.29	12.12	18.45	---	---
PTB	8.3	3.4	3.16	7.11	8.30	8.15	4.17	12.30	12.89	13.42	4.29	7.73	20.87	17.71	8.75	6.78
BEV	5.4	5.0	0.24	8.02	5.38	8.96	1.25	12.85	9.97	13.92	1.37	8.58	17.95	18.10	5.83	7.73
METAS	-1.3	4.6	-6.49	7.92	-1.35	8.86	-5.48	12.78	3.23	13.86	-5.36	8.48	11.22	18.05	-0.90	7.62
VSL	-3.7	7.8	-8.86	10.02	-3.72	10.79	-7.85	14.18	0.86	15.16	-7.73	10.47	8.85	19.07	-3.27	9.79
ENEA	-0.9	7.6	-6.08	9.83	-0.94	10.61	-5.07	14.05	3.64	15.03	-4.95	10.29	11.63	18.97	-0.49	9.59
NIST	3.4	6.4	-1.78	8.92	3.37	9.77	-0.77	13.43	7.95	14.46	-0.65	9.43	15.93	18.51	3.82	8.66
NRC	4.2	4.8	-1.01	7.86	4.13	8.81	0.00	12.75	8.71	13.83	0.12	8.43	16.70	18.03	4.58	7.56
LNMRI	2.4	13.7	-2.76	15.15	2.38	15.67	-1.75	18.17	6.96	18.95	-1.63	15.45	14.95	22.20	2.83	15.00
VNIIM	-0.8	4.0	-5.94	7.42	-0.80	8.42	-4.93	12.48	3.79	13.58	-4.81	8.02	11.77	17.84	-0.35	7.11
ARPANSA	-1.0	10.6	-6.18	12.08	-1.03	12.68	-5.17	15.67	3.55	16.57	-5.05	12.38	11.53	20.20	-0.58	11.85
CNEA_CAE	1.8	10.0	-3.34	11.90	1.80	12.55	-2.33	15.57	6.38	16.47	-2.21	12.29	14.37	20.12	2.25	11.71
MKEH	4.7	4.0	-0.52	7.42	4.63	8.42	0.49	12.48	9.21	13.58	0.61	8.02	17.19	17.84	5.08	7.11

The bolded NMIs are traceable to other primary standard than the BIPM

Appendix B Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$ for air kerma standards

lab i ⇩	lab j ⇨		PTB		BEV		METAS		VSL		ENEA		NIST		NRC	
air kerma	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-1.9**	**4.8**	-10.28	5.58	-7.36	6.70	-0.62	6.58	1.75	9.00	-1.03	8.79	-5.34	7.76	-6.10	6.51
CIEMAT	**-1.5**	**3.9**	-9.80	5.04	-6.88	6.26	-0.15	6.13	2.22	8.68	-0.56	8.46	-4.86	7.38	-5.63	6.06
CMI	**-5.8**	**14.1**	-14.19	14.41	-11.27	14.88	-4.53	14.82	-2.16	16.05	-4.94	15.93	-9.25	15.38	-10.01	14.79
LNMC-RMTC	**-1.3**	**9.6**	-9.68	10.12	-6.76	10.78	-0.02	10.70	2.35	12.34	-0.43	12.19	-4.74	11.47	-5.50	10.66
SSM	**1.0**	**7.5**	-7.31	8.15	-4.39	8.96	2.34	8.86	4.71	10.79	1.93	10.61	-2.37	9.77	-3.13	8.81
STUK	**-2.3**	**7.3**	-10.63	7.95	-7.70	8.78	-0.97	8.68	1.40	10.64	-1.38	10.46	-5.69	9.61	-6.45	8.63
NRPA	**5.1**	**7.1**	-3.26	7.81	-0.34	8.64	6.39	8.55	8.76	10.53	5.98	10.34	1.68	9.49	0.91	8.50
SMU	**5.2**	**6.5**	-3.16	7.11	-0.24	8.02	6.49	7.92	8.86	10.02	6.08	9.83	1.78	8.92	1.01	7.86
IAEA	**0.0**	**7.5**	-8.30	8.15	-5.38	8.96	1.35	8.86	3.72	10.79	0.94	10.61	-3.37	9.77	-4.13	8.81
HAEC-HIRCL	**4.2**	**11.9**	-4.17	12.30	-1.25	12.85	5.48	12.78	7.85	14.18	5.07	14.05	0.77	13.43	0.00	12.75
BIM	**-4.5**	**13.0**	-12.89	13.42	-9.97	13.92	-3.23	13.86	-0.86	15.16	-3.64	15.03	-7.95	14.46	-8.71	0.00
IRB	**4.1**	**7.2**	-4.29	7.73	-1.37	8.58	5.36	8.48	7.73	10.47	4.95	10.29	0.65	9.43	-0.12	8.43
GUM	**-12.5**	**17.4**	-20.87	17.71	-17.95	18.10	-11.22	18.05	-8.85	19.07	-11.63	18.97	-15.93	18.51	-16.70	18.03
ITN-LMRIR	**-0.4**	**6.0**	-8.75	6.78	-5.83	7.73	0.90	7.62	3.27	9.79	0.49	9.59	-3.82	8.66	-4.58	7.56
PTB	**8.3**	**3.4**	---	---	2.92	5.76	9.65	5.62	12.02	8.33	9.24	8.09	4.94	6.96	4.18	5.54
BEV	**5.4**	**5.0**	-2.92	5.76	---	---	6.73	6.74	9.10	9.12	6.32	8.90	2.02	7.89	1.26	6.67
METAS	**-1.3**	**4.6**	-9.65	5.62	-6.73	6.74	---	---	2.37	9.03	-0.41	8.81	-4.71	7.79	-5.48	6.54
VSL	**-3.7**	**7.8**	-12.02	8.33	-9.10	9.12	-2.37	9.03	---	---	-2.78	10.74	-7.09	9.92	-7.85	8.98
ENEA	**-0.9**	**7.6**	-9.24	8.09	-6.32	8.90	0.41	8.81	2.78	10.74	---	---	-4.30	9.72	-5.07	8.76
NIST	**3.4**	**6.4**	-4.94	6.96	-2.02	7.89	4.71	7.79	7.09	9.92	4.30	9.72	---	---	-0.76	7.73
NRC	**4.2**	**4.8**	-4.18	5.54	-1.26	6.67	5.48	6.54	7.85	8.98	5.07	8.76	0.76	7.73	---	---
LNMRI	**2.4**	**13.7**	-5.92	14.09	-3.00	14.57	3.73	14.51	6.10	15.76	3.32	15.64	-0.98	15.08	-1.75	14.48
VNIIM	**-0.8**	**4.0**	-9.10	4.89	-6.18	6.14	0.55	6.01	2.92	8.60	0.14	8.37	-4.16	7.28	-4.92	5.93
ARPANSA	**-1.0**	**10.6**	-9.34	10.62	-6.42	11.27	0.31	11.23	2.69	12.80	-0.10	12.68	-4.40	12.19	-5.16	11.23
CNEA_CAE	**1.8**	**10.0**	-6.51	10.52	-3.59	11.15	3.15	11.08	5.52	13.49	2.74	12.52	-1.57	11.82	-2.33	11.04
MKEH	**4.7**	**4.0**	-3.68	4.89	-0.76	6.14	5.97	6.01	8.35	8.60	5.56	8.37	1.26	7.28	0.50	5.93

The bolded NMIs are traceable to other primary standard than the BIPM

Appendix B Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$ for air kerma standards

lab i	lab j		LNMRI		VNIIM		ARPANSA		CNEA_CAE		MKEH	
air kerma	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-1.9**	**4.8**	-4.35	14.50	-1.18	5.97	-0.94	11.63	-3.77	11.06	-6.60	5.97
CIEMAT	**-1.5**	**3.9**	-3.88	14.30	-0.70	5.48	-0.46	10.95	-3.30	10.80	-6.12	5.48
CMI	**-5.8**	**14.1**	-8.26	19.66	-5.09	14.56	-4.85	17.36	-7.68	17.28	-10.51	14.56
LNMC-RMTC	**-1.3**	**9.6**	-3.75	16.78	-0.58	10.34	-0.34	14.03	-3.17	13.91	-6.00	10.34
SSM	**1.0**	**7.5**	-1.39	15.67	1.79	8.42	2.03	12.68	-0.80	12.55	-3.63	8.42
STUK	**-2.3**	**7.3**	-4.70	15.56	-1.53	8.23	-1.29	12.56	-4.12	12.43	-6.95	8.23
NRPA	**5.1**	**7.1**	2.66	15.49	5.84	8.09	6.08	12.46	3.24	12.33	0.42	8.09
SMU	**5.2**	**6.5**	2.76	15.15	5.94	7.42	6.18	12.08	3.34	11.90	0.52	7.42
IAEA	**0.0**	**7.5**	-2.38	15.67	0.80	8.42	1.03	12.68	-1.80	12.55	-4.63	8.42
HAEC-HIRCL	**4.2**	**11.9**	1.75	18.17	4.93	12.48	5.17	15.67	2.33	15.57	-0.49	12.48
BIM	**-4.5**	**13.0**	-6.96	18.95	-3.79	13.58	-3.55	16.57	-6.38	16.47	-9.21	13.58
IRB	**4.1**	**7.2**	1.63	15.45	4.81	8.02	5.05	12.38	2.21	12.29	-0.61	8.02
GUM	**-12.5**	**17.4**	-14.95	22.20	-11.77	17.84	-11.53	20.20	-14.37	20.12	-17.19	17.84
ITN-LMRIR	**-0.4**	**6.0**	-2.83	15.00	0.35	7.11	0.58	11.85	-2.25	11.71	-5.08	7.11
PTB	**8.3**	**3.4**	5.92	14.09	9.10	4.89	9.34	10.62	6.51	10.52	3.68	4.89
BEV	**5.4**	**5.0**	3.00	14.57	6.18	6.14	6.42	11.27	3.59	11.15	0.76	6.14
METAS	**-1.3**	**4.6**	-3.73	14.51	-0.55	6.01	-0.31	11.23	-3.15	11.08	-5.97	6.01
VSL	**-3.7**	**7.8**	-6.10	15.76	-2.92	8.60	-2.69	12.80	-5.52	13.49	-8.35	8.60
ENEA	**-0.9**	**7.6**	-3.32	15.64	-0.14	8.37	0.10	12.68	-2.74	12.52	-5.56	8.37
NIST	**3.4**	**6.4**	0.98	15.08	4.16	7.28	4.40	12.19	1.57	11.82	-1.26	7.28
NRC	**4.2**	**4.8**	1.75	14.48	4.92	5.93	5.16	11.23	2.33	11.04	-0.50	5.93
LNMRI	**2.4**	**13.7**	---	---	3.18	14.25	3.42	17.11	0.58	17.02	-2.25	14.25
VNIIM	**-0.8**	**4.0**	-3.18	14.25	---	---	0.24	10.86	-2.59	10.71	-5.42	3.63
ARPANSA	**-1.0**	**10.6**	-3.42	17.11	-0.24	10.86	---	---	-2.83	14.32	-5.66	10.86
CNEA_CAE	**1.8**	**10.0**	-0.58	17.02	2.59	10.71	2.83	14.32	---	---	-2.83	9.33
MKEH	**4.7**	**4.0**	2.25	14.25	5.42	3.63	5.66	10.86	2.83	9.33	---	---

The bolded NMIs are traceable to other primary standard than the BIPM

Appendix C. Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$, for absorbed dose to water standards

lab i	lab j		**LNE-LNHB**		CIEMAT		CMI		LNMC-RMTC		SSM		STUK		NRPA	
Absorbed dose to waterd	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-4.8**	**10.3**	---	---	0.03	11.22	-0.84	25.07	0.47	14.72	-3.40	13.14	-0.90	12.07	-8.03	12.23
CIEMAT	**-4.9**	**7.3**	-0.03	11.22	---	---	-0.87	23.30	0.44	11.43	-3.43	9.31	-0.93	7.73	-8.06	7.98
CMI	**-4.0**	**23.6**	0.84	25.07	0.87	23.30	---	---	1.31	25.17	-2.56	24.28	-0.06	23.72	-7.19	23.80
LNMC-RMTC	**-5.3**	**12.0**	-0.47	14.72	-0.44	11.43	-1.31	25.17	---	---	-3.87	13.32	-1.37	12.27	-8.50	12.43
SSM	**-1.4**	**10.0**	3.40	13.14	3.43	9.31	2.56	24.28	3.87	13.32	---	---	2.50	10.32	-4.63	10.51
STUK	**-3.9**	**8.5**	0.90	12.07	0.93	7.73	0.06	23.72	1.37	12.27	-2.50	10.32	---	---	-7.14	9.14
NRPA	**3.2**	**8.8**	8.03	12.23	8.06	7.98	7.19	23.80	8.50	12.43	4.63	10.51	7.14	9.14	---	---
SMU	**-4.7**	**24.7**	0.16	25.79	0.19	25.10	-0.68	33.66	0.63	26.85	-3.24	26.01	-0.74	25.49	-7.87	25.57
IAEA	**-0.4**	**10.0**	4.45	13.14	4.48	9.31	3.61	24.28	4.92	13.32	1.05	11.55	3.55	10.32	-3.58	10.51
HAEC-HIRCL	**3.0**	**12.4**	7.83	15.05	7.86	11.85	7.00	25.36	8.30	15.20	4.44	13.68	6.94	12.66	-0.20	12.81
IRB	**-6.6**	**20.3**	-1.76	21.57	-1.73	20.74	-2.60	30.55	-1.30	22.83	-5.16	21.84	-2.66	21.22	-9.80	21.31
ITN-LMRIR	**-7.1**	**13.0**	-2.27	15.54	-2.24	12.48	-3.11	25.66	-1.80	15.70	-5.67	14.23	-3.17	13.25	-10.30	13.39
PTB	**-3.6**	**7.4**	1.22	10.41	1.25	8.56	0.38	24.00	1.68	12.81	-2.18	10.96	0.32	9.65	-6.82	9.85
BEV	**-1.7**	**10.1**	3.16	12.38	3.19	11.03	2.32	24.99	3.62	14.57	-0.24	12.97	2.26	11.89	-4.88	12.05
METAS	**0.4**	**10.6**	5.24	12.90	5.27	11.46	4.41	25.18	5.71	14.90	1.84	13.35	4.35	12.30	-2.79	12.45
VSL	**-3.4**	**8.5**	1.49	11.13	1.52	9.51	0.65	24.35	1.96	13.46	-1.91	11.71	0.59	10.50	-6.54	10.68
ENEA	**-1.1**	**8.3**	3.79	11.02	3.82	9.34	2.95	24.29	4.26	13.34	0.39	11.57	2.89	10.35	-4.24	10.53
NIST	**-0.6**	**11.1**	4.29	13.32	4.32	11.93	3.45	25.40	4.75	15.27	0.89	13.75	3.39	12.73	-3.75	12.89
NRC	**-1.8**	**10.4**	3.04	12.77	3.07	11.31	2.20	25.11	3.50	14.79	-0.36	13.21	2.14	12.15	-5.00	12.31
LNMRI	**1.0**	**15.0**	5.84	17.25	5.87	14.55	5.00	26.73	6.31	17.39	2.44	16.07	4.94	15.21	-2.19	15.34
ARPANSA	**2.4**	**9.1**	7.20	11.72	7.23	10.06	6.36	24.57	7.67	13.85	3.80	12.16	6.30	11.00	-0.84	11.17
CNEA_CAE	**12.0**	**17.9**	16.90	18.31	16.93	15.78	16.06	27.42	17.36	18.43	13.50	17.20	16.00	16.40	8.86	16.52
MKEH	**-2.4**	**9.6**	2.43	11.93	2.46	10.44	1.59	24.73	2.90	14.13	-0.97	12.48	1.53	11.35	-5.60	11.52

The bolded NMIs are traceable to other primary standard than the BIPM, graphite calorimeters are marked with **underline**, water calorimeters are marked with ***italic***

Appendix C. Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$, for absorbed dose to water standards

lab i	lab j		SMU		IAEA		HAEC-HIRCL		IRB		ITN-LMRIR		***PTB***		**BEV**	
Absorbed dose to waterd	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-4.8**	**10.3**	-0.16	25.79	-4.45	13.14	-7.83	15.05	1.76	21.57	2.27	15.54	-1.22	10.41	-3.16	12.38
CIEMAT	**-4.9**	**7.3**	-0.19	25.10	-4.48	9.31	-7.86	11.85	1.73	20.74	2.24	12.48	-1.25	8.56	-3.19	11.03
CMI	**-4.0**	**23.6**	0.68	33.66	-3.61	24.28	-7.00	25.36	2.60	30.55	3.11	25.66	-0.38	24.00	-2.32	24.99
LNMC-RMTC	**-5.3**	**12.0**	-0.63	26.85	-4.92	13.32	-8.30	15.20	1.30	22.83	1.80	15.70	-1.68	12.81	-3.62	14.57
SSM	**-1.4**	**10.0**	3.24	26.01	-1.05	11.55	-4.44	13.68	5.16	21.84	5.67	14.23	2.18	10.96	0.24	12.97
STUK	**-3.9**	**8.5**	0.74	25.49	-3.55	10.32	-6.94	12.66	2.66	21.22	3.17	13.25	-0.32	9.65	-2.26	11.89
NRPA	**3.2**	**8.8**	7.87	25.57	3.58	10.51	0.20	12.81	9.80	21.31	10.30	13.39	6.82	9.85	4.88	12.05
SMU	**-4.7**	**24.7**	---	---	-4.29	26.01	-7.68	27.03	1.92	10.02	2.43	27.31	-1.06	24.41	-3.00	25.65
IAEA	**-0.4**	**10.0**	4.29	26.01	---	---	-3.38	13.68	6.21	21.84	6.72	14.23	3.23	10.96	1.29	12.97
HAEC-HIRCL	**3.0**	**12.4**	7.68	27.03	3.38	13.68	---	---	9.60	23.04	10.10	16.00	6.62	13.18	4.68	14.90
IRB	**-6.6**	**20.3**	-1.92	10.02	-6.21	21.84	-9.60	23.04	---	---	0.50	23.37	-2.98	19.42	-4.92	21.40
ITN-LMRIR	**-7.1**	**13.0**	-2.43	27.31	-6.72	14.23	-10.10	16.00	-0.50	23.37	---	---	-3.48	13.75	-5.42	15.41
PTB	**-3.6**	**7.4**	1.06	24.41	-3.23	10.96	-6.62	13.18	2.98	19.42	3.48	13.75	---	---	-1.94	10.05
BEV	**-1.7**	**10.1**	3.00	25.65	-1.29	12.97	-4.68	14.90	4.92	21.40	5.42	15.41	1.94	10.05	---	---
METAS	**0.4**	**10.6**	5.09	25.15	0.79	13.35	-2.59	15.23	7.01	20.80	7.51	15.72	4.03	8.71	2.09	12.61
VSL	**-3.4**	**8.5**	1.33	25.58	-2.96	11.71	-6.34	13.82	3.26	21.32	3.76	14.36	0.28	9.87	-1.66	10.85
ENEA	**-1.1**	**8.3**	3.63	25.18	-0.66	11.57	-4.04	13.70	5.55	20.84	6.06	14.25	2.58	8.80	0.63	10.74
NIST	**-0.6**	**11.1**	4.13	25.37	-0.16	13.75	-3.55	15.58	6.05	21.07	6.55	16.06	3.07	9.31	1.13	13.04
NRC	**-1.8**	**10.4**	2.88	25.08	-1.41	13.21	-4.80	15.11	4.80	20.72	5.30	15.61	1.82	8.51	-0.12	12.48
LNMRI	**1.0**	**15.0**	5.68	28.31	1.39	16.07	-1.99	17.67	7.61	24.54	8.11	18.09	4.63	15.65	2.68	17.13
ARPANSA	**2.4**	**9.1**	7.04	25.31	2.75	12.16	-0.64	14.20	8.96	21.00	9.46	14.73	5.98	9.17	4.04	11.45
CNEA_CAE	**12.0**	**17.9**	16.74	28.97	12.45	17.20	9.06	18.70	18.66	25.29	19.16	19.10	15.68	16.81	13.74	18.19
MKEH	**-2.4**	**9.6**	2.27	25.94	-2.02	12.48	-5.40	14.47	4.19	21.75	4.70	16.30	1.22	10.77	-0.73	11.67

The bolded NMIs are traceable to other primary standard than the BIPM, graphite calorimeters are marked with **underline**, water calorimeters are marked with ***italic***

Appendix C. Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$, for absorbed dose to water standards

lab i ⇩	lab j ⇨		***METAS***		**VSL**		**ENEA**		***NIST***		***NRC***		LNMRI		**ARPANSA**	
Absorbed dose to waterd	Di (mGy/Gy)	U(Di) (mGy/Gy)	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-4.8**	**10.3**	-5.24	12.90	-1.49	11.13	-3.79	11.02	-4.29	13.32	-3.04	12.77	-5.84	17.25	-7.20	11.72
CIEMAT	**-4.9**	**7.3**	-5.27	11.46	-1.52	9.51	-3.82	9.34	-4.32	11.93	-3.07	11.31	-5.87	14.55	-7.23	10.06
CMI	**-4.0**	**23.6**	-4.41	25.18	-0.65	24.35	-2.95	24.29	-3.45	25.40	-2.20	25.11	-5.00	26.73	-6.36	24.57
LNMC-RMTC	**-5.3**	**12.0**	-5.71	14.90	-1.96	13.46	-4.26	13.34	-4.75	15.27	-3.50	14.79	-6.31	17.39	-7.67	13.85
SSM	**-1.4**	**10.0**	-1.84	13.35	1.91	11.71	-0.39	11.57	-0.89	13.75	0.36	13.21	-2.44	16.07	-3.80	12.16
STUK	**-3.9**	**8.5**	-4.35	12.30	-0.59	10.50	-2.89	10.35	-3.39	12.73	-2.14	12.15	-4.94	15.21	-6.30	11.00
NRPA	**3.2**	**8.8**	2.79	12.45	6.54	10.68	4.24	10.53	3.75	12.89	5.00	12.31	2.19	15.34	0.84	11.17
SMU	**-4.7**	**24.7**	-5.09	25.15	-1.33	25.58	-3.63	25.18	-4.13	25.37	-2.88	25.08	-5.68	28.31	-7.04	25.31
IAEA	**-0.4**	**10.0**	-0.79	13.35	2.96	11.71	0.66	11.57	0.16	13.75	1.41	13.21	-1.39	16.07	-2.75	12.16
HAEC-HIRCL	**3.0**	**12.4**	2.59	15.23	6.34	13.82	4.04	13.70	3.55	15.58	4.80	15.11	1.99	17.67	0.64	14.20
IRB	**-6.6**	**20.3**	-7.01	20.80	-3.26	21.32	-5.55	20.84	-6.05	21.07	-4.80	20.72	-7.61	24.54	-8.96	0.00
ITN-LMRIR	**-7.1**	**13.0**	-7.51	15.72	-3.76	14.36	-6.06	14.25	-6.55	16.06	-5.30	15.61	-8.11	18.09	-9.46	14.73
PTB	**-3.6**	**7.4**	-4.03	8.71	-0.28	9.87	-2.58	8.80	-3.07	9.31	-1.82	8.51	-4.63	15.65	-5.98	9.17
BEV	**-1.7**	**10.1**	-2.09	12.61	1.66	10.85	-0.63	10.74	-1.13	13.04	0.12	12.48	-2.68	17.13	-4.04	11.45
METAS	**0.4**	**10.6**	---	---	3.75	12.47	1.45	11.64	0.96	11.45	2.21	10.81	-0.60	17.41	-1.95	11.92
VSL	**-3.4**	**8.5**	-3.75	12.47	---	---	-2.30	9.27	-2.79	12.90	-1.54	12.33	-4.35	16.19	-5.70	10.09
ENEA	**-1.1**	**8.3**	-1.45	11.64	2.30	9.27	---	---	-0.50	12.10	0.75	11.49	-2.05	16.09	-3.41	9.97
NIST	**-0.6**	**11.1**	-0.96	11.45	2.79	12.90	0.50	12.10	---	---	1.25	11.30	-1.55	17.72	-2.91	12.37
NRC	**-1.8**	**10.4**	-2.21	10.81	1.54	12.33	-0.75	11.49	-1.25	11.30	---	---	-2.81	17.31	-4.16	11.77
LNMRI	**1.0**	**15.0**	0.60	17.41	4.35	16.19	2.05	16.09	1.55	17.72	2.81	17.31	---	---	-1.36	16.52
ARPANSA	**2.4**	**9.1**	1.95	11.92	5.70	10.09	3.41	9.97	2.91	12.37	4.16	11.77	1.36	16.52	---	---
CNEA_CAE	**12.0**	**17.9**	11.65	18.45	15.40	17.31	13.11	17.22	12.61	18.75	13.86	18.36	11.05	20.51	9.70	17.62
MKEH	**-2.4**	**9.6**	-2.81	13.20	0.94	10.34	-1.36	10.22	-1.86	13.60	-0.60	13.06	-3.41	16.76	-4.77	10.97

The bolded NMIs are traceable to other primary standard than the BIPM, graphite calorimeters are marked with **underline**, water calorimeters are marked with ***italic***

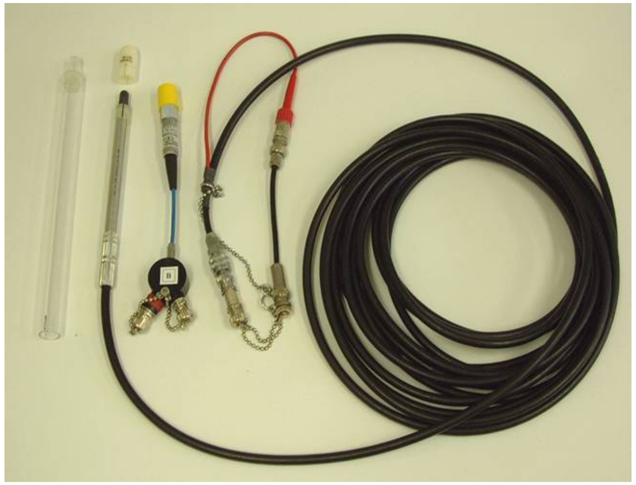
Appendix C. Pair-wise degrees of equivalence, D_{ij}, with its expanded uncertainty, $U(D_{ij})$, for absorbed dose to water standards

lab i ⇩	**lab j ⇨**		CNEA_CAE		**MKEH**	
Absorbed dose to waterd	**Di (mGy/Gy)**	**U(Di) (mGy/Gy)**	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
LNE-LNHB	**-4.8**	**10.3**	-16.90	18.31	-2.43	11.93
CIEMAT	**-4.9**	**7.3**	-16.93	15.78	-2.46	10.44
CMI	**-4.0**	**23.6**	-16.06	27.42	-1.59	24.73
LNMC-RMTC	**-5.3**	**12.0**	-17.36	18.43	-2.90	14.13
SSM	**-1.4**	**10.0**	-13.50	17.20	0.97	12.48
STUK	**-3.9**	**8.5**	-16.00	16.40	-1.53	11.35
NRPA	**3.2**	**8.8**	-8.86	16.52	5.60	11.52
SMU	**-4.7**	**24.7**	-16.74	28.97	-2.27	25.94
IAEA	**-0.4**	**10.0**	-12.45	17.20	2.02	12.48
HAEC-HIRCL	**3.0**	**12.4**	-9.06	18.70	5.40	14.47
IRB	**-6.6**	**20.3**	-18.66	25.29	-4.19	21.75
ITN-LMRIR	**-7.1**	**13.0**	-19.16	19.10	-4.70	16.30
PTB	**-3.6**	**7.4**	-15.68	16.81	-1.22	10.77
BEV	**-1.7**	**10.1**	-13.74	18.19	0.73	11.67
METAS	**0.4**	**10.6**	-11.65	18.45	2.81	13.20
VSL	**-3.4**	**8.5**	-15.40	17.31	-0.94	10.34
ENEA	**-1.1**	**8.3**	-13.11	17.22	1.36	10.22
NIST	**-0.6**	**11.1**	-12.61	18.75	1.86	13.60
NRC	**-1.8**	**10.4**	-13.86	18.36	0.60	13.06
LNMRI	**1.0**	**15.0**	-11.05	20.51	3.41	16.76
ARPANSA	**2.4**	**9.1**	-9.70	17.62	4.77	10.97
CNEA_CAE	**12.0**	**17.9**	---	---	14.46	17.84
MKEH	**-2.4**	**9.6**	-14.46	17.84	---	---

The bolded NMIs are traceable to other primary standard than the BIPM, graphite calorimeters are marked with **underline**, water calorimeters are marked with ***italic***

Appendix D:

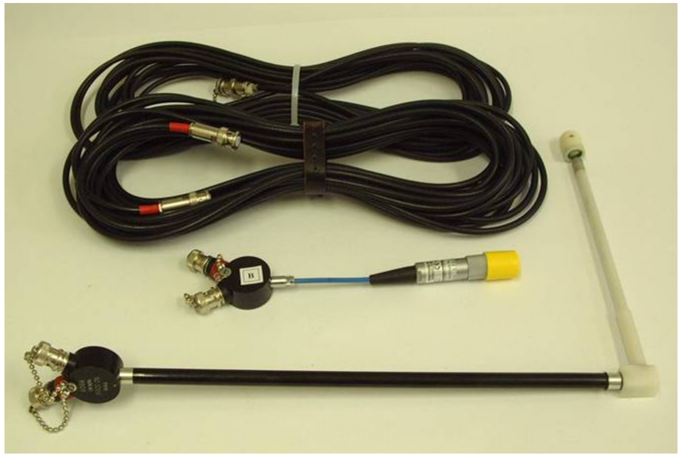
Photographs of the transfer chambers and electrometers


NE 2561


PTW 30001


PAM 2001


Wellhöffer FC-65 G


ND 1006


UNIDOS

Physical constants and correction factors with their estimated relative uncertainties for the determination of air kerma of Co-6 radiation at the OMH

The cylindrical shape chamber wall and electrode materials are ultra pure graphite EK 51 Ringsdorf, of density 1.75gcm^{-3} and with impurities less than 1.5e-4. The applied insulators made from PTFE (teflon).

		Co-60	**Etalon type ND1005**	
		value	u_A	u_B
Physical Constants				
ρ	dry air density	1.2046E-06		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985		0.05
$s_{c,a}$		1.0010		0.11
W/e	J/C	33.97		
g	bremsstrahlung loss	0.0032		0.02
Correction factors:				
k_s	recombination losses	1.0019	0.04	0.05
k_h	humidity	0.9970		0.03
k_{st}	stem scattering	0.9998	0.05	
k_{wall}	wall effects	1.0212	0.01	0.05
k_{pn}	point source non-uniformity	0.9999	0.04	0.05
k_{rn}	radial non-uniformity	1.0000		0.05
k_{pol}	polarity	1.0000		0.05
Charge measurement				
V / cm^3	chamber volume	1.0227	0.10	
Q	charge		0.03	0.05
distance				0.02
N_K / Gy/C	**calibration factor**	**2.8195E+07**		
quadratic summation			0.13	0.18
combined uncertainty			**0.22**	

Etalon type ND1005	
Dimensions (mm)	
Outer height	19
Outer diameter	19
Inner height	11
Inner diameter	11
Min. wall	4
Electrode diameter	2
Electrode height	8.97
Volume of air cavity(cm^3)	1.0227
Applied voltage	±250 volt
Leakage current	4 fA
Electrode height	8.97
Volume of air cavity(cm^3)	1.0227
Applied voltage	±250 volt
Leakage current	4 fA

standard uncertainties of therapy chamber calibration in Co-60		
Reference air kerma rate		0.22
Ionization current	0.03	
Reference distance	–	0.04
Correction for standard air temperature and pressure	–	0.04
Correction for air humidity	–	0.01
Correction for source decay	–	0.03
	0.03	0.23
Combined uncertainty of chamber calibration	**0.23**	

Relative standard uncertainties for calibrations in terms of absorbed dose to water for 60Co gamma rays at the OMH.	relative standard uncertainty	
	100 $u_{i\,\mathrm{A}}$	100 $u_{i\,\mathrm{B}}$
Measurement of absorbed dose rate to graphite [1]		
Electrical calibration power	0.03	0.15
Mass of the core		0.02
Temperature sensitivity by radiatio	0.20	
Temperature sensitivity by electrical heatin	0.20	
Electrical calibration time		0.03
Correction factors		
Impurities		0.08
Heat loss (temperature gradiens)		0.05
Electrical power loss in lead		0.01
Axial non-uniformit		0.02
Depth of point of measurement		0.02
Vacuum and air gaps		0.08
Homogenity of graphite		0.02
Long-term stability of the dose rate (1991-2002) (Including the half –life of 60Co)	0.09	0.03
Quadratic summation	0.298	0.203
Uncertainty of absorbed dose rate to graphite	**0.36**	
Transfer absorbed dose from graphite to water		
Correction for scaled (5.556 g cm^{-2}) measurement depth, $k_{\mathrm{c,d}}$	–	0.01
Correction phantom scatter, $k_{\mathrm{w,p}}$	–	0.09
Ratio of mass energy-absorption coefficients	–	0.30
Ratio of dose-to-kerma ratios $\beta_\mathrm{w}/\beta_\mathrm{c}$	–	0.06
Deviation from scaling theorem,k_{dev}	–	0.10
Uncertainty of transfer from graphite to water	–	0.334
Calibration of ionization chambers		
Ionization current	0.03	0.05
Correction to reference distance	–	0.02
Correction to reference depth	–	0.05
Correction for air temperature and pressure	–	0.04
Correction for air humidity	–	0.01
Correction for source decay	–	0.03
Uncertainty of chamber calibration	0.03	0.089
	0.09	
Quadratic summation	0.300	0.401
Combined standard uncertainty of $N_{D_\mathrm{w},\mathrm{OM}}$	**0.50**	

	100 $u_{i\,A}$	100 $u_{i\,B}$
Determination of D_c		
measurement		
temperature rise signal	0.05	
irradiation time		0.005
calorimeter		
mass of the core		0.020
electrical calibration		
electrical power calibration		0.015
temprature rise signal		0.020
calibration time		0.005
Correction Factors		
impurities		0.100
temperature gradient		0.050
heat defect		0.100
depth		0.100
distance		0.010
vacuum gaps		0.150
entrance foil attenuation		0.010
axial non-uniformity		
radial non-uniformity		0.010
Quadratic Summation	0.05	0.24
		0.24
Transfer chamber in graphite phantom		
ionization current	0.01	0.03
distance		0.02
depth in graphite		0.05
Transfer chamber in water phantom		
ionization current	0.01	0.03
distance		0.02
depth in water		0.03
Ratios of Correction Factors		
stopping powers		0.03
wall + cavity effects		0.20
$(\mu en/\rho)_{w,c}$		0.15
$\beta_{w,c}$		0.05
Ionometric transfer from the old source to the new source	0.02	0.29
Quadratic Summation	0.02	0.39
		0.40
Quadratic Summation	0.06	0.46
		0.46

Kair	100 $u_{i\,A}$	100 $u_{i\,B}$
Physical Constants		
ρ_0		0.01
$(\mu_{en}/\rho)_{a,c}$		0.07
$W/e\ S_{c,a}$		0.27
g		0.02
Correction Factors		
k_s	0.03	0.02
k_h		0.03
k_{st}		0.05
$k_{at}\ k_{sc}\ k_{cep}$		0.21
k_{an}		0.03
k_{rn}	0.01	0.02
V	0.01	0.03
I	0.01	0.02
Quadratic	0.03	0.37
		0.38

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LABORATORIO DE METROLOGÍA
DE RADIACIONES IONIZANTES
Laboratorio
de
Patrones
Nacionales
(Asociado al CEM)

RELATIVE STANDARD UNCERTAINTIES OF THE AIR KERMA RATE FOR Co-60 GAMMA RADIATION (CIEMAT NATIONAL LABORATORY, SPAIN)

	$s_i \times 10^2$	$u_j \times 10^2$
Ionization current	*0.015*	*0.09*
Air pressure		*0.055*
Air temperature		*0.02*
Correction for 50 % R.H.		*0.003*
Calibration coefficient, $N_{K, BIPM}$	*0.04*	*0.17*
Beam spectral difference CIEMAT-BIPM		*0.1*
Long term stability of Shonka chambers		*0.058*
Ratio $(k_s)_{CIEMAT}/(k_s)_{BIPM}$		*0.01*
Ratio $(k_{rn})_{CIEMAT}/(k_{rn})_{BIPM}$		*0.05*
Correction to FDD=100 cm		*0.033*
Thermal expansion correction		*0.004*
Quadratic sum	*0.043*	*0.240*
Combined uncertainty		*0.24*

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RELATIVE STANDARD UNCERTAINTIES OF THE ABSORBED DOSE RATE TO WATER AT 5 g cm^{-2} FOR Co-60 GAMMA RADIATION (CIEMAT NATIONAL LABORATORY, SPAIN)

	$s_i \times 10^2$	$u_j \times 10^2$
Ionization current	0.031	0.09
Air pressure		0.055
Air temperature		0.005
Correction for 50 % R.H.		0.003
Calibration coefficient, $N_{W,\,BIPM}$		0.30
Beam spectral difference CIEMAT-BIPM		0.1
Long term stability of Shonka chambers		0.058
Ratio $(k_s)_{CIEMAT}/(k_s)_{BIPM}$		0.01
Ratio $(k_{rn})_{CIEMAT}/(k_{rn})_{BIPM}$		0.09
Non-equivalence to water of the PMMA window of the CIEMAT phantom		0.07
Correction to FDD=100 cm		0.026
Thermal expansion correction		0.003
Quadratic sum	0.031	0.358
Combined uncertainty		0.36

Absorbed dose rate uncertainty budget

source of uncertainty	u_B (%)	u_A (%)
calibration coefficient	1	
ionisation current	0.23	0.05
leakage current	0.23	0.1
temperature	0.15	
pressure	0.1	
air humidity	0.1	
distance (SDD)	0.06	
depth in water	0.2	
quadratic summation	1.09	0.11
combined uncertainty	1.097	
Expanded standard uncertainty (k=2)	2.195	

Air kerma rate uncertainty budget

source of uncertainty	u_B (%)	u_A (%)
calibration coefficient	0.55	
ionisation current	0.23	0.05
leakage current	0.23	0.1
temperature	0.15	
pressure	0.1	
air humidity	0.1	
distance (SDD)	0.06	
quadratic summation	0.671	0.112
combined uncertainty	0.683	
Expanded standard uncertai	1.367	

Calibration coefficient uncertainty budget

source of uncertainty	u_B (%)	u_A (%)
air kerma rate	1.097	
response of user electrometer	0.3	0.1
distance (SDD)	0.06	
temperature	0.15	
pressure	0.1	
air humidity	0.1	
depth in water	0.2	
quadratic summation	1.175	0.1
combined uncertainty	1.179	
Expanded standard uncertainty (k=2)	2.358	

Calibration coefficient uncertainty budget

source of uncertainty	u_B (%)	u_A (%)
air kerma rate	0.683	
response of user electromete	0.3	0.1
distance (SDD)	0.06	
temperature	0.15	
pressure	0.1	
air humidity	0.1	
quadratic summation	0.776	0.1
combined uncertainty	0.783	
Expanded standard uncertai	1.565	

Radiation Metrology and Testing cent Latvia

Calibration coeficent uncertainty Nk

	standard uncertainty
Position in the beam	0.10%
Air kerma rate uncertainty	0.41%
Pressure determination unceratainty	0.05%
Temperature determination unceratainty	0.07%
Air humidity	0.10%
Decay variation during the calibration	0.02%
User electrometer	0.02%
Field non-uniformity	0.23%
Depth in wather	0.03%
Combined uncertainty	0.50%
Expanded uncertainty (k=2), 95%	1.00%

Our reference standard PTW chamber 30013 S/N 0759 chamber certificate traceable to BIPM

Calibration coeficent uncertainty Ndw

	standard uncertainty
Position in the beam	0.10%
Air kerma rate uncertainty	0.50%
Pressure determination unceratainty	0.10%
Temperature determination unceratainty	0.14%
Air humidity	0.10%
Decay variation during the calibration	0.02%
User electrometer	0.02%
Field non-uniformity	0.23%
Depth in wather	0.03%
Combined uncertainty	0.60%
Expanded uncertainty (k=2), 95%	1.20%

Our reference standard PTW chamber 30013 S/N 0759 chamber certificate traceable to BIPM

Source of uncertainty	**Kerma rate**		***N_K***	
	Type A	Type B	Type A	Type B
	s_i (%)	u_i (%)	s_i (%)	u_i (%)
Calibration coeff sec. Standard from BIPM	0.03	0.17	0.03	0.17
Stability sec. Standard	0.04		0.04	
Is: current corrected for T and p	0.02	0.02	0.02	0.02
Recombination		0.01		0.01
Humidity		0.03		0.03
Field inhomogeneity		0.06		0.06
Spectral differences BIPM-SSI		0.2		0.2
Field size		0.00		0.00
decay correction		0.01		0.01
Positioning of ionchamber		0.01		0.01
Iu: current corrected for T and p			0.1	0.02
Humidity				0.03
decay correction				0.04
Field size				0.01
Positioning of ionchamber				0.05
quadratic sum	0.05	0.27	0.11	0.28
combined standard uncertainty	0.28		0.30	

Source of uncertainty	**Absorbed dose to water rate**		***N* *Dw***	
	Type A	Type B	Type A	Type B
	s_i (%)	u_i (%)	s_i (%)	u_i (%)
Calibration coeff. Second. standard from BIPM	0.2	0.22	0.22	0.22
Stability sec. Standard	0.04		0.04	
Is: current corrected for T and p	0.004	0.02	0.004	0.02
Recombination		0.01		0.01
Humidity		0.03		0.03
front wall correction		0.01		0.01
spectral differences, BIPM SSI		0.2		0.2
Inhomogeneity		0.06		0.06
decay correction		0.012		0.012
Field size		0.003		0.003
positioning of the phantom		0.010		0.010
positioning of the ionchamber		0.013		0.013
water level		0.000		0.000
water density		0.002		0.002
Iu: corrected for T and p			0.02	0.02
Humidity				0.03
decay correction				0.038
Field size				0.014
positioning of the phantom				0.046
positioning of the ionchamber				0.047
water level				0.001
water density				0.008
quadratic sum	0.2	0.3	0.2	0.3
combined standard uncertainty	0.37		0.39	

EUROMET 813

Air kerma rate in ^{60}Co beam at 1m distance, uncertainty budget according to GUM **1st measurement (NE 2561 062) 12.10.2005**

Model function: $$\dot{K}_{air} = N_{Kair}^{std} \cdot dQ/dt \cdot k_{pT}$$

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	N_{Kair}(std)	9.462E+07	Gy C^{-1}	3.1209E+05	Gy C^{-1}	0.33	Combined uncertainty	3.914E-08	mC s^{-1}	1.222E-02	mGy s^{-1}		Air kerma calibration factor for ionisation chamber NE 2561 S/N 062 (standard) calibrated at STUK in 2005
2	k(stab,std)	1.000		0.0017		0.17	Rectangular (TypeB)	3.703E+00	mGy s^{-1}	6.296E-03	mGy s^{-1}		Stability for the standard
3	dQ_{corr}	2.1527E-09	C	1.448E-12	C	0.067	Combined uncertainty	1.720E+09	mGy s^{-1}C^{-1}	2.491E-03	mGy s^{-1}		Measured ionisation current. Corrected with leakage current.
4	dt	55	s	5.500E-03	s	0.01	Rectangular (TypeB)	6.733E-02	mGy s^{-2}	3.703E-04	mGy s^{-1}		Uncertainty of timer (electrometer internal cklok)
5	k(pT)	1.000		0.0008		0.08	Rectangular (TypeB)	3.703E+00	mGy s^{-1}	2.963E-03	mGy s^{-1}		Temperature and air pressure correction
	K_{air} (rate)	3.703	mGy s^{-1}	-			-	-		1.4282E-02	mGy s^{-1}	0.39	standard uncertainty, k = 1
										2.8563E-02	mGy s^{-1}	0.77	standard uncertainty, k = 2

*) Used for the determination of the standard uncertainty

**) Mean ionization current is corrected for 293,15 K and 101,325 kPa. Not with leakage, but uncertainty of measured current is combined uncertainty of charge and time and includes contribution of leakage current (<10fA).

$I_{corr} = dQ_{corr}/dt$

$dQ_{corr} = dQ*k_{pT}$

EUROMET 813

Air kerma rate in ^{60}Co beam at 1m distance, uncertainty budget according to GUM **2nd measurement (NE 2561 062) 18.10.2005**

Model function: $$\dot{K}_{air} = N_{Kair}^{std} \cdot dQ/dt \cdot k_{pT}$$

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	N_{Kair}(std)	9.462E+07	Gy C^{-1}	3.1209E+05	Gy C^{-1}	0.33	Combined uncertainty	3.914E-08	mC s^{-1}	1.222E-02	mGy s^{-1}		Air kerma calibration factor for ionisation chamber NE 2561 S/N 062 (standard) calibrated at STUK in 2005
2	k(stab,std)	1.000		0.0017		0.17	Rectangular (TypeB)	3.703E+00	mGy s^{-1}	6.296E-03	mGy s^{-1}		Stability for the standard
3	dQ_{corr}	2.1469E-09	C	1.238E-12	C	0.058	Combined uncertainty	1.725E+09	mGy s^{-1}C^{-1}	2.135E-03	mGy s^{-1}		Measured ionisation current. Corrected with leakage current.
4	dt	55	s	5.500E-03	s	0.01	Rectangular (TypeB)	6.733E-02	mGy s^{-2}	3.703E-04	mGy s^{-1}		Uncertainty of timer (electrometer internal cklok)
5	k(pT)	1.000		0.0008		0.08	Rectangular (TypeB)	3.703E+00	mGy s^{-1}	2.963E-03	mGy s^{-1}		Temperature and air pressure correction
	K_{air} (rate)	3.693	mGy s^{-1}	-			-	-		1.4224E-02	mGy s^{-1}	0.39	standard uncertainty, k = 1
										2.8448E-02	mGy s^{-1}	0.77	standard uncertainty, k = 2

*) Used for the determination of the standard uncertainty

**) Mean ionization current is corrected for 293,15 K and 101,325 kPa. Not with leakage, but uncertainty of measured current is combined uncertainty of charge and time and includes contribution of leakage current (<10fA).

$I_{corr} = dQ_{corr}/dt$

$dQ_{corr} = dQ*k_{pT}$

EUROMET 813

Dose to water rate in ^{60}Co beam at 50mm depth uncertainty budget according to GUM **1st measurement (NE 2561 sno. 097) 19.10.2005**

Model function: $\dot{D}_w = N_{Dw}^{std} \cdot dQ/dt \cdot k_{pT}$

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	[1] N_w(std)	1.0248E+08	Gy C^{-1}	3.0469E+05	Gy C^{-1}	0.30	Combined uncertainty	3.278E-08	mC s^{-1}	9.988E-03	mGy s^{-1}		Dose to water calibration factor for ionisation chamber NE 2561 S/N 062 (standard) calibrated at STUK in 2005
2	k(stab,std)	1.000		0.0017		0.17	Rectangular (TypeB)	3.359E+00	mGy s^{-1}	5.711E-03	mGy s^{-1}		Stability for the standard
3	dQ_{corr}	1.8030E-09	C	1.115E-12	C	0.062	Combined uncertainty	1.863E+09	mGy $s^{-1}C^{-1}$	2.078E-03	mGy s^{-1}		Measured ionisation current. Corrected with leakage current.
4	dt	55	s	5.500E-03	s	0.01	Rectangular (TypeB)	6.108E-02	mGy s^{-2}	3.359E-04	mGy s^{-1}		Uncertainty of timer (electrometer internal cklok)
6	k(pT)	1.000		0.0008		0.08	Rectangular (TypeB)	3.359E+00	mGy s^{-1}	2.688E-03	mGy s^{-1}		Temperature and air pressure correction
	D_w (rate)	3.359	mGy s^{-1}	-			-	-		1.2001E-02	mGy s^{-1}	0.36	standard uncertainty, k = 1
										2.4003E-02	mGy s^{-1}	0.71	standard uncertainty, k = 2

*) Used for the determination of the standard uncertainty

[1] Secondary standard NE 2561 (097) calibrated in PSDL (BIPM).

EUROMET 813

Dose to water rate in ^{60}Co beam at 50mm depth uncertainty budget according to GUM **2nd measurement (NE 2561 sno. 062) 20.10.2005**

Model function: $\dot{D}_w = N_{Dw}^{std} \cdot dQ/dt \cdot k_{pT}$

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	[2] N_w(std)	1.0326E+08	Gy C^{-1}	4.4832E+05	Gy C^{-1}	0.43	Combined uncertainty	3.249E-08	mC s^{-1}	1.457E-02	mGy s^{-1}		Dose to water calibration factor for ionisation chamber NE 2561 S/N 062 (standard) calibrated at STUK in 2005
2	k(stab,std)	1.000		0.0017		0.17	Rectangular (TypeB)	3.355E+00	mGy s^{-1}	5.704E-03	mGy s^{-1}		Stability for the standard
3	dQ_{corr}	1.7871E-09	C	8.980E-13	C	0.050	Combined uncertainty	1.877E+09	mGy $s^{-1}C^{-1}$	1.686E-03	mGy s^{-1}		Measured ionisation current. Corrected with leakage current.
4	dt	55	s	5.500E-03	s	0.01	Rectangular (TypeB)	6.100E-02	mGy s^{-2}	3.355E-04	mGy s^{-1}		Uncertainty of timer (electrometer internal cklok)
6	k(pT)	1.000		0.0008		0.08	Rectangular (TypeB)	3.355E+00	mGy s^{-1}	2.684E-03	mGy s^{-1}		Temperature and air pressure correction
	D_w (rate)	3.355	mGy s^{-1}	-			-	-		1.5965E-02	mGy s^{-1}	0.48	standard uncertainty, k = 1
										3.1930E-02	mGy s^{-1}	0.95	standard uncertainty, k = 2

*) Used for the determination of the standard uncertainty

**) Mean ionization current is corrected for 293,15 K and 101,325 kPa. Not with leakage, but uncertainty of measured current is combined uncertainty of charge and time and includes contribution of leakage current (<10fA).

$I_{corr} = dQ_{corr}/dt$

$dQ_{corr} = dQ * k_{pT}$

[2] Working standard NE 2561 (062) calibrated in SSDL-Helsinki (STUK). Tracebility of calibration factor to primary dosimetry laboratory BIPM.

Cobolt-60 air Kerma **Uncertaintybudget Doslab NRPA**

Utarbeidet av	Rev. Nr./Dato	Dokument nr.
Berit Sundby Avset Hans Bjerke	02/05.01.2006	V-3-03-01

	Source of uncertainty	**Quantity** X_i	**Estimate** x_i	**Deviation** u_c	**rel. st. unc** $u(x_i)$	**Prob. dist.**	**Sens. Coeff.** c_i	$u(x_i)$ **%**
1	**Factors due to radiation field, set-up and calibration:**							
1.1	Differences in energy spectra of radiation beams	$\mathbf{k_{spec}}$	1	0	0.0000		1	0.00
1.2	Field inhomogeneity	$\mathbf{k_{inhom}}$	1	0.0010	0.0010	N	1	0.10
1.3	Uncertainty of the calibration coefficient reported by PSDL	$\mathbf{N_K}$ [Gy/µC]	45.78	0.08	0.0017	N	1	0.17
1.4	Constancy of the calibration coefficient		45.76	0.0447	0.0010	N	1	0.10
	Quadratic sum							0.05
	Combined uncertainty						**u_c(y) %**	0.22
2	**Factors influencing the reference standard:**							
2.1	Calibration factor of electrometer	$\mathbf{k}_{elec}$	1		0.0005	N	1	0.05
2.2	Ionization current (pA)	**I** [pA]	50	0.026	0.0001	N	1	0.01
2.3	Leakage current	**ΔI** [pA]	0.01	0.002	0.0000	N	0.02	0.00
2.4	Recombination	$\mathbf{k}_s$	1	0.0014	0.0008	R	1	0.08
2.5	Polarity effect	$\mathbf{k}_{pol}$	1	0.0005	0.0003	R	1	0.03
2.6	Temperature (K)	$\mathbf{k}_T$	1	0.0006	0.0006	N	1	0.06
2.7	Pressure (kPa)	$\mathbf{k}_P$	1	0.0001	0.0001	N	1	0.01
2.8	Humidity	$\mathbf{k}_h$	1	0.0004	0.0002	R	1	0.02
2.9	Chamber orientation		1	0.0008	0.0005	R	1	0.05
2.10	Reproduction of source to chamber distance		1	0.0008	0.0008	N	1	0.08
2.1	Stem effect and reproduction of field size (10 cm x 10 cm).		1	0.0001	0.0001	R	1	0.01
	Quadratic sum							0.02
	Combined uncertainty						**u_c(y) %**	0.15
3	**Total uncertainty determination of air kerma rate**							
	Quadratic sum							0.07
	Combined uncertainty						**u_c(y) %**	0.27
	Expanded uncertainty (k=2)							0.54
4	**Factors influencing the transfer chamber**							
3.1	Calibration factor of electrometer *Separate input in the res*	$\mathbf{k}_{elec}$	1		0.0000	N	1	
3.2	Ionization current (pA) *Separate input in the results*	**I** [pA]	50	0.026	0.0001	N	1	
3.3	Leakage current *Separate input input in the results*	**ΔI** [pA]	0.01	0.002	0.0000	N	0.02	
3.4	Recombination	$\mathbf{k}_s$	1	0.0014	0.0008	R	1	0.08
3.5	Polarity effect	$\mathbf{k}_{pol}$	1	0.0005	0.0003	R	1	0.03
3.6	Temperature (K) *Separate input input in the results*	$\mathbf{k}_T$	1	0.0006	0.0006	N	1	
3.7	Pressure (kPa) *Separate input input in the results*	$\mathbf{k}_P$	1	0.0001	0.0001	N	1	
3.8	Humidity	$\mathbf{k}_h$	1	0.0004	0.0002	R	1	0.02
3.9	Chamber orientation		1	0.0008	0.0005	R	1	0.05
3.10	Reproduction of source to chamber distance		1	0.0008	0.0008	N	1	0.08
3.1	Stem effect and reproduction of field size (10 cm x 10 cm).		1	0.0001	0.0001	R	1	0.01
	Quadratic sum							0.02
	Combined uncertainty						**u_c(y) %**	0.13
5	**Total uncertainty air kerma calibration coefficient**							
	Quadratic sum							0.09
	Combined uncertainty						**u_c(y) %**	0.30
	Expanded uncertainty (k=2)							0.60

Cobolt-60 absorbed dose to water

Uncertaintybudget Doslab NRPA

Utarbeidet av	Rev. Nr./Dato	Dokument nr.
Berit Sundby Avset Hans Bjerke	02/03.01.200	V-3-04-01

	Source of uncertainty	Quantity X_i	Estimate x_i	Deviation u_c	rel. st. un $u(x_i)$	Prob. dist.	Sens. Coeff. c_i	$u(x_i)$ %
1	**Factors due to radiation field, set-up and calibration:**							
1.1	Phantom	$\mathbf{k}_{\mathbf{NRPA}}$	1	0.0004	0.0004	N	1	0.04
1.2	Differences in energy spectra of radiation beams	$\mathbf{k}_{\mathbf{spec}}$	1	0	0.0000		1	0.00
1.3	Field inhomogeneity	$\mathbf{k}_{\mathbf{inhom}}$	1	0.0010	0.0010	N	1	0.10
1.4	Uncertainty of the calibration coefficient reported by PSDL	$\mathbf{N}_{\mathbf{D,W}}$ [Gy/µC]	50.09	0.15	0.0030	N	1	0.30
1.5	Constancy of the calibration coefficient		50.09	0.0427	0.0009	N	1	0.09
	Quadratic sum							0.11
	Combined uncertainty						**$u_c(y)$ %**	0.33
2	**Factors influencing the reference standard:**							
2.1	Calibration factor of electrometer	$\mathbf{k}_{\mathrm{elec}}$	1		0.0005	N	1	0.05
2.2	Ionization current (pA)	**I** [pA]	50	0.026	0.0001	N	1	0.01
2.3	Leakage current	**ΔI** [pA]	0.01	0.002	0.0000	N	0.02	0.00
2.4	Recombination	$\mathbf{k}_{\mathrm{s}}$	1	0.0014	0.0008	R	1	0.08
2.5	Polarity effect	$\mathbf{k}_{\mathrm{pol}}$	1	0.0005	0.0003	R	1	0.03
2.6	Temperature (K)	$\mathbf{k}_{\mathrm{T}}$	1	0.0002	0.0002	N	1	0.02
2.7	Pressure (kPa)	$\mathbf{k}_{\mathrm{P}}$	1	0.0001	0.0001	N	1	0.01
2.8	Humidity	$\mathbf{k}_{\mathrm{h}}$	1	0.0004	0.0002	R	1	0.02
2.9	Chamber orientation		1	0.0008	0.0005	R	1	0.05
2.10	Reproduction of distance and sleeve positioning		1	0.001	0.0010	N	1	0.10
2.11	Stem effect and reproduction of field size (10 cm x 10 cm).		1	0.0001	0.0001	R	1	0.01
	Quadratic sum							0.02
	Combined uncertainty						**$u_c(y)$ %**	0.15
3	**Total uncertainty determination of dose rate**							
	Quadratic sum							0.13
	Combined uncertainty						**$u_c(y)$ %**	0.36
	Expanded uncertainty (k=2)							0.73
4	**Factors influencing the transfer chamber**							
3.1	Calibration factor of electrometer *Separate input in the res*	$\mathbf{k}_{\mathrm{elec}}$	1		0.0000	N	1	
3.2	Ionization current (pA) *Separate input in the results*	**I** [pA]	50	0.026	0.0001	N	1	
3.3	Leakage current *Separate input in the results*	**ΔI** [pA]	0.01	0.002	0.0000	N	0.02	
3.4	Recombination	$\mathbf{k}_{\mathrm{s}}$	1	0.0014	0.0008	R	1	0.08
3.5	Polarity effect	$\mathbf{k}_{\mathrm{pol}}$	1	0.0005	0.0003	R	1	0.03
3.6	Temperature (K) *Separate input in the results*	$\mathbf{k}_{\mathrm{T}}$	1	0.0002	0.0002	N	1	
3.7	Pressure (kPa) *Separate input in the results*	$\mathbf{k}_{\mathrm{P}}$	1	0.0001	0.0001	N	1	
3.8	Humidity	$\mathbf{k}_{\mathrm{h}}$	1	0.0004	0.0002	R	1	0.02
3.9	Chamber orientation		1	0.0008	0.0005	R	1	0.05
3.10	Reproduction of distance and sleeve position		1	0.001	0.0010	N	1	0.10
3.11	Stem effect and reproduction of field size (10 cm x 10 cm).		1	0.0001	0.0001	R	1	0.01
	Quadratic sum							0.02
	Combined uncertainty						**$u_c(y)$ %**	0.14
5	**Total uncertainty absorbed dose to water calibration coefficient**							
	Quadratic sum							0.15
	Combined uncertainty						**$u_c(y)$ %**	0.39
	Expanded uncertainty (k=2)							0.78

SMU

Physical constants and correction factors with their estimated relative uncertainty for the determination of air kerma in ^{60}Co radiation at SMU.
Ionisation chamber is the cylindrical shape chamber, wall and electrode materials are made of ultra pure graphite.

	SMU values	relative $^{(1)}$ uncertainty [%]	
		u_A	u_B
Physical constants			
ρ dry air density [kg·m^{-3}] (for reference conditions)	1.2048	-	0.01
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05
$\bar{s}_{c,a}$ stopping power ratio	1.001 0	-	0.11
W/e [J C^{-1}] (J·C^{-1})	33.97		
$\bar{g}$ fraction of energy lost by bremsstrahlung	0.003 2	-	0.02
Correction factors			
k_s recombination losses	1.001 7	0.01	0.03
k_h humidity	0.997 0	-	0.03
k_{st} stem scattering	0.999 7	0.01	-
k_{wall} wall effects	1.0191	0.03	0.08
k_{an} axial non-uniformity	0.9998	-	0.01
k_{rn} radial non-uniformity	1.0003	-	0.01
k_{pol} polarity	0.9989		0.08
Measurement of $I/v\rho$			
v volume [cm^3]	1.0185	0.19	0.10
I ionization current		0.02	0.05
distance			0.02
long term stability			0.11
N_k [Gy/C] calibration factor	**2.8215+E07**		
Uncertainty			
quadratic summation		0.19	0.23
combined uncertainty		**0.30**	

Characteristics of the SMU standard of air kerma

Type	ND1005/A - 8111	
		Nominal values
Chamber	Outer height [mm]	19
	Outer diameter [mm]	19
	Inner diameter [mm]	11
	Wall thickness [mm]	4
Electrode	Diameter [mm]	2
	Height [mm]	10
Volume	Air cavity [cm^3]	1.0185
	relative uncertainty [cm^3]	0.0019
Wall	Material	ultra pure graphite
	Density [g·cm^{-3}]	1.71
	Impurity fraction	$< 1.5 \times 10^{-4}$
Applied tension	Voltage [V]	300

(1) Expressed as one standard deviation.

SMU

Calibration factor uncertainty N_k

Quantiy	Value	Uncertainty	Probability distribution	Divisor	c_i	u_i	v_i
Air kerma rate, primary standard [m	5.55E-03	0.30%	normal	1.000	1	0.300	∞
Mean ionisation current of calibrate	111.106	0.009	normal	1.000	1	0.008	9
Mean background reading of calibr	0.007	0.001	normal	1.000	1	0.001	9
Recombination - calibrated chamber		0.10%	rectangular	1.732	1	0.058	∞
Polarity efect - calibrated chamber		0.10%	normal	1.000	1	0.080	∞
Electrometer stability		0.10%	rectangular	1.732	1	0.058	∞
Air pressure [kPa]	100.625	0.1	rectangular	1.732	1	0.057	∞
Temperature measured [°C]	20.18	0.2	rectangular	1.732	1	0.039	∞
Real temperature inside the chamb	20.18	0.3	rectangular	1.732	1	0.059	∞
Air relative humidity		0.05%	rectangular	1.732	1	0.029	∞
FDD [mm]	1000	0.3	rectangular	1.732	1	0.035	∞
Variation of air kerma during the day		0.04%	rectangular	1.732	1	0.023	∞
Field non-uniformity		0.05%	normal	1.000	1	0.050	
u_c Relative combined uncertainty [%]						**0.35**	85
U Expanded standard uncertainty (k = 2)						**0.70**	

SMU

Absorbed dose to water uncertainty - secondary standard D_w

Quantiy	Value	Uncertainty	Probability distribution	Divisor	c_i	u_i	v_i
Mean ionisation current of secondary standard, M	100.816	0.009	normal	1.000	1	0.009	9
Mean background reading, M_B	0.007	0.001	normal	1.000	1	0.001	9
Secondary standard chamber TW 30013 s.n. 1452 calibration,certifiacte [Gy/C]	5.38E+07	1.9%	normal	2.000	1	0.950	∞
Long-term stability of ionisation chamber		0.1%	normal	1.000	1	0.100	∞
Electrometer factor	1.00016	0.00001	rectangular	1.732	1	0.001	∞
Electrometer stability		0.05%	normal	1.000	1	0.050	∞
Recombination - calibrated chamber	1.000	0.05%	normal	1.000	1	0.050	∞
Polarity efect		0.1%	normal	1.000	1	0.100	∞
FDD [mm]	1000	0.35	rectangular	1.732	2	0.040	∞
5 g/cm2 in water	5.000	0.02	rectangular	1.732	2	0.462	∞
Air pressure	100.625	0.1	rectangular	1.732	1	0.057	∞
Temperature measured	19.244	0.2	rectangular	1.732	1	0.040	∞
Real temperature inside the chamber	19.244	0.1	rectangular	1.732	1	0.020	∞
air humidity		0.05%	rectangular	1.732	1	0.029	∞
Field non-uniformity		0.05%	normal	1.000	1	0.050	∞
u_c relative combined uncertainty [%]						**1.1**	85
U Expanded standard uncertainty (k=2)						**2.2**	

Chamber TW 30013 s.n.1452 certificate traceable to PTB

SMU

Calibration factor uncertainty N_{Dw}

Absorbed dose to water rate, secondary standar	5.4302	1.1%	normal	1.000	1	1.100	∞
Mean ionisation current of calibrated chamber, M	111.106	0.01	normal	1.000	1	0.009	9
Mean background reading, M_B	0.007	0.005	normal	1.000	1	0.005	9
Recombination - calibrated chamber		0.10%	rectangular	1.732	1	0.058	∞
Polarity efect - calibrated chamber		0.10%	normal	1.000	1	0.100	∞
Electrometer stability		0.10%	rectangular	1.732	1	0.058	∞
Air pressure	100.625	0.1	rectangular	1.732	1	0.057	∞
Temperature measured	19.244	0.2	rectangular	1.732	1	0.040	∞
Real temperature inside the chamber	19.244	0.1	rectangular	1.732	1	0.020	∞
Air humidity		0.05%	rectangular	1.732	1	0.029	∞
FDD	1000	0.4	rectangular	1.732	2	0.046	∞
5 g/cm2 in water	5	0.02	rectangular	1.732	2	0.462	∞
Variation of air kerma during the day		0.04%	rectangular	1.732	1	0.023	∞
Field non-uniformity		0.05%	normal	1.000	1	0.050	
u_c relative combined uncertainty [%]						**1.2**	85
U Expanded standard uncertainty (k=2)						**2.4**	

IAEA Secondary Standards

Air kerma

Air kerma is realized at the IAEA with a secondary standard NE-2561 ion chamber calibrated at the BIPM.
The Voltemeter and capacitor are calibrated at BEV. Temperature and pressure sensors are calibrated at BEV.

The calibrations are based on a measurement of air-kerma rate with the IAEA reference chamber, at the position of the chamber's reference point. In the first step, the IAEA chamber is placed at a reference point in air. In the second step, the EUROMET cha

Uncertainty budget - ^{60}Co NK

Working

Notes	Influence quantity	Value	Unit	Expanded uncertainty U_i	Distribution	Uncertainty Type	Confidence level	Coverage factor k	Standard uncertainty u_i	Sensitivity coefficient c_i	Uncertainty component $c_i u_i$	Effective degrees of freedom ν_{eff}	$(c_i u_i)^2$
measurement of absorbed dose to water rate													
1	**calibration at BIPM**		mGy/nC	0.22%	normal	Type B	68%	1.00	0.22%	1.00	0.22%	50	4.84E-06
2	**stability of DOL reference instrument**	1		0.25%	normal	Type A	68%	1.00	0.25%	1.00	0.25%	50	6.25E-06
measurement with the reference instrument													
3	**mean reading**		pA	0.10%	normal	Type A	68%	1.00	0.10%	1.00	0.10%	50	1.00E-06
4	**current**		pA	0.10%	rectang.	Type B	68%	1.73	0.06%	1.00	0.06%	8	3.34E-07
temperature measurments during reference measurement													
5	**resolution**		deg	0.20%		Type B	100%	1.73	0.12%	0.08	0.01%	1000	8.53E-09
pressure measurments during reference measurement													
6	**resolution**		kPa	0.10%		Type B	100%	1.73	0.06%	0.27	0.02%	1000	2.43E-08
chamber positioning													
7	**deviation in chamber depth in phantom**		mm	0.04%		Type B	100%	1.73	0.02%	1.00	0.02%	1000	5.35E-08
current measurement with the instrument to be calibrated													
8	**mean reading**			0.02%		Type A	68%	1.00	0.02%	1.00	0.02%	8	4.00E-08
9	**resolution**			0.10%		Type B	100%	1.73	0.06%	1.00	0.06%	8	3.33E-07
temperature measurments during user measurement													
10	**resolution**		deg	0.20%		Type B	100%	1.73	0.12%	0.08	0.01%	1000	8.53E-09
11	**diff (ion chamb.cavity & amb)**		deg	0.50%		Type B	100%	1.73	0.29%	0.08	0.02%	1000	5.33E-08
pressure measurments during user measurement													
12	**resolution**		kPa	0.10%		Type B	100%	1.73	0.06%	1.00	0.06%	1000	3.33E-07
13	**field non-uniformity**			0.10%		Type B	68%	1.00	0.10%	1.00	0.10%	8	1.00E-06
calibration result													
14	**calibration coefficient of user instrument**		**-**	**0.8%**		**Combined**	95%	2			0.38%	157	1.43E-05

IAEA Secondary Standards

Absorbed dose rate to water

Absorbed dose to water is realized at the IAEA with a secondary standard NE-2561 ion chamber calibrated at the BIPM.
The Voltemeter and capacitor are calibrated at BEV. Temperature and pressure sensors are calibrated at BEV.

The calibrations are based on a measurement of absorbed-dose rate with the IAEA reference chamber, at the position of the chamber’s reference point. In the first step, the IAEA chamber is placed so that it is close to the reference depth in the water phan

Uncertainty budget - ^{60}Co NDw

Working

Notes	Influence quantity	Value	Unit	Expanded uncertainty U_i	Distribution	Uncertainty Type	Confidence level	Coverage factor k	Standard uncertainty u_i	Sensitivity coefficient c_i	Uncertainty component $c_i u_i$	Effective degrees of freedom v_{eff}	$(c_i u_i)^2$
measurement of absorbed dose to water rate													
1	**calibration at BIPM**		mGy/nC	0.30%	normal	Type B	68%	1.00	0.30%	1.00	0.30%	50	9.00E-06
2	**stability of DOL reference instrument**	1		0.25%	normal	Type A	68%	1.00	0.25%	1.00	0.25%	50	6.25E-06
measurement with the reference instrument													
3	**mean reading**		pA	0.10%	normal	Type A	68%	1.00	0.10%	1.00	0.10%	50	1.00E-06
4	**current**		pA	0.10%	rectang.	Type B	68%	1.73	0.06%	1.00	0.06%	8	3.34E-07
temperature measurments during reference measurement													
5	**resolution**		deg	0.20%		Type B	100%	1.73	0.12%	0.08	0.01%	1000	8.53E-09
pressure measurments during reference measurement													
6	**resolution**		kPa	0.10%		Type B	100%	1.73	0.06%	0.27	0.02%	1000	2.43E-08
chamber positioning during reference measurement (distance)													
7	**deviation in chamber depth in phantom**		mm	0.26%		Type B	100%	1.73	0.15%	1.00	0.15%	1000	2.26E-06
current measurement with the instrument to be calibrated													
8	**mean reading**			0.02%		Type A	68%	1.00	0.02%	1.00	0.02%	8	4.00E-08
9	**resolution**			0.10%		Type B	100%	1.73	0.06%	1.00	0.06%	8	3.33E-07
temperature measurments during user measurement													
10	**resolution**		deg	0.20%		Type B	100%	1.73	0.12%	0.08	0.01%	1000	8.53E-09
11	**diff (ion chamb.cavity & amb)**		deg	0.50%		Type B	100%	1.73	0.29%	0.08	0.02%	1000	5.33E-08
pressure measurments during user measurement													
12	**resolution**		kPa	0.10%		Type B	100%	1.73	0.06%	1.00	0.06%	1000	3.33E-07
chamber positioning during user measurement (distance)													
13	**chamber depth in phantom**		mm	0.26%		Type B	95%	1.73	0.15%	1.00	0.15%	1000	2.26E-06
14	**field non-uniformity**			0.10%		Type B	68%	1.00	0.10%	1.00	0.10%	8	1.00E-06
calibration result													
15	**calibration coefficient of user instrument**		-	**1.0%**		**Combined**	95%	2.00			0.48%	#HIV!	2.29E-05

Nk	**Type A %**	**Type B %**	**Calc Distr**	**COMMENTS**	
Measurements of Kair by SSDchamber					
Nk from BIPM		**0.17**	0.168	: +/- from BIPM cerificate	
Nk stability (from Kair reproducibility)	**0.26**			from stability of Kair measur	
Electrometer inaccuracy		**0.29**		0.5 % from Electr. Specifications unless is included in Nk	
Scale reading / resolution	**0.00**	**0.00**	**0.000**	A: SD =0,0, B: scale / measurement eg 0,01pC / 8500 pC	
Uniformity of radiation beam		**0.06**	0.058	Co60 uniformity is < 0.1 %	
Difference in Co60 energy spectra (PSSD / SSDL)		**0.05**	?	Taken from litterarture	
Temperature & Pressure measurements	**0.17**	**0.08**	**0.50**	Change in temp during measurements - D12 -> I5 - See H-J columns	
Temperature difference at thermo & chamber		**0.05**		0.00 : thermometer very close & chamber left for > 2 hrs	
Chamber Positioning in distance		**0.231**	**2.0**	Distance indicator - detector size +/- 2 mm at FDD 1000 mm	
Electrometer Built-In timer		**0.00**		From measurements & included in Nk stability	
Leakage current		**0.00**		Measured < 0.1 pC for nC measurement	
Recombination loss		**0.00**		Measured for Co60	0
Humidity		**0.00**			
Kair QUADRATIC SUM	**0.31**	**0.42**			
	0.52				
User chamber measurements					
Reproducibility of measurement	**0.05**			%SD of succesive measurements	
Scale reading / resolution	*	**0.00**	**0.000**	A: SD =0,0, B: scale / measurement eg 0,01pC / 8500 pC	
Positioning in same distance		**0.231**	**2.0**	Distance indicator - detector size +/- 2 mm at FDD 1000 mm	
Uniformity of radiation beam (for different chamb)		**0.06**		Co60 uniformity is < 0.1 % & SSDL & user chamber at same beam	
Temperature & Pressure	**0.17**	**0.08**	**0.50**	Change in temp during measurements - D12 -> I5 - See H-J columns	
Difference in Temperature at two places		**0.05**		0.00 : thermometer very close & chamber left for > 2 hrs	
Leakage current		**0.00**		Measured < 0.1 pC for nC measurement	
Radiation background		**0.00**		Measured & taken the % acceptable value	
Electrometer accuracy				Included in calibration factor	
Electrometer built-in timer	*	**0.00**		Included in calibration factor	
Humidity		**0.00**		Taken from litterarture	
Recombination loss		**0.00**			
User QUADRATIC SUM	**0.17**	**0.26**			
	0.31				
QUADRATIC SUM (ALL)	**0.35**	**0.50**			
COMBINED UNCERTAINTY	**0.61**	**%**			
EXPANDED UNCERTAINTY	**1.22**	**%**			

	for REFERENCE INSTRUMENT		
kPT uncertainty	TYPE A	TYPE B	

uT=	**0.500**	0.23094	: oC temp flactuation during measurement / +/- 0,4 oC :certificate
To=	293	293	
uP=	0	0.288675	: 0 hPa flactuation during measurement +/- 0.5 hPa:certificate
Po=	1013	1013	
T=	300	300	
P=	990	990	
kpt	1.04767815	1.047678	
uk=	0.00174613	0.000862	

%uk	**0.17**	**0.08**
Combined	**0.19**	

	for USER's INSTRUMENT		
kPT uncertainty	TYPE A	TYPE B	

uT=	**0.500**	0.23094	: oC temp flactuation during measurement / +/- 0,4 oC :certificate
To=	293	293	
uP=	0	0.288675	: 0 hPa flactuation during measurement +/- 0.5 hPa:certificate
Po=	1013	1013	
T=	300	300	
P=	990	990	
kpt	1.04767815	1.047678	
uk=	0.00174613	0.000862	

%uk	**0.17**	**0.08**
Combined	**0.19**	

ND,w	Type A %	Type B %	Calc Distr	COMMENTS
Measurements of Dose to Water by SSDchamber				
ND,w from BIPM		0.29	0.288	: +/- from BIPM cerificate
Nd,w stability (from Kair reproducibility)	0.26			from stability of Dw measur
Electrometer inaccuracy		0.29		0.5 % from Electr. Specifications unless is included in Nk
Scale reading / resolution	0.00	0.00	0.000	A: SD =0,0, B: scale / measurement eg 0,01pC / 8500 pC
Uniformity of radiation beam		0.06	0.058	Co60 uniformity is < 0.1 %
Difference in Co60 energy spectra (PSSD / SSDL)		0.05	?	Taken from litterarture
Temperature & Pressure measurements	0.07	0.08	0.20	Change in temp during measurements - D12 -> I5 - See H-J columns
Temperature difference at thermo & chamber		0.05		0.00 : thermometer very close & chamber left for > 2 hrs
Chamber Positioning in distance		0.231	2.0	Distance indicator - detector size +/- 2 mm at FDD 1000 mm
Electrometer Built-In timer		0.00		From measurements & included in Nk stability
Leakage current		0.00		Measured < 0.1 pC for nC measurement
Recombination loss		0.00		Measured for Co60
Humidity		0.00		
Kair QUADRATIC SUM	0.27	0.48		
	0.55			
User chamber measurements				
Reproducibility of measurement	0.05			%SD of succesive measurements
Scale reading / resolution	*	0.00	0.000	A: SD =0,0, B: scale / measurement eg 0,01pC / 8500 pC
Positioning in same distance		0.231	2.0	Distance indicator - detector size +/- 2 mm at FDD 1000 mm
Uniformity of radiation beam (for different chamb)		0.06		Co60 uniformity is < 0.1 % & SSDL & user chamber at same beam
Temperature & Pressure	0.07	0.08	0.20	Change in temp during measurements - D12 -> I5 - See H-J columns
Difference in Temperature at two places		0.05		0.00 : thermometer very close & chamber left for > 2 hrs
Leakage current		0.00		Measured < 0.1 pC for nC measurement
Radiation background		0.00		Measured & taken the % acceptable value
Electrometer accuracy				Included in calibration factor
Electrometer built-in timer	*	0.00		included in b18
Humidity		0.00		Taken from litterarture
Recombination loss		0.00		Measured for Co60 for USER's chamber
User QUADRATIC SUM	0.08	0.26		
	0.27			
QUADRATIC SUM (ALL)	0.28	0.55		
COMBINED UNCERTAINTY	0.62	%		
EXPANDED UNCERTAINTY	1.23	%		

	for REFERENCE INSTRUMENT			
kPT uncertainty	TYPE A	TYPE B		

uT=	**0.200**	0.23094	: oC temp flactuation during measurement / +/- 0,4 oC :certificate	
To=	293	293		
uP=	0	0.288675	: 0 hPa flactuation during measurement +/- 0.5 hPa:certificate	
Po=	1013	1013		
T=	300	300		
P=	990	990		
kpt	1.047678	1.047678		
uk=	0.000698	0.000862		

%uk	**0.07**	**0.08**		
Combined	**0.11**			

	for USER's INSTRUMENT			
kPT uncertainty	TYPE A	TYPE B		

uT=	**0.200**	0.23094	: oC temp flactuation during measurement / +/- 0,4 oC :certificate	
To=	293	293		
uP=	0	0.288675	: 0 hPa flactuation during measurement +/- 0.5 hPa:certificate	
Po=	1013	1013		
T=	300	300		
P=	990	990		
kpt	1.047678	1.047678		
uk=	0.000698	0.000862		

%uk	**0.07**	**0.08**		
Combined	**0.11**			

Relative uncertainty for the determination of air kerma of Co-60

Etalon type ND1001

	Relative standard uncertainty	
Uncertainty sources	si/type A/, %	ui/type B/, %
Calibration coefficient		0.30
*Ionization current	0.10	0.42
Temperature		0.20
Pressure		0.10
Air humidity		0.10
Distance	0.05	

0.34 see BIPM rapport 02/03

* corrected with leakage

Quadratic sum, %	**0.11**	**0.57**
Combined uncertainty, %	**0.58**	

Relative uncertainty for the determination of air kerma of Co-60

Etalon type ND1001

	Relative standard uncertainty	
Uncertainty sources	si/type A/, %	ui/type B/, %
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Pressure		0.10
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* corrected with leakage

Quadratic sum, %	**0.11**	**0.57**
Combined uncertainty, %	**0.58**	

Ionization chamber TW 30013 (PTW), Serial number 1684, calibrated at PTB,2005-09-29
Reference No. 6.62-29/05K

1. Standard uncertainty of FDD	(%)	0.1
2. Standard uncertainty of K	(%)	0.35
3. Standard uncertainty kTP	(%)	0.075
4. Standard uncertainty of (Icorr)	(%)	0.039
Standard uncertainty of N_{kair}		**0.375**

Ionization chamber TW30013 (PTW), Serial number 1684, Calibrated at PTB 2005-09-28
Reference No. 6.21-29/05 K

1. Standard uncertainty of 5g/cm2 in water	(%)	0.05
2. Standard uncertainty of FDD	(%)	0.1
3. Standard uncertainty of D	(%)	0.96
4. Standard uncertainty kTP	(%)	0.075
5. Standard uncertainty of (Icorr)	(%)	0.023
Standard uncertainty of N_{Dw}		**0.970**

Physical constants and correction factors with their estimated relative uncertainties for the determination of air kerma of Co-60 radiation at the GUM

The material of the chamber wall and collecting electrode is a ultra pure graphite, type EK 50, a production of Ringsdorff, of density 1.71 g cm-3 and with purity higher as 99,985 % and porosity 14 %

		Co-60	Etalon type ND 1005/A	
		value	u_A	u_B
Physical constants				
$\rho^{(1)}$	dry air density / kg · m^3	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985		0.05
$s_{c,a}$		1.0011		0.30
W/e		33.9700		0.15
g	bremsstrahlung loss	0.0032		0.02
Correction factors				
k_s	recombination loss	1.0023	0.02	0.03
k_h	humidity	0.9970		0.03
k_{st}	stem scattering	0.9994	0.01	
k_{sc}	wall scattering	1.0155	0.01	0.10
k_{CEP}	mean origin of electrons	0.9955		0.10
k_{an}	axial non-uniformity	1.0000		0.01
k_{rm}	radial non-uniformity	1.0003		0.01
Current measurement				
V	chamber volume / cm^3	1.013		0.20
I	ionization current		0.03	0.06
quadratic summation			0.04	0.43
combined uncertainty			**0.43**	

Etalon type ND 1005/A	
Dimensions (mm)	
Outer height	19
Outer diameter	19
Inner height	11
Inner diameter	11
Min.wall	4
Electrode diameter	2
Electrode height	10
Volume of air cavity (cm^3)	1.013
Applied voltage	±250 volt
Leakage current	2 fA

(1) at 101 325 Pa and 273.15 K

Uncertainty for NE 2561

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,564E-01 (Gy)	3,129E-04 (Gy)	normal	6,070E+08 (1/C)	0.2
2	measurement, M	1,668E-09 (C)	6,845E-13 (C)	normal	-5,692E+16 (Gy/C2)	0.04
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-3,238E+05 (Gy/C.?K)	0.1
5	pressure, p	1025,9 (hPa)	2 (hPa)	rectangular	9,254E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for PTW 30001

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,565E-01 (Gy)	3,130E-04 (Gy)	normal	3,210E+08 (1/C)	0.2
2	measurement, M	3,143E-09 (C)	4,973E-13 (C)	normal	-1,599E+16 (Gy/C2)	0.02
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-1,714E+05 (Gy/C.?K)	0.1
5	pressure, p	1022,4 (hPa)	2 (hPa)	rectangular	4,914E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for WS FC65-G

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,565E-01 (Gy)	3,130E-04 (Gy)	normal	2,826E+08 (1/C)	0.2
2	measurement, M	3,570E-09 (C)	1,135E-12 (C)	normal	-1,239E+16 (Gy/C2)	0.03
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20,2 (?C)	0,5 (?C)	rectangular	-1,507E+05 (Gy/C.?K)	0.1
5	pressure, p	1022,8 (hPa)	2 (hPa)	rectangular	4,323E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for ND 1006

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,564E-01 (Gy)	3,129E-04 (Gy)	normal	7,297E+08 (1/C)	0.2
2	measurement, M	1,388E-9 (C)	3,071E-13 (C)	normal	-8,222E+16 (Gy/C2)	0.02
3	distance, d	1000 (mm)	3 (mm)	rectangular		0.35
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-3,893E+05 (Gy/C.?K)	0.1
5	pressure, p	1026,2 (hPa)	2 (hPa)	rectangular	1,112E+05 (Gy/C.hPa)	0.1
					combined uncertainty	**0.4**

Uncertainty for PTW 30001

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,521E-01 (Gy)	6,084E-04 (Gy)	normal	3,526E+08 (1/C)	0.4
2	measurement, M	2,861E-9 (C)	1,642E-12 (C)	normal	-1,875E+16 (Gy/C2)	0.1
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20,5 (?C)	0,5 (?C)	rectangular	-1,826E+05 (Gy/C.?K)	0.1
5	pressure, p	1023.9	2 (hPa)	rectangular	5,238E+04 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for WS FC65-G

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,549E-01 (Gy)	6,195E-04 (Gy)	normal	3,049E+08 (1/C)	0.4
2	measurement, M	3,263E-9 (C)	1,572E-12 (C)	normal	-1,447E+16 (Gy/C2)	0.05
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	21,4 (?C)	0,5 (?C)	rectangular	-1,603E+05 (Gy/C.?K)	0.1
5	pressure, p	1013	2 (hPa)	rectangular	4,662E+04 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for NE 2561

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,548E-01 (Gy)	6,192E-04 (Gy)	normal	8,205E+08 (1/C)	0.4
2	measurement, M	1,530E-9 (C)	1,045E-12 (C)	normal	-6,678E+16 (Gy/C2)	0.07
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	19,2 (?C)	0,5 (?C)	rectangular	-3,495E+05 (Gy/C.?K)	0.1
5	pressure, p	1019.8	2 (hPa)	rectangular	1,002E+05 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for ND 1006

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,548E-01 (Gy)	6,192E-04 (Gy)	normal	7,828E+08 (1/C)	0.4
2	measurement, M	1,285E-9 (C)	5,634E-13 (C)	normal	-9,430E+16 (Gy/C2)	0.04
3	distance, d	1000 (mm)	2 (mm)	rectangular		0.23
4	temperature, T	20,1 (?C)	0,5 (?C)	rectangular	-4,132E+05(Gy/C.?K)	0.1
5	pressure, p	1019.6	2 (hPa)	rectangular	1,189E+05 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,1 (cm)	rectangular		0.3
					combined uncertainty	**0.6**

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Uncertainty budget of the calibration of the ND1006 (0.28 cc) ionization chamber in terms of air kerma in the Co-60 field of PTB

Model equation:

$$N_{Ka} = \frac{\dot{K}_{a_0} * e^{-\lambda \Delta d}}{(I - I_0) * k_\rho * (r / r_0)^2}$$

Quantity	Unit	Definition
N_{Ka}	Gy/C	Calibration coefficient in terms of air kerma free in air
K_{a0}	Gy/s	air kerma rate at a fixed reference date (2005-09-01 0:00 UTC)
λ	1/d	decay constant of Co-60
Δd	d	number of days counted from the reference date
I	A	measured current of secondary ionization chamber
I_0	A	measured leackage of ionization chamber
k_ρ	1	air density correction
r_0	m	nominal distance of the chamber reference point from the source
r	m	actual distance of the ionization chamber from the source

PTB chamber	**HRK-1**	**HRK-2**	**HRK-3**
shape	cylinder	cylinder	parallel-plate
Dimensions /mm			
outer height	24	24	8.5
outer diameter	10	14	48
inner height	20	20	4.5
inner diameter	6	10	44
minimum wall thickness	2	2	2
electrode diameter	1	2	40
electrode height	17.5	16	0.5
volume of air cavity /cm^3	0.5539	1.519	6.138
applied voltage (both polarities)	100 V	200 V	100 V

Uncertainty Budget:

Quantity	**Value**	**Standard Uncertainty**	**Degrees of Freedom**	**Sensitivity Coefficient**	**Uncertainty**	**Index**
K_{a0}	0.0186270	0.190 %	50	$6.1\cdot10^{9}$	$220\cdot10^{3}$	94.9 %
λ	0.000359983	0.0150 %	∞	$-49\cdot10^{9}$	-2600	0.0 %
Δd	427.500 d	0.0675 %	∞	-41000	-12000	0.3 %
I	$139.8400\cdot10^{-}$	0.00715 %	10	$-820\cdot10^{15}$	-8200	0.1 %
I_0	$55.00\cdot10^{-15}$ A	9.09 %	2	$820\cdot10^{15}$	4100 Gy/C	0.0 %
k_ρ	1.000200 1	0.0129 %	50	$-110\cdot10^{6}$	-15000	0.4 %
r_0	1.0 m					
r	1.000000 m	0.0200 %	10	$230\cdot10^{6}$	46000	4.2 %
N_{Ka}	$114.22\cdot10^{6}$	0.195 %	54			

Physical constants and correction factors with their estimated relative standard uncertainties for the determination of the air kerma at Co-60 gamma radiation at PTB in September 2006:

		HRK-1			**HRK-2**			**HRK-3**		
		value	u_A	u_B	value	u_A	u_B	value	u_A	u_B
			%	%		%	%		%	%
Physical Constants										
ρ	dry air density / kg cm^3	1.2046E-06		0.01	1.2046E-06		0.01	1.2046E-06		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985		0.05	0.9985		0.05	0.9985		0.05
$s_{c,a}$		1.0010		0.11	1.0010		0.11	1.0010		0.11
W/e	J/C	33.97			33.97			33.97		
g	bremsstrahlung loss	0.0032		0.02	0.0032		0.02	0.0032		0.02
Correction factors:										
k_s	recombination losses	1.0045	0.1	0.05	1.0051	0.1	0.05	1.0017	0.05	0.05
k_h	humidity	0.9970		0.03	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	0.9989	0.05		0.9982	0.05		0.9992	0.05	
k_{wall} *	wall effects	1.0097	0.01	0.05	1.0134	0.01	0.05	1.0004	0.01	0.05
k_{pn}	point source non-uniformity	1.0005	0.03	0.05	1.0002	0.04	0.05	1.0015	0.03	0.05
k_{bn} **	beam non-uniformity	1.0005		0.05	1.0005		0.05	1.0028		0.1
Charge measurement										
V / cm^3	chamber volume	0.5539	0.1		1.5190	0.03		6.138	0.08	
Q	charge		0.02	0.02		0.03	0.02		0.03	0.02
N_K / Gy/C	**calibration factor**	**5.1617E+07**			**1.8883E+07**			**4.6187E+06**		
quadratic summation			0.15	0.16		0.13	0.16		0.12	0.18
combined uncertainty			**0.22**			**0.21**			**0.22**	

* $k_{wall} = k_{at} * k_{sc} * k_{cep}$

** In the PTB beam

The conventional true value of the air kerma is the mean value of the results obtained by the three chambers.
Correlations are taken into account in the estimation of the combined uncertainty.

	u / %
HRK-1	0.22
HRK-2	0.21
HRK-3	0.22
Mean	**0.19**

The uncertainty budget for the PTB water calorimeter (primary standard for absorbed dose to water) can be found in:

A. Krauss, The PTB water calorimeter for the absolute determination of absorbed dose to water in 60Co radiation. Metrologia 43 (2006), 259-272

Calibration at ^{60}Co

index	influence quantity, source of uncertainty	relative expanded	xpansion fact	relative standard	sensitivity coefficient	degree of freedom				**Uncertainty of the ionization current**		**total uncertainty**	
i	X_i	U_i / X_i	k_i	$u(X_i) / X_i$	c_i	ν_i	$\lvert c_i * u(X_i) / X_i \rvert$	$\lvert c_i * u(X_i) / X_i \rvert^2$	$\lvert c_i * u(X_i) / X_i \rvert^4 / \nu_i$	Type-A contribution	Type-B contribution	Type-A contribution	Type-B contribution
1	**primary standard; reference field**	*0.200%*											
1.1	uncertainty of the primary standard	0.200%	1	0.200%	1	50	0.200%	0.000400%	3.2E-13				0.000400%
1.2	stability of the reference field	0.002%	1	0.002%	1	50	0.002%	0.000000%	3.2E-21	0.000000%		0.000000%	
1.3	uncertainty of the half-life value	0.004%	1.73	0.002%	1	50	0.002%	0.000000%	5.68889E-21		0.000000%		0.000000%
2	**reading of the dosimeter ($M - M_0$)**	*0.025%*										*0.0247%*	*0.0000%*
2.1	uncertainty of electrometer calibration	0.000%	1	0.000%	1	50	0.000%	0.000000%	0		0.000000%		0.000000%
2.2	Type-A-uncertainty of the reading (random effects)	0.020%	1	0.020%	1	8	0.020%	0.000004%	2E-16	0.000004%		0.000004%	
2.3	incomplete settling	0.020%	1.73	0.012%	1	2	0.012%	0.000001%	8.88889E-17	0.000001%		0.000001%	
2.4	leakage current	0.015%	1.73	0.009%	1	2	0.009%	0.000001%	2.8125E-17		0.000001%	0.000001%	
3	**correction for air density k_{TP}**	*0.042%*											
3.1	uncertainty of the calibration of the barometer	0.005%	1	0.005%	-1	8	0.005%	0.000000%	1.08516E-18		0.000000%		0.000000%
3.2	change of air pressure during the measurement	0.020%	1.73	0.012%	-1	2	0.012%	0.000001%	8.74808E-17	0.000001%		0.000001%	
3.3	uncertainty of the calibration of the thermometer	0.034%	1	0.034%	1	8	0.034%	0.000012%	1.69605E-15		0.000012%		0.000012%
3.4	change of temperature during the measurement	0.007%	1.73	0.004%	1	2	0.004%	0.000000%	1.20608E-18	0.000000%		0.000000%	
3.5	deviation between temperature measured in the phantom and temperature in the cavity	0.034%	1.73	0.020%	1	2	0.020%	0.000004%	7.53802E-16		0.000004%	0.000004%	
4	**correction for humidity k_h**												
4.1	deviation of humidity from its reference value (50 % rel. hum.)	0.020%	1.73	0.012%	1	8	0.012%	0.000001%	2.22222E-17		0.000001%	0.000001%	
5	**correction for incomplete saturation k_S**												
5.1	correction for incomplete saturation is not considered	0.100%	1.73	0.058%	1	2	0.058%	0.000033%	5.55556E-14				0.000033%
6	**correction for further influences of temperature (except on air density) k_T**												
6.1	uncertainty of the correction factor k_T	0.000%	1	0.000%	1	2	0.000%	0.000000%	0		0.000000%	0.000000%	
7	**correction for the influence of field size k_F**												
7.1	deviation of the field size from the reference value 10cmx10cm	0.000%	1	0.000%	1	8	0.000%	0.000000%	0		0.000000%		0.000000%
8	**positioning of the chamber and the phantom**	*0.042%*											
8.1	uncertainty due to depth positioning in phantom	0.061%	1.73	0.035%	1	8	0.035%	0.000012%	1.92303E-15			0.000012%	
8.2	uncertainty due to deviation of SSD	0.040%	1.73	0.023%	1	2	0.023%	0.000005%	1.42222E-15			0.000005%	
8.3	influence of rotation/tilt of the chamber	0.000%	1	0.000%	1	2	0.000%	0.000000%	0		0.000000%	0.000000%	
							Σ =	0.000476%	3.8178E-13	6.85138E-08	1.79625E-07	0.024695%	0.000445%
									√ =	**0.0262%**	**0.0424%**	**1.571%**	**0.211%**

Relative combined standard uncertainty $u(N) / N$ = **0.218%**

Effective degrees of freedom ν_{eff} = 59

Probability of coverage p = 95%

Student's t-value for given probability t_p = 2.00

Expansion factor to use k = 2

Relative expanded uncertainty $U(N) / N$ = **0.436%**

Calibration coefficient N_K combined uncertainty

$S_{(i)}$	UNCERTAINTY SOURCES	VALUE±	Unit	Distribut.	DIV.	$C_{(i)}$	u(i) (%)
1	Air kerma rate uncertainty	**0.396**	%	normal	1.000	1.000	0.396
2	Positioning in the beam	0.020	%	normal	1.000	1.000	0.020
3	PTW Unidos (OMH PAM)	0.090	%	rectangular	1.732	1.000	0.052
4	DPI141 resolution	0.001	%	rectangular	1.732	1.000	0.001
5	DPI141	0.020	%	normal	2.000	1.000	0.010
6	Real pressure	0.040	%	rectangular	1.732	1.000	0.023
7	Thermometer PT100	0.020	%	normal	2.000	1.000	0.010
8	Thermometer resolution	0.001	%	rectangular	1.732	1.000	0.000
9	Temperature floating	0.005	%	normal	1.000	1.000	0.005
10	Timer stability	0.010	%	normal	2.000	1.000	0.005
11	Air humidity	0.100	%	rectangular	1.732	1.000	0.058
12	Long-term stability	0.025	%	normal	1.000	1.000	0.025
13	Energy dependence	0.030	%	normal	1.000	1.000	0.030
14	Real temperature inside the chamber	0.040	%	rectangular	1.732	1.000	0.023
15	Field non-uniformity	0.100	%	normal	1.000	1.000	0.100
16	Decay variation during the day	0.015	%	rectangular	1.732	0.043	0.000
u_c	**Combined uncertainty**						**0.420**
U	**Expanded standard uncertainty (95,45%)**				**for k= 2.00**		**0.839**

u (k_{Tp}) = 0.028

Physical constants, correction factors and estimated uncertainties

		After 01.01.2004 value	u_A %	u_B %
Physical constants				
ρ_graphite	(g/cm³)	1.72		
ρ_air (293,15 K and 101 325 Pa)	(kg/m³)	1.204 5		0.01
(μ_{en}/ρ)a,c		0.998 5		0.05
$s_{c,a}$		1.001 0		0.30
W/e	(J/C)	33.97		0.15
g		0.003 2		0.02
Correction factors				
k_s recombination		1.002 7	0.02	0.02
k_h humidity		0.997 0		0.03
k_{st} stem		0.999 5	0.02	0.02
k_{at} * k_{sc} wall		1.021 0	0.02	0.10

k_{cep}	mean origin of electrons		-		
k_{an}	axial non-uniformity		1.000 0		0.10
k_{rn}	radial non-uniformiy		1.000 0		0.02
product k_i		Πk_i	**1.020 2**		

Measurement of I/v*rho

v	volume	(cm³)	1.018 7		0.12
I+	ionisation current			0.02	0.05
I+ / I-	polarity		1.001 2	0.02	
by quadratic summation				**0.045**	**0.393**
Combined uncertainty in air kerma,u_c%				**0.396**	
Expanded standard uncertainty in air kerma (k=2), U %				**0.791**	

Air kerma rate, BEV teletherapy source

SDD = 1m, field-size: 10 cm x 10 cm

Reference date			**2004.12.31**
Halflife		(d)	1925.5
$I+_{ref}$ (20 °C and 101 325 Pa)		(pA)	**216.6 0**
k_{pol}	polarity		0.999 4

$K_a = (I+ * k_{pol}) * (\rho[g/cm^3] * v[cm^3])^{-1} * W/e * (1-g)^{-1} * (\mu_{en}/\rho)_{a,c} * s_{c,a} * \Pi\ k_i$

X = Ka / 0,008792

Air kerma rate $\dot{K}_a =$ **6.13 0** **mGy/s**

Calibration coefficient N_{Dw} combined uncertainty

$s_{(i)}$	UNCERTAINTY SOURCES	VALUE±	Unit	Distribut.	DIV.	$C_{(i)}$	u(i) (%)
1	Absorbed dose to water uncertainty	**0.371**	%	normal	1.000	1.000	0.371
2	Position in the beam	0.020	%	normal	1.000	1.000	0.020
3	Depth in water	0.050	%	normal	2.000	1.000	0.025
4	Phantom front face distortion	0.020	%	rectangular	1.732	1.000	0.012
5	PTW Unidos (OMH PAM)	0.090	%	rectangular	1.732	1.000	0.052
6	DPI141 resolution	0.001	%	rectangular	1.732	1.000	0.001
7	DPI141	0.020	%	normal	2.000	1.000	0.010
8	Real pressure	0.040	%	rectangular	1.732	1.000	0.023
9	Thermometer PT100	0.020	%	normal	2.000	1.000	0.010
10	Thermometer resolution	0.001	%	rectangular	1.732	1.000	0.000
11	Temperature floating	0.005	%	normal	1.000	1.000	0.005
12	Real temperature inside the chamber	0.100	%	rectangular	1.732	1.000	0.058
13	Air humidity	0.100	%	rectangular	1.732	1.000	0.058
14	Timer stability	0.001	%	normal	2.000	1.000	0.001
15	Effect of waterproofing sleeves	0.150	%	rectangular	1.732	1.000	0.087
16	Decay variation during the day	0.015	%	rectangular	1.732	0.043	0.000
17	Field non-uniformity	0.100	%	normal	1.000	1.000	0.100
18	Long-term stability	0.025	%	normal	1.000	1.000	0.025
19	Energy dependence	0.030	%	normal	1.000	1.000	0.030
u_c	**Combined uncertainty**						**0.410**
U	**Expanded standard uncertainty (95,45%)**				**for k= 2.00**		**0.820**

u (k_{Tp}) = 0.028

Relative standard uncertainties for calibrations in terms of absorbed dose to water for ^{60}Co
60Co gamma radiation of BEV teletherapy source
Absorbed dose to water with cylindrical chamber CC01/105

	BEV After 01.01.2004 u_A %	 u_B %
Determination of D_g (by graphite calorimeter) Method1		
Electrical power to core		**0.15**
Core mass during irradiation		**0.12**
Irradiation time		**0.03**
Determination of correction for deviation from **quasi-isothermal** op	**0.03**	**0.01**
Vacuum and air gaps		**0.15**
Long-term stability of dose rate (including the half-life ^{60}Co)	**0.02**	**0.02**
Interpolation on depth dose curve		0.03
by quadratic summation	**0.036**	**0.248**
Combined uncertainty	**0.251**	

Conversion to absorbed dose to water D_w			
method 1: by calculation			
Distance from the source to the phantom			0.20
Depths in graphite and in water			0.10
Front wall of water phantom			0.05
Deviation from scaling theorem			
Physical constants			
Ratio of mass energy-absorption coefficients			**0.10**
Ratio of dose-to-kerma ratios β_w / β_c			0.10
metho by quadratic summation			**0.269**
Combined uncertainty		**0.368**	
method 2: with ionisation chamber			
Measurement of ionisation current ratio	0.05		**0.03**
Position of chamber in graphite phantom			0.05
Position of chamber in water			0.05
Envelope of chamber			0.05
Front wall of the water phantom			0.05
Replacement factor			0.20
Correction for air temperature and pressure			**0.03**
Correction for air humidity			**0.05**
Correction for source decay			**0.00**
Physical constants			
Ratio of mass energy-absorption coefficients			**0.10**
Ratio of dose-to-kerma ratios β_w / β_c			**0.10**
metho by quadratic summation	**0.050**		**0.273**
Combined uncertainty		**0.374**	
Combined uncertainty in absorbed dose to water, u_c%		**0.371**	
Expanded standard uncertainty in air kerma (k=2), U %		0.742	

Measuring Set-up 155.1

Co-60 Air kerma

Chamber Types: EUROMET 813

Relative uncertainty in the air kerma calibration coefficient N_K(in %, k=2): **0.54**

Reference conditions		
Source -chamber distance SCD:	1000 mm	
Field size:	10x10 cm^2 @ 1000 mm	
Air temperature in ionisation chamber:	20 °C	
Air pressure in ionisation chamber:	101325 Pa	
Humidity in ionisation chamber:	50% rF	
Radiation source:	^{60}Co Alcyon II	
Uncertainty in the measurement of:	s_i [%]	u_i [%]
Secondary Standard (traceable to BIPM):		
Uncertainty of secondary standard in N_K :	**0.03**	**0.17**
Long-term stability of secondary standard:	**0.06**	
Electrometer reading (charge):	**0.02**	**0.06**
Recombination:	**0.09**	
Leakage current:	**0.01**	
Soruce chamber distance SCD:	**0.01**	
Lateral position/orientation of chamber:	**0.03**	
Field size:	**0.03**	
Beam profile correction:	**0.05**	
Air temperature correction:	**0.02**	
Air pressure correction:	**0.04**	
Humidity:	**0.03**	
Combined standard uncertainty of secondary standard in K_a-rate:	**0.23**	
DUT:		
Electrometer reading (charge):	**0.02**	**0.06**
Recombination:	**0.09**	
Leakage current:	**0.01**	
Soruce chamber distance SCD:	**0.01**	
Lateral position/orientation of chamber:	**0.03**	
Field size:	**0.03**	
Beam profile correction:	**0.05**	
Air temperature correction:	**0.02**	
Air pressure correction:	**0.04**	
Humidity:	**0.03**	
Quadratic summation:	**0.02**	**0.13**
Combined standard uncertainty of working standard reading:	**0.14**	
Uncertainty in N_K:		
Quadratic summation:	**0.04**	**0.26**
Combined uncertainty of working standard in N_K, (k=1) in %:	**0.27**	
s_i represents the relative standard uncertainty estimated by statistical methods, type A		
u_i represents the relative standard uncertainty estimated by other means, type B		
07.02.2007/St		

Measuring Set-up 155.1

Co-60 Absorbed dose to water

Chamber tpyes: EUROMET 813

Uncertainty in the absorbed dose to water calibration coefficient N	$_{w,Q}$**(in %, k=2):0.88**
Reference conditions	
Reference depth in water:	5 gcm^{-2}
Source -chamber/vessel distance SCD:	1000 mm
Field size:	10x10 cm^2 @ 1000 mm
Air temperature in ionisation chamber:	20 °C
Air pressure in ionisation chamber:	101325 Pa
Humidity in ionisation chamber:	50% rF
Radiation source:	^{60}Co Alcyon II

Relative uncertainties in the calibration coefficient N$_{W,Co}$

(standard deviation, in %)

Uncertainty in the measurement of:	s_i	u_i
Primary standard (water calorimeter):		
Absorbed dose rate in water:	**0.21**	**0.35**
Combined standard uncertainty of primary standard in D_W:	**0.409**	
DUT:		
Short-term stability of ion chamber:	**0.03**	
Electrometer reading (charge):	**0.02**	**0.06**
Saturation correction:	**0.09**	
Leakage current:	**0.01**	
Source chamber distance SCD:	**0.01**	
Depth in water:	**0.04**	
Lateral position:	**0.03**	
Field size:	**0.03**	
Beam profile correction:	**0.05**	
Air temperature correction:	**0.04**	
Air pressure correction:	**0.04**	
Humidity:	**0.03**	
Quadratic summation:	**0.020**	**0.145**
Combined standard uncertainty of DUT reading:	**0.15**	
Uncertainty in N$_{W,Co}$:		
Quadratic summation:	**0.216**	**0.376**
Combined uncertainty of N$_W$,	$_{Co}$ **(coverage factor k=1):0.44**	

s_i represents the relative standard uncertainty estimated by statistical methods, type A

u_i represents the relative standard uncertainty estimated by other means, type B

07.02.2007/St

Estimated uncertainty in the determination of the air-kerma calibration coefficient for gamma radiation of Co-60

Quantity	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution %
1. Realization of the air-kerma with the NMi primary 5 cm3 air-kerma standard					
Volume	4.845 cm3	0.10%	normal	1	0.10
Density of air	1.19656 g/cm3	0.01 g/cm3	normal	1	0.01
Stopping power ratio	1.00062	0.20%	normal	1	0.20
Absorption coefficient ratio	0.999	0.05%	normal	1	0.05
Energy per ion pair	33.97 J/C	0.15 J/C	rectangular	1	0.09
Correction for bremstrahlung losses	1.0032	0.03%	normal	1	0.03
Correction for recombination	*)	0.03%	normal	1	0.03
Correction for stem scatter	0.999	0.05%	normal	1	0.05
Correction for wall absorption	1.026	0.20%	normal	1	0.20
Correction for displacement	0.995	0.20%	normal	1	0.20
Correction for air humidity	0.997	0.05%	rectangular	1	0.03
Correction for radial nonuniformity	1	0.03%	rectangular	1	0.02
Correction for radial nonuniformity	1	0.15%	rectangular	1	0.09
Combined uncertainty					**0.40**
2. Estimated uncertainty in the reference measurement with the NMi primary 5 cm3 air-kerma standard					
Volume fluctuation		0.10%	normal	1	0.10
Time measurement	1.000 s	0.01 s	normal	1	0.01
Pressure	100 kPa	0.03%	normal	1	0.03
Temperature	295 K	0.02%	normal	1	0.02
Charge measurement (type A)		0.05%	normal	1	0.05
Distance	100 cm	0.05 cm	normal	1	0.10
Scattered radiation		0.10%	normal	1	0.10
Combined uncertainty					**0.19**
3. Estimated uncertainty in the calibration measurement of the ionization chamber					
Pressure	100 kPa	0.03%	normal	1	0.03
Temperature	295 K	0.02%	normal	1	0.02
Decay correction		0.02%	normal	1	0.02
Correction air density		0.04%	normal	1	0.04
Distance	100 cm	0.05 cm	normal	1	0.10
Charge meaurement (type A)		0.10%	normal	1	0.10
Combined uncertainty					**0.16**
Expanded uncertainty (*k* = 2) in the air-kerma calibration coefficient					**0.95**

Estimated uncertainty in the determination of the absorbed dose to water calibration coefficient for gamma radiation of Co-60

Quantity	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution %
1. Realization of the absorbed dose to graphite with the primary NMi graphite calorimeter standard					
Electrical calibration	1.506 mJ/ohm	0.13%	normal	1	0.13
Long term mean dose rate	7.095 mGy/s	0.07%	normal	1	0.07
Mass of calorimeter core	1.56893 g	0.03%	normal	1	0.03
Time measurement	1.0000	0.03%	normal	1	0.03
Correction for calorimeter gaps	1.0039	0.07%	normal	1	0.07
Correction to reference distance	1.0000	0.03%	normal	1	0.03
Correction to reference depth	1.0000	0.13%	normal	1	0.13
Combined uncertainty					**0.22**
2. Transfer from graphite to water					
Correction for scaled measured depth	0.98394	0.01%	normal	1	0.01
Correction for phantom scatter	1/1.0418	0.09%	normal	1	0.09
Ratio of mass energy absorption coefficients	1.1130	0.30%	normal	1	0.30
Ratio of absorbed dose and collision kerma	1.0022	0.06%	normal	1	0.06
Deviation from scaling theorem	1.0000	0.12%	normal	1	0.12
Combined uncertainty					**0.34**
3. Estimated uncertainty in the absorbed dose to water calibration measurement of the ionization chamber					
Correction to reference depth	5 cm	0.05%	normal	1	0.05
Correction to reference distance	100 cm	0.02%	normal	1	0.02
PMMA sheath		0.05%	normal	1	0.05
Correction air density		0.04%	normal	1	0.04
Influence of air humidity in 10% to 70% range	1	0.10%	normal	1	0.10
Charge measurements (type A)		0.07%	normal	1	0.10
Decay correction		0.02%	normal	1	0.02
Pressure	100 kPa	0.03%	normal	1	0.03
Temperature	295 K	0.02%	normal	1	0.02
Combined uncertainty					**0.17**
Expanded uncertainty (*k* = 2) in the absorbed dose to water calibration coefficient					**0.88**

Estimated uncertainties, of the secondary standard chambers calibration in terms of air kerma at the INMRI-ENEA in Co-60 gamma radiation beam

Source of component of relative standard uncertainty	100 s_i	100 u_i
Primary standard		0.35
Ionization current	0.03	0.15
Recombination loss, Ks		0.05
Distance	0.05	
Pressure	0.05	0.035
Temperature		
Humidity		
Finite chamber dimensions		0.05
Leakage		0.01
Radial non-uniformity		0.01
Relative uncertainty on N_k		
quadratic sum	0.077	0.389
combined uncertainty u_c	0.397	
expanded standard uncertainty U (95,45%)	**0.79**	

Relative standard uncertainty of the $N_{D,w}$ calibration coefficient

	Type A	Type B
Absorbed dose to water, Dw	100 s_i	100 u_i
calorimetric measurement of D_c	0.15	0.23
positioning of the Thick Walled chamber in graphite		0.04
measurement of I_c for the Thick Walled chamber	0.02	0.08
positioning of the Thick Walled chamber in water		0.06
measurement of I_w for the Thick Walled chamber	0.02	0.08
ratio of the mean mass energy-absorption coefficients in water and graphite at the measurement point in water	0.02	0.14
ratio of the absorbed dose to collision kerma ratios in water and graphite, at the measurement point in water	0.01	0.10
ratio of the photon energy fluences in water and in a small mass of graphite, respectively, at the measurement point in water	0.05	0.06
$N_{D,w}$ determination for the transfer chamber		
ionization current measurement	0.02	0.06
correction for influence quantities, k_i		0.06
distance		0.02
depth in water		0.06
quadratic summation	**0.16**	**0.34**
combined relative standard uncertainty	**0.38**	

Uncertainty analysis for the primary-standard measurement of air-kerma rate, $\overline{\dot{K}}$.

$\dot{K}_1$ and $\dot{K}_{10}$ represent the air-kerma rate measured with each one of the primary standard chambers with nominal volumes of 1 cm^3 and 10 cm^3 respectively. Values shown are for the relative standard uncertainties in %. Analysis for NIST vertical ^{60}Co beam facility.

Uncertainty component	$\dot{K}_1$		$\dot{K}_{10}$	
	Type A	Type B	Type A	Type B
charge	0.10	0.10	0.06	0.10
time		0.05		0.05
volume	0.10	0.10	0.16	0.10
air-density correction (temperature and pressure)		0.03		0.03
distance (axial)		0.02		0.02
k_{sat} , loss of ionization due to recombination	0.01	0.05	0.05	0.10
stem scatter		0.05		0.05
axial nonuniformity		0.02		0.05
radial nonuniformity		0.01		0.01
density of dry air at $T = 0$ °C and P =101.325 kPa		0.02		0.02
humidity correction		0.06		0.06
k_{wall}, wall correction		0.17		0.17
ratio of mean photon mass energy-absorption coefficients, air/graphite		0.04		0.04
product of W_{air}/e and ratio of mean electron mass electronic stopping powers, graphite/air		0.11		0.11
$(1-\bar{g})$, radiative-loss correction.		0.03		0.03
quadratic sums	0.14	0.28	0.18	0.29
relative combined standard uncertainties of $\dot{K}_1$ and $\dot{K}_{10}$	0.31		0.34	
relative combined standard uncertainty of $\overline{\dot{K}}$	0.31			
relative expanded ($k = 2$) uncertainty of $\overline{\dot{K}}$	0.62			

Uncertainty Analysis of the calibration coefficient, N_K.

Uncertainty analysis for the calibration of a reference-class ionization chamber in terms of air-kerma. Values are for the relative standard uncertainties in %.

Uncertainty component	Type A	Type B
charge	0.10	0.10
time		0.05
air-density correction (temperature and pressure)		0.03
distance		0.02
k'_{sat} , loss of ionization due to recombination	0.01	0.05
probe orientation		0.01

humidity		0.06
^{60}Co decay[a]		0.01
quadratic sum	0.10	0.14
relative combined standard uncertainty of the chamber current I	0.17	
relative combined standard uncertainty of $\overline{K}$	0.31	
relative combined standard uncertainty of the calibration coefficient N_{K}	0.35	
relative expanded ($k = 2$) uncertainty of the calibration coefficient, N_{K}	0.71 (→ 0.8)	

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[a] The air-kerma rate, determined by the primary-standard instruments, of the ^{60}Co source is decay corrected to the time of the calibration measurement. For this correction NIST uses a half life of 1925.3 days.

Uncertainy Analysis of the calibration coefficient, $N_{D,w}$.

Uncertainty analysis for the calibration of an ionization chamber in terms of absorbed dose to water. The relative uncertainties are expressed in %.

Uncertainty Components	$N_{D,w}$	
	Type A	Type B
charge	0.10	0.10
time		0.05
air-density correction (temperature and pressure)		0.03
positioning at 1 m reference distance		0.05
positioning at 5 cm reference depth		0.03
measurement reproducibility		0.05
k_{sat}, loss of ionization due to recombination (NIST chambers)	0.01	0.05
humidity		0.06
^{60}Co decay constant[1]		0.05
quadratic sum	0.10	0.17
relative combined standard uncertainty of the chamber reading	0.20	
relative combined standard uncertainty of D_w (from Table 3)	0.42	
relative combined standard uncertainty of the calibration coefficient $N_{D,w}$.	0.47	
relative expanded uncertainty of the calibration coefficient, $N_{D,w}$ ($k = 2$)	0.94 (→ 1.0)	

Uncertainty analysis for the primary-standard measurement of the absorbed-dose-to-water rate, $\dot{D}_w$.

The relative uncertainties are expressed in %.

Uncertainty Components	$\dot{D}_w$	
	Type A	Type B
heat defect		0.30
reproducibility of measurement groups	0.15	
beam attenuation from glass wall		0.10
beam attenuation from calorimeter lid	0.05	
field size		0.23
vessel positioning		0.02
thermistor calibration		0.01
water density		0.02
quadratic sum	0.16	0.39
relative combined standard uncertainty of the absorbed-dose-to-water rate measurement at 5 cm in water	0.42	

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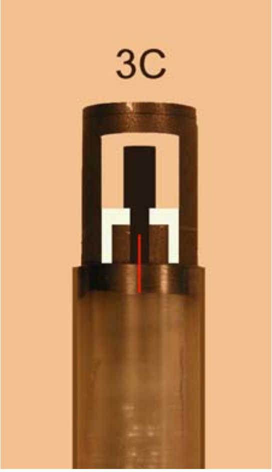
[1] The absorbed-dose-to-water rate determined by the primary-standard instruments has been transferred to the ^{60}Co source and is then decay-corrected to the time of the calibration measurement. For this correction

Physical constants and correction factors with their estimated relative uncertainties for the determination of air kerma of ^{60}Co radiation for the NRC 3C Air Kerma Standard

The 3C Air Kerma Standard is a cylindrical graphite ionization chamber.

	NRC values	NRC uncertainty $^{(1)}$	relative
		100 s_i	100 u_i
Physical Constants			
dry air den	1.2929	-	0.01
$(\mu_{en}/\rho)_{a,c}$	0.9987	-	0.10
$\overline{S}_{c,a}$	1.0005	-	0.12$^{(3)}$
W/e /(J*C	33.97	-	-
$\overline{g}$ fraction bremsstrahlung	0.0032	-	0.05
Correction Factors			
k_s recomb	1.0016	0.03	0.03
k_h humidit	0.9970	-	0.05
k_a stem sc	0.9960	0.02	-
k_{sc} wall sc	1.0220$^{(4)}$	-	0.03$^{(4)}$
k_{comp} com	1.0046	0.03	0.17
$k_{a\,n}$ axial r	1.0004$^{(5)}$	0.04$^{(5)}$	0.05$^{(5)}$
$k_{r\,n}$ radial non-uniformity			
Measurement of $I/V\rho$			
V volume	2.7552	-	0.09
I ionization current	/	0.04	0.06
Relative Standard Uncertainty			
quadratic summation		0.08	0.31
combined uncertainty		0.32	

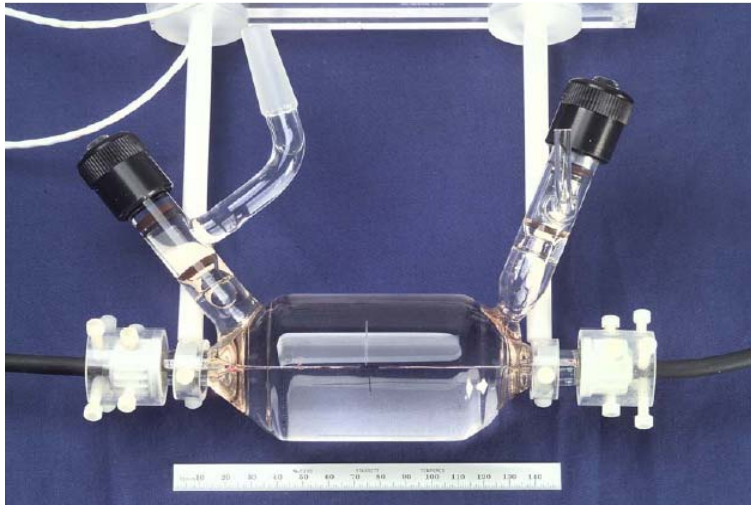


(1) s_i represents the relative standard uncertainty $u(x_i)/x_i$
estimated by statistical methods, type A
u_i represents the relative standard uncertainty $u(x_i)/x_i$
estimated by other means, type B
(2) at 0° C and 101.325 kPa
(3) combined uncertainty for the product ($\overline{S}_{c,a}$ * W/e)
(4) combined value for k_{wall}
(5) combined values for $k_{r\,n}k_{a\,n}$

Air Kerma Standard 3C	
Dimensions (cm)	
Outer height	3.210
Outer diameter	2.350
cavity height	1.614
cavity diameter	1.584
Electrode height	1.200
Electrode diameter	0.670
Sidewall thickness	0.383
End cap thickness	0.456
Volume of air cavity (c	2.7552
Graphite density (g/cm	1.66
Applied voltage (V)	-300
Leakage current (fA)	50

Physical constants and correction factors with their estimated relative uncertainties for the determination of absorbed dose to water of ^{60}Co radiation for the NRC Calorimetric Standard

Source of uncertainty	**NRC values**	**NRC relative uncertainty** [(1)]	
		100 s_i	100 u_i
		0.20	-
Thermistor calibration	-	-	0.1
Thermistor positioning	-	-	<0.01
Specific heat of water / (Jg^{-1}K$^{-1)}$	4.2048	-	0.15
k_c heat flow of conduction	0.9986	-	<0.01
k_v heat flow of convection	1.0000	-	-
k_p field perturbation	1.0021	0.05	-
k_{dd} lateral dose profile	1.0004	<0.01	<0.01
k_{ρ} water density	1.0006	-	0.3
Chemical heat defect, *h*	(3 systems)	-	-
Reproducibility of calorimeter response (n-90)	-	0.06	-
Quadradtic summation		0.21	0.35
Combined relative standard uncertainty in $D_{W,NRC}$		0.41	



Uncertainty for NE 2561

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,564E-01 (Gy)	3,129E-04 (Gy)	normal	6,070E+08 (1/C)	0.2
2	measurement, M	1,668E-09 (C)	6,845E-13 (C)	normal	-5,692E+16 (Gy/C2)	0.04
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-3,238E+05 (Gy/C.?K)	0.1
5	pressure, p	1025,9 (hPa)	2 (hPa)	rectangular	9,254E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for PTW 30001

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,565E-01 (Gy)	3,130E-04 (Gy)	normal	3,210E+08 (1/C)	0.2
2	measurement, M	3,143E-09 (C)	4,973E-13 (C)	normal	-1,599E+16 (Gy/C2)	0.02
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-1,714E+05 (Gy/C.?K)	0.1
5	pressure, p	1022,4 (hPa)	2 (hPa)	rectangular	4,914E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for WS FC65-G

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,565E-01 (Gy)	3,130E-04 (Gy)	normal	2,826E+08 (1/C)	0.2
2	measurement, M	3,570E-09 (C)	1,135E-12 (C)	normal	-1,239E+16 (Gy/C2)	0.03
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20,2 (?C)	0,5 (?C)	rectangular	-1,507E+05 (Gy/C.?K)	0.1
5	pressure, p	1022,8 (hPa)	2 (hPa)	rectangular	4,323E+04 (Gy/C.hPa)	0.1
					combined uncertainty	**0.3**

Uncertainty for ND 1006

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Ka	1,564E-01 (Gy)	3,129E-04 (Gy)	normal	7,297E+08 (1/C)	0.2
2	measurement, M	1,388E-9 (C)	3,071E-13 (C)	normal	-8,222E+16 (Gy/C2)	0.02
3	distance, d	1000 (mm)	3 (mm)	rectangular		0.35
4	temperature, T	20 (?C)	0,5 (?C)	rectangular	-3,893E+05 (Gy/C.?K)	0.1
5	pressure, p	1026,2 (hPa)	2 (hPa)	rectangular	1,112E+05 (Gy/C.hPa)	0.1
					combined uncertainty	**0.4**

Uncertainty for PTW 30001

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,521E-01 (Gy)	6,084E-04 (Gy)	normal	3,526E+08 (1/C)	0.4
2	measurement, M	2,861E-9 (C)	1,642E-12 (C)	normal	-1,875E+16 (Gy/C2)	0.1
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	20,5 (?C)	0,5 (?C)	rectangular	-1,826E+05 (Gy/C.?K)	0.1
5	pressure, p	1023.9	2 (hPa)	rectangular	5,238E+04 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for WS FC65-G

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,549E-01 (Gy)	6,195E-04 (Gy)	normal	3,049E+08 (1/C)	0.4
2	measurement, M	3,263E-9 (C)	1,572E-12 (C)	normal	-1,447E+16 (Gy/C2)	0.05
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	21,4 (?C)	0,5 (?C)	rectangular	-1,603E+05 (Gy/C.?K)	0.1
5	pressure, p	1013	2 (hPa)	rectangular	4,662E+04 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for NE 2561

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,548E-01 (Gy)	6,192E-04 (Gy)	normal	8,205E+08 (1/C)	0.4
2	measurement, M	1,530E-9 (C)	1,045E-12 (C)	normal	-6,678E+16 (Gy/C2)	0.07
3	distance, d	1000 (mm)	1 (mm)	rectangular		0.12
4	temperature, T	19,2 (?C)	0,5 (?C)	rectangular	-3,495E+05 (Gy/C.?K)	0.1
5	pressure, p	1019.8	2 (hPa)	rectangular	1,002E+05 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,05 (cm)	rectangular		0.17
					combined uncertainty	**0.5**

Uncertainty for ND 1006

No.	quantity	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty
1	conventional true value, Dw	1,548E-01 (Gy)	6,192E-04 (Gy)	normal	7,828E+08 (1/C)	0.4
2	measurement, M	1,285E-9 (C)	5,634E-13 (C)	normal	-9,430E+16 (Gy/C2)	0.04
3	distance, d	1000 (mm)	2 (mm)	rectangular		0.23
4	temperature, T	20,1 (?C)	0,5 (?C)	rectangular	-4,132E+05(Gy/C.?K)	0.1
5	pressure, p	1019.6	2 (hPa)	rectangular	1,189E+05 (Gy/C.hPa)	0.1
6	depth in water	5 (cm)	0,1 (cm)	rectangular		0.3
					combined uncertainty	**0.6**

Characteristics, physical constants, correction factors and uncertainties of the VNIIM primary standard cavity chamber C1 in the field of Co-60 gamma radiation

Cobalt-60 Standard chamber C1				
		Value	u_A, %	u_B, %
Physical constants				
ρ	density of dry air, kg/m^3	1.2930	-	0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985	-	0.05
$s_{c,a}$		1.0010	-	0.11
W/e	J/C	33.97	-	
g	fraction of energy lost by bremsstrahlung	0.0032	-	0.02
Correction factors				
k_s	recombination losses	1.0021	0.03	0.03
k_h	humidity	0.9970	-	0.03
k_{st}	stem scattering	0.9994	0.02	0.02
k_{wall}	wall effects	1.0189	0.01	0.07
k_{an}	axial non-uniformity	1.0004	0.04	0.08
k_{rn}	radial non-uniformity	1.0004	0.02	0.05
V	chamber volume, cm^3	1.040	-	0.12
I	ionization current	-	0.03	0.03
R	distance	-	-	0.02
Relative standard uncertainty				
quadratic summation		-	0.07	0.22
combined uncertainty		0.23		

Standard chamber C1	
Dimensions, mm	
Outer diameter	19.0
Outer height	19.0
Inner diameter	11.07
Inner height	11.06
Electrode diameter	1.98
Electrode height	7.95
Wall thickness	4.0
Volume of air cavity, cm^3	1.040
Wall and electrode material	ultra pure graphite
Graphite density, g/cm^3	1.634
Isolator material	polyethylene
Polarizing voltage, V	±250
Leakage current, fA	5

U4. Co-60 air kerma chamber calibration

By **Duncan Butler** Calculation of the uncertainty in the calibration factor of an ionization chamber (eg NE2571) calibrated
Date **2007.06.28** using the air kerma rate measured by the graphite cavity chamber in a Co-60 therapy beam
NK = calibration coefficient for air kerma at Co-60
Model : NK = Kdot . kt / Iref Kdot = air kerma rate as determined by primary standard graphite cavity chamber (CCC)
Iref = current from ionization chamber under test

No	Uncertainty component	How assessed	Reference	Standard u(%)	DOF	[ciui]^2	[ciui]^4/DOF
[1]	Primary standard chamber uncertainty	Calculated by Rob Huntley	Tab A1.2 of ARL/TR126	0.49	413	0.2401	1.40E-04
[2]	Revised wall correction	See spreadsheet U11	Note [2]				
[3]	Saturation correction - standard chamber	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.03	200	0.0009	4.05E-09
[4]	Radial non-uniformity - standard chamber	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.05	200	0.0025	3.13E-08
[5]	Current from standard chamber	Calculated for ARPANSA Current Integrator	U3	0.07	132	0.0049	1.82E-07
[6]	TPH correction - standard chamber	Calculated for correction to dry air, standard TP	U1	0.04	182	0.0016	1.41E-08
[7]	Current from chamber under test	Calculated for ARPANSA Current Integrator	U3	0.07	132	0.0049	1.82E-07
[8]	Correction for background leakage current	Measurement of BLB current	See Note [8]	0.01	200	0.0001	5.00E-11
[9]	Correction to reference conditions - chamber u	Calculated for standard TP, no H correction	U2	0.05	280	0.0025	2.23E-08
[10]	Radial non-uniformity - chamber under test	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.05	200	0.0025	3.13E-08
[11]	Position error relative to standard chamber	Based on 0.5 mm at 1 m and inverse square law	Note [11]	0.10	200	0.01	5.00E-07
[12]	Decay correction - half life	Uncertainty in half-life and 5 year interval	Note [12], U16	0.02	200	0.0004	8.00E-10
[13]	Decay correction - date	Uncertainty in date of measurement 0.5 days	Note [13], U16	0.02	200	0.0004	8.00E-10
[14]	Repeatability	From QA data on ARPANSA chambers - Type A	FORM-2100F, U18	0.06	40	0.0036	3.24E-07
					Sum =	0.2744	0.0001409
					Combined u =	**0.52**	%
					DOF =	534	
					k =	1.96	
					U (95%)=	1.03	%

Conditions for which uncertainty is valid: Normal ambient conditions. Air kerma rates 1 - 10 mGy/s

Notes:

[1] The uncertainty in the air kerma determined by the chamber has been calculated by Rob Huntley in ARL/TR126
[2] This item is now included in spreadsheet U11
[3] This has been calculated as in [1] but appears in a different table (Table A3.1)
[4] "
[5] See calculation in spreadsheet U3
[6] See calculation in spreadsheet U1
[7] See calculation in spreadsheet U3
[8] ARPANSA current integrator can measure backgrounds of order 10 fA with accuracy of about 5 fA. The resulting uncertainty in a current measurement of 50 pA is 0.01%
[9] See calculation in U2
[10] From same reference as [3] (given here for NE2571 chamber)
[11] Assuming a standard uncertainty of 0.5 mm in 1000 mm SDD, the uncertainty can be found from the inverse square law to be 2*(0.5/1000) = 0.001, or 0.1%
[12]- The air kerma rate is determined on a reference date and a decay correction used to work out the rate on the day of the chamber calibration.
[13] Co-60 half-life from ISO 3047-1 Table 12: 1925.5 days (no uncertainty given) and IAEA TECDOC 619 value 1925.5 days (standard uncertainty 0.5 days).
The uncertainty arising from the decay correction is given in MR-IRC-SUP-1110A v2 Appendix I.
See analysis U16, 0.02% from half-life uncertainty (assuming 5 years correction) and 0.02% from an uncertainty in the date of measurement of half a day.
[14] From QA history of NE2571 chambers (see spreadsheet U18) the stdev of about 20 calibrations of two chambers was 0.06%.
Essentially, this component takes into account any random uncertainties not already considered (eg effect of connector box, cables, electronic noise, possible contamination in connectors).

U11. Graphite cavity chamber Co-60 air kerma determination

By **Duncan Butler** Calculation of the uncertainty in the air kerma rate in the ARPANSA Co beam
Date **2007.06.26** as determined by the graphite cavity chamber
Based on calculation in ARL/TR126
Model : K = Iref * correction factors Iref = current from ionization chamber under test

No	Uncertainty component	How assessed	Reference	Standard u(%)	DOF	[ciui]^2	[ciui]^4/DOF
[1]	mean mass energy abs coeff (air/graphite)	From 1989 BIPM data	ARL126 Table A1.1	0.05	200	0.0025	3.13E-08
[2]	energy to create ion pair in dry air W/e = 33.97	From published data	ARL126 Table A1.1	0.15	200	0.0225	2.53E-06
[3]	uncertainty due to stopping power ratios is considered to be included in value of W/e		ARL126 Table A1.1	0	200	0	0.00E+00
[4]	bremsstrahlun loss 1-g	From published data	ARL126 Table A1.1	0.02	50	0.0004	3.20E-09
[5]	volume	Calulated from uncertainties in dimensions	ARL126 Table A1.2	0.05	50	0.0029	1.68E-07
[6]	stem effect	Measured using dummy stem	ARL126 Table A1.2	0.02	200	0.0004	8.00E-10
[7]	centre of electron production	Replace with [10]	ARL126 Table A1.2	0.00	200	0	0.00E+00
[8]	scattering from the walls	Replace with [10]	ARL126 Table A1.2	0.00	200	0	0.00E+00
[9]	attenuation in the walls	Replace with [10]	ARL126 Table A1.2	0.00	200	0	0.00E+00
[10]	revision of wall correction (items [7]-[9])*	Estimate of change in standard using MC	Literature	0.40	200	0.16	1.28E-04
					Sum =	0.1887	0.0001307
		Subtotal - inherent uncertainty in chamber			**Combined u =**	**0.43** %	
					DOF =	272	
[11]	Uncertainty inherent in primary standard cham	Table above	Table above	0.43	272	0.1887	1.31E-04
[12]	Axial non-uniformity of Co beam	Calculated by Rob Huntley	ARL126 Table A1.2	0.20	200	0.04	8.00E-06
[13]	Saturation correction - standard chamber	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.03	200	0.0009	4.05E-09
[14]	Radial non-uniformity - standard chamber	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.05	200	0.0025	3.13E-08
[15]	Current from standard chamber	Calculated for ARPANSA Current Integrator	U3	0.07	132	0.0049	1.82E-07
[16]	TPH correction - standard chamber	Calculated for correction to dry air, standard TP	U1	0.04	182	0.0016	1.41E-08
[17]	Repeatability of standard chamber measurem	From CCC measurements	"CCC measurements.xls	0.03	17	0.0009	4.76E-08
					Sum =	0.2395	1.39E-04
					Combined u =	**0.49** %	
					DOF =	413	
Conditions for which uncertainty is valid:		Normal ambient conditions. Air kerma rates 1 - 10 mGy/s			k =	1.97	
					U (95%)=	0.96 %	

Notes:

[1] ARL/TR126 p39. The original source is a report: BIPM-89/11 (1989)

[2] Metrologia, 34, 169-175 (1997) standard uncertainty 0.15%.

[3] The uncertainty in the stopping power ratio is taken to be zero since the uncertainty in W/e is correlated (see ARL/TR126 p38, second last paragraph)

[4] ARL/TR126 p39. The original source is a report: BIPM-89/11 (1989)

[5] Calculated from measurements of the chamber dimensions

[6] Measured using dummy stem. ARL/TR126 p40

[7-9] These uncertainties have been replaced by an uncertainty in the overall wall correction (see [10]).

[10] The correction for scatter and attenuation in the chamber walls has been estimated in ARL/TR126 using semi-empirical methods which have recently been replaced by most laboratories with Monte Carlo calculations.
We have yet to revise this correction factor, but expect the correction to change by around 0.4%, based on the experience of other laboratories: NIST (US) 1%, NRCC (Canada) 0.8%, NMi (Nehterlands) 0.025%, BEV (Austria) 0.8% [refs below]
As the magnitude of the change is not well known at this stage, we will adopt 0.4% as the standard uncertainty, with low degrees of freedom.
"Changes in the US primary standards for the air kerma from gamma ray beams", J.Res.Natl.Inst.Stand.Technol. 108 359-381 (2003)
"The 2003 revision of the NRC standard for air kerma in a Co-60 beam", PIRS-876, (2003)
"Wall correction factors for cavity chambers and Co-60 radiation using Monte Carlo Methods", NMi report nr: VSL-ESL-IO-2006/1
"Change of air kerma standards of the BEV for Cs-137 and Co-60 gamma rays", Metrologia, 41 (2004) L1-L2

[11] The combined uncertainty of the above gives the uncertainty in the chamber itself

[12] The Co-60 beam changes with distance and a correction is applied for the fact that the geometrical centre of the chamber is not the effective point of measurement
The uncertainty in this correction has been estimated by Robert Huntley (ARL/TR126 p40)

[13] From measurements of the recombination correction by Robert Huntley ARL/TR126 p40

[14] The Co-60 beam falls off with the distance from the axis, and a correction is applied to obtain the air kerma rate on the axis from the chamber measurement.
The uncertainty is taken from ARL/TR126 p40.

[15] As measured by the ARPANSA current integrator, uncertainty calculated in spreadsheet U3

[16] The current is corrected to standard temperature and pressure and 0% relative humidity. Uncertainty from spreadsheet U2.

[17] Repeatability from measurements made over the last few years. History kept in file "CCC measurements.xls"

– The calibration coefficient for each chamber for gamma rays in air from the ARPANSA ^{60}Co teletherapy source was derived from a comparison with the current best value of the air kerma rate from the teletherapy source, as determined by the ARPANSA Carbon

U5. Co-60 absorbed dose to water chamber calibration

By **Duncan Butler**
Date **2007.06.27**

Model : ND,w = Dw,dot . kt / Iref

Calculation of the uncertainty in the calibration factor of an ionization chamber (eg NE2571) calibrated in water using the absorbed dose rate measured by the graphite calorimeter in a Co-60 therapy beam

ND,w = calibration coefficient for absorbed dose to water at Co-60
Dw,dot = absorbed dose to water as determined by primary standard CCC
Iref = current from ionization chamber under test

No	Uncertainty component	How assessed	Reference	Standard u(%)	DOF	[ciui]^2	[ciui]^4/DOF
[1]	Calorimeter uncertainty - abs dose to graphite	Calculated by Rob Huntley	U12	0.24	22	0.0576	1.51E-04
[2]	Dose ratio conversion to abs dose to water	Calculated by Rob Huntley	Tab A2.3 of ARL/TR126	0.098	200	0.009604	4.61E-07
[3]	Correction for front wall of tank	Uncertainty in thickness of 0.05 mm in 1.85 mm	Note [3]	0.02	200	0.0004	8.00E-10
[4]	Density of water correction for tempertature	In range 17 - 23 degrees, 0.012%	Note [4]	0.01	200	0.000144	1.04E-10
[5]	Waterproofing sheath	No correction	Note [5]	0	200	0	0.00E+00
[6]	Current from chamber under test	See Spreadsheet U3	U3	0.07	132	0.0049	1.82E-07
[7]	Correction for background leakage current	Measurement of BLB current	Note [7]	0.01	200	0.0001	5.00E-11
[8]	Correction to reference conditions - chamber	Calculated for standard TP, no H correction	U2	0.05	280	0.0025	2.23E-08
[9]	Radial non-uniformity - chamber under test	Calculated by Rob Huntley	Tab A3.1 of ARL/TR126	0.05	200	0.0025	3.13E-08
[10]	Position error relative to calorimeter	Estimated from geometry	Note [10]	0.20	200	0.04	8.00E-06
[11]	Depth in water	Estimated from depth dose gradient	Note [11]	0.11	200	0.0121	7.32E-07
[12]	Decay correction	Uncertainty in half-life and 5 year interval	U16	0.02	200	0.0004	8.00E-10
[13]	Decay correction	Uncertainty in date of measurement 0.5 days	U16	0.02	200	0.0004	8.00E-10
[14]	Repeatability	From QA data on ARPANSA chambers - Type A	FORM-2100F, U17	0.17	40	0.0289	2.09E-05
					Sum =	0.159548	0.0001811
					Combined u =	**0.40**	%
					DOF =	141	
					k =	1.98	
					U (95%)=	0.79	%

Conditions for which uncertainty is valid: Depth in water = 50 mm, SSD = 1000 mm
17-23 degrees, humidity 20-80%, pressure 97-103 kPa

Notes:

[1] The uncertainty in the chamber itself has been calculated by Rob Huntley in ARL/TR126 (Table A2.1) and redone in U12

[2] As above, in Table A2.3

[3] The correction for the non-water equivalence of the thin front wall of the tank (1.85 mm of Perspex) is 0.9988. The uncertainty in this figure is of order 0.02% (ARL/TR126 Table A3.3)

[4] The density of water changes with temperature, but the chamber is always placed with its centre at a depth of 50 mm from the surface of the tank. The resulting uncertainty is about 0.012% over the temperature range 17 - 23 degrees.

[5] Waterproofing sheath (if present) included as part of the chamber - so no uncertainty due to added thickness of sheath

[6] See calculation in spreadsheet "U3. ARPANSA Current Integrator Raw Measurement Uncertainty Calculation"

[7] ARPANSA current integrator can measure backgrounds of order 10 fA with accuracy of about 5 fA. The resulting uncertainty in a current measurement of 50 pA is 0.01%

[8] See calculation in U2

[9] Same as [2]

[10] Assuming a standard uncertainty of 1 mm in 1000 mm SDD, the uncertainty can be found from the inverse square law to be 2*(1/1000) = 0.002, or 0.2%
This is an estimate, including positioning of chamber under test, depth of graphite core in calorimeter, and positioning of calorimeter. Uncertainty due to the photon fluence scaling theorem is included at item [2].

[11] Assuming uncertainty in 50 mm depth of 0.2 mm and depth dose gradient of -0.55% per mm at 50 mm (See Table A4.2 of ARL/TR126, where the gradient is [(75.8% - 80.4%) / 10] / 80.4% x 100 = -0.548%/mm) gives 0.2 x .55% = 0.11%

[12] - The absorbed dose to water rate is determined on a reference date and a decay correction used to work out the rate on the day of the chamber calibration.

[13] Co-60 half-life from ISO 3047-1 Table 12: 1925.5 days (no uncertainty given) and IAEA TECDOC 619 value 1925.5 days (standard uncertainty 0.5 days).
The uncertainty arising from the decay correction is given in MR-IRC-SUP-1110A v2 Appendix I.
See analysis U16: 0.02% from half-life uncertainty (assuming 5 years correction) and 0.02% from an uncertainty in the date of measurement of half a day

[14] From QA history of NE2571 chambers (see U17) the stdev of about 20 calibrations of two chambers was 0.17%.
Essentially, this component takes into account any random uncertainties not already considered (eg effect of connector box, cables, electronic noise, possible contamination in connectors).

U12. Graphite calorimeter Co-60 absorbed dose to graphite determination

By **Duncan Butler**
Date **2007.06.28**

Calculation of the uncertainty in the absorbed dose to water rate in the ARPANSA Co beam
as determined by the graphite calorimeter
Based on calculation in ARL/TR126

Model : Dc = (P/m) * correction factors
Dw = Dc * scaling theorem corrections (see U5)

No	Uncertainty component	How assessed	Reference	Standard u(%)	DOF	[ciui]^2	[ciui]^4/DOF
[1]	Vacuum gaps correction	ARL/TR126 Table A2.1	Note [1]	0.024	200	0.000576	1.66E-09
[2]	Correction to graphite reference depth	Calculated from measured data	Note [2]	0.05	200	0.0025	3.13E-08
[3]	Correction to reference distance	Estimated from inverse square law	Note [3]	0.06	200	0.0036	6.48E-08
[4]	Radial non-uniformity of Co beam	ARL/TR126 Table A2.1	Note [4]	0.05	200	0.0025	3.13E-08
[5]	Axial non-uniformty of Co beam	ARL/TR126 Table A2.1	Note [5]	0.05	200	0.0025	3.13E-08
[6]	Core mass	ARL/TR126 Table A2.1	Note [6]	0.001	200	0.000001	5.00E-15
[7]	Repeatability of dose measurements	From history of calorimeter runs	Note [7]	0.20	10	0.04	1.60E-04
[8]	core heater voltage before exposure	Model of isothermal mode measurements	ARL/126 p41-43	0.02	200	0.000225	2.53E-10
[9]	(core + Ri) voltage before exposure	Model of isothermal mode measurements	ARL/126 p41-43	0.02	200	0.0004884	1.19E-09
[10]	current sense resistance	Model of isothermal mode measurements	ARL/126 p41-43	0.001	200	0.000001	5.00E-15
[11]	leads resistance	Model of isothermal mode measurements	ARL/126 p41-43	0.001	200	1.323E-06	8.75E-15
[12]	electrical heating off time	Model of isothermal mode measurements	ARL/126 p41-43	0.00	200	0.000004	8.00E-14
[13]	drift correction (chart recorder)	Model of isothermal mode measurements	ARL/126 p41-43	0.08	200	0.0064	2.05E-07
[14]	chart recorder calibration	Model of isothermal mode measurements	ARL/126 p41-43	0.001	200	5.776E-07	1.67E-15
[15]	electrical calibration	Model of isothermal mode measurements	ARL/126 p41-43	0.001	200	5.041E-07	1.27E-15
[16]	radiation heating on time	Model of isothermal mode measurements	ARL/126 p41-43	0.003	200	0.000009	4.05E-13
					Sum =	0.0588068	0.0001604
					Combined u =	**0.24**	%
					DOF =	22	
					k =	2.08	
					U (95%)=	0.50	%

Conditions for which uncertainty is valid: Normal ambient conditions. Air kerma rates 1 - 10 mGy/s

Notes:

[1] Vaccum gaps are 2.33 +- 0.07 mm. Correction determined by Monte Carlo calculation. Uncertainty from these calculations. (ARPANSA Technical Report 132 pA-5) For 3.5 cm radius beam correction is 1.00744 with standard uncertainty 0.024%

[2] The core depth is 29.92 mm. The scaling theorem requires the dose at the reference depth of 30.98 mm. A correction of 0.9943 is used (from measured data reported in ARL/126 p43) with an uncertainty of 0.05%.

[3] The position of the calorimeter has an uncertainty of about 0.2 mm in 650 mm. The ISL gives an uncertainty of 2*(0.2/650) = 0.06%

[4] The calorimeter measures the absorbed dose over the whole of the core. A correction of 1.0026 is applied to take into account that the beam is not uniform over this region. The correction gives the dose on the axis from the dose averaged over the core. An uncertainty of 0.05% is estimated.

[5] As for [4], except that in this case it is the non-linearity in the fall off of the radiation along the beam axis that is corrected. Since the fall off is non-linear, the dose at the centre of the core is not exactly equal to the average dose. A correction of 1.0005 is applied, with uncertainty 0.05%.

[6] From the manufacturers, an uncertainty of 0.01 mg in 1562.2 mg

[7] For example, ESDM of last 11 measurements with ARPANSA calorimeter was 0.2% (see RES00119)

[8-16] These items calculated for a model of an isothermal measurement in ARL/TR126 p41-43.

– The calibration coefficient for each chamber, in terms of absorbed dose to water from gamma rays from the ARPANSA ^{60}Co teletherapy source, was derived from a comparison with the current best value of the absorbed dose to water rate at the reference poin

– Each ionization chamber, without buildup cap, was placed in a water phantom of dimensions 30 cm x 30 cm x 30 cm. The radiation beam entered the phantom horizontally through a side window of thickness 2 mm. The centre of the chamber was placed 50 mm behi

Tabla de Incertidumbre

Kerma en aire - Cobalto 60

F Cantidad X_i	Estimación x_i	Desvío	Inc. Std. $u(x_i)$	Dist. Prob.	Coef. Sens. c_i	$u_i(y)$ %
Kerma air rate uncertainty						
1 N_k	41.64		0.07	N	1	0.17
1.2 Long term Stabilit	41.66	0.01	0.01	N	1	0.02
1 k_{elec}	1			R	1	0.30
1 I				N	1	0.15
1.5 leakage				N	1	0.20
1 k_s	1		0.0011	R	1	0.11
1 k_{pol}	1	0.0005	0.0003	R	1	0.03
1 k_T	293.15		0.2630	N	1	0.09
1 k_P	101.325		0.0600	R	1	0.06
1 k_h	1	0.0004	0.0002	R	1	0.02
1.11 Chamber Orient	1			N	1	0.00
1.12 Distance reprodı	1		0.00006	R	1	0.01
1.13 Field and stem.	1		0.0000			0.00
1.13 Field non-unifori	1		0.0010	N	1	0.00
1.15 Energy depende	1					0.00
Cuadratic sum						0.21
Combined Uncertainty						0.45
calibration coefficient uncertainty N_K						
2 I				N	1	0.02
2,2 leakage				N	1	0.20
2 k_s	1		0.0011	R	1	0.11
2 k_{pol}	1	0.0005	0.0003	R	1	0.03
2 k_T	293.15		0.2630	N	1	0.09
2 k_P	101.325		0.0600	R	1	0.06
2 k_h	1	0.0004	0.0002	R	1	0.02
2.8 Chamber Orienta	1			N	1	0.00
2.9 Distance reprodu	1		0.00006	N	1	0.01
2.10 Field and stem.	1					0.00
Cuadratic sum						0.07
Combined Uncertainty						0.26
3. Incertidumbre total						
Cuadratic sum						0.27
Combined Uncertainty						0.52
Expanded Uncertainty (k=2)						1.04

Tabla de Incertidumbre

Dosis absorbida en agua en Cobalto 60

F Cantidad X_i	**Estimación** x_i	**Desvío**	**Inc. Std.** $u(x_i)$	**Dist. Prob.**	**Coef. Sens.** c_i	$u_i(y)$ **%**
Absorbed dose rate to water uncertainty						
1, $N_{D,W}$	45.72		0.14	N	1	0.31
1.2 Long term Stabilit	45.81	0.06	0.045	N	1	0.10
1. k_{elec}	1			R	1	0.30
1. I				N	1	0.04
1.5 leakage				N	1	0.20
1. k_s	1		0.0011	R	1	0.11
1. k_{pol}	1	0.0005	0.0003	R	1	0.03
1. k_T	293.15		0.2630	N	1	0.09
1. k_P	101.325		0.0600	R	1	0.06
1. k_h	1	0.0004	0.0002	R	1	0.02
1.11 Chamber Orient	1			N	1	0.00
1.12 Deph in water	1		0.004	N	1	0.40
1.13 Field non-uniforr	1		0.0000			0.00
1.14 Field and stem	1		0.0010	N	1	0.10
1.15 Energy depende	1					0.00
Cuadratic sum						0.43
Combined Uncertainty						0.66
calibration coefficient uncertainty $N_{D,w}$						
2, I				N	1	0.07
2,2 leakage				N	1	0.20
2. k_s	1		0.0011	R	1	0.11
2. k_{pol}	1	0.0005	0.0003	R	1	0.03
2. k_T	293.15		0.2630	N	1	0.09
2. k_P	101.325		0.0600	R	1	0.06
2. k_h	1	0.0004	0.0002	R	1	0.02
2.8 Chamber Orientat	1			N	1	0.00
2.9 Distance and Dep	1		0.004	N	1	0.40
2.10 Field and stem.	1					0.00
Cuadratic sum						0.23
Combined Uncertainty						0.48
3.total uncertainty						
Cuadratic sum						0.66
Combined Uncertainty						0.81
Expanded Uncertainty (k=2)						1.63