Final Report 12/05/05

Comparison of the standards for absorbed dose to water of the BNM-LNHB and the BIPM for ^{60}Co γ rays

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Abstract
A comparison of the standards for absorbed dose to water of the Bureau National de Métrologie - Laboratoire National Henri Becquerel (BNM-LNHB), Saclay, France and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co radiation under the auspices of the key comparison BIPM.RI(I)-K4. The comparison result expressed as a ratio of the BNM-LNHB and the BIPM standards for absorbed dose to water is 0.9970 (0.0053). The degrees of equivalence between the BNM-LNHB and the other participants in this comparison have been calculated and the results are given in the form of a matrix for the twelve national metrology institutes (NMIs) 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 for absorbed dose to water of the Bureau National de Métrologie - Laboratoire National Henri Becquerel, Saclay, France and of the Bureau International des Poids et Mesures, was carried out in the ^{60}Co radiation beam at the BIPM in December 2003. The primary standard of the BNM-LNHB for absorbed dose to graphite is a quasi-adiabatic graphite calorimeter and is described in [1]. The BNM-LNHB derives the absorbed dose to water from its calorimetric determination by measurements with a transfer chamber in both graphite and water, and using Fricke dosimetry [2]. The BIPM primary standard for absorbed dose to water is a graphite cavity ionization chamber of pancake geometry as described in [3].

The comparison was undertaken using two BNM-LNHB ionization chambers as transfer instruments for absorbed dose to water. The result of the comparison is given in terms of the ratio of the calibration coefficients of the transfer chambers determined at the two laboratories under the same experimental conditions. The absorbed dose to water comparison is the second such comparison made between the two laboratories and agrees to 1.8×10^{-3} with the first that was conducted in 1996 [4].

In this report an outline is given of the standards for absorbed dose to water of the BIPM and of the BNM-LNHB. The experimental conditions under which the transfer standards were calibrated are described in Section 3 and the result of the comparison is presented in Section 4.

The comparison result has been approved by the CCRI(I) and the degrees of equivalence between the BNM-LNHB 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 absorbed dose to water

At the BIPM, the rate of absorbed dose to water is determined by an ionometric method [3]. The dose rate is given by

$$\dot{D}_{\mathrm{w,BIPM}} = \frac{I}{m}\frac{W}{e}\bar{s}_{\mathrm{c,a}}\left(\bar{\mu}_{\mathrm{en}}/\rho\right)_{\mathrm{w,c}}\Psi_{\mathrm{w,c}}\left(1+\varepsilon\right)_{\mathrm{w,c}}\Pi k_{\mathrm{i}}\,, \qquad (1)$$

where I / m is the ionization current per unit mass of air measured by the standard, W is the average energy spent by an electron of charge e to produce an ion pair in dry air, $\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean stopping powers of graphite and air, $(\bar{\mu}_{\mathrm{en}} / \rho)_{\mathrm{w,c}}$ is the ratio of the mean mass energy-absorption coefficients, $\Psi_{\mathrm{w,c}}$ is the ratio of the photon energy fluences, $(1 + \varepsilon)_{\mathrm{w,c}}$ is the ratio of the absorbed dose to collision kerma ratios, and Πk_{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) for the BIPM standard are given in [5] together with their uncertainties. The uncertainty budget is given in Table 1. The combined relative standard uncertainty is 2.9×10^{-3} when the uncertainty of the product $(W/e)\ \bar{s}_{\mathrm{c,a}}$ is taken into consideration. The value for the rate of absorbed dose to water $\dot{D}_{\mathrm{w,BIPM}}$ is taken as the mean of all the results of 2003 and is given by convention at the beginning of the year for each comparison, 01/01/2003 in this case.

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

Quantity	BIPM value	BIPM relative standard uncertainty[(1)]	
		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Dry air density [(2)] /(kg m^{-3})	1.293 0	–	0.01
W/e (J C^{-1})	33.97	–	0.11[(3)]
$\bar{s}_{\mathrm{c,a}}$	1.003 0		
k_{cav} (air cavity)	0.990 0	0.03	0.04
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	1.112 5	0.01	0.14
$\Psi_{\mathrm{w,c}}$ (photon-fluence ratio)	1.006 5	0.04	0.06
$(1+\varepsilon)_{\mathrm{w,c}}$ (dose-to-kerma ratio)	1.001 5	–	0.06
k_{ps} (polythene envelope)	0.999 4	0.00_5	0.01
k_{pf} (phantom window)	0.999 6	–	0.01
k_{rn} (radial non-uniformity)	1.005 1	0.00_5	0.03
k_{s} (recombination losses)	1.001 5	0.00_4	0.01
k_{h} (humidity)	0.997 0	–	0.03
Volume of standard CH4-1 /cm^3	6.881 0	0.19	0.03
I (ionization current)	–	0.01	0.02
Positioning	–	0.03	–
Quadratic summation		0.20	0.21
Combined standard uncertainty of $\dot{D}_{\mathrm{w,BIPM}}$		0.29	

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

(2) At 0 °C and 101.325 kPa.

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

The BNM-LNHB standard for absorbed dose to water for ^{60}Co gamma radiation is based on the determination of absorbed dose to graphite using a graphite calorimeter [1]. This calorimeter is of a quasi-adiabatic design. The main characteristics are given in Table 2.

Table 2. Characteristics of the BNM-LNHB graphite calorimeter

Component	**characteristic**	**unit**	**value**
Core	diameter	mm	16
	length	mm	3
	mass	g	1.1177
	graphite density	g cm^{-3}	1.85
Gap widths*	gap 1	mm	1.12
	gap 2	mm	1.19
	gap 3	mm	1.00
Depth from entrance window to middle plane of the core		g cm^{-2}	2.2499
Phantom	section	mm^2	300 × 300
	length	mm	200
	graphite density	g cm^{-3}	1.76

* width of lateral gaps : 2 mm

The absorbed dose rate at depth *d* is given by

$$\dot{D}_{c,\mathrm{LNHB}} = \frac{L_{\mathrm{c}d}}{m} F_{\mathrm{el}} \Pi k_i \,, \qquad (2)$$

where

$L_{\mathrm{c}d}$	is the rate of change of resistance as measured by the calorimeter at depth *d*; the values refer to an evacuated path length between the source and phantom,
F_{el}	is the electrical calibration coefficient expressed in terms of energy per unit resistance change,
m	is the mass of the core,
Πk_i	is the product of the correction factors to be applied to the calorimetric measurements.

The numerical values entering in (2) are given in Table 3, together with their uncertainties.

Table 3. Quantities, correction factors and their uncertainties in the BNM-LNHB calorimetric determination of the absorbed dose rate in graphite at a depth *d*

Measured quantity		Numerical value	Standard uncertainty	
Symbol	Quantity		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
L_c				
α_rad	temperature rise signal (radiation)		0.05	
Δt_rad	irradiation time			0.00_5
m	mass of the core / g	1.1177		0.02
F_el				
P_el	electrical power calibration			0.01_5
α_{el}	temperature rise signal (electrical)			0.02
Δt_el	calibration time			0.00_5
Correction factors				
k_1	impurities	0.9989		0.10
k_2	heat loss (temperature gradient)	1.0000		0.05
k_3	heat defect	1.0000		0.10
k_4	depth at point of measurement	1.0000		0.10
k_5	distance	1.0003		0.01
k_6	vacuum gaps	0.9909		0.15
k_7	entrance foil attenuation	1.0004		0.01
k_8	axial non-uniformity	1.0000		–
k_9	radial non-uniformity	1.0002		0.01
Uncertainty				
Quadratic summation			0.05	0.24
Combined standard uncertainty of $\dot{D}_{c,\mathrm{LNHB}}$			0.25	

The absorbed dose to water is determined at the BNM-LNHB by transfer from absorbed dose to graphite using a graphite cavity ionization chamber type NE 2571.

The absorbed dose rate in water at the BNM-LNHB is given by :

$$\dot{D}_\mathrm{w,\,LNHB} = \dot{D}_\mathrm{c,\,LNHB}\frac{I_\mathrm{w}}{I_\mathrm{c}}k_\mathrm{stop}k_\mathrm{wall}k_\mathrm{cav}\left(\mu_\mathrm{en}/\rho\right)_\mathrm{w,c}\beta_\mathrm{w,c} \qquad (3)$$

where

$D_\mathrm{c,LNHB}$ is the absorbed dose to graphite at the depth of 5.042 g cm^{-2} determined with the BNM-LNHB calorimetric standard,

I_c is the ionization current measured by the transfer chamber, with its centre at the depth of 5.042 g cm^{-2} in the BNM-LNHB graphite phantom,

I_w is the ionization current measured by the transfer chamber in the water phantom at the BNM-LNHB,

k_stop is the ratio of the graphite to air stopping power ratios in the water and graphite phantoms,

k_wall is the ratio of the wall perturbation factors in the water and graphite phantoms,

k_{cav} is the ratio of the cavity perturbation factors in the water and graphite phantoms,
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$ is the ratio of the mean mass-energy absorption coefficients of water and graphite in the water phantom,
$\beta_{\mathrm{w,c}}$ is the ratio of the kerma factors in water and graphite, in the water phantom.

The physical constants and correction factors are given together with their uncertainties in Table 4 for the BNM-LNHB standard.

Table 4. Physical constants, correction factors and relative standard uncertainties for the BNM-LNHB determination of absorbed dose to water

Quantity	**BNM-LNHB value**	**BNM-LNHB relative standard uncertainty**	
Determination of $\dot{D}_{\mathrm{c,LNHB}}$		**100 $u_{i\mathrm{A}}$**	**100 $u_{i\mathrm{B}}$**
calorimetric measurement in graphite (see Table 3)		0.05	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 graphite		–	0.03
Transfer from graphite to water			
k_{stop}	1.0000	–	0.03
k_{wall}	1.0088	–	0.20
k_{cav}	1.0017	–	
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	1.1110	–	0.15
$\beta_{\mathrm{w,c}}$	1.0000	–	0.05
Ionometric transfer from the old to the new source		0.02	0.29
Uncertainty quadratic summation		0.06	0.46
Combined standard uncertainty of $\dot{D}_{\mathrm{w,LNHB}}$		**0.46**	

3. Experimental conditions for transfer chamber calibration

The chambers used for the transfer from graphite to water at the BNM-LNHB were brought to the BIPM and their calibration factors determined against the BIPM absorbed dose to water standard.

The environmental conditions at the two laboratories were as follows. The air and water temperature at the BIPM was controlled at around 19.6 °C (stable to better than 0.005 °C during a series of measurements) and at the BNM-LNHB varied between 18.9 °C and 21.8 °C. Measured transfer chamber ionization currents were normalized to the standard environmental conditions of 293.15 K and 101.325 kPa using k_{TP} and adjusted for attenuation in the beam using k_{att}. At the BIPM the relative humidity of around 50 % changed by not more than 5 % and no correction for humidity is applied. At the BNM-LNHB the humidity varied between 20 % and 60 %. Under these conditions the BNM-LNHB normally applies a correction of 0.9970 (3) to the ionization current but for the present comparison no correction was applied.

The transfer standards used in the comparison are cavity ionization chambers of type NE 2571 (serial numbers 2343 and 2791). An appropriate voltage (300 V positive polarity to the collector) was applied to each chamber at each laboratory so that although the BNM-LNHB has measured the polarity effect for each chamber, no correction for this was applied.

The ionization current of the chambers was measured using a Keithley electrometer at the BIPM and a cross comparison was made of the BNM-LNHB measuring system using the BNM-LNHB primary standard and one transfer chamber. The ratio of the two systems BIPM/BNM-LNHB was 1.0006. An independent assessment using a current ramp and the BIPM capacitors for both systems gave the value 0.9997. The main cause of this 9×10^{-4} difference appears to be due to the calibration of the BNM-LNHB capacitors. The uncertainty in the current measurement is expanded to allow for this.

The absorbed dose rate at the BNM-LNHB was about 950 mGy/min (reference date 01/01/2002) and at the BIPM about 126 mGy/min (reference date 01/01/2003), k_t being used to correct for source decay. The BNM-LNHB has measured the recombination correction for each chamber and identified that it is almost exclusively due to initial recombination. Consequently no correction was applied to either of the transfer chambers.

The standard deviation of the measured ionization currents during one series at the BIPM was less than 2 fA, which in relative terms corresponds to less than 4×10^{-5} of the mean measured currents.

The calibration coefficient for a transfer standard in terms of absorbed dose to water is

$$N_{D_{\mathrm{w}},\mathrm{lab}} = \frac{\dot{D}_{\mathrm{w,lab}}}{I_{\mathrm{w,lab}}}, \qquad (4)$$

where $\dot{D}_{\mathrm{w,lab}}$ is the rate of absorbed dose to water as determined by each laboratory and $I_{\mathrm{w,lab}}$ is the measured ionization current of the transfer chamber under the same experimental conditions:

$$N_{D_\mathrm{w}} = \dot{D}_\mathrm{w} / \left(I \times k_{TP} k_d k_z k_t k_\mathrm{att} k_\mathrm{rn} \right) \tag{5}$$

Both the BNM-LNHB and the BIPM ^{60}Co beams are horizontal. All measurements were performed at a reference distance (from source to chamber axis) of 1 m at both laboratories, any small distance corrections k_d being applied as necessary. The BIPM field size is a square of side 10 cm and at the BNM-LNHB it is circular with diameter 16 cm. The appropriate correction k_rn for the radial non-uniformity of the beam, of value 1.000 40 or 1.000 09, was applied at the BNM-LNHB and the BIPM [6] respectively. For measurements in water, both laboratories used a cubic water phantom of side length 30 cm and the same protective waterproof sleeve in each laboratory, the BNM-LNHB sleeve for the NE2571-2791 and a BIPM sleeve for the NE2571-2343 chamber. The calibration coefficients for absorbed dose to water were determined at a reference depth of 5 g cm^{-2} at the BIPM and at 5 cm (4.6 cm water and 0.4 cm plexiglass) at the BNM-LNHB, with k_z to correct for small differences to match the reference depth for each primary standard.

The uncertainties determined for the comparison are given in Table 5, using the two transfer chambers.

Table 5. Relative standard uncertainties associated with calibration coefficients and the comparison value using the BNM-LNHB transfer chambers

	Uncertainty in $N_{D,\mathrm{w\ BNM\text{-}LNHB}}$		**Uncertainty in** $N_{D,\mathrm{w\ BIPM}}$		**Uncertainty in** $D_{\mathrm{w,\ BNM\text{-}LNHB}} / D_{\mathrm{w,\ BIPM}}$	
Relative standard uncertainty in the measurement of	100 s_i	100 u_i	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate	0.06	0.46	0.20	0.21	0.20	0.47*
Ionization current of transfer chamber	0.00_1	0.11	0.01_5	0.02	0.01	0.11
Chamber position/depth	–	0.02_5	0.01	0.05	0.01	0.07
Source decay	–	0.00_4	–	–	–	–
Radial non-uniformity correction	0.00_8	0.01_7	0.00_5	0.01	0.01	0.02
Combined relative standard uncertainty						
Quadratic summation	0.06_1	0.47_4	0.20_0	0.21_7	0.20_1	0.48_8
Combined uncertainty	0.48		0.30		0.53	

* Taking into account the correlations of the uncertainties in the ($\overline{\mu}_\mathrm{en} / \rho$) and the β ratios.

4. Results of the comparison

Calibration coefficients in terms of absorbed dose to water were determined at the BNM-LNHB and at the BIPM. The measurements at the BNM-LNHB were performed before and after the measurements at the BIPM in December 2003, and the BNM-LNHB data sets were averaged. The differences between the sets of measurements were not more than 6.4 × 10^{-4}. At the BIPM, each transfer chamber was measured twice over the 5 days of the comparison and the deviations of the calibration coefficients were less than 4 × 10^{-4}. Using the transfer chambers, the mean ratio of the calibration coefficients of the two laboratories is taken to represent the ratio of the absorbed dose to water standards. The results are presented in Table 6. Taking the mean of the ratios given produces a comparison result of

$$R_{\text{BNM-LNHB}} = D_{\text{w,BNM-LNHB}} \,/\, D_{\text{w,BIPM}} = 0.9970\ (0.0053).$$

The uncertainty of the ratio $D_{\text{w,BNM-LNHB}}$ / $D_{\text{w,BIPM}}$ is derived from the uncertainty budgets of both standards (see Tables 1 and 4), together with the uncertainties associated with the use of the transfer chambers (see Table 5). The correlations arising from the use of mass energy-absorption coefficients and absorbed dose to kerma ratios in both methods are taken into account by applying estimated correlation coefficients f_{k} of 0.95 and 0.7, respectively, to the uncertainties $u_{k,\text{corr}}$ from both laboratories as given in:

$$u_{R,\text{NMI}}{}^{2} = u_{\text{c,NMI}}{}^{2} + u_{\text{c, BIPM}}{}^{2} - \sum\left(f_k u_{k,\text{corr}}\right)^2_{\text{NMI}} - \sum\left(f_k u_{k,\text{corr}}\right)^2_{\text{BIPM}} . \qquad (6)$$

Table 6. Comparison of the BNM-LNHB and BIPM calibration coefficients in terms of absorbed dose to water

Ionization Chamber	$N_{D_{\text{w}},\text{BNM-LNHB}}$ /(Gy µC^{-1})	$N_{D_{\text{w}},\text{BIPM}}$ /(Gy µC^{-1})	$R_{\text{BNM-LNHB}}$ = ($D_{\text{w,BNM-LNHB}}$ / $D_{\text{w,BIPM}}$)	u_R ($D_{\text{BNM-LNHB}}/D_{\text{BIPM}}$)
NE 2571 - 791	44.888	45.018 45.037	**0.9968_9**	0.0053
NE 2571 - 2343	45.185	45.316 45.322	**0.9970_4**	0.0053
Mean value			**0.9970**	0.0053

The previous result of an absorbed dose to water comparison with the BNM-LNHB is given in Table 7 where it can be seen that the difference is of the order of the relative combined standard uncertainty of using transfer standards at both laboratories.

5. Comparison with other metrology institutes

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 BNM-LNHB, is given in [7] and the results are available in the key comparison database of the CIPM MRA [8].

The relative combined standard uncertainty associated with a determination of absorbed dose to water at an NMI is designated $u_{D\text{w,NMI}}$. The relative combined standard uncertainty $u_{R,\text{NMI}}$ of each comparison result R_{NMI} takes into account the standard uncertainty $u_{\text{c,NMI}}$ of $N_{D\text{w,NMI}}$ derived from the uncertainty budget and the standard uncertainty $u_{\text{c,BIPM}}$ of $N_{D\text{w,BIPM}}$ (see Table 5). For comparison between the metrology institutes, the correlations between the measurement methods need to be taken into account, 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

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,\,BIPM}}{}^2 - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}} - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{BIPM}} \qquad (7)$$

where all the standard uncertainties are expressed as relative values.

The numerical values for $u_{R,\mathrm{NMI}}$ using this consistent approach are as listed for the BNM-LNHB in Table 7 and are those used for the key comparison database (KCDB) entries. The correlated parts of the uncertainty budgets for the BNM-LNHB and the other NMIs with graphite calorimeters are given in Table 8.

Table 7. Results for the BNM-LNHB key comparisons of absorbed dose to water

NMI	**Year**	$u_{D\mathrm{w,NMI}}$	R_{NMI}	$u_{R,\mathrm{NMI}}$	**Primary standard**	**Ref.**
		in relative value				
BNM-LNHB	1993	0.0034	0.9988	0.0040	graphite calorimeter	[4]
BNM-LNHB	2003	0.0047	0.9970	0.0053	graphite calorimeter	–

In Table 8, $u_{D\mathrm{w,NMI}}$ 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. The uncertainty in the calculation of the correction for graphite calorimeter gaps, k_{gap}, is also taken to have some correlated component as shown.

Table 8. Correlated components in the uncertainty budgets for absorbed dose to water from graphite calorimetry primary standards, standard uncertainties per 10^3

NMI	k_{gap}	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	$(\beta)_{w,c}$	$u_{D\mathrm{w,NMI}}$	u_{transfer}	$u_{\mathrm{c,NMI}}$	$\sqrt{\sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}}}$
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
BNM-LNHB	1.5	1.5	0.5	4.7	1.1	4.8	1.6
$f_{k,\mathrm{BIPM}}$	–	0.95	0.7				
$f_{k,\mathrm{NMI}}$	0.5	0.95	0.7				

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the key comparison reference value (KCRV) [8]. The degree of equivalence is expressed quantitatively in terms of the deviation of the comparison result from the key comparison reference value, R_{ref}, 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

$$D_{\mathrm{NMI}} = R_{\mathrm{NMI}} - 1 \qquad (8)$$

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

$$U_{\mathrm{NMI}} = 2u_{R,\mathrm{NMI}}\,. \qquad (9)$$

Table 9 gives the values for D_{NMI} and U_{NMI} for each NMI taken from [7] and this report, using (8) and (9), and forms the basis of the entries in MRA Appendix B. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1995.

Figure 1. Degrees of equivalence with the KCRV for absorbed dose to water standards

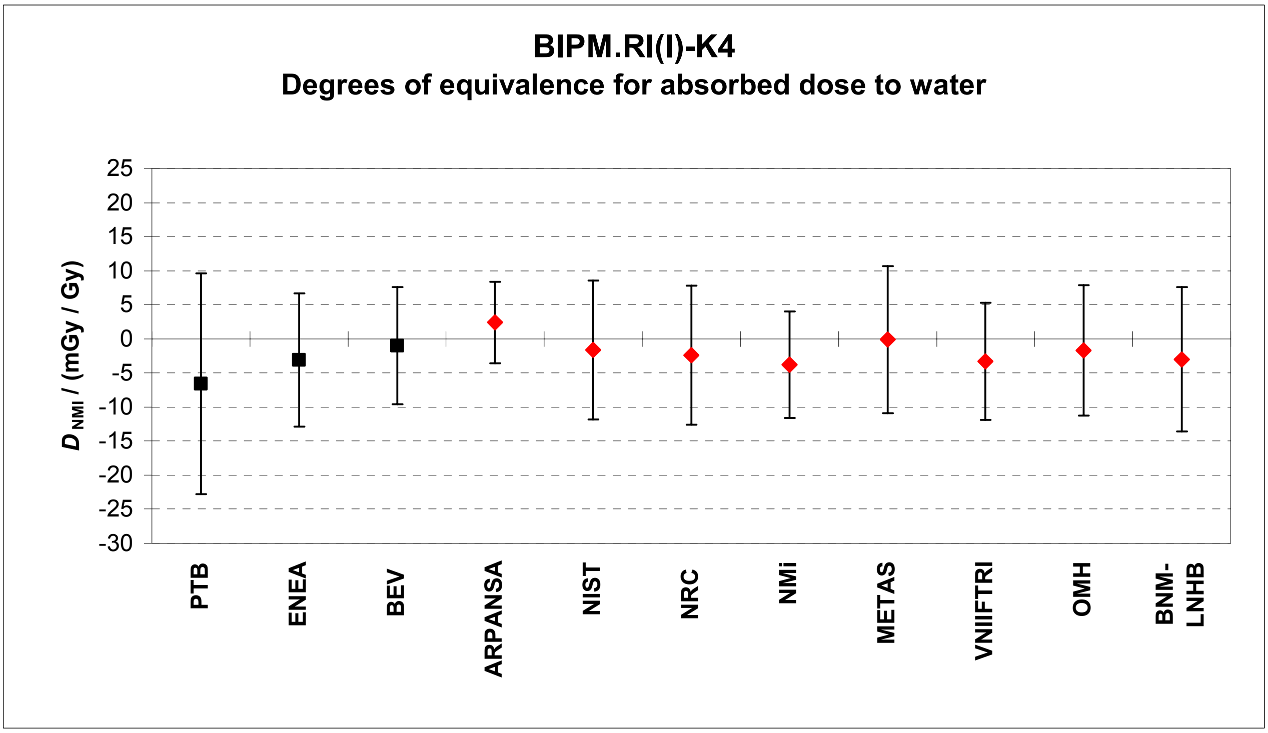

Table 9. Degrees of equivalence of each NMI's measurement standard

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
BNM-LNHB	2003	4.8	-3.0	10.6

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

$$D_{ij} = D_i - D_j = R_i - R_j \qquad (10)$$

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

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 . \qquad (11)$$

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs and is given in Table 10 in the form that 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 results have been agreed by the participants.

An updated summary of the results is presented to each CCRI(I) meeting. Scientific decisions to remove results from the KCDB are made only 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 Key Comparison Working Group. Such approval requires that the comparison is declared in advance and that at least one of the NMIs already has a BIPM comparison result.

Table 10. Degrees of equivalence between the metrology institutes

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 ($k = 2$), expressed in units of mGy / Gy, 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 ($k = 2$), bexpressed in units of mGy / Gy.
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		ENEA		BEV		ARPANSA		NIST		NRC	
	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}
	/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)	
PTB	**-6.6**	16.2			**-3.5**	17.8	**-5.6**	16.9	**-9.0**	15.8	**-5.0**	17.4	**-4.2**	17.4
ENEA	**-3.1**	9.8	**3.5**	17.8			**-2.1**	10.7	**-5.5**	8.9	**-1.5**	12.5	**-0.7**	12.5
BEV	**-1.0**	8.6	**5.6**	16.9	**2.1**	10.7			**-3.4**	7.6	**0.6**	11.2	**1.4**	11.2
ARPANSA	**2.4**	6.0	**9.0**	15.8	**5.5**	8.9	**3.4**	7.6			**4.0**	9.4	**4.8**	9.4
NIST	**-1.6**	10.2	**5.0**	17.4	**1.5**	12.5	**-0.6**	11.2	**-4.0**	9.4			**0.8**	10.3
NRC	**-2.4**	10.2	**4.2**	17.4	**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	**-0.7**	10.1	**-2.8**	9.0	**-6.2**	6.6	**-2.2**	11.7	**-1.4**	11.7
METAS	**-0.1**	10.8	**6.5**	17.7	**3.0**	12.9	**0.9**	11.7	**-2.5**	9.9	**1.5**	10.8	**2.3**	9.8
VNIIFTRI	**-3.3**	8.6	**3.3**	17.7	**-0.2**	10.8	**-2.3**	9.8	**-5.7**	7.7	**-1.7**	12.3	**-0.9**	12.3
OMH	**-1.7**	9.6	**4.9**	18.2	**1.4**	11.6	**-0.7**	10.6	**-4.1**	8.7	**-0.1**	13.1	**0.7**	13.1
BNM-LNHB	**-3.0**	10.6	**3.6**	17.9	**0.1**	12.1	**-2.0**	11.2	**-5.4**	9.4	**-1.4**	12.6	**-0.6**	12.6

Lab *j* ⇨

Lab *i* ⇩

			NMi		METAS		VNIIFTRI		OMH		BNM-LNHB	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)		/ (mGy / Gy)	
PTB	**-6.6**	16.2	**-2.8**	17.3	**-6.5**	17.7	**-3.3**	17.7	**-4.9**	18.2	**-3.6**	17.9
ENEA	**-3.1**	9.8	**0.7**	10.1	**-3.0**	12.9	**0.2**	10.8	**-1.4**	11.6	**-0.1**	12.1
BEV	**-1.0**	8.6	**2.8**	9.0	**-0.9**	11.7	**2.3**	9.8	**0.7**	10.6	**2.0**	11.2
ARPANSA	**2.4**	6.0	**6.2**	6.6	**2.5**	9.9	**5.7**	7.7	**4.1**	8.7	**5.4**	9.4
NIST	**-1.6**	10.2	**2.2**	11.7	**-1.5**	10.8	**1.7**	12.3	**0.1**	13.1	**1.4**	12.6
NRC	**-2.4**	10.2	**1.4**	11.7	**-2.3**	9.8	**0.9**	12.3	**-0.7**	13.1	**0.6**	12.6
NMi	**-3.8**	7.8			**-3.7**	12.2	**-0.5**	9.1	**-2.1**	10.0	**-0.8**	10.5
METAS	**-0.1**	10.8	**3.7**	12.2			**3.2**	12.7	**1.6**	13.5	**2.9**	13.0
VNIIFTRI	**-3.3**	8.6	**0.5**	9.1	**-3.2**	12.7			**-1.6**	10.7	**-0.3**	11.3
OMH	**-1.7**	9.6	**2.1**	10.0	**-1.6**	13.5	**1.6**	10.7			**1.3**	12.0
BNM-LNHB	**-3.0**	10.6	**0.8**	10.5	**-2.9**	13.0	**0.3**	11.3	**-1.3**	12.0		

7. Conclusions

A key comparison has been carried out between the BNM-LNHB and the BIPM of standards of absorbed dose to water for ^{60}Co gamma rays, using two ionization chambers as transfer standards. From air-kerma calibrations made at the same time [9] it is concluded that both transfer chambers have a stable and predictable response. The mean comparison result derived from the two sets of calibrations shows that the BNM-LNHB determination of absorbed dose to water is 3×10^{-3} lower in relative terms than that of the BIPM. This is compatible with the combined relative standard uncertainty of the comparison (5.2×10^{-3}) and is in agreement with the previous result of 1993. 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 BNM-LNHB standard for absorbed dose to water is in satisfactory agreement, being well within the standard uncertainty of the distribution of these results.

8. References

[1] Daures J., Ostrowsky A., Simoën J.-P., Mesure calorimétrique en dosimétrie des rayonnements ionisants, Réalisations au LPRI, 1990, *Bulletin du BNM*, **82**, 28.

[2] Chauvenet B., Baltès D. and Delaunay F., Comparison of graphite-to-water absorbed-dose transfers for ^{60}Co photon beams using ionometry and Fricke dosimetry, *Phys. Med. Biol.* 1997, **42**, 2053-63.

[3] Boutillon M. and Perroche A.-M., Ionometric determination of absorbed dose to water for cobalt-60 gamma rays, *Phys. Med. Biol.* 1993, **38**, 439-54.

[4] Perroche A.-M., Boutillon, M., Daures J., Delaunay F., Leroy E., Ostrowsky A., 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 pp.

[5] Allisy-Roberts P.J., Burns D.T., Kessler C., Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM*-2004/17, 20 pp

[6] Boutillon M., Perroche A.-M., Radial non-uniformity of the BIPM ^{60}Co beam, 1989, Rapport BIPM-89/2, 9 pages.

[7] Allisy-Roberts P.J., Burns D.T., Summary of the BIPM.RI(I)-K4 comparison for absorbed dose to water in ^{60}Co gamma radiation, *Metrologia,* 2005, **42**, *Tech. Suppl.,* 06002

[8] 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.

[9] Allisy-Roberts P.J., Burns D.T., Kessler C., Delaunay F., Comparison of the standards for air kerma of the BNM-LNHB and the BIPM for ^{60}Co γ rays, *Rapport BIPM-2005/XX* in preparation.

May 2005