

Final Report 2010/04/16

**Comparison of the standards for absorbed dose to water  
of the NRC and the BIPM for  $^{60}\text{Co}$  gamma radiation**

C. Kessler<sup>1</sup>, D.T. Burns<sup>1</sup>, P.J. Allisy-Roberts<sup>1</sup>,  
J.P. McCaffrey<sup>2</sup>, M.R. McEwen<sup>2</sup>, and C.K. Ross<sup>2</sup>

<sup>1</sup> Bureau International des Poids et Mesures, F-92312 Sèvres Cedex, France

<sup>2</sup> National Research Council of Canada, Ottawa, Canada

**Abstract**

A comparison of the standards for absorbed dose to water of the National Research Council of Canada (NRC) and of the Bureau International des Poids et Mesures (BIPM) was carried out in the  $^{60}\text{Co}$  radiation beam of the BIPM in May 2009 under the auspices of the key comparison BIPM.RI(I)-K4. The comparison result, based on the calibration coefficients for two transfer standards and expressed as a ratio of the NRC and the BIPM standards for absorbed dose to water, is 0.9980 (52). This result replaces the 1998 NRC value of 0.9976 (51) in this key comparison. The degrees of equivalence between the NRC and the other participants in this comparison have been calculated and the results are given in the form of a matrix for the ten national metrology institutes (NMIs) with published results that have taken part in the ongoing comparison for absorbed dose to water. A graphical presentation is also given.

**1. Introduction**

An indirect comparison of the standards of absorbed dose to water of the National Research Council of Canada (NRC) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in  $^{60}\text{Co}$  radiation. The measurements at the BIPM took place in May 2009. This absorbed dose to water comparison replaces the indirect comparison made between the two laboratories in 1998 [1] that was previously registered in the BIPM.RI(I)-K4 key comparison [2].

The absorbed dose to water is determined at the NRC using a Domen type [3] sealed water calorimeter as modified by Seuntjens [4] and described in [5]. The BIPM primary standard is a parallel-plate graphite cavity ionization chamber [6].

The comparison was undertaken using two ionization chambers of the NRC as transfer standards. The result of the comparison is given in terms of the mean ratio of the calibration coefficients of the transfer chambers determined at the two laboratories under the same reference conditions.

The comparison result has been approved by the Consultative Committee for Ionizing Radiation (CCRI) and the degrees of equivalence between the NRC and the other participants in this ongoing comparison for absorbed dose to water have been evaluated and are presented in the form of a matrix in Section 5. A graphical presentation is also given.

## 2. Determination of the absorbed dose to water

At the BIPM, the absorbed dose rate to water is determined from

$$\dot{D}_{w, \text{BIPM}} = (I/m)(W/e)\bar{s}_{c,a}\Pi k_i, \quad (1)$$

where

- $I$  is the ionization current measured by the standard,
- $m$  is the mass of air in the ionization chamber,
- $W$  is the mean energy expended in dry air per ion pair formed,
- $e$  is the electronic charge,
- $\bar{s}_{c,a}$  is the ratio of the mean mass stopping powers of graphite and air, and
- $\Pi k_i$  is the product of the correction factors to be applied to the standard.

The values of the physical constants and the correction factors entering in (1) are given in [6] together with their uncertainties, the combined relative standard uncertainty being  $2.9 \times 10^{-3}$ . The uncertainty budget is reproduced in Table 1.

At the NRC, the absorbed dose to water  $D_w$  is determined using

$$D_{w, \text{NRC}} = \Delta T_w c_w \Pi k_i \frac{1}{1-h}, \quad (2)$$

where

- $\Delta T_w$  is the measured temperature rise,
- $c_w$  is the specific heat capacity of water at the calorimeter operating temperature of 4 °C,
- $\Pi k_i$  is the product of the correction factors to be applied to the standard, and
- $(1-h)^{-1}$  is a correction factor for the heat defect of water.

The design and operation of the calorimeter is described in [5]. A summary of the components of uncertainty is indicated in Table 2, giving a combined relative standard uncertainty of  $4.1 \times 10^{-3}$ .

The absorbed dose to water at the NRC is maintained through the use of a series of secondary standard ionization chambers calibrated directly against the water calorimeter.

**Table 1. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water**

Symbol	Parameter / unit	Value	Relative standard uncertainty <sup>(1)</sup>	
			100 $s_i$	100 $u_i$
<i>Physical constants</i>				
$\rho_a$	dry air density (0°C, 101.325 kPa) / kg m <sup>-3</sup>	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,c}$	ratio of mass energy-absorption coefficients	1.1125 <sup>(2)</sup>	0.01 <sup>(2)</sup>	0.14 <sup>(2)</sup>
$s_{c,a}$	ratio of mass stopping powers	1.0030	}	0.11 <sup>(3)</sup>
$W/e$	mean energy per charge / J C <sup>-1</sup>	33.97		
<i>Correction factors</i>				
$k_p$	fluence perturbation	1.1107	0.05	0.17
$k_{ps}$	polythene envelope of the chamber	0.9994	0.01	0.01
$k_{pf}$	front face of the phantom	0.9996	–	0.01
$k_{rn}$	radial non-uniformity <sup>(4)</sup>	1.0056	0.01	0.03
$k_s$	saturation <sup>(4)</sup>	1.0017	0.01	0.01
$k_h$	humidity	0.9970	–	0.03
<i>Measurement of <math>I/\nu</math></i>				
$\nu$	effective volume / cm <sup>3</sup>	6.8810 <sup>(5)</sup>	0.19	0.03
$I$	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) <sup>(6)</sup>		0.02	–
<i>Combined uncertainty of the BIPM determination of absorbed dose to water rate</i>				
quadratic summation			0.20	0.21
combined relative standard uncertainty			0.29	

<sup>(1)</sup> expressed as one standard deviation.

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

$u_i$  represents the relative uncertainty estimated by other methods, type B.

<sup>(2)</sup> included in the uncertainties for  $k_p$ .

<sup>(3)</sup> uncertainty value for the product  $s_{c,a} W/e$ .

<sup>(4)</sup> values for the CISBio beam adopted in November 2007.

<sup>(5)</sup> standard CH4-1.

<sup>(6)</sup> over a period of 3 months. The long-term reproducibility over a period of 15 years,  $u_R$  is 0.0006.

**Table 2. Relative standard uncertainties for the NRC water calorimeter for absorbed dose to water**

Source of uncertainty	Value	Relative standard uncertainty	
		100 $s_i$	100 $u_j$
Thermistor calibration	–	0.20	–
Thermistor positioning	–	–	0.10
Specific heat of water / ( $\text{J g}^{-1} \text{K}^{-1}$ )	4.2048	–	<0.01
$k_c$ heat flow by conduction	0.9986	–	0.15
$k_v$ heat flow by convection	1.0000	–	<0.01
$k_p$ field perturbation	1.0021	0.05	–
$k_{dd}$ lateral dose profile	1.0004	<0.01	–
$k_\rho$ water density	1.0006	–	<0.01
Chemical heat defect, $h$	(3 systems)	–	0.30
Reproducibility of calorimeter response ( $n = 90$ )	–	0.06	–
Quadratic summation		0.21	0.35
Combined relative standard uncertainty in $D_{w,NRC}$		0.41	

*Reference conditions*

Absorbed dose is determined at the BIPM under reference conditions defined by the CCRI, previously known as the CCEMRI [7]:

- the distance from the source to the reference plane (centre of the detector) is 1 m;
- the field size in air at the reference plane is 10 cm  $\times$  10 cm, the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre of the square; and
- the reference depth is 5 g cm<sup>-2</sup>.

The reference conditions at the NRC are similar to those at the BIPM. However, the experimental arrangement used to establish the absorbed dose via water calorimetry and that used to disseminate the dose are not identical. Water calorimetry is performed in a small cubic tank of side length 30 cm. The source to surface distance is about 70 cm and the depth to the reference point in the tank is set to 5 g cm<sup>-2</sup> including the PMMA window of 3 mm thickness. The field size at this reference point is 10 cm  $\times$  10 cm. There is an additional 5 cm of Styrofoam insulation in the beam path outside the tank, which is not included in the 5 g cm<sup>-2</sup>. Ionization chambers were calibrated in the calorimeter tank and then used as the transfer to a larger tank for dissemination. In this larger calibration tank, the distance from the source to the plane at the inside front surface is nominally 1 m. At this plane, the field size in air is a square of side dimension 10 cm as indicated above. The reference depth for the calibration of ionization chambers including the transfer chambers used in this comparison is 5 cm water plus a 3 mm PMMA window.

*Reference values*

The  $\dot{D}_{w,BIPM}$  value is taken from the mean of the four measurements made around the period of the comparison. The value is given at the reference date of 2009-01-01, 0 h UTC. The half-life of  $^{60}\text{Co}$  is taken as 1925.19 d,  $\sigma = 0.3$  d [8].

The value of  $\dot{D}_{w,NRC}$  used for the comparison is the mean of measurements made over a period of six months before and one month after the measurements at the BIPM. The value is normalized to the date and time of 2009-01-01, 0 h Eastern Standard Time as is the ionization current of the transfer chambers. The NRC uses a half-life of  $^{60}\text{Co}$  of 1925.02 days [9].

**3. The transfer chambers and their calibration**

The comparison of the NRC and BIPM standards was made indirectly using the calibration coefficients  $N_{D,w}$  for two transfer chambers given by

$$N_{D,w,lab} = \dot{D}_{w,lab} / I_{lab}, \quad (3)$$

where  $\dot{D}_{w,lab}$  is the water absorbed dose rate at each lab and  $I_{lab}$  is the ionization current of a transfer chamber measured at the NRC or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers PTW30013 serial number 1527 and FC65G serial number 1233, belonging to the NRC, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 3. These chambers were calibrated over several months at the NRC before and one month after the measurements at the BIPM.

**Table 3. Characteristics of the NRC transfer chambers**

Characteristic/Nominal values		PTW 30013-1527	FC65G-1233
Dimensions	Inner diameter / mm	6.1	6.2
	Wall thickness / mm	0.335	0.4
	Cavity length / mm	23.0	23.1
	Tip to reference point /mm	13.0	13.0
Electrode	Length / mm	21.2	18.8
	Diameter / mm	1.1	1.0
Volume	Air cavity / mm <sup>3</sup>	600	650
Wall	Material	graphite-coated PMMA	graphite
	Density / (kg m <sup>-3</sup> )	1190	1820
Voltage (positive polarity) applied to outer electrode, BIPM	Positive charge collected	300 V	300 V
Voltage (negative polarity) applied to inner electrode, NRC	Positive charge collected	300 V	300 V

The experimental method for calibrations at the NRC is described in [10] and that for the BIPM in [11] and the essential details are reproduced here.

#### *Positioning*

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem (engraved lines) facing the source.

#### *Applied voltage and polarity*

At the BIPM, a collecting voltage of 300 V (positive polarity) was applied to the outer electrode of each chamber at least 30 min before any measurements were made (positive charge collected). At the NRC, a collecting voltage of 300 V (negative polarity) was applied to the central electrode of each chamber at least 30 min before any measurements were made (positive charge collected). No corrections were applied at either laboratory for polarity.

#### *Volume recombination*

Volume recombination is negligible at a dose rate of less than  $15 \text{ mGy s}^{-1}$  for these chambers at these polarizing voltages, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied.

#### *Charge and leakage measurements*

The charge  $Q$  collected by each transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. The source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the NRC, the charge was measured similarly using a Keithley electrometer model 35617. The chambers were pre-irradiated for at least 20 min ( $\approx 10 \text{ Gy}$ ) at the NRC, and for at least 30 min ( $\approx 10 \text{ Gy}$ ) at the BIPM before any measurements were made.

The ionization current measured from each transfer standard was corrected for the leakage current at both the BIPM and the NRC. This correction was less than  $1 \times 10^{-4}$  in relative value at each laboratory.

#### *Ambient conditions*

During a series of measurements, the water temperature is measured for each current measurement and was stable to better than  $0.01 \text{ }^\circ\text{C}$  at both the BIPM and the NRC. The ionization current is corrected to 293.15 K and 295.15 K at the BIPM and the NRC, respectively, and normalized to 101.325 kPa at both laboratories.

Relative humidity is controlled at  $(50 \pm 5) \%$  at both the BIPM and  $(40 \pm 20) \%$  at the NRC. No correction for humidity is applied to the ionization current measured.

#### *Radial non-uniformity correction*

In the BIPM, the radial non-uniformity correction factor for this chamber type when irradiated in the water phantom is 1.0008 for the transfer chambers with an uncertainty of  $2 \times 10^{-4}$ . Measurements in the water phantom at the NRC indicate a radial non-uniformity over the section of the transfer chambers that would result in a correction of 0.15 %. No adjustment was made for the 0.07 % difference in radial non-uniformity correction factors between the two laboratories.

#### *PMMA phantom window*

Both laboratories use a horizontal radiation beam and, at the BIPM, the thickness of the PMMA front window of the phantom is included as a water-equivalent thickness in  $\text{g cm}^{-2}$

when positioning the chamber. In addition, the BIPM applies a correction factor  $k_{pf}$  (0.9996) that accounts for the non-equivalence to water of the PMMA in terms of interaction coefficients. At the NRC, the reference depth is 5 cm behind a 3 mm thick PMMA window and no additional correction is applied. This reference depth is the same for both the standard and the transfer chambers. As the chambers are waterproof, no sleeves were used.

#### Uncertainties

Contributions to the relative standard uncertainty of  $N_{D,w,lab}$  are listed in Table 4. As the two laboratories determine absorbed dose to water by methods that are quite different and not correlated, the combined uncertainty of the result of the comparison is obtained by summing in quadrature the uncertainties of  $\dot{D}_{w,BIPM}$  and  $\dot{D}_{w,NRC}$  and including the contributions arising from the use of transfer chambers. These latter terms include the uncertainties of the ionization currents measured, the distance to the reference plane and the depth positioning.

**Table 4.** Estimated relative standard uncertainties of the calibration coefficient,  $N_{D,w,lab}$ , of the transfer chambers and of the comparison result,  $R_{D,w}$

Relative standard uncertainty of	NRC		BIPM	
	100 $s_i$	100 $u_i$	100 $s_i$	100 $u_i$
Absorbed dose rate to water (tables 1 and 2), $u_{Dw}$	0.21	0.35	0.20	0.21
Ionization current of the transfer chambers	0.03	0.07	0.02	0.02
Distance	–	–	0.02	–
Depth in water	–	0.02	0.02	0.06
Correction $T, P$	0.05	0.10	–	–
<b>Relative standard uncertainties of <math>N_{D,w,lab}</math></b>				
quadratic summation	0.22	0.37	0.20	0.22
combined uncertainty	0.43		0.30	
<b>Relative standard uncertainties of <math>R_{D,w}</math></b>				
quadratic summation	0.43		0.30	
combined uncertainty, $u_R$	0.52			

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the period of calibration was estimated to be  $2 \times 10^{-4}$  (two calibrations with repositioning, in a series of 30 measurements for each chamber) at the BIPM. At the NRC, repeated measurements exhibited a relative standard uncertainty of  $3 \times 10^{-4}$ . The calibration of each chamber was repeated with repositioning at least ten times before and twice after the measurements at the BIPM. The relative standard uncertainty of the mean normalized ionization current measured at the NRC with a given transfer chamber over the several months required for this comparison was typically  $8 \times 10^{-4}$ . The calibrations were repeated at the NRC after the comparison at the BIPM and the results are consistent as shown in Table 5.

#### 4. Results of the comparison

The result of the comparison,  $R_{D,w}$ , is expressed in the form

$$R_{D,w} = N_{D,w,NRC} / N_{D,w,BIPM} \quad (4)$$

in which the average value of measurements made at the NRC prior to those made at the BIPM (pre-BIPM) and those made afterwards (post-BIPM) for each chamber is compared with the mean of the measurements made at the BIPM. Table 5 lists the relevant values of  $N_{D,w}$  for each chamber at the stated reference conditions.

The comparison result is taken as the unweighted mean value for both transfer chambers,  $R_{D,w} = 0.9980$  with a combined standard uncertainty for the comparison of 0.0052. The difference between the absorbed dose to water standards of the NRC and the BIPM is not significant given the combined uncertainty.

**Table 5. Results of the comparison**

Transfer Chamber	$N_{D,w,NRC}$ / Gy $\mu\text{C}^{-1}$ pre-BIPM *	$N_{D,w,BIPM}$ / Gy $\mu\text{C}^{-1}$	$N_{D,w,NRC}$ / Gy $\mu\text{C}^{-1}$ post-BIPM *	$N_{D,w,NRC}$ / Gy $\mu\text{C}^{-1}$ overall mean	$R_{D,w}$	$u_c$
PTW 30013-1527	53.793	53.881	53.794	53.793	0.9984	0.0052
FC65G-1233	48.189	48.306	48.198	48.194	0.9977	0.0052
Mean values					<b>0.9980</b>	<b>0.0052</b>

\*  $N_{D,w}$  normalized to 293.15 K for comparison purposes.

#### 5. Comparison with other National Metrology Institutes

##### *Comparison of a given NMI with the key comparison reference value*

Comparisons of absorbed dose to water at the BIPM have been undertaken since 1988. A summary report of the most recent comparisons, including the previous comparison with the NRC, is given in [2]. Subsequent comparisons with the LNE-LNHB, PTB, VSL, ENEA and the VNIIFTRI have been published [12, 13, 14, 15, 16] and the results are available in the key comparison database (KCDB) of the CIPM MRA [17].

The degree of equivalence of a given measurement standard,  $D_i$ , is the degree to which this standard is consistent with the key comparison reference value (KCRV) [17]. The degree of equivalence is expressed quantitatively by two terms: the deviation of the comparison result from the key comparison reference value and the expanded uncertainty of this deviation ( $k = 2$ ).

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities [18].

It follows that for each NMI  $i$  having a BIPM comparison result  $R_{D,w,i}$  (denoted  $x_i$  in the KCDB) with combined standard uncertainty  $u_i$ , the degree of equivalence with respect to the reference value is given by a pair of terms as described in [18]:

$$\text{the relative difference } D_i = (D_{wi} - D_{w,BIPM}) / D_{w,BIPM} = R_{D,w,i} - 1 \quad (5)$$

and the expanded uncertainty ( $k = 2$ ) of this difference,

$$U_i = 2 u_i. \quad (6)$$

The results for  $D_i$  and  $U_i$ , are expressed in mGy/Gy.

Table 6 gives the values for the NMI absorbed dose uncertainty  $u_{Dw,i}$ ,  $D_i$  and  $U_i$  for each NMI,  $i$  taken from [2, 12, 13, 14, 15 and 16] and this report, using (5) and (6), and forms the basis of the entries in the KCDB of the CIPM MRA [16]. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1999; note that the NPL and the BEV have each undertaken comparisons more recently and the results are awaiting publication. The results of a published SIM comparison [19] are also presented in the graph. Note that the data presented in the tables and graph, while correct at the time of publication of the present report, will become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those given in the KCDB where the NMI acronyms are also given.

**Table 6. Degrees of equivalence of each NMI's measurement standard**

NMI	Year	$u_{Dw,NMI} \times 10^{-3}$	$D_{NMI} \times 10^{-3}$	$U_{NMI} \times 10^{-3}$
BEV	1994	3.7	-1.0	8.6
ARPANSA	1997	2.0	2.4	6.0
NIST	1997 <sup>1</sup>	3.5	-1.6	10.2
LSDG <sup>2</sup>	1999	6.6	-5.2	14.8
METAS	2000	4.1	-0.1	10.8
MKEH <sup>3</sup>	2001	4.8	-1.7	9.6
LNE-LNHB <sup>4</sup>	2003	4.8	-3.0	10.6
PTB	2005	2.0	-3.9	7.4
VSL <sup>5</sup>	2005	3.9	-7.4	9.8
ENEA	2007	3.6	-0.1	8.8
VNIFTRI	2009	4.0	-2.4	8.6
NRC	1998	4.1	-2.4	10.2
NRC	2009	4.1	-2.0	10.4

<sup>1</sup> Replaced by the NIST result in the SIM comparison

<sup>2</sup> This Belgium laboratory is not a designated institute

<sup>3</sup> Previously known as the OMH

<sup>4</sup> Previously known as the BNM-LNHB.

<sup>5</sup> Previously known as the NMI

*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 two terms, the difference

$$D_{ij} = D_i - D_j = R_i - R_j \quad (7)$$

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

$$u_{ij}^2 = u_i^2 + u_j^2 - \sum_k (f_k u_{k,\text{corr}})_i^2 - \sum_k (f_k u_{k,\text{corr}})_j^2 \quad (8)$$

of which the final two terms take into account the correlations between the primary standard methods.

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs as indicated in (8). The common components of the uncertainty budgets for the NRC and the other NMIs with water calorimeters are given in Table 7. In this table,  $u_{Dw,i}$  is the combined standard uncertainty of the NMI primary standard (all components being included),  $u_{\text{transfer}}$  is the combined standard uncertainty associated with the transfer standard and  $u_{c,i}$  is the combined standard uncertainty for an absorbed dose to water calibration by the NMI; all uncertainties being in relative value.

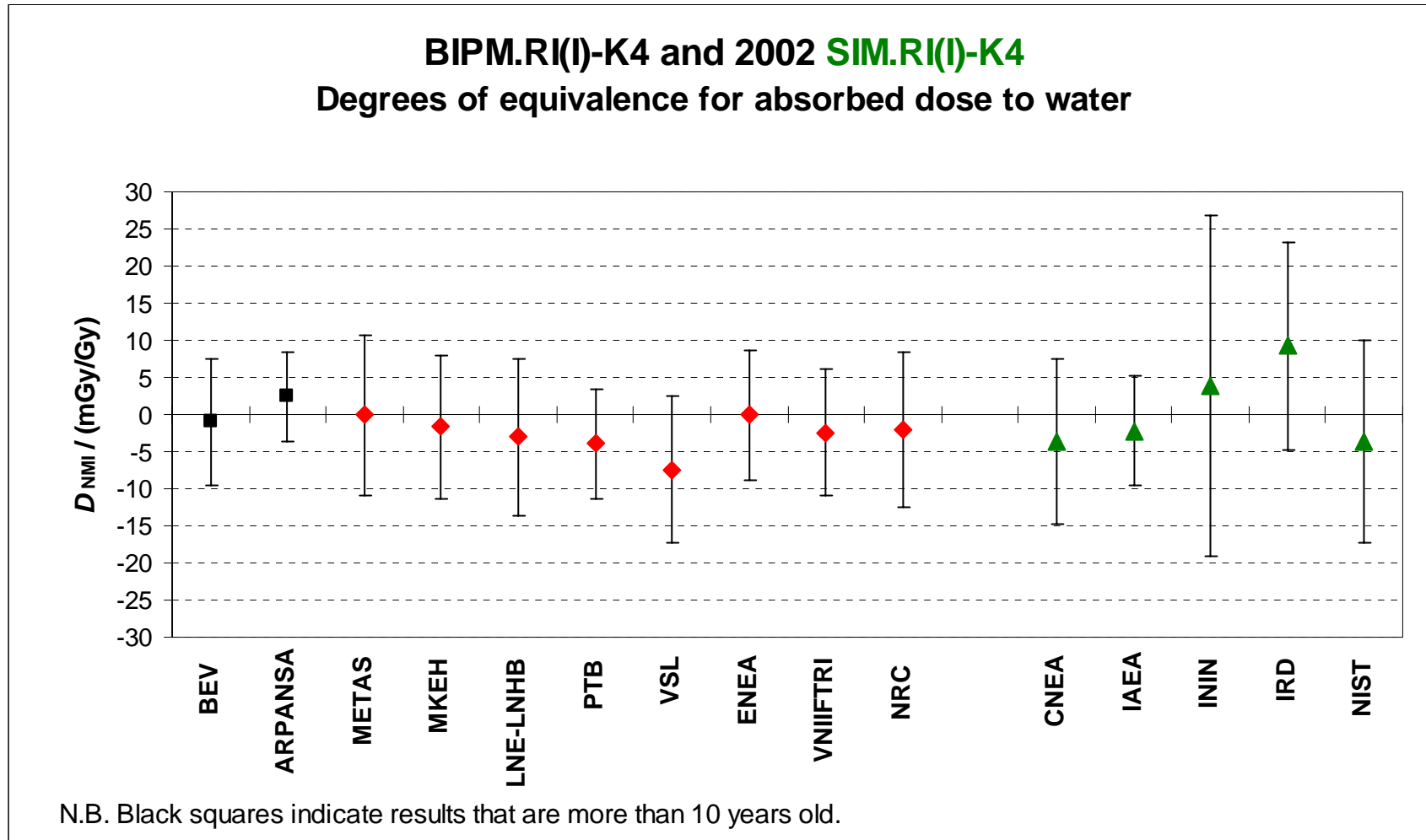
**Table 7. Correlated components in the uncertainty budgets for absorbed dose to water from water calorimetry primary standards, standard uncertainties per  $10^3$**

NMI, $i$	$k_c$	$k_{sc}$ or $k_p$	$k_{dd}$	$h$	$u_{Dw,i}$	$u_{\text{transfer}}$	$u_{c,i}$	$\sqrt{(\sum_k (f_k u_{k,\text{corr}})_i^2)}$
NIST	1.0			3.0	3.5	2.2	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
PTB	0.7	0.5	0.1	1.4	2.0	0.8	2.2	1.0
VSL	1.0	1.5	0.1	2.0	3.8	1.4	4.1	1.4
NRC	1.5	0.5	0.1	3.0	4.1	2.1	4.2	2.1
$f_{k,\text{NMI}}$	-	-	-	0.7				

Values for other National Metrology Institutes are taken from [2, 13, 14] where the acronyms are also explained.

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs and is given in Table 8 in the form that appears in the KCDB.

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



**Table 8. Evaluation of degrees of equivalence as presented in the KCDB**

The key comparison reference value is the BIPM evaluation of absorbed dose to water.

The degree of equivalence of each laboratory  $i$  with respect to the reference value is given by a pair of terms both expressed in mGy/Gy:

$D_i$  and  $U_i$ , its expanded uncertainty ( $k = 2$ ), with  $U_i = 2u_i$ .

The degree of equivalence between two laboratories is given by a pair of terms both expressed in mGy/Gy:

$D_{ij} = D_i - D_j$  and  $U_{ij}$ , its expanded uncertainty ( $k = 2$ ). In evaluating  $U_{ij} = 2u_{ij}$  for the Matrix of equivalence account is taken of correlations between  $u_i$  and  $u_j$ .

- **Linking SIM.RI(I)-K4 to BIPM.RI(I)-K4**

The value  $x_i/x_R$  is the comparison result for laboratory  $i$  participant in SIM.RI(I)-K4 having been normalized to the value of the NRC as the linking laboratory (see SIM.RI(I)-K4 Final Report [19]).

The degree of equivalence of each laboratory  $i$  participant in SIM.RI(I)-K4 with respect to the reference value is given by a pair of terms both expressed in mGy/Gy:

$D_i$  and  $U_i$ , its expanded uncertainty ( $k = 2$ ).

See SIM.RI(I)-K4 Final Report for the computation of  $D_i$  and the approximation used for  $U_i$  in the Matrix of equivalence.

The degree of equivalence between two laboratories  $i$  and  $j$ , one participant in BIPM.RI(I)-K4 and one in SIM.RI(I)-K4, or both participant in SIM.RI(I)-K4, is given by a pair of terms both expressed in mGy/Gy:

$D_{ij} = D_i - D_j$  and  $U_{ij}$ , its expanded uncertainty ( $k = 2$ ).

The approximation for  $U_{ij}$  is given in the SIM.RI(I)-K4 Final Report [19].

Lab $i$ ↓	$D_i$ $U_i$ / (mGy/Gy)		NRC	
	$D_i$	$U_i$	$D_{ij}$	$U_{ij}$
BEV	-1.0	8.6	1.0	11.2
ARPANSA	2.4	6.0	4.4	9.4
METAS	-0.1	10.8	1.9	9.8
MKEH	-1.7	9.6	0.3	13.1
LNE-LNHB	-3.0	10.6	-1.0	12.6
PTB	-3.9	7.4	-1.9	8.3
VSL	-7.4	9.8	-5.4	10.6
ENEA	-0.1	8.8	1.9	11.3
VNIIFTRI	-2.4	8.6	-0.4	12.2
NRC	-2.0	10.4		
CNEA	-3.7	11.1	-1.7	15.2
IAEA	-2.2	7.4	-0.2	12.7
ININ	3.9	23.0	5.9	25.2
IRD	9.2	14.0	11.2	17.4
NIST	-3.7	13.6	-1.7	13.6

The laboratory acronyms are given in the KCDB.

## 6. Conclusions

A key comparison has been carried out between the NRC (Canada) and the BIPM of standards for absorbed dose to water in  $^{60}\text{Co}$  gamma rays, using two ionization chambers as transfer standards. The comparison result, expressed as a ratio of the calibration coefficients measured by the NRC against their primary standard for absorbed dose to water using a water calorimeter to that of the BIPM is 0.9980 (52), which is consistent with the results of the previous comparison in 1998.

When compared with the results of the other National Metrological Institutes that have carried out comparisons in terms of absorbed dose to water at the BIPM, the NRC standard for absorbed dose to water is in satisfactory agreement.

## References

- [1] Allisy-Roberts P.J., Burns D.T., Shortt K. and Ross C.K., 1999, Comparisons of the standards of absorbed dose to water of the NRC, Canada and the BIPM for  $^{60}\text{Co}$  gamma rays, *Rapport BIPM-99/13*, 12 pp.
- [2] Allisy-Roberts P.J., Burns D.T., 2005, Summary of the BIPM.RI(I)-K4 comparison for absorbed dose to water in  $^{60}\text{Co}$  gamma radiation, *Metrologia*, 2005, 42, *Tech. Suppl.*, [06002](#).
- [3] Domen S.R., 1994, A sealed water calorimeter for measuring absorbed dose, *J. Res. Nat. Bur. Stand.*, 1994, 99, 121-141.
- [4] Seuntjens J.P., 1991, Comparative study of ion chamber dosimetry and water calorimetry in medium energy x-ray beams, Ph.D. thesis, 1991, Gent University, Gent, Belgium.
- [5] Seuntjens J.P., Ross C.K., Klassen N.V., Shortt K.R., 1999, A status report on the NRC sealed water calorimeter, NRC Report PIRS-0584, National Research Council, Ottawa, Canada.
- [6] Boutillon M., Perroche A.-M., 1993, Ionometric determination of absorbed dose to water for cobalt-60 gamma rays, *Phys. Med. Biol.*, 1993, 38, 439-454.
- [7] BIPM, 1985, Constantes physiques pour les étalons de mesure de rayonnement, *BIPM Com. Cons. Etalons Mes. Ray. Ionisants*, 1985, Section (I) 11, p. R45 (Paris : Offilib).
- [8] Bé M.-M., Chisté V, Dulieu C., Browne E., Baglin C., Chechev V., Kuzmenko N., Helmer R., Kondev F., MacMahon D., Lee K.B., 2006, Table of Radionuclides (Vol. 3 – A = 3 to 244) *Monographie BIPM-5*
- [9] Rutledge A.R., Smith L.V. and Merritt J.S., 1983, Experimental study of half-life determinations using  $^{60}\text{Co}$ , *Nuclear Instruments and Methods*, 1983, 206, 211-217.

- [10] McCaffrey, J.P., 2004, *Standard Operating Procedure 33-0124-IRS-302, <sup>60</sup>Co Absorbed Dose to Water Calibrations*, Institute for National Measurement Standards Quality System, Ionizing radiation Standards group, NRC Canada, Ottawa.
- [11] Allisy-Roberts P.J., Burns D.T. and Kessler C., 2009, Measuring conditions used for the calibration of national ionometric standards at the BIPM, 2009, [\*Rapport BIPM-09/04\*](#), 20 pp.
- [12] Allisy-Roberts P.J., Burns D.T., Kessler C., Delaunay F., Leroy E., 2005, Comparison of the standards for absorbed dose to water of the BNM-LNHB and the BIPM for <sup>60</sup>Co  $\gamma$ -rays, [\*Metrologia\*, 2005, 42, Tech. Suppl., 06006](#).
- [13] Kessler C., Allisy P.J., Burns D.T., Krauss A., Kapsch R.-P., 2006, Comparison of the standards for absorbed dose to water of the PTB, Germany and the BIPM for <sup>60</sup>Co  $\gamma$ -rays, [\*Metrologia\*, 2006, 43, Tech. Suppl., 06005](#)
- [14] Kessler C., Allisy-Roberts P.J., Burns D.T., Roger P., de Prez L.A., de Pooter J.A., Damen P.M.G., 2009, Comparison of the standards for absorbed dose to water of the VSL and the BIPM for <sup>60</sup>Co  $\gamma$ -rays, [\*Metrologia\*, 2009, 46, Tech. Suppl., 06009](#)
- [15] Kessler C., Allisy-Roberts P.J., Burns D.T., Guerra A.S., Laitano R.F., Pimpinella M., 2010, Comparison of the standards for absorbed dose to water of the ENEA-INMRI (Italy) and the BIPM for <sup>60</sup>Co  $\gamma$ -rays, [\*Metrologia\*, 2010, 47, Tech. Suppl., 06002](#)
- [16] Allisy-Roberts P.J., Kessler C., Burns D.T., Berlyand V., Berlyand A., 2010, Comparison of the standards for absorbed dose to water of the VNIIFTRI, Russia and the BIPM in <sup>60</sup>Co  $\gamma$ -rays, [\*Metrologia\*, 2010, 47, Tech. Suppl., 06003](#)
- [17] CIPM 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>.
- [18] Allisy P.J., Burns D.R., Andreo P., 2009, International framework of traceability for radiation dosimetry quantities, [\*Metrologia\*, 2009, 46\(2\), S1-S8](#)
- [19] Ross, C.R. Shortt K.R., Saravi M., Meghzifene A., Tovar V.M., Barbosa R.A., da Silva C.N., Carrizales L. and Seltzer S.M., 2008, Final report of the SIM <sup>60</sup>Co absorbed-dose-to-water comparison SIM.RI(I)-K4 [\*Metrologia\*, 2008, 45, Tech. Suppl., 06011](#).