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

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Abstract

A comparison of the standards of 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. The results show that the VNIIFTRI and the BIPM standards for absorbed dose to water are in agreement, yielding a mean ratio of 0.9967 for the calibration factors of the transfer chambers, the difference from unity being within the combined standard uncertainty (0.0043) for this result.

1. Introduction

An indirect comparison of the standards of 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 March 2001. This absorbed dose to water comparison is the first such comparison made between the two laboratories.

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 [1]. 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 [2]. The

BIPM primary standard is a graphite cavity ionization chamber of pancake geometry [3].

This comparison was undertaken using two 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 factors 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 [3] 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 [4]:

- 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 of absorbed dose to water

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

(4) PMMA is the acronym for polymethylmethacrylate.

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 thermopiles 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 [1]. 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

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

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 2001-03-01 at 12:00 UCT[1]. The half-life of ^{60}Co was taken as 1 925.5 d, σ = 0.5 d [5].

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

	VNIIFTRI values	VNIIFTRI relative standard uncertainty 100 u_{iA}	100 u_{iB}
1. Measurement of absorbed dose rate to graphite			
a. Long-term mean dose rate (1990-2001)		0.12	–
b. Electrical calibration[2]		–	0.15
c. Mass of calorimeter core m / g	1 .5826	–	0.05
d. Time measurements		–	0.02
d. Calorimeter gaps correction k_{gap}	1.0050	–	0.10
e. Reference distance correction k_d	1	–	0.04
f. Reference depth correction k_{depth}	1	–	0.12
g. Radial non-uniformity correction k_{rn}	1.0005	–	0.01
h. Axial non-uniformity correction k_{an}	1.0000	–	0.01
Uncertainty of absorbed dose rate to graphite		0.12	0.23

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

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

where

D_c is the absorbed dose to graphite at the reference point in graphite,

$I_{w,c}$ is the ratio of the ionization currents of the cavity chamber at the reference points in water and graphite,

$(\bar{\mu}_{en}/\rho)_{w,c}$ is the ratio of the mean mass energy-absorption coefficients for water and graphite for the photon energy spectra at the corresponding reference points,

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

$p_{w,c}$ is the correction factor for the replacement of water by graphite with a volume equal to the entire volume of the ionization chamber [6].

[1] UCT is Universal Coordinated Time
[2] The statistical uncertainty (u_{iA}) in the electrical calibration is accounted for in the statistical uncertainty in the long-term mean dose rate (1a).

The factors $(\bar{\mu}_{en}/\rho)_{w,c}$ and $\beta_{w,c}$ 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 [2]. The perturbation factor $p_{w,c}$ 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.

	VNIIFTRI values	VNIIFTRI relative standard uncertainty 100 u_{iA}	100 u_{iB}
2. Transfer absorbed dose from graphite to water			
a. Ratio of mass energy-absorption coefficients $(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$	1.1125	–	0.29
b. Correction for the replacement of water by graphite ($p_{w,c}$)	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
Quadratic summation		0.13	0.38
Combined relative standard uncertainty of $D_{w,\,VNIIFTRI}$		0.40	

The value of $\dot{D}_{w,VNIIFTRI}$ 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 2001-01-01 T00:00:00 UTC as is the ionization current of the transfer chambers (using the weighted mean half-life value of 1925.5 d, σ = 0.5 d [5]).

The $\dot{D}_{w,\,BIPM}$ value is the mean of measurements made over a period of three months before and after the comparison. By convention it is given at the reference date of 2001-01-01 T00:00:00 UTC, as is the value of the ionization current, using the same half-life as above.

3. The transfer chambers and their calibration

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

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

where $\dot{D}_{\mathrm{w,\,lab}}$ is the water absorbed dose rate 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 NE2505/3 ionization chambers belonging to the VNIIFTRI with serial numbers 2404 and 2410. Their main characteristics are listed in Table 4. These chambers were calibrated at the VNIIFTRI immediately before and after the measurements at the BIPM. The uncertainty budget for a VNIIFTRI calibration is given in Table 5.

Table 4. Characteristics of the VNIIFTRI transfer chambers

Characteristic/Nominal values		NE2505/3
Dimensions	Inner diameter	6.3 mm
	Wall thickness	0.36 mm
	Cavity length	24.1 mm
	Tip to reference point	13.0 mm
Electrode (Al)	Length	20.6 mm
	Diameter	1.0 mm
Volume	Air cavity	0.69 cm^3
Wall	Material	graphite
	Density	1.8 g cm^{-3}
Applied voltage	Positive polarity	250 V

The experimental method for calibrations at the VNIIFTRI is described in [2] and that for the BIPM in [7]. At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the markings on both chamber and envelope facing the source. This was particularly important as measurements at the VNIIFTRI of the chamber with serial number 2410 show a significant change response with chamber orientation (0.16 %).

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

	VNIIFTRI values	VNIIFTRI relative standard uncertainty 100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
1. Determination of absorbed dose to graphite		0.12	0.23
2. Conversion to absorbed dose to water		0.05	0.32
3. 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
Quadratic summation		0.13	0.43
Combined relative standard uncertainty of $N_{D_\mathrm{w},\mathrm{VNIIFTRI}}$		0.45	

A collecting voltage of 250 V (positive polarity), 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. A recombination correction of 1.0008 is applied at the VNIIFTRI. The same correction was applied at the BIPM as volume recombination is negligible at an air kerma rate of less than 15 mGy s^{-1} for these chambers at this polarizing voltage. The initial recombination loss will be the same in the two laboratories where the absorbed dose rates are 4 mGy s^{-1} and 3 mGy s^{-1} at the VNIIFTRI and the BIPM, respectively.

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 (≈ 5 Gy) at the VNIIFTRI and for at least 30 min (≈ 5 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 3×10^{-4}. 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 but was about 70 % at the VNIIFTRI. Consequently, a correction to 50 % humidity of 1.0003 (0.0003) [8] is applied to the ionization current measured at the VNIIFTRI.

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 less than 0.03 % [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 %.

Both laboratories use a horizontal beam of radiation and the thickness of the PMMA front window 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.

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration was estimated to be 10^{-4} at the BIPM (2 to 4 calibrations with repositioning, in series of 30 measurements for each chamber). 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:

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

4. Results of the comparison

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

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

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, $R_{D,\mathrm{w}}$ = 0.9967 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 6. Estimated relative standard uncertainties of the calibration factor, $N_{D,\mathrm{w\,lab}}$, 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 and 5)	0.13	0.38	0.20	0.21	0.24	0.30
Ionization current of each transfer chamber	0.03	0.18	0.02	0.02	0.04	0.18
Distance	–	0.01	–	0.02	–	0.02
Depth in water	–	0.05	–	0.05	–	0.07
Relative standard uncertainties of $N_{D,\mathrm{w\,lab}}$						
quadratic summation	0.13	0.42	0.20	0.22		
combined uncertainty	0.44		0.30			
Relative standard uncertainties of $R_{D,\mathrm{w}}$						
quadratic summation					0.24	0.36
combined uncertainty, u_c					0.43	

Table 7. Results of the comparison

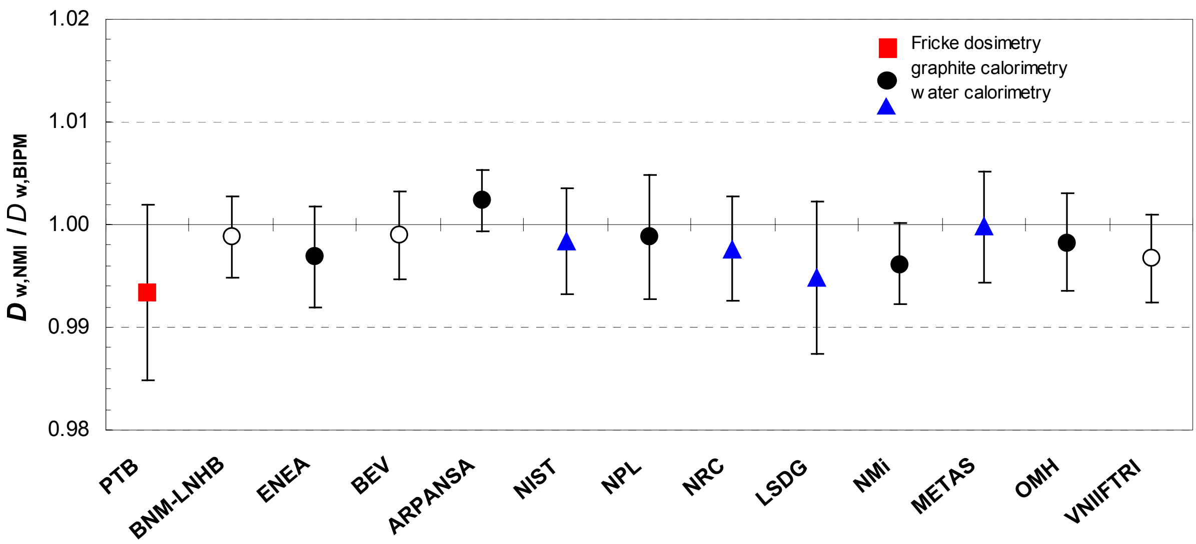
NE Chamber	$N_{D,\mathrm{w\,VNIIFTRI}}$ / Gy µC^{-1}	$N_{D,\mathrm{w\,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
2404	44.64	44.78_7	0.9967	0.0043
2410	44.05	44.20_1	0.9966	0.0043
		Mean values	0.9967	0.0043

6. Conclusions

The primary standards of absorbed dose to water of the VNIIFTRI (Russia) and the BIPM are in agreement ($R_{\mathrm{D,w}}$ = 0.9967, u_c = 0.0043) within the comparison uncertainties. The result will be used as the basis for an entry to the BIPM key comparison database and the determination of degrees of equivalence between each of the national metrology institutes (NMIs) that have made such comparisons.

Figure 1 shows the results of the comparisons to date between each NMI and the BIPM [10 - 17]. The uncertainties shown on the graph are the standard uncertainties for each comparison result. The distribution of the results of the BIPM comparisons for the thirteen NMIs shown has a standard uncertainty of 2.3×10^{-3}. When similar methods are used there are correlations between the results that need to be taken into account when comparing one NMI with another. However, the results for absorbed dose to water obtained from graphite calorimetry and cavity theory, shown as open circles in the figure, do not indicate any systematic difference between this method and that using photon-fluence scaling (black circles).

Figure 1 International comparison of absorbed dose to water
(standard uncertainties are of each comparison result)



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