Summary of the BIPM.RI(I)-K4 comparison for absorbed dose to water in ^{60}Co gamma radiation

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Abstract

International comparisons of absorbed dose have been made at the Bureau International des Poids et Mesures (BIPM) since 1988. Thirteen national metrology institutes have taken part, some of which have repeated the comparison over the years. The key comparison reference value (KCRV) is taken as unity, each comparison result being the ratio of the national metrology institute's (NMI) evaluation to that of the BIPM's stable standard. The degrees of equivalence between each NMI and the KCRV, and between each pair of NMIs, are given in the form of a matrix, using the most recent result for each of eleven NMIs. A graphical presentation is also given.

The results of this comparison, identified as BIPM.RI(I)-K4, have been approved by Section I of the Consultative Committee for Ionizing Radiation (CCRI(I)).

1. Introduction

National primary standards of absorbed dose to water in ^{60}Co gamma radiation are compared at the BIPM against the BIPM primary standard in a continuous programme that started in 1988. There are now thirteen absorbed dose to water standards that have been compared and all except one of the standards have been compared within the last ten years, which is the comparison frequency agreed by the CCRI(I) [1]. The acronyms and details of the NMIs are given in Table 1.

The results of these comparisons form the basis for degrees of equivalence [2] entered in the key comparison database (KCDB) for BIPM.RI(I)-K4 held on the BIPM/MRA web site. It was agreed at the CCRI(I) meeting in 1999 that the key comparison reference value would be unity, each comparison result being the ratio of the NMI evaluation to the BIPM evaluation of absorbed dose to water in the same reference conditions at the BIPM.

2. National standards

The national primary standards for the determination of absorbed dose to water in ^{60}Co are almost exclusively based on calorimetry, the exception being the PTB in which case a Fricke chemical method was used [3]. This comparison will be updated in 2005 using their new determination of absorbed dose that is based on calorimetry.

If the absorbed dose to graphite is determined using a graphite calorimeter, the conversion from absorbed dose to graphite to absorbed dose to water is obtained either by calculation using the photon-fluence scaling theorem or by using cavity theory applied to a graphite-

Table 1 Details of the participants in the key comparison BIPM.RI(I)-K4

NMI acronym	Full name	Country	Regional metrology organization	Most recent year of comparison
PTB	Physikalisch-Technische Bundesanstalt	Germany	EUROMET	1989*
BNM-LNHB	Bureau National de Métrologie - Laboratoire National Henri Becquerel	France	EUROMET	1993**
ENEA	Ente per le Nuove Technologie, l'Energia e l'Ambiente	Italy	EUROMET	1994
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	EUROMET	1994
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency	Australia	APMP	1997
NIST	National Institute of Standards and Technology	USA	SIM	1997
NPL	National Physical Laboratory	UK	EUROMET	1997***
NRC	National Research Council Canada	Canada	SIM	1998
LSDG$	Laboratorium voor Standaarddosimetrie, Gent	Belgium	EUROMET	1999
NMi	Nederlands Meetinstituut	Netherlands	EUROMET	2000
METAS	Swiss Federal Office of Metrology and Accreditation	Switzerland	EUROMET	2000
VNIIFTRI	Institute for Physical-Technical and Radiotechnical Measurements, Gosstandart of Russia	Russian Federation	COOMET	2001
OMH	Országos Mérésügyi Hivatal/ National Office of Measures	Hungary	EUROMET	2001

[*] A new comparison is scheduled for 2005

[**] A new comparison was made in 2003 but is not yet published

[***] Not yet published. [$]Not yet the designated institute for Belgium.

walled ionization chamber. Alternatively, the absorbed dose to water is determined directly using a water calorimeter, usually based on the Domen type. The fact that several standards are based on similar methods results in correlations in the uncertainties that need to be taken into account when determining the degrees of equivalence between the NMI standards.

The transfer of the primary realization to the ionization chambers that are commonly used as transfer standards is undertaken by each NMI and has an associated uncertainty. Indeed each recent comparison with the BIPM has been made indirectly through the use of the NMIs' transfer standards.

3 Data from each national metrology institute

When a comparison is undertaken at the BIPM, both the NMI and the BIPM measure the absorbed dose rate to water using their own standard. The BIPM value using the primary standard is $\dot{D}_{\mathrm{w,BIPM}}$ and the NMI's best estimate of absorbed dose at the BIPM, $\dot{D}_{\mathrm{w,NMI\text{-}BIPM}}$ is made using their transfer standard, calibrated as $N_{D\mathrm{w,NMI}}$ against their primary standard at the NMI. Hence

$$\dot{D}_{\mathrm{w,NMI\text{-}BIPM}} = N_{D\mathrm{w,NMI}} \times I_{\mathrm{BIPM}} \qquad (1)$$

where I_{BIPM} is the ionization current measured by the NMI transfer chamber in the BIPM beam. The ratio of the absorbed dose rate measured by the NMI at the BIPM and that measured by the BIPM is

$$\frac{\dot{D}_{\mathrm{w,NMI\text{-}BIPM}}}{\dot{D}_{\mathrm{w,BIPM}}} = \frac{N_{D\mathrm{w,NMI}} \times I_{\mathrm{BIPM}}}{\dot{D}_{\mathrm{w,BIPM}}} = \frac{N_{D\mathrm{w,NMI}}}{N_{D\mathrm{w,BIPM}}} \qquad (2)$$

Each comparison result using a transfer standard is then expressed as

$$R_{\mathrm{NMI}} = N_{D\mathrm{w,NMI}} / N_{D\mathrm{w,BIPM}} \qquad (3)$$

The most recent comparison result, R_{NMI}, for each laboratory is listed in Table 2, together with the reported comparison uncertainty, $u'_{R,\mathrm{NMI}}$. One of the standards has not been compared for more than 10 years (PTB) but the CCRI(I) agreed in 2003 that this comparison result should still be included in the KCDB as long as the PTB detailed uncertainty budget is given (see Appendix 1), as this was not published in the report of the comparison. The result of the BNM-LNHB will be updated as soon as their more recent comparison is published. The result of the NPL will be included once their uncertainty budget is submitted and the report of their comparison is published. The result of the LSDG will be included in the KCDB once this laboratory is designated for this purpose by the Belgian authorities.

The relative combined standard uncertainty associated with a determination of absorbed dose to water at an NMI is designated $u_{D\mathrm{w,NMI}}$. The relative combined standard uncertainty $u_{R,\mathrm{NMI}}$ of each comparison result R_{NMI} takes into account the standard uncertainty $u_{\mathrm{c,NMI}}$ of $N_{D\mathrm{w,NMI}}$ (derived from the uncertainty budget supplied by the NMI as given in the corresponding

Table 2 Data set for BIPM key comparisons of absorbed dose to water

NMI	**Year**	$u_{D\mathrm{w,NMI}}$	R_{NMI}	$u'_{R,\mathrm{NMI}}$	$u_{R,\mathrm{NMI}}$	**Primary standard**	**Ref.**
		in relative value					
PTB	1990	0.0076	0.9934	0.0086	0.0081	Fricke solution	[4]
BNM-LNHB	1993	0.0034	0.9988	0.0039	0.0040	graphite calorimeter	[5]
ENEA	1994	0.0044	0.9969	0.0050	0.0049	graphite calorimeter	[6]
BEV	1994	0.0037	0.9990	0.0042	0.0043	graphite calorimeter	[7]
ARPANSA	1997	0.0020	1.0024	0.0029	0.0030	graphite calorimeter	[8]
NIST	1997	0.0035	0.9984	0.0051	0.0051	water calorimeter	[9, 10]
NRC	1998	0.0041	0.9976	0.0052	0.0051	water calorimeter	[11]
LSDG	1999	0.0066	0.9948	0.0075	0.0074	water calorimeter	[12]
NMi	2000	0.0040	0.9962	0.0038	0.0039	graphite calorimeter	[13]
METAS	2000	0.0041	0.9999	0.0054	0.0054	water calorimeter	[14]
VNIIFTRI	2000	0.0040	0.9967	0.0043	0.0043	graphite calorimeter	[15]
OMH	2001	0.0048	0.9983	0.0049	0.0049	graphite calorimeter	[16]

reference, see also Tables 3 and 4) and the standard uncertainty $u_{\mathrm{c,BIPM}}$ of $N_{D\mathrm{w,BIPM}}$ (see Appendix 2) as well as correlations between the measurement methods, as follows.

As the BIPM absorbed dose to water is measured ionometrically, there are few correlations between the NMI and the BIPM uncertainty budgets. Indeed the only significant correlations arise from the common use of data relating to mass energy absorption coefficients and the ratios of absorbed dose to the collision part of the kerma (β), for those NMIs using graphite calorimetry. The uncertainties are not necessarily fully correlated and this is taken into account by applying an approximate factor, f_k, as indicated in the tables. Thus, the relative standard uncertainty $u_{R,\mathrm{NMI}}$ for a comparison of a given NMI with the BIPM is given by

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,BIPM}}{}^2 - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}} - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{BIPM}} \qquad (4)$$

where all the standard uncertainties are expressed as relative values.

The numerical values for $u_{R,\mathrm{NMI}}$ using this consistent approach are listed in Table 2 and are those used for the KCDB entries. It is of interest to note that they are not significantly different from the original published values $u'_{R,\mathrm{NMI}}$ for which the correlation coefficients were not always stated. The correlated parts of the uncertainty budgets for the NMIs with graphite calorimeters and water calorimeters are given in Tables 3 and 4 respectively.

In Tables 3 and 4, $u_{D\mathrm{w,NMI}}$ is the combined standard uncertainty of the NMI primary standard (all components being included), u_{transfer} is the combined standard uncertainty associated with the transfer standard and $u_{\mathrm{c,NMI}}$ is the combined standard uncertainty for an absorbed dose to water calibration by the NMI; all uncertainties being in relative value.

In Table 3, the uncertainty in the calculation of the correction for graphite calorimeter gaps, k_{gap} is taken to have some correlated component as shown.

Table 3 Correlated components in the uncertainty budgets for absorbed dose to water from graphite calorimetry primary standards, standard uncertainties per 10^3

NMI	k_{gap}	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	$(\beta)_{\mathrm{w,c}}$	$u_{D\mathrm{w,NMI}}$	u_{transfer}	$u_{\mathrm{c,NMI}}$	$\sqrt{\sum(f_k u_{k,\mathrm{corr}})^2_{\mathrm{NMI}}}$
BNM-LNHB	0.8	1.5	0.6	3.4		3.4	1.5
ENEA	–	2.0	1.0	4.4	1.5	4.6	2.0
BEV	1.5	1.0	1.0	3.7		3.7	1.4
ARPANSA	0.4	1.4	0.1	2.0	0.6	2.1	1.3
NMi	0.7	3.0	0.6	4.0	0.9	4.1	2.9
VNIIFTRI	1.0	2.9	0.5	4.0	1.8	4.3	2.8
OMH	0.8	3.0	0.6	4.8	1.1	5.0	2.9
$f_{k,\mathrm{BIPM}}$	–	0.95	0.7				
$f_{k,\mathrm{NMI}}$	0.5	0.95	0.7				

Table 4 Correlated components in the uncertainty budgets for water calorimetry primary standards, standard uncertainties per 10^3

NMI	k_{c}	k_{sc} or k_{p}	k_{dd}	h	$u_{D\mathrm{w,NMI}}$	u_{transfer}	$u_{\mathrm{c,NMI}}$	$\sqrt{\sum(f_k u_{k,\mathrm{corr}})^2_{\mathrm{NMI}}}$
NIST	1.0			3.0	3.5	2.2	4.2	2.1
NRC	1.5	0.5	0.1	3.0	4.1	2.1	4.2	2.1
LSDG	2.5	0.4	0.1	5.0	6.6	3.5	6.8	3.5
METAS	1.5	0.5	0.2	3.0	4.1	2.1	4.5	2.1
$f_{k,\mathrm{NMI}}$	-	-	-	0.7				

In Table 4, k_{c} is the heat flow correction factor, k_{sc} (also referred to as k_{p}) is the scatter correction factor or field perturbation, k_{dd} is the lateral dose distribution and h is the chemical heat defect; the uncertainty components and uncertainties are given in relative value. The values of k_{c} and k_{p} for the METAS are the same as for the NRC [17] so a correlation coefficient of 1.0 has been taken for these uncertainties in the pair-wise matrix in Table 6.

4. The key comparison reference value

As agreed at the CCRI(I) meeting in 1999, the key comparison reference value, R_{ref} is taken to be unity as the BIPM standard is common to all comparisons and is stable with time. The relative standard uncertainty of the distribution of absorbed dose to water measurements at the BIPM is about 4 10^{-4} although the measurements have shown a small drift over the last 15 years. Repeat calibrations of the BIPM transfer standard type NE 2571 show a relative standard uncertainty of the distribution of the calibration coefficients of 3 10^{-4} over several years.

As a consequence of this choice of R_{ref} , the degree of equivalence between each NMI and the key comparison reference value remains constant between their comparisons and the degree of equivalence between any two NMIs is not affected by the reference value. Comparison results can be added to the database as soon as they are approved and published.

5. Expression of the degree of equivalence

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the key comparison reference value [2]. The degree of equivalence is expressed quantitatively in terms of the deviation of the comparison result from the key comparison reference value and the expanded uncertainty of this deviation ($k = 2$).

The degree of equivalence between any pair of national measurement standards is expressed in terms of the difference in the two comparison results and the expanded uncertainty of this difference; consequently, it is independent of the choice of key comparison reference value.

Comparison of a given NMI with $R_{\mathrm{ref}} = 1$

The degree of equivalence of a particular NMI, i, with the key comparison reference value is expressed as the difference

$$D_{\mathrm{NMI}} = R_{\mathrm{NMI}} - 1 \tag{5}$$

and the expanded uncertainty ($k = 2$) of this difference, U_{NMI}, known as the equivalence uncertainty. It follows that

$$U_{\mathrm{NMI}} = 2u_{R,\mathrm{NMI}}\,. \tag{6}$$

Table 5 gives the values for D_{NMI} and U_{NMI} for each NMI taken from Table 2 using (5) and (6) and forms the basis of the entries in MRA Appendix B. These data are presented graphically in Figure 1.

Table 5 Degrees of equivalence of each NMI's measurement standard

NMI	**Year**	$u_{D\mathrm{w,NMI}} \times 10^{-3}$	$D_{\mathrm{NMI}} \times 10^{-3}$	$U_{\mathrm{NMI}} \times 10^{-3}$
PTB	1990	7.6	-6.6	16.2
BNM-LNHB	1993	3.4	-1.2	8.0
ENEA	1994	4.4	-3.1	9.8
BEV	1994	3.7	-1.0	8.6
ARPANSA	1997	2.0	2.4	6.0
NIST	1997	3.5	-1.6	10.2
NRC	1998	4.1	-2.4	10.2
LSDG	1999	6.6	-5.2	14.8
NMi	2000	4.0	-3.8	7.8
METAS	2000	4.1	-0.1	10.8
VNIIFTRI	2000	4.0	-3.3	8.6
OMH	2001	4.8	-1.7	9.6

Comparison of any two NMIs with each other

The degree of equivalence, D_{ij}, between any pair of NMIs, *i* and *j*, is expressed as the difference

$$D_{ij} = D_i - D_j = R_i - R_j \tag{7}$$

and the expanded uncertainty ($k = 2$) of this difference, $U_{ij} = 2\, u_{ij}$, where

$$u_{ij}^{\ 2} = u_{c,i}^{\ 2} + u_{c,j}^{\ 2} - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 . \tag{8}$$

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs and is given in Table 6 in the form as it appears in the KCDB.

6. Comments on future comparisons

The CCRI(I) has agreed that comparisons should be repeated at least every ten years and new comparison results added to the database as soon as they are approved. Each NMI's results are published in a report of the comparison, which includes an update of the matrix of degrees of equivalence and the corresponding graphical presentation as they will appear in the KCDB. This report is sent to the CCRI(I) for approval once the participant and the CCRI(I) Key Comparison Working Group (KCWG) have agreed on the result.

An updated summary of the results is presented to each CCRI(I) meeting. Scientific decisions to remove results from the KCDB are only made at the CCRI(I).

If an NMI makes a bilateral comparison for this quantity, the results can be included in the database with the approval of the KCWG. Such approval requires that the comparison is declared in advance and that at least one of the NMIs already has a BIPM comparison result.

7. Conclusion

The BIPM ongoing key comparison for absorbed dose to water, BIPM.RI(I)-K4, currently comprises twelve results. These have been analysed with respect to the KCRV of unity and with respect to each other. The matrix of degrees of equivalence has been approved by the CCRI(I) and is published in the BIPM key comparison database for eleven laboratories. Results may be updated and other results may be added as and when other NMIs make absorbed dose to water comparisons at the BIPM.

Table 6 Introductory text and degrees of equivalence for absorbed dose to water

Key comparison BIPM.RI(I)-K4

MEASURAND : **Absorbed dose to water relative to the BIPM evaluation**

Key comparison reference value: x_R is taken as unity

The degree of equivalence of each laboratory *i* with respect to the reference value is given by a pair of terms:
$D_i = (x_i - 1)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless, where
$U_i = 2u_i$.

The degree of equivalence between two laboratories is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2u_{ij}$ for the table below account is taken of correlations between u_i and u_j
(see Section 5 of the Final report).

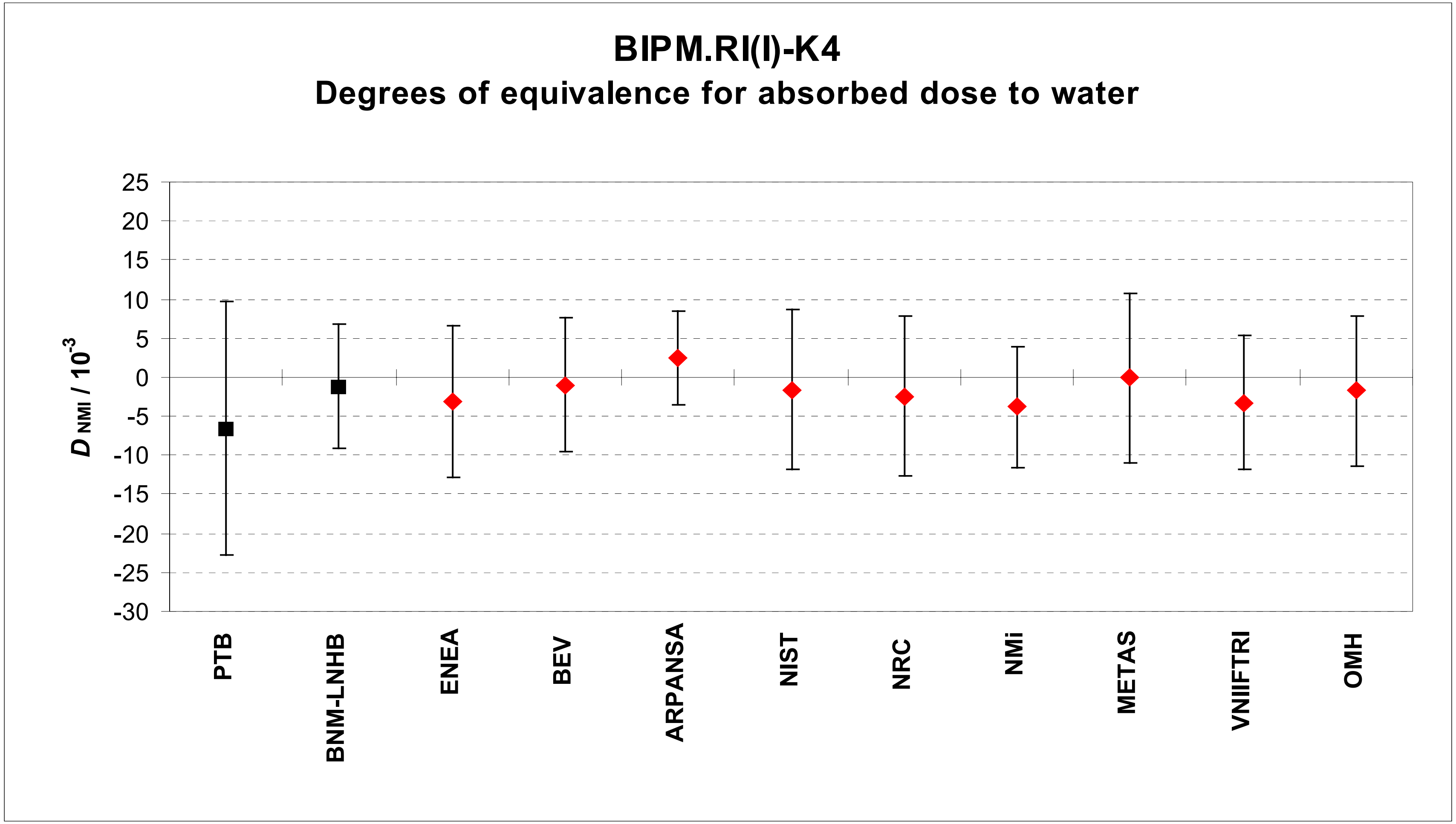
Lab *j* ⇒

Lab *i* ⇓			**PTB**		**BNM-LNHB**		**ENEA**		**BEV**		**ARPANSA**		**NIST**	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}	
PTB	**-6.6**	16.2			**-5.4**	16.7	**-3.5**	17.8	**-5.6**	16.9	**-9.0**	15.8	**-5.0**	17.4
BNM-LNHB	**-1.2**	8.0	**5.4**	16.7			**1.9**	10.2	**-0.2**	9.1	**-3.6**	6.9	**0.4**	10.8
ENEA	**-3.1**	9.8	**3.5**	17.8	**-1.9**	10.2			**-2.1**	10.7	**-5.5**	8.9	**-1.5**	12.5
BEV	**-1.0**	8.6	**5.6**	16.9	**0.2**	9.1	**2.1**	10.7			**-3.4**	7.6	**0.6**	11.2
ARPANSA	**2.4**	6.0	**9.0**	15.8	**3.6**	6.9	**5.5**	8.9	**3.4**	7.6			**4.0**	9.4
NIST	**-1.6**	10.2	**5.0**	17.4	**-0.4**	10.8	**1.5**	12.5	**-0.6**	11.2	**-4.0**	9.4		
NRC	**-2.4**	10.2	**4.2**	17.4	**-1.2**	10.8	**0.7**	12.5	**-1.4**	11.2	**-4.8**	9.4	**-0.8**	10.3
NMi	**-3.8**	7.8	**2.8**	17.3	**-2.6**	8.4	**-0.7**	10.1	**-2.8**	9.0	**-6.2**	6.6	**-2.2**	11.7
METAS	**-0.1**	10.8	**6.5**	17.7	**1.1**	11.3	**3.0**	12.9	**0.9**	11.7	**-2.5**	9.9	**1.5**	10.8
VNIIFTRI	**-3.3**	8.6	**3.3**	17.7	**-2.1**	9.3	**-0.2**	10.8	**-2.3**	9.8	**-5.7**	7.7	**-1.7**	12.3
OMH	**-1.7**	9.6	**4.9**	18.2	**-0.5**	10.1	**1.4**	11.6	**-0.7**	10.6	**-4.1**	8.7	**-0.1**	13.1

Lab *j* ⇒

Lab *i* ⇓			**NRC**		**NMi**		**METAS**		**VNIIFTRI**		**OMH**	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}	
PTB	**-6.6**	16.2	**-4.2**	17.4	**-2.8**	17.3	**-6.5**	17.7	**-3.3**	17.7	**-4.9**	18.2
BNM-LNHB	**-1.2**	8.0	**1.2**	10.8	**2.6**	8.4	**-1.1**	11.3	**2.1**	9.3	**0.5**	10.1
ENEA	**-3.1**	9.8	**-0.7**	12.5	**0.7**	10.1	**-3.0**	12.9	**0.2**	10.8	**-1.4**	11.6
BEV	**-1.0**	8.6	**1.4**	11.2	**2.8**	9.0	**-0.9**	11.7	**2.3**	9.8	**0.7**	10.6
ARPANSA	**2.4**	6.0	**4.8**	9.4	**6.2**	6.6	**2.5**	9.9	**5.7**	7.7	**4.1**	8.7
NIST	**-1.6**	10.2	**0.8**	10.3	**2.2**	11.7	**-1.5**	10.8	**1.7**	12.3	**0.1**	13.1
NRC	**-2.4**	10.2			**1.4**	11.7	**-2.3**	9.8	**0.9**	12.3	**-0.7**	13.1
NMi	**-3.8**	7.8	**-1.4**	11.7			**-3.7**	12.2	**-0.5**	9.1	**-2.1**	10.0
METAS	**-0.1**	10.8	**2.3**	9.8	**3.7**	12.2			**3.2**	12.7	**1.6**	13.5
VNIIFTRI	**-3.3**	8.6	**-0.9**	12.3	**0.5**	9.1	**-3.2**	12.7			**-1.6**	10.7
OMH	**-1.7**	9.6	**0.7**	13.1	**2.1**	10.0	**-1.6**	13.5	**1.6**	10.7		

Figure 1. Graph of the degrees of equivalence with the KCRV



The black squares indicate results more than ten years old that are in the process of being renewed.

References

[1] Comité Consultatif des Rayonnements Ionisants *Rapport de la 17e session*, 2001, CCRI(I), 168.

[2] MRA: *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 1999, 45 pp. http://www.bipm.org/pdf/mra.pdf.

[3] Feist H., Determination of the absorbed dose to water for high-energy photons and electrons by total absorption of electrons in ferrous sulphate solution, *Phys.Med.Biol.* 1982, **27** 1435-1447.

[4] Shortt K.R., Ross C.K., Schneider M., Hohlfeld K., Roos M., Perroche A.-M., A comparison of absorbed dose standards for high-energy x-rays, *Phys.Med.Biol.* 1993, **38**, 1937-1955.

[5] Perroche A.-M., Boutillon M., Daures J., Delaunay F., Leroy E., Ostrowsky A. and Chauvenet B. Comparison of the standards of air kerma and absorbed dose of the LPRI and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**94/6**, 1994, 10 p.

[6] Perroche A.-M., Boutillon M., Guerra A.S., Laitano R.F. and Pimpinella, M. Comparison of the standards of absorbed dose of the ENEA and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**94/4**, 1994, 6 p.

[7] Perroche A.-M., Boutillon M. and Leitner, A. Comparison of the standards of air kerma and absorbed dose to water of the BEV and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**94/7**, 1994, 7 p.

[8] Allisy-Roberts P.J., Burns D.T., Boas J., Huntley R. and Wise K. Comparison of the standards of absorbed dose to water of the ARPANSA and the BIPM for ^{60}Co gamma radiation, *Rapport BIPM*-**99/17**, 2001, 15 p.

[9] Allisy-Roberts P.J. and Shobe J. Comparison of the standards of absorbed dose to water of the NIST and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**98/5**, 1998, 9 p.

[10] Seltzer S.M. and Shobe J. Present status of the NIST standard for absorbed dose to water in ^{60}Co gamma-ray beams, *CCRI(I)/***99-8**, 1999, 3 p.

[11] Allisy-Roberts P. J., Burns D. T., Shortt K., Ross C.K. and Seuntjens J.P. Comparison of the standards of absorbed dose to water of the NRC, Canada and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**99/13**, 2000, 12 p.

[12] Allisy-Roberts P.J., Burns D.T. and Palmans H. Comparison of the standards of absorbed dose to water of the LSDG, Belgium and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**2000/01**, 2000, 10 p.

[13] Pieksma M, van Dijk E, Burns D T, Allisy-Roberts P J, Comparison of the standards for absorbed dose to water of the NMi and the BIPM for ^{60}Co gamma rays, 2001, *NMi-Report S-TS*-**2001.01**, 14 p.

[14] Allisy-Roberts P.J., Burns D.T., Stucki G., Comparison of the standards for absorbed dose to water of the METAS and the BIPM for ^{60}Co gamma radiation, *Rapport BIPM*-**2003/02**, 2003, 11 p.

[15] Allisy-Roberts P.J., Burns D.T., Berlyand V. and Korostin S., Comparison of the standards of absorbed dose to water of the VNIIFTRI, Russian Federation and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**2003/09**, 2003, 12 p.

[16] Allisy-Roberts P.J., Csete, S. Comparison of the standards of absorbed dose to water of the OMH, Hungary and the BIPM for ^{60}Co γ rays, *Rapport BIPM*-**2003/08**, 2003,11 p.

[17] Medin J., Ross C.K., Stucki G., Klassen N.V., Seuntjens J.P., Commissioning of an NRC-type sealed water calorimeter at METAS using ^{60}Co γ-rays, *Phys.Med.Biol.* 2004, **49** 4073-4086.

Appendix 1 Uncertainty budget for the PTB 1989 determination of absorbed dose to water

Part 1. Determination of the energy imparted to the Fricke solution

model equation: $W = E \cdot \frac{C \cdot u \cdot n}{f \cdot e} \cdot k_{\Delta E} \cdot k_{bs} \cdot k_{be}$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
E	1.0	0.2	initial electron energy
C	1.0	0.1	effective capacitance of the Faraday cup integrator
u	1.0	0.05	voltage of the Faraday cup integrator per output signal of the beam monitor
n	1.0	0.1	output signal of the beam monitor
f	-1.0	0.1	charge collection efficiency of the Faraday cup integrator
e	constant		charge of the electron
$k_{\Delta E}$	1.0	0.1	correction for energy losses in air gap and foils
k_{bs}	1.0	0.05	correction for energy loss by backscatter of electrons
k_{be}	1.0	0.15	correction for energy loss by bremsstrahlung escape
W		0.33	energy imparted to the solution

Part 2. Determination of the calibration factor of the solution

model equation: $N_F = \frac{W}{m_L} \cdot \frac{1}{\Delta S_0 \cdot (k_{Tb})_0 \cdot (k_{Tm})_0}$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
W	1.0	0.33	energy imparted to the solution
m_L	-1.0	0.01	mass of the solution
ΔS_0	-1.0	0.2	change in the optical density of the solution
$(k_{Tb})_0$	-1.0	0.03	correction for temperature at irradiation
$(k_{Tm})_0$	-1.0	0.09	correction for temperature at measurement
N_F		0.40	calibration factor of the solution

Part 3. Calibration of a ^{60}Co field as absorbed dose to water standard

model equation: $\dot{D}_{w,ref} = N_F \cdot \frac{\Delta S_1}{(t_B)_1} \cdot (k_{Tb})_1 \cdot (k_{Tm})_1 \cdot k_G \cdot k_{wall} \cdot k_{repro}$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
N_F	1.0	0.4	calibration factor of the solution
ΔS_1	1.0	0.2	change in the optical density of the solution
$(t_B)_1$	-1.0	0.01	duration of irradiation
$(k_{Tb})_1$	1.0	0.03	correction for temperature at irradiation
$(k_{Tm})_1$	1.0	0.09	correction for temperature at measurement
k_G	1.0	0.3	correction for difference of G -values
k_{wall}	1.0	0.1	effect of dosemeter glass walls
k_{repro}	1.0	0.08	reproducibility of reference conditions
$\dot{D}_{w,ref}$		0.56	absorbed dose rate to water

Part 4. Calibration of new ^{60}Co reference field with ionization chamber

model equation: $\dot{D}_{w,ref2} = \dot{D}_{w,ref1} \cdot \frac{M_2}{M_1} \cdot (k_{geom})_1 \cdot (k_{geom})_2$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
$\dot{D}_{w,ref1}$	1.0	0.57	absorbed dose rate to water (old radiation source)
M_1	-1.0	0.1	reading of dosemeter (ionization chamber, old source)
M_2	1.0	0.1	reading of dosemeter (ionization chamber, new source)
$(k_{geom})_1$	1.0	0.2	reproducibility of reference geometry (old radiation source) – see below
$(k_{geom})_2$	1.0	0.2	reproducibility of reference geometry (new radiation source) – see below
$\dot{D}_{w,ref2}$		0.66	absorbed dose rate to water (new radiation source)

remark: k_{geom} is composed of several factors (see overleaf)

$$k_{geom} = k_{SSD} \cdot k_F \cdot k_z \cdot k_h \cdot k_{ang}$$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
k_{SSD}	1	0.1	source-surface distance
k_F	1	0.1	field size
k_z	1	0.12	depth in phantom
k_{ang}	1	0.07	angular orientation
k_{geom}		0.2	correction for reproducibility of reference geometry

Part 5. Calibration of transfer ionization chamber

model equation: $$N_D = \frac{\dot{D}_{w,ref2} \cdot \mathrm{e}^{-\lambda t} \cdot t_m}{M \cdot k_\rho \cdot k_s \cdot k_p \cdot k_{geom} \cdot k_{repeat}}$$

quantity	sensitivity coefficient	relative standard uncertainty × 100	comment
$\dot{D}_{w,ref2}$	1	0.7	absorbed dose rate to water (new radiation source)
$\mathrm{e}^{-\lambda t}$	1	0.01	radioactive decay
t_m	1	0.01	duration of measurement
M	-1	0.05	electrometer reading
k_ρ	-1	0.07	correction for air density
k_s	-1	0.1	recombination correction
k_p	-1	0.05	polarity effect
k_{geom}	-1	0.2	reproducibility of reference geometry
k_{repeat}	-1	0.2	repeatability over a longer period
N_D		0.76	calibration factor

Appendix 2. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard of absorbed dose to water

Quantity	BIPM value	BIPM relative standard uncertainty(1)	
		$100\,s_i$	$100\,u_i$
Dry air density (2) / (kg m^{-3})	1.2930	–	0.01
W/e / (J C^{-1})	33.97	–	0.11(3)
$\bar{s}_{\mathrm{c,a}}$	1.0030	–	
k_{cav} (air cavity)	0.9900	0.03	0.04
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	1.1125	0.01	0.14
$\Psi_{\mathrm{w,c}}$ (photon fluence ratio)	1.0065	0.04	0.06
$(1+\varepsilon)_{\mathrm{w,c}}$ (dose to kerma ratio)	1.0015	–	0.06
k_{ps} (PMMA(4) envelope)	0.9999	0.00_5	0.01
k_{pf} (phantom window)	0.9996	–	0.01
k_{rn} (radial non-uniformity)	1.0051	0.00_5	0.03
k_{s} (recombination losses)	1.0016	0.00_4	0.01
k_{h} (humidity)	0.9970	–	0.03
Volume of standard CH4-1 / cm^3	6.8810	0.19	0.03
I (ionization current)	–	0.01	0.02
Quadratic summation		0.20	0.21
Combined relative standard uncertainty of $D_{\mathrm{w,BIPM}}$		0.29	

(1) s_i represents the Type A relative standard uncertainty $u_{\mathrm{A}}(x_i)/\bar{x}_i$, estimated by statistical means; u_i represents the Type B relative standard uncertainty $u_{\mathrm{B}}(x_i)/\bar{x}_i$ estimated by other means.

(2) At 0 °C and 101.325 kPa.

(3) Combined uncertainty of the product $(W/e)\bar{s}_{\mathrm{c,a}}$.

(4) Polymethylmethacrylate.

Relative standard uncertainties for the calibration of an ionization chamber in terms of absorbed dose to water at the BIPM

	Uncertainty in $N_{D,\mathrm{w\ BIPM}}$	
Relative standard uncertainty in the measurement of	$100\,s_i$	$100\,u_i$
Absorbed dose rate (see above)	0.20	0.21
Ionization current of transfer chamber	0.01	-
Chamber position/depth	0.01	0.02
Relative standard uncertainty		
Quadratic summation	0.20	0.21
Combined uncertainty $u_{c,\mathrm{BIPM}}$	0.29	