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Comparison of the standards for absorbed dose to water of the VNIIFTRI, Russia and the BIPM in ^{60}Co γ rays

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Abstract

A new comparison of the standards for absorbed dose to water of the All-Russian Scientific Research Institute for Physical-Technical and Radiotechnical Measurements (VNIIFTRI), Russia and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation in 2009. The results show that the VNIIFTRI and the BIPM standards for absorbed dose to water are in agreement, yielding a mean ratio of 0.9976 for the calibration coefficients of the transfer chambers, the difference from unity being within the combined standard uncertainty (0.0043) for this result. This result is consistent with the earlier 2001 comparison result of 0.9967 (43). The updated degrees of equivalence for the VNIIFTRI are compared with those of the other national metrology institutes as presented in the BIPM key comparison database.

1. Introduction

An indirect comparison of the standards for absorbed dose to water of the All-Russian Scientific Research Institute for Physical-Technical and Radiotechnical Measurements (VNIIFTRI) 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 2009. This absorbed dose to water comparison is the second such comparison made between the two laboratories, the first having been held in 2001 [1].

The primary standard of the VNIIFTRI for absorbed dose is a pair of identical heat-flow calorimeters mounted in a graphite phantom as described in [2]. The absorbed dose to water is determined by transferring from absorbed dose to graphite using cavity theory and a thick-walled graphite cavity chamber as described in [3]. The BIPM primary standard is a graphite-walled cavity ionization chamber of parallel-plate design [4].

This comparison was undertaken using two Farmer-type ionization chambers belonging to the VNIIFTRI as transfer instruments. 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.

2. Determination of the absorbed dose to water

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

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

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 the collision component of kerma, 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) are given in [4, 5] together with their uncertainties, the combined relative standard uncertainty being 2.9×10^{-3}. The uncertainty budget is given in Table 1.

Absorbed dose is determined at the BIPM under reference conditions defined by the Consultative Committee for Ionizing Radiation (CCRI), previously known as the CCEMRI [6]:

- 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 × 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;
- the reference depth is 5 g cm^{-2}.

Table 1. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water [5]

Symbol	Parameter / unit	Value	Relative standard uncertainty (1)	
			s_i	u_i
Physical constants				
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,c}$	ratio of mass energy-absorption coefficients	1.1125 (2)	0.01 (2)	0.14 (2)
$s_{c,a}$	ratio of mass stopping powers	1.0030		0.11 (3)
W/e	mean energy per charge / J C^{-1}	33.97		
Correction factors				
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 (4)	1.0056	0.01	0.03
k_s	saturation (4)	1.0017	0.01	0.01
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	effective volume / cm^3	6.8810 (5)	0.19	0.03
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) (6)		0.02	–
Combined uncertainty of the BIPM determination of absorbed dose to water rate				
quadratic summation			0.20	0.21
combined relative standard uncertainty			0.29	

(1) 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.
(2) included in the uncertainties for k_p.
(3) uncertainty value for the product $s_{c,a}$ W/e, as agreed by the CCRI.
(4) values for the CISBio beam adopted in November 2007.
(5) standard CH4-1.
(6) over a period of 3 months. The long-term reproducibility over a period of 15 years, u_R is 0.0006.

At the VNIIFTRI the absorbed dose to water is derived from the calorimetric determination of the absorbed dose to graphite. The principal element of the standard is a pair of identical heat-flow calorimeters mounted in a graphite phantom. One of the calorimeters (working) is located in the radiation field and the other (reference) is located outside the field. The temperature response to radiation is measured with thermistors that are connected in a differential circuit, the reference calorimeter being used to reduce the effect of phantom temperature variations on the response of the working calorimeter.

The design and operation of the calorimeters is described in [2]. The correction factors applied to the standard are described below, followed by the transfer to the absorbed dose to water from the absorbed dose to graphite. These factors and the components of uncertainty are given in Tables 2 and 3, producing a combined relative standard uncertainty of 4×10^{-3} for the absorbed dose to water.

The absorbed-dose rate to graphite, $\dot{D}_{\mathrm{c}}$, at the reference point in graphite is given by

$$\dot{D}_{\mathrm{c}} = (P/m)k_{\mathrm{gap}}k_{\mathrm{depth}}k_{\mathrm{d}}k_{\mathrm{rn}}k_{\mathrm{an}}k_{\mathrm{t}} \,. \tag{2}$$

The physical quantities and correction factors in (2) are described below and listed with their relative standard uncertainties in Table 2.

The radiation power absorbed in the graphite core, P

The calorimeters are operated in the quasi-isothermal mode in which the electrical power input to the calorimeter core in the absence of radiation is matched as closely as possible to the anticipated radiation power. The electric heating is switched off at the same time as the radiation source is switched on, so that the rate of heating of the core remains approximately constant. The radiation power input can thus be determined readily against the VNIIFTRI working standards of resistance and voltage.

The mass of the calorimeter core, m

This was measured at the VNIIFTRI and corrected for impurities and buoyancy.

Correction factor for the calorimeter gaps, k_{gap}

The difference between the absorbed dose rate at the centre of the calorimeter core and that at the same position in a solid graphite phantom is calculated using Monte-Carlo codes and the correction factor, k_{gap}, is derived from these results. The gap correction is calculated for a 110 mm diameter field incident on the calorimeter with the centre of the core at a depth in graphite of 3.2 mm (5.46 g cm^{-2}) and at a distance of 700 mm from the source.

Correction factor for the reference depth in graphite, k_{depth} *and correction factor for the reference distance from the source in graphite,* k_{d}

A hole for the ionization chamber is made in the same phantom as the calorimeter assembly and at the same position (at the same depth) at which the calorimeter core is located. Therefore correction factors for both k_{depth} and k_{d} were taken as unity.

Correction factor for radial non-uniformity of the ^{60}Co *beam over the calorimeter core,* k_{rn}

This factor was obtained experimentally by measuring the radial profile of the beam using a thimble ionization chamber.

Correction for the axial non-uniformity of the ^{60}Co *beam over the calorimeter core,* k_{an}

This correction factor was obtained from the departure from linearity of the measured depth-dose distribution over the calorimeter core.

Normalization factor for the reference date and time, k_t

The calorimeter measurements are corrected to the reference date and time of 2009-03-01 at 12:00 UCT[1]. The half-life of ^{60}Co was taken as 1 925.2 d, $\sigma = 0.3$ d [7].

Table 2. Relative standard uncertainties for absorbed dose to graphite for ^{60}Co gamma rays at the VNIIFTRI.

		Value	Relative standard uncertainty	
			s_i	u_i
Measurement of absorbed dose rate to graphite				
a.	Long-term mean dose rate (1990-2009)		0.12	–
b.	Electrical calibration $^{(1)}$		–	0.15
c.	Mass of calorimeter core m / g	1.5826	–	0.05
d.	Time measurements		–	0.02
e.	Calorimeter gaps correction k_{gap}	1.0050	–	0.10
f.	Reference distance correction k_d	1	–	0.04
g.	Reference depth correction k_{depth}	1	–	0.12
h.	Radial non-uniformity correction k_{rn}	1.0005	–	0.01
i.	Axial non-uniformity correction k_{an}	1.0000	–	0.01
Uncertainty of absorbed dose rate to graphite			0.12	0.23

(1) The statistical uncertainty (s_i) in the electrical calibration is accounted for in the statistical uncertainty in the long-term mean dose rate (a).

The absorbed dose to water at the VNIIFTRI is derived from the graphite absorbed dose by

$$D_{\text{w,VNIIFTRI}} = D_c I_{\text{w,c}} \left(\bar{\mu}_{\text{en}}/\rho\right)_{\text{w,c}} \beta_{\text{w,c}} p_{\text{w,c}} \tag{3}$$

where

D_c	is the absorbed dose to graphite at the reference point in graphite,
$I_{\text{w,c}}$	is the ratio of the ionization currents of the cavity chamber at the reference points in water and graphite,
$(\bar{\mu}_{\text{en}}/\rho)_{\text{w,c}}$	is the ratio of the mean mass energy-absorption coefficients for water and graphite for the photon energy spectra at the corresponding reference points,

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[1] UCT is Universal Coordinated Time

$\beta_{\mathrm{w,c}}$ is the ratio of the absorbed dose to the collision component of kerma, at the reference points in water (w) and in graphite (c),

$p_{\mathrm{w,c}}$ is the correction factor for the replacement of water by graphite with a volume equal to the entire volume of the ionization chamber [8].

The factors $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$ and $\beta_{\mathrm{w,c}}$ are derived by calculation using published data for the coefficients and parameters of the measured energy spectra at the reference points in the water and graphite phantoms [3]. The perturbation factor $p_{\mathrm{w,c}}$ was evaluated experimentally.

Absorbed dose to water is determined at the VNIIFTRI under the same reference conditions as at the BIPM and is maintained through the use of a series of secondary standard ionization chambers calibrated directly against the graphite calorimeter.

Table 3. Relative standard uncertainties for the conversion to absorbed dose to water for ^{60}Co gamma rays at the VNIIFTRI.

		Value	Relative standard uncertainty	
			s_i	u_i
Transfer absorbed dose from graphite to water				
a.	Ratio of mass energy-absorption coefficients $(\mu_{\mathrm{en}}/\rho)_{\mathrm{w}}/(\mu_{\mathrm{en}}/\rho)_{\mathrm{c}}$	1.1125	–	0.29
b.	Correction for the replacement of water by graphite ($p_{\mathrm{w,c}}$)	1.0089	–	0.10
c.	Ratio of absorbed dose and the collision component of kerma (β_{w}/ β_{c})	1.000	–	0.05
d.	Position of chamber in graphite		–	0.05
e.	Position of chamber in water		–	0.05
f.	Measurement of ionization current ratio		0.05	0.05
Uncertainty of transfer from graphite to water			0.05	0.32
Uncertainty of absorbed dose to graphite (Table 2)			0.12	0.23
Uncertainty of the VNIIFTRI determination of absorbed dose to water rate				
Quadratic summation			0.13	0.38
Combined relative standard uncertainty			0.40	

The value of $\dot{D}_{\mathrm{w,VNIIFTRI}}$ used for the comparison is the mean of measurements made over a period of four months before and after the measurements at the BIPM. The value is normalized to the date and time of 2009-01-01 T00:00:00 UTC as is the ionization current of the transfer chambers (using the half-life value of 1925.2 d, σ = 0.3 d [7]).

The $\dot{D}_{\mathrm{w,\,BIPM}}$ value is the mean of measurements made over a period of three months around the comparison. By convention it is given at the reference date of 2009-01-01 T00:00:00 UTC, as is the value of the ionization current, using the same half-life as above [7].

3. The transfer chambers and their calibration

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

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

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

The transfer chambers are two FC65-G ionization chambers belonging to the VNIIFTRI with serial numbers 767 and 1478. Their main characteristics are listed in Table 4. These chambers were calibrated at the VNIIFTRI immediately before and after the measurements at the BIPM.

Table 4. **Characteristics of the VNIIFTRI transfer chambers**

Characteristic/Nominal values		FC65-G
Dimensions	Inner diameter	6.2 mm
	Wall thickness	0.36 mm
	Cavity length	23.1 mm
	Tip to reference point	13.0 mm
Electrode (Al)	Length	20.6 mm
	Diameter	1.0 mm
Volume	Air cavity	0.65 cm^3
Wall	Material	graphite
	Density	1.8 g cm^{-3}
Applied voltage	Negative polarity[2]	300 V

The experimental method for calibrations at the VNIIFTRI is described in [3] and that for the BIPM in [5] and the essential details are reproduced here.

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[2] Polarity applied to the central electrode

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the engraved lines on both chamber stems and on the envelope facing the source.

Applied voltage and polarity

A collecting voltage of 300 V (positive polarity applied to the outer electrode at the BIPM), supplied at each laboratory, was applied to each chamber at least 30 min before measurements were made. No corrections were applied at either laboratory for polarity.

Ion 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 and an electrometer model DKS-101 at the VNIIFTRI. The chambers were pre-irradiated for at least 20 min (≈ 20 Gy) at the VNIIFTRI and for at least 30 min (≈ 10 Gy) at the BIPM before any measurements were made.

The ionization current measured by each transfer chamber was corrected for the leakage current at the BIPM and at the VNIIFTRI, a relative effect of about 1×10^{-5} at the BIPM and 5×10^{-6} at the VNIIFTRI.

Ambient conditions

During a series of measurements, the water temperature was stable to better than 0.02 °C at the VNIIFTRI and better than 0.01 °C at the BIPM. The ionization current was normalized to 293.15 K and 101.325 kPa at both laboratories.

Relative humidity is controlled at (50 ± 5) % at the BIPM and about 55 % at the VNIIFTRI. Consequently, no corrections for humidity were applied.

Radial non-uniformity correction

No correction was made for the radial non-uniformity of the beam over the section of the transfer chambers as there is no significant difference in uniformity between the two laboratories. In the BIPM, the correction factor for this chamber type when irradiated in the water phantom is 8×10^{-4} [9]. Measurements in the water phantom at the VNIIFTRI indicate a radial non-uniformity over the section of the transfer chambers that would also result in a correction of less than 0.03 %.

PMMA phantom window and sleeve

Both laboratories use a horizontal beam of radiation and the thickness of the PMMA[3] front window of the phantom is included at the BIPM as a water-equivalent thickness in g cm^{-2} in the positioning of 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 window in terms of interaction coefficients. The same waterproof sleeves were used at both laboratories and consequently no correction for the influence of the sleeve was necessary at either laboratory.

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[3] Polymethylmethacrylate

Uncertainties

The uncertainty budget for a VNIIFTRI calibration is given in Table 5.

Table 5. Relative standard uncertainties for the calibration of a transfer chamber in terms of absorbed dose to water at the VNIIFTRI.

		Value	Relative standard uncertainty	
			s_i	u_i
Measurement of ionization current				
a.	Electrometer reading		0.03	0.17
b.	PMMA waterproof sleeve	1.0000	–	0.03
c.	Correction for air temperature and pressure		–	0.04
d.	Correction for air humidity	1.0003	–	0.03
e.	Time measurement		–	0.01
Uncertainty of absorbed dose to graphite (Table 2)			0.12	0.23
Uncertainty of transfer from graphite to water (Table 3)			0.05	0.32
Uncertainty of $N_{D_{\mathrm{w}},\mathrm{VNIIFTRI}}$				
Quadratic summation			0.13	0.43
Combined relative standard uncertainty			0.45	

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration was estimated to be 1×10^{-4} for the chamber 767 (3 calibrations, with repositioning) and 2×10^{-4} for the chamber 1478 (two calibrations, with repositioning) at the BIPM (a series of 30 measurements for each calibration). At the VNIIFTRI, a relative standard uncertainty of 3×10^{-4} is more appropriate.

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w\,lab}}$ are listed in Table 6. The two laboratories determine absorbed dose by methods that are quite different and not correlated except in terms of the data used to calculate the mass energy-absorption coefficient ratios. Consequently, the combined uncertainty of the result of the comparison is obtained by summing in quadrature the uncertainties of $\dot{D}_{\mathrm{w,BIPM}}$ and $\dot{D}_{\mathrm{w,VNIIFTRI}}$, taking into account the correlations mentioned above, together with the contributions arising from the use of transfer chambers. These latter contributions are the uncertainty in determining the ionization currents, in establishing the distance to the reference plane and in their depth positioning.

The uncertainty of the ratio $D_{\mathrm{w,VNIIFTRI}}$ / $D_{\mathrm{w,BIPM}}$ is derived from the uncertainty budgets of both laboratories (see Tables 1 and 2), and adding the uncertainties associated with the use of transfer chambers (see Table 5). The correlations arising from the use of mass energy absorption coefficients and absorbed dose to kerma ratios in the measurement methods at both laboratories are taken into account by applying estimated correlation coefficients f_k of 0.95 and 0.7, respectively, to the uncertainties $u_{k,\mathrm{corr}}$ from both laboratories, as given in:

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,\,BIPM}}{}^2 - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}} - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{BIPM}} . \qquad (5)$$

Table 6. Estimated relative standard uncertainties of the calibration coefficient, $N_{D,\mathrm{w\ lab}}$, of the transfer chambers and of the comparison result, $R_{D,\mathrm{w}}$.

	VNIIFTRI		**BIPM**		**VNIIFTRI/BIPM**	
Relative standard uncertainty of	100 s_i	100 u_i	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate to water (Tables 1 to 3)	0.13	0.39	0.20	0.21	0.24	0.30
Ionization current of each transfer chamber (Table 5)	0.03	0.18	0.02	0.02	0.04	0.18
Distance	–	0.01	0.02	–	–	0.02
Depth in water (Table 3)	–	0.05	0.02	0.06	–	0.07
Relative standard uncertainties of $N_{D,\mathrm{w\ lab}}$						
quadratic summation	0.13	0.43	0.20	0.22		
combined uncertainty	0.45		0.30			
Relative standard uncertainties of $R_{D,\mathrm{w}}$						
quadratic summation					0.24	0.36
combined uncertainty, u_c					0.43	

4. Results of the comparison

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

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w\ VNIIFTRI}} / N_{D,\mathrm{w\ BIPM}} , \qquad (6)$$

where the mean value of measurements made at VNIIFTRI prior to and following those made at the BIPM for each chamber is compared with the mean of the measurements made at the BIPM under the same conditions as indicated in section 3. Table 7 gives the relevant values of $N_{D,\mathrm{w}}$ for the two transfer chambers.

The comparison result is taken as the unweighted mean value of both transfer chambers, $R_{D,\mathrm{w}} = 0.9976$ with a combined standard uncertainty for the comparison of 0.0043. The difference between the absorbed dose to water standards of the VNIIFTRI and the BIPM is not significant given the combined uncertainty.

Table 7. Results of the comparison

Transfer Chamber	$N_{D,\mathrm{w}\ \mathrm{VNIIFTRI}}$ / Gy µC^{-1} before BIPM	$N_{D,\mathrm{w}\ \mathrm{BIPM}}$ / Gy µC^{-1}	$N_{D,\mathrm{w}\ \mathrm{VNIIFTRI}}$ / Gy µC^{-1} after BIPM	$N_{D,\mathrm{w}\ \mathrm{VNIIFTRI}}$ / Gy µC^{-1} mean	$R_{D,\mathrm{w}}$	u_c
767	47.476	47.589	47.476	47.476	0.9976	0.0043
1478	47.883	47.994	47.873	47.878	0.9976	0.0043
Mean values					**0.9976**	**0.0043**

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 VNIIFTRI, is given in [10] and the results are available in the key comparison database (KCDB) of the CIPM MRA [11].

The relative combined standard uncertainty associated with a determination of absorbed dose to water at an NMI, *i*, is designated $u_{D\mathrm{w},I}$ and that associated with a calibration coefficient $N_{D\mathrm{w},i}$ designated u_c. Almost all the comparisons are made indirectly using transfer standards and the relative combined standard uncertainty u_{Ri} of each comparison result R_i takes this into account together for the combined standard uncertainty $u_{\mathrm{c},i}$ of $D_{\mathrm{w},i}$ and the combined standard uncertainty $u_{\mathrm{c,BIPM}}$ of $D_{\mathrm{w,BIPM}}$ (see Tables 1, 3, 5 and Table 6 for the combined uncertainty budgets for the calibration of the transfer standards for the VNIIFTRI and the BIPM). For comparisons between the metrology institutes, the correlations between the primary measurement methods need to be taken into account.

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 (5).

The numerical value of u_{Ri} for the VNIIFTRI is given in Table 8 and this is used for the KCDB entry.

Table 8. Results for the VNIIFTRI key comparisons of absorbed dose to water

Year	$u_{D\text{w},i}$	R_i	u_{Ri}	Primary standard	Ref.
	in relative value				
2001	0.0044	0.9967	0.0043	graphite calorimeter	[1]
2009	**0.0044**	**0.9976**	**0.0043**	graphite calorimeter	–

The common components of the uncertainty budgets for the VNIIFTRI and the other NMIs with graphite calorimeters are given in Table 9 [10] together with the values of f_k that have been used. In this table, $u_{D\text{w},i}$ 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 $u_{\text{c},i}$ is the combined standard uncertainty for an absorbed dose to water calibration by the NMI, i; all uncertainties being in relative value.

In Table 9, the uncertainty in the calculation of the correction for graphite calorimeter gaps, k_{gap} is taken to have some correlated component as shown.

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

NMI [1]	k_{gap}	$(\bar{\mu}_{\text{en}}/\rho)_{\text{w,c}}$	$(\beta)_{w,c}$	$u_{D\text{w,NMI}}$	u_{transfer}	$u_{\text{c,NMI}}$	$\sqrt{\Sigma\left(f_k u_{k,\text{corr}}\right)^2_{\text{NMI}}}$
LNE-LNHB	0.8	1.5	0.6	3.4		3.4	1.5
ENEA	–	2.0	1.0	4.4	1.5	4.6	2.0
BEV	1.5	1.0	1.0	3.7		3.7	1.4
ARPANSA	0.4	1.4	0.1	2.0	0.6	2.1	1.3
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
VNIIFTRI	1.0	2.9	0.5	4.0	1.8	4.3	2.8
$f_{k,\text{BIPM}}$	–	0.95	0.7				
$f_{k,\text{NMI}}$	0.5	0.95	0.7				

[1] The NMI acronyms are given in [10]

Comparison of a given NMI with the key comparison reference value

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) [11]. 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, here $D_{\mathrm{w,BIPM}}$, is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities [12]. 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:

the relative difference $$D_i = (D_{\mathrm{w},i} - D_{\mathrm{w,BIPM}i}) / D_{\mathrm{w,BIPM}i} = R_i - 1 \tag{7}$$

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

$$U_i = 2\,u_i. \tag{8}$$

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

Table 10 gives the values for D_i and U_i for each NMI, i taken from [13 to 16] and this report, using (7) and (8), and forms the basis of the entries in the KCDB of the CIPM MRA. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1998 although the BEV and the NRC have undertaken new comparisons recently. The results of a recently published SIM comparison are also presented [17].

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 thus expressed as the difference

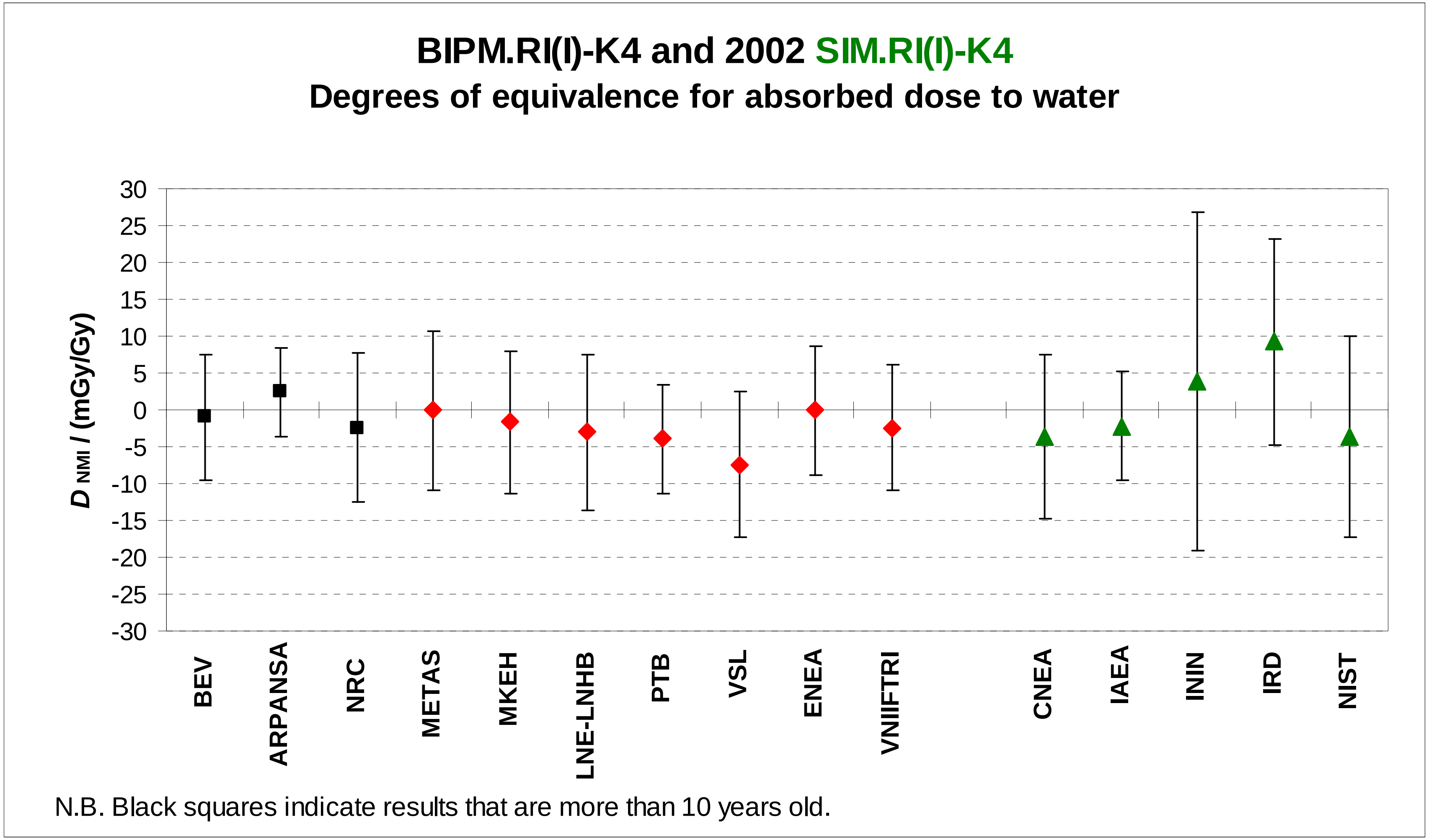
and the expanded uncertainty (k = 2) of this difference, $U_{ij} = 2\,u_{ij}$, where

$$u_{ij}^{\;2} = u_{c,i}^{\;2} + u_{c,j}^{\;2} - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{10}$$

and 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 (10) using the values for graphite calorimetry in Table 9. The matrix is given in Table 10 in the form that appears in the KCDB. The data presented in the table, 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.

Figure 1 Graph of the degrees of equivalence with the KCRV



N.B. Black squares indicate results that are more than 10 years old.

◆ BIPM.RI(I)-K4 comparison
▲ SIM.RI(I)-K4 comparison

Table 10 Evaluation of degrees of equivalence as presented in the KCDB

The key comparison reference value, x_R, 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.

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

MEASURAND : Absorbed dose to water

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 [17]).

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 [17].

			Lab *j*	
			VNIIFTRI	
Lab *i* ⇩	D_i / (mGy/Gy)	U_i	D_{ij} / (mGy/Gy)	U_{ij}
BEV	**-1.0**	8.6	**1.4**	9.5
ARPANSA	**2.4**	6.0	**4.8**	7.3
NRC	**-2.4**	10.2	**0.0**	12.2
METAS	**-0.1**	10.8	**2.3**	12.6
MKEH	**-1.7**	9.6	**0.7**	10.5
LNE-LNHB	**-3.0**	10.6	**-0.6**	11.0
PTB	**-3.9**	7.4	**-1.5**	9.8
VSL	**-7.4**	9.8	**-5.0**	12.0
ENEA	**-0.1**	8.8	**2.3**	9.6
VNIIFTRI	**-2.4**	8.6		
CNEA	**-3.7**	11.1	**-1.3**	15.4
IAEA	**-2.2**	7.4	**0.2**	13.0
ININ	**3.9**	23.0	**6.3**	25.3
IRD	**9.2**	14.0	**11.6**	17.6
NIST	**-3.7**	13.6	**-1.3**	15.1

6. Conclusions

A key comparison has been carried out between the VSL and the BIPM standards of absorbed dose to water for ^{60}Co gamma rays, using two transfer ionization chambers of the VNIIFTRI as transfer standards. The comparison result, expressed as a ratio of the calibration coefficients in terms of absorbed dose to water measured by the VNIIFTRI using their primary standard graphite calorimeter to that of the BIPM is 0.9976 (0.0043). This is within the uncertainties of that expected from the results of the previous comparison in 2001. The VNIIFTRI comparison for absorbed dose to water is in agreement within the uncertainties with the results of the other NMIs with primary standards for absorbed dose to water.

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