

Final Report 2010-01-12

Comparison of the standards for absorbed dose to water of the ENEA-INMRI (Italy) 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 Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy (ENEA-INMRI), and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation under the auspices of the key comparison BIPM.RI(I)-K4. The comparison result, based on the calibration coefficients for three transfer standards and expressed as a ratio of the ENEA and the BIPM standards for absorbed dose to water, is 0.9999 (0.0044). The present 2007 result replaces the earlier ENEA value in this key comparison. The degrees of equivalence between the ENEA 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) that have published results in this 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 Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy, and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. The measurements at the BIPM took place in April 2007. This absorbed dose to water comparison replaces the indirect comparison made between the two

laboratories in 1994 [1] that was previously registered in the BIPM.RI(I)-K4 key comparison [2].

The primary standard of the ENEA is based on a graphite calorimeter of the Domen type [3, 4]. The BIPM primary standard is a graphite-walled cavity ionization chamber of parallel-plate design [5].

The comparison was undertaken using three ionization chambers of the ENEA 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 ENEA 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
- Πk_i is the product of the correction factors to be applied to the standard.

The values for the physical constants and the correction factors entering in (1) are given in [5, 6] together with their uncertainties, the combined relative standard uncertainty being 2.9×10^{-3} . The uncertainty budget is reproduced in Table 1.

At the ENEA, the absorbed dose rate to water is determined by an assembly of apparatus including a graphite calorimeter, a graphite phantom, a water phantom and a thick-walled (TW) ionization chamber. The TW chamber is used to transfer the absorbed dose from graphite to water [4]. To this end measurements using the TW chamber are made at two corresponding depths in graphite and water, respectively. These depths are such that similar energy spectra of radiation occur at the measurement points, so that undesired effects due to the TW chamber energy response are negligible when passing from measurements in the graphite phantom to measurements in the water phantom. To obtain similar energy spectra at the measurement points the graphite phantom has dimensions identical to the graphite calorimeter whereas the water phantom has a similar cylindrical shape but dimensions scaled according to the inverse ratio of the electron concentrations of graphite and water (diameter 48 cm, height 30 cm). For the measurements in the water phantom the source-to-detector-distance (SDD), field size and measurement depth are also scaled with respect to graphite.

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 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⁾
$\bar{s}_{c,a}$	1.0030	–	
k_{cav} (air cavity)	0.9900	0.03	0.04
$(\bar{\mu}_{en}/\rho)_{w,c}$	1.1125	0.01	0.14
$\Psi_{w,c}$ (photon fluence ratio)	1.0065	0.04	0.06
$(1+\epsilon)_{w,c}$ (dose to kerma ratio)	1.0015	–	0.06
k_{ps} (polyethylene envelope)	0.9994	0.01	0.01
k_{pf} (phantom window)	0.9996	–	0.01
k_{rn} (radial non-uniformity)	1.0051	0.01	0.03
k_s (recombination losses)	1.0016	0.01	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 $D_{w,BIPM}$		0.29	

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

(2) At 0 °C and 101.325 kPa.

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

The value 5.54 g cm⁻² is the scaled depth in graphite, derived from scaling to graphite the reference depth of 5 cm in water. To achieve the value 5.54 g cm⁻² for the measurement depth, the graphite plates to be added in front of the calorimeter were machined specifically. The mass and thickness of these graphite plates were measured. The values of the scaled depth and of the measurement depth were the same, within the measurement uncertainties ($4 \cdot 10^{-4}$). This is taken into account in the uncertainty budget of $D_{w,ENEA}$ (Table 2), as “positioning of the TW chamber in graphite”. The details of the procedure are described in [4].

Accordingly the absorbed dose rate to water is determined as

$$\dot{D}_{w,ENEA} = I_w \frac{\dot{D}_{c,ENEA}}{I_c} (\bar{\mu}_{en}/\rho)_{w,c} \beta_{w,c} \Psi_{w,c}, \quad (2)$$

where

I_w is the ionization current measured by the TW chamber in water at the depth 5.0 g cm⁻², field size 10 cm × 10 cm and SDD 100 cm,

$\dot{D}_{c,ENEA}$ is the absorbed dose rate to graphite determined by the graphite calorimeter at the measurement depth 5.54 g cm⁻², the value of the scaled depth in graphite [4], with field size 6.25 cm × 6.25 cm and SDD 62.5 cm,

- I_c is the ionization current determined by the TW chamber at the measurement point in graphite,
 $(\bar{\mu}_{en}/\rho)_{w,c}$ is the ratio of the mean mass energy-absorption coefficients in water and graphite at the measurement point in water
 $\beta_{w,c}$ is the ratio of the absorbed dose to collision kerma ratios in water and graphite, at the measurement point in water, and
 $\Psi_{w,c}$ is the ratio of the photon energy fluence in water and in a small mass of graphite, respectively, at the measurement point in water [4].

The absorbed dose rate to graphite determined by the graphite calorimeter is given by

$$\dot{D}_{c,ENE A} = \frac{f_c k_{qa} k_{hd} k_{gap}}{m}, \quad (3)$$

where

- f_c is the rate of the fractional change of the core thermistor resistance during the irradiation,
 k_{qa} is the quasi-adiabatic electrical calibration coefficient,
 k_{hd} is the correction factor for the heat defect in graphite,
 k_{gap} is the correction factor for calorimeter vacuum gaps,
 m is the mass of the calorimeter core.

The quantities and factors in equations (2) and (3) with their relative standard uncertainties are reported in Table 2 and Table 3, respectively.

Table 2. Relative standard uncertainties for the ENEA determination of absorbed dose to water

Source of uncertainty	ENEA value	ENEA relative standard uncertainty	
		100 s_i	100 u_j
calorimetric measurement of $D_{c,ENE A}$ (Table 3)	–	0.15	0.23
positioning of the TW chamber in graphite	–	–	0.04
measurement of I_c for the TW chamber	–	0.02	0.08
positioning of the TW chamber in water	–	–	0.06
measurement of I_w for the TW chamber	–	0.02	0.08
$(\bar{\mu}_{en}/\rho)_{w,c}$	1.1124	0.02	0.14
$\beta_{w,c}$	1.0009	0.01	0.1
$\Psi_{w,c}$	1.0068	0.05	0.06
Quadratic summation		0.16	0.32
Combined relative standard uncertainty of $D_{w,ENE A}$		0.36	

The design and operation of the calorimeter and the procedure to convert the absorbed dose from graphite to water are described in [4]. The changes to the standard adopted since that publication are given in the following paragraphs. The best estimate of the graphite absorbed

dose also accounts for the calorimeter long term stability. The long term stability data are corrected for source decay using the half life value of 1925.2 (3) days for ^{60}Co [7].

The absorbed dose to water at the ENEA is determined through the TW transfer ionization chamber used to realize the absorbed dose to water in a cylindrical water phantom.

Working standard chambers are used to transfer the absorbed-dose determination in the scaled cylindrical phantom to a cubic calibration phantom of side 30 cm. However, the three transfer chambers used for the present comparison were calibrated in the cylindrical phantom.

A summary of the components of uncertainty in $D_{w,ENE A}$ is indicated in Table 3, giving a combined relative standard uncertainty of 3.6×10^{-3} .

Table 3. Relative standard uncertainties for the ENEA determination of absorbed dose to graphite

Quantity	ENEA value	ENEA relative standard uncertainty	
		100 s_i	100 u_j
f_c	–	0.10	0.03
k_{qa}	–	0.03	0.15
k_{hd}	1.0000	–	0.10
k_{gap}	1.0064	0.05	0.06
m / g	1.5358	–	0.12
long term reproducibility of $D_{c,ENE A}$		0.10	–
Quadratic summation		0.15	0.23
Combined relative standard uncertainty of $D_{c,ENE A}$		0.27	

The changes to the ENEA standard since the last comparison [1] concern the calorimeter gap correction, k_{gap} , the ratio of the photon energy fluences, $\Psi_{w,c}$ and the $(\bar{\mu}_{en}/\rho)_{w,c}$ ratio. The previous values $k_{gap} = 1.0051$ and $\Psi_{w,c} = 1.0072$ were originally determined experimentally. The new k_{gap} and $\Psi_{w,c}$ values used in the present comparison were obtained by a Monte Carlo calculation based on the EGSnrc code, taking into account the photon spectrum of the new ^{60}Co gamma beam operating at ENEA. For the $(\bar{\mu}_{en}/\rho)_{w,c}$ ratio the previous value 1.113 was updated to 1.1124 by adopting more recent values of the mass energy-absorption coefficients of water and graphite [8]. The mass energy-absorption coefficients were averaged over the photon spectrum of the ENEA ^{60}Co beam calculated in unperturbed water and in a small mass of graphite placed at the measurement point in water.

Reference conditions

Absorbed dose is determined at the BIPM under reference conditions defined by the CCRI, previously known as the CCEMRI [9]:

- 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 $^{-2}$.

The reference conditions at the ENEA are the same as those at the BIPM noted above. However, the experimental arrangement used to establish the absorbed dose to water via graphite calorimetry and that used to disseminate the absorbed dose are not identical, for practical reasons. In particular, the cubic water phantom of side 30 cm used to disseminate absorbed dose differs from the larger cylindrical water phantom used to realize the requirements of the scaling theorem. As noted above, for the present comparison, the transfer chamber calibrations at the ENEA have been made in the cylindrical phantom.

Reference values

The $\dot{D}_{w,BIPM}$ value is the mean of measurements made over a period of six months before and one month after the comparison. By convention it is given at the reference date of 2007-01-01 T 00:00:00 Coordinated Universal Time (UTC) as is the value of the ionization current, using the half-life value of 1925.2 d, $\sigma = 0.3$ d for ^{60}Co [7]).

The value of $\dot{D}_{w,ENE A}$ used for the comparison is the mean of measurements made over a period of 6 months before and 2 months after the measurements at the BIPM. The value is normalized to the date and time of 2007-01-01 T 00:00:00 UTC as is the ionization current of the transfer chambers using the same half-life as above.

3. The transfer chambers and their calibration

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

$$N_{D,w,lab} = \dot{D}_{w,lab} / I_{lab} \quad (4)$$

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

The transfer chambers are: one NE 2571 ionization chamber serial number 1906, one NE 2611A serial number 124 and one chamber built at ENEA, ESC/87 serial number 14, all three of thimble (cylindrical) shape, belonging to the ENEA. Their main characteristics are listed in Table 4. These chambers were calibrated over several months at the ENEA before and after the measurements at the BIPM.

The experimental method for calibrations at the ENEA is described in [10] and that for the BIPM in [6].

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the relevant markings on the chambers and envelopes facing the source.

Applied voltage and polarity

A collecting voltage as indicated in Table 4 was applied to the outer electrode of each chamber at least 30 min before measurements were made. No corrections were applied at either laboratory for polarity.

Table 4. Characteristics of the ENEA transfer chambers

Characteristic/Nominal values		NE 2571-1906	NE 2611A-124	ESC/87-14
Dimensions	Inner diameter	6.3 mm	7.4 mm	4 mm
	Wall thickness	0.4 mm	0.5 mm	0.5 mm
	Cavity length	24.1 mm	9.2 mm	21.4 mm
	Tip to reference point	13 mm	5 mm	11.5 mm
Electrode	Length	20.6 mm	6.4 mm	20.2 mm
	Diameter	1.0 mm	1.7 mm	1.0 mm
Volume	Air cavity	0.69 cm ³	0.325 cm ³	0.24 cm ³
Wall	Material	graphite	graphite	graphite
	Density	1.7 g cm ⁻³	1.8 g cm ⁻³	1.7 g cm ⁻³
Voltage applied to outer electrode	Positive polarity	300 V	250 V	200 V

Volume recombination

Volume recombination is negligible at a dose rate of less than 15 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. At the ENEA, the current was measured using a Keithley 617 electrometer. The chambers were pre-irradiated for at least 5 min (≈ 3 Gy) at the ENEA, and for at least 30 min (≈ 3 Gy) at the BIPM before any measurements were made.

The ionization current measured from each transfer chamber was corrected for the leakage current. At the BIPM, leakage currents of typically 3 fA were measured for the NE chambers, and around 8 fA for the ESC/87 chamber. At the ENEA, leakage currents of around 10 fA were measured for all chambers, but this is known to be limited by the inherent leakage of the electrometer.

Ambient conditions

During a series of measurements, the water temperature is measured for each current measurement and was stable to better than 0.01 °C at the BIPM and 0.02 °C at the ENEA. The ionization current is corrected to 293.15 K and 101.325 kPa at both laboratories. Relative humidity is controlled at (50 \pm 5) % at the BIPM and (50 \pm 20) % at the ENEA. Consequently, no correction for humidity is applied to the ionization current measured.

Radial non-uniformity correction

At the BIPM, the radial non-uniformity of the beam over the section of the transfer chambers would result in a correction factor of at most 1.0003(2), this being for the NE 2571 chamber type [11]. As this effect is small and is likely to significantly cancel at the BIPM and the ENEA, no corrections are made at either laboratory.

PMMA phantom window and sleeve

Both laboratories use a horizontal beam of radiation and, at the BIPM, the thickness of the

PMMA¹ front window of the water phantom is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber at the reference depth of 5 g cm^{-2} . In addition, the BIPM applies a correction factor k_{pf} (0.9996) that accounts for the non-equivalence to water of PMMA in terms of interaction coefficients. At the ENEA, the reference depth is also 5 g cm^{-2} . The cylindrical phantom has a PMMA window of thickness 4.1 mm. This is taken into account when positioning the chamber, as a water-equivalent thickness of 0.47 g cm^{-2} according to the ratio of the electron densities of water and PMMA. Individual waterproof sleeves of 0.5 mm thick PMMA were supplied by the ENEA for each chamber. The same sleeves were used at both laboratories and, consequently, no correction for the influence of each sleeve was necessary at either laboratory.

Uncertainties

Contributions to the relative standard uncertainty of $N_{D,w,\text{lab}}$ are listed in Table 5.

The relative combined standard uncertainty associated with the determination of absorbed dose to water at the two laboratories is designated u_{D_w} and that associated with the calibration coefficient N_{D_w} is designated u_c . The two laboratories determine absorbed dose by methods that are quite different. Nevertheless, some correlation exists in the values used for $(\bar{\mu}_{\text{en}}/\rho)_{w,c}$ and $\beta_{w,c}$. In accordance with the analysis used for the existing data for the BIPM.RI(I)-K4 comparison [2], these are taken to have correlation coefficients $f_k = 0.95$ and $f_k = 0.7$, respectively. Consequently, the combined uncertainty, u_R , of the result of the comparison, $R_{D,w}$, is obtained by summing in quadrature the uncertainties of $\dot{D}_{w,\text{BIPM}}$ and $\dot{D}_{w,\text{ENEA}}$, together with the contributions arising from the use of transfer chambers, and removing the correlated components noted above. The contribution from the transfer chambers includes the uncertainties of the measured ionization currents, the distance to the reference plane and the depth positioning.

Table 5. Estimated relative standard uncertainties of the calibration coefficient, $N_{D,w,\text{lab}}$, of the transfer chambers and of the comparison result, $R_{D,w}$

Relative standard uncertainty of	ENEA		BIPM	
	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate to water (tables 1 and 2), u_{D_w}	0.16	0.32	0.20	0.21
Ionization current of the transfer chambers	0.02	0.08	0.02	0.02
Distance		0.02	–	0.02
Depth in water		0.06	–	0.05
Reproducibility of the transfer chambers' calibration coefficients		0.08		
Relative standard uncertainties of $N_{D,w,\text{lab}}$				
quadratic summation	0.16	0.35	0.20	0.22
combined uncertainty, u_c	0.38		0.30	
Relative standard uncertainties of $R_{D,w}$				
quadratic summation taking correlation into account	100 s		100 u	
	0.26		0.36	
combined uncertainty, u_R	0.44			

¹ Polymethylmethacrylate

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration at the BIPM was estimated to be 10^{-4} (for each chamber, two calibrations with repositioning, each calibration a series of 30 measurements). At the ENEA, a single series of five repeated measurements each one lasting about 100 s exhibited a relative standard uncertainty lower than 2×10^{-4} . The calibration of each chamber was repeated with repositioning in the cylindrical phantom two times before the measurements at the BIPM. The relative standard uncertainty of the mean ionization current measured at the ENEA with a given transfer chamber was typically better than 1×10^{-3} . The calibrations were repeated at the ENEA after the measurements at the BIPM and the results are reasonably consistent, as shown in Table 6.

4. Results of the comparison

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

$$R_{D,w} = N_{D,w,ENE A} / N_{D,w,BIPM}, \quad (5)$$

in which the average value of measurements made at the ENEA before and after those made at the BIPM for each chamber is compared with the mean of the measurements made at the BIPM. Table 6 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 all three transfer chambers, $R_{D,w} = 0.9999$. The combined standard uncertainty for the comparison is 0.0044. Consequently, the difference between the absorbed dose to water standards of the ENEA and the BIPM is not significant.

Two of the transfer chambers were also calibrated in terms of air kerma in ^{60}Co at the BIPM to compare the relative responses of the transfer chambers. The ratios of $N_{D,w}/N_K$ at the BIPM for the two chambers were within the expected values for similar thimble-type transfer chambers measured at the BIPM. The consistency of this ratio within each type of chamber is a check on the stability of the chambers while at the BIPM.

Table 6. Results of the present comparison

Transfer Chamber	$N_{D,w,ENE A}$ / Gy μC^{-1} pre-BIPM	$N_{D,w,BIPM}$ / Gy μC^{-1}	$N_{D,w,ENE A}$ / Gy μC^{-1} post-BIPM	$N_{D,w,ENE A}$ / Gy μC^{-1} overall mean	$R_{D,w}$	u_R
NE 2571-1906	45.086	45.135	45.125	45.105	0.9993	0.0044
NE 2611-124	103.31	103.31	103.42	103.37	1.0006	0.0044
ESC/87-14	123.82	123.88	123.90	123.86	0.9998	0.0044
Mean values					0.9999	0.0044

The present result for the ENEA compares well within the standard uncertainties with the previous result of 1994 as shown in Table 7.

Table 7. Results for the ENEA key comparisons of absorbed dose to water

Year	u_{D_w}	$R_{D,w}$	u_R	Primary standard	Ref.
	in relative value				
1994	0.0045	0.9969	0.0049	graphite calorimeter	[1]
2007	0.0036	0.9999	0.0044		–

5. Comparison with other National Metrology Institutes

Comparisons of absorbed dose to water at the BIPM have been undertaken since 1988. Almost all the absorbed dose to water comparisons have been made indirectly using transfer standards. A summary report of the more recent comparisons, including the previous comparison with the ENEA, is given in [2]. Subsequent comparisons with the LNE-LNHB, PTB and the VSL have also been published [12, 13, 14] and the results are available in the key comparison database (KCDB) of the CIPM MRA [15] while those of the VNIIFTRI are awaiting publication [16].

Comparison of a given NMI with the key comparison reference value

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) [15]. 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 KCRV, for each of the CCRI radiation qualities [17]. It follows that for each NMI i having a BIPM comparison result R_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:

$$\text{the relative difference } D_i = (D_{w,i} - D_{w,BIPM}) / D_{w,BIPM} = R_i - 1 \quad (6)$$

$$\text{and the expanded uncertainty } (k = 2) \text{ of this difference,} \\ U_i = 2 u_i. \quad (7)$$

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

Table 8 gives the values for the NMI absorbed dose uncertainty $u_{D_{w,i}}$, D_i and U_i for each NMI, i taken from [2, 12, 13, 14 and 16] and this report, using (6) and (7), and forms the basis of the entries in the KCDB of the CIPM MRA for the BIPM.RI(1)-K4 ongoing comparison. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1999; note that the BEV and the NRC have each undertaken comparisons more recently and the results are awaiting publication. The results of a published SIM comparison [18] 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.

Table 8. Degrees of equivalence of each NMI's measurement standard

NMI, i	Country	Year	$u_{Dw,i} \times 10^{-3}$	$D_i \times 10^{-3}$	$U_i \times 10^{-3}$
BEV	Austria	1994	3.7	-1.0	8.6
ARPANSA	Australia	1997	2.0	2.4	6.0
NIST	United States of America	1997 ²	3.5	-1.6	10.2
NRC	Canada	1998	4.1	-2.4	10.2
LSDG ³	Belgium	1999	6.6	-5.2	14.8
METAS	Switzerland	2000	4.1	-0.1	10.8
MKEH ⁴	Hungary	2001	4.8	-1.7	9.6
LNE-LNHB ⁵	France	2003	4.8	-3.0	10.6
PTB	Germany	2005	2.0	-3.9	7.4
VSL ⁶	Netherlands	2005	3.9	-7.4	9.8
VNIIFTRI	Russian Federation	2009	4.0	-2.4	8.6
ENEA	Italy	1994	4.5	-3.1	9.8
ENEA	Italy	2009	3.6	-0.1	8.8

Comparison of any two NMIs with each other

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.

The degree of equivalence, D_{ij} , between any pair of NMIs, i and j , is expressed by two terms: the difference

$$D_{ij} = D_i - D_j = R_i - R_j \quad (8)$$

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

$$u_{ij}^2 = u_{c,i}^2 + u_{c,j}^2 - \sum_k (f_k u_{k,\text{corr}})_i^2 - \sum_k (f_k u_{k,\text{corr}})_j^2 \quad (9)$$

of which the final two terms take into account the correlations between the primary standard methods as explained below [2]. In (9), $u_{c,i}$ and $u_{c,j}$ are the combined standard uncertainty of $N_{Dw,i}$ and $N_{Dw,j}$, derived from the uncertainty budgets of the pair of NMIs, i and j .

The significant correlated components of the uncertainty budgets for the ENEA and the other NMIs with graphite calorimeters are given in Table 9. The table includes the relative standard uncertainty u_{transfer} associated with the transfer standard. The uncertainty in the calculation of the correction for graphite calorimeter gaps, k_{gap} , is also taken to have some correlated component as shown.

² Replaced by the NIST result in the SIM comparison

³ This Belgian laboratory is not a designated institute

⁴ Previously known as the OMH

⁵ Previously known as the BNM-LNHB.

⁶ Previously known as the NMI

Table 9. Components in the uncertainty budgets for absorbed dose to water from graphite calorimetry primary standards, standard uncertainties per 10^3 [2, 12]

NMI	k_{gap}	$(\bar{\mu}_{\text{en}}/\rho)_{\text{w,c}}$	$(\beta)_{\text{w,c}}$	$u_{D_{\text{w},i}}$	u_{transfer}	$u_{\text{c},i}$	$\sqrt{\sum (f_k u_{k,\text{corr}})^2}_{\text{NMI}}$
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
VSL	0.7	3.0	0.6	4.0	0.9	4.1	2.9
MKEH	0.8	3.0	0.6	4.8	1.1	5.0	2.9
LNE-LNHB	1.5	1.5	0.5	4.7	1.1	4.8	1.6
VNIIFTRI	1.0	2.9	0.5	4.0	1.8	4.3	2.8
ENEA	0.6	1.4	1.0	3.6	1.0	3.8	1.5
$f_{k,\text{BIPM}}$	–	0.95	0.7				
$f_{k,\text{NMI}}$	0.5	0.95	0.7				

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. Conclusions

A key comparison has been carried out between the ENEA-INMRI (Italy) and the BIPM of standards for absorbed dose to water in ^{60}Co gamma rays, using three ionization chambers as transfer standards. From BIPM air kerma calibrations made at the same time it is concluded that the transfer chambers have a predictable and stable response. The mean comparison result shows that the ENEA determination of absorbed dose to water is equivalent to that of the BIPM; it is compatible within the combined relative standard uncertainty of the comparison (4.4×10^{-3}) and is consistent with the changes made to the ENEA standard since the previous result of 1994. 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 ENEA standard for absorbed dose to water is in satisfactory agreement.

Acknowledgements

The significant contributions to the measurement set-up at the BIPM of P. Roger, and at the ENEA for the contributions of M. Quini are gratefully acknowledged.

Table 10. 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 $U_i = 2u_i$.

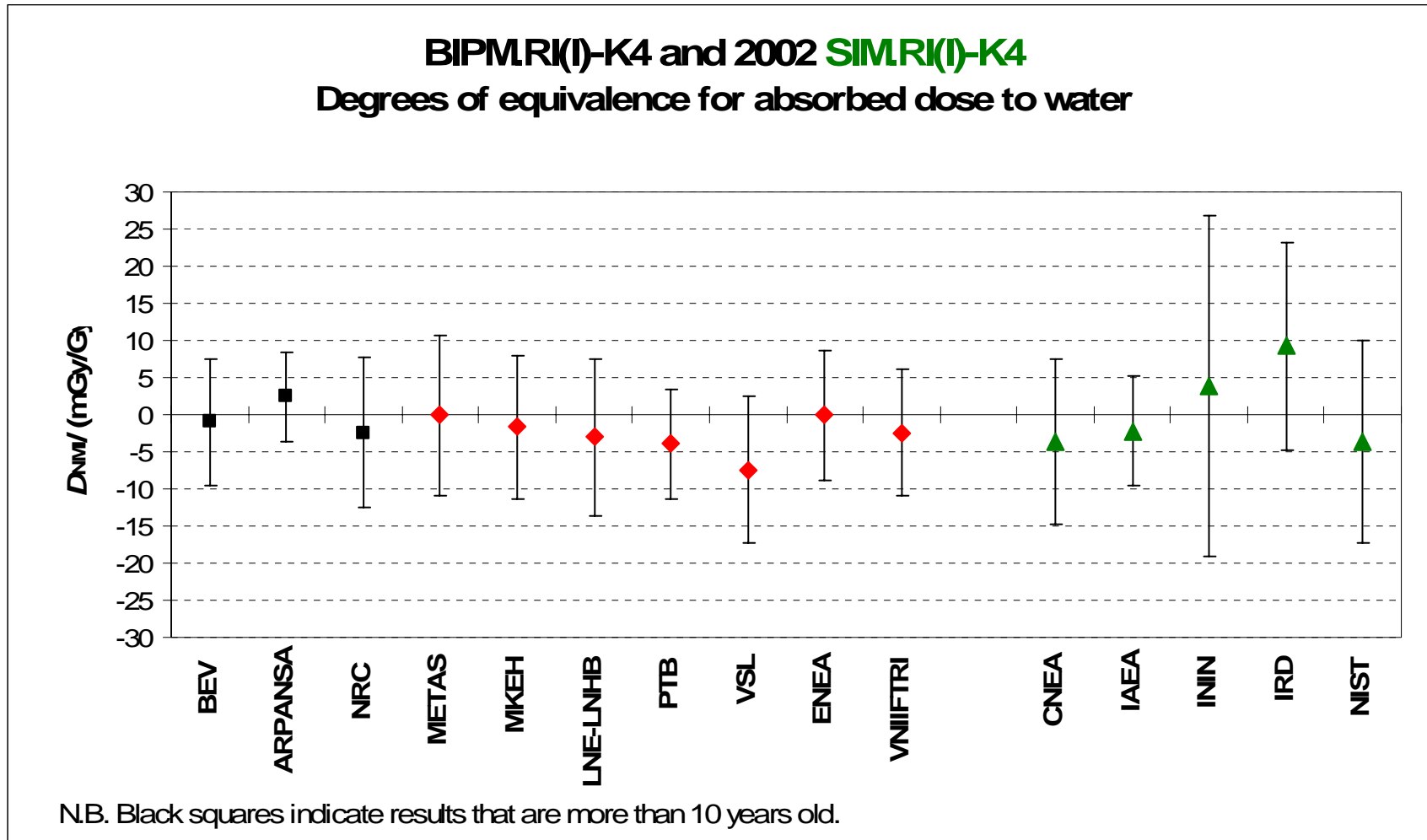
The degree of equivalence between two laboratories is given by a pair of terms both expressed in mGy/Gy:

$D_{ij} = D_i - D_j$ and U_{ij} , its expanded uncertainty ($k = 2$). In evaluating $U_{ij} = 2 u_{ij}$ for the matrix of equivalence account is taken of correlations between u_i and u_j , see section 5 of the Report.

Lab i			Lab j	
	D_i	U_i	D_{ij}	U_{ij}
	/ (mGy/Gy)		/ (mGy/Gy)	
BEV	-1.0	8.6	-0.9	9.8
ARPANSA	2.4	6.0	2.5	7.7
NRC	-2.4	10.2	-2.3	11.3
METAS	-0.1	10.8	0.0	11.8
MKEH	-1.7	9.6	-1.6	10.7
LNE-LNHB	-3.0	10.6	-2.9	11.2
PTB	-3.9	7.4	-3.8	8.8
VSL	-7.4	9.8	-7.3	11.2
ENEA	-0.1	8.8		
VNIFTRI	-2.4	8.6	-2.3	9.6
CNEA	-3.7	11.1	-3.6	14.7
IAEA	-2.2	7.4	-2.1	12.2
ININ	3.9	23.0	4.0	24.9
IRD	9.2	14.0	9.3	17.0
NIST	-3.7	13.6	-3.6	14.4

See [2, 12, 14, 16 and 18] for the acronyms of the National Metrology Institutes

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



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