Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the NRC, Canada and the BIPM in ^{60}Co gamma radiation

C. Kessler[1], D. Burns[1], B. Downton[2], M. McEwen[2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
[2] National Research Council of Canada (NRC), Ottawa, Canada

Abstract

A new key comparison of the standards for absorbed dose to water of the National Research Council of Canada (NRC), Canada and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in October 2020. The comparison result, based on the calibration coefficients for three transfer standards and evaluated as a ratio of the NRC and the BIPM standards for absorbed dose to water, is 0.9995 with a combined standard uncertainty of 3.4 parts in 10^3. The result agrees within the uncertainties with the comparison carried out in 2009. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison of the standards for absorbed dose to water of the National Research Council of Canada (NRC), Canada, and the Bureau International des Poids et Mesures (BIPM) was carried out in October 2020 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2009 (Kessler *et al.* 2010) published in the BIPM key comparison database (KCDB 2021) under the reference BIPM.RI(I)-K4. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The indirect comparison was made using three thimble-type ionization chambers as transfer instruments. The final results were supplied by the NRC in September 2021.

2. Details of the standards and the transfer chambers

The primary standard of the NRC for absorbed dose is a Domen-type sealed water calorimeter described by Seuntjens *et al.* (1999).

The BIPM primary standard is a parallel-plate graphite cavity ionization chamber positioned at the reference depth in a water phantom (Boutillon and Perroche 1993, Burns and Kessler 2018). The main dimensions are given in Table 1.

Details of the transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM standard

Dimensions		Standard CH7.1
Cavity	Diameter / mm	45.0
	Thickness / mm	5.147
	Measuring volume / cm^3	6.7928
Electrode	Diameter / mm	41.0
	Thickness / mm	1.027
Wall	Thickness / mm	2.848
	Material	Graphite
	Density / g cm^{-3}	1.85
Voltage applied to outer electrode / V	(both polarities)	80

Table 2. Characteristics of the NRC transfer chambers

Nominal values		NE 2571	FC65G	PTW 30013	
Chamber	Outer diameter / mm	7.0	7.0	7.0	
	Outer length / mm	24.5	23.5	23.6	
Electrode	Diameter / mm	1.0	1.0	1.1	
	Length / mm	20.6	20.5	21.2	
Cavity	Nominal volume / cm^3	0.7	0.65	0.60	
Wall	Thickness / mm	0.36	0.4	0.335	0.09
	Material	graphite	graphite	PMMA	graphite
	Density / g cm^{-3}	1.7	1.8	1.19	1.85
Voltage applied (1) / V		300	300	300	

(1) At the BIPM, positive polarity was applied to the outer electrode; at the NRC the outer electrode is held at ground potential and the polarizing voltage is applied to the collecting electrode to create an equivalent electric field within the air cavity.

3. Determination of the absorbed dose to water

At the BIPM the absorbed-dose-to-water rate is determined using the primary standard cavity ionization chamber with measuring volume V by the relation

$$\dot{D}_{\mathrm{w,BIPM}} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W}{e} \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{w,g}} \bar{s}_{\mathrm{g,a}} \Psi_{\mathrm{w,g}} \beta_{\mathrm{w,g}} \prod k_i \qquad (1)$$

where

ρ_{air} is the density of air under reference conditions,

I is the ionization current measured by the standard,

W is the average energy spent by an electron of charge e to produce an ion pair in dry air,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,g}}$ is the ratio water-to-graphite of mass energy-absorption coefficients,

$\bar{s}_{\mathrm{g,a}}$ is the ratio of the mean mass stopping powers graphite-to-air,

$\Psi_{\mathrm{w,g}}$	is the photon energy fluence ratio water-to-graphite
$\beta_{\mathrm{w,g}}$	is the absorbed-dose-to-collision-kerma ratio, and
$\Pi\, k_i$	is the product of the correction factors to be applied to the standard.

The values for the physical constants, the correction factors, the volume of the primary standard entering in equation (1) and the associated uncertainties (Kessler and Burns 2018) are given in Table 3.

Table 3. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water [(1)]

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty [(2)] $u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Physical constants				
ρ_{a}	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,g}}$	ratio of mass energy-absorption coefficients	1.1131	–	0.05
W/e	mean energy per charge / J C^{-1}	33.97	–	– [(3)]
$D_{\mathrm{g,air}} = s_{\mathrm{g,air}} k_{\mathrm{cav}}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13 [(3)]
$\psi_{\mathrm{w,g}}$	photon energy fluence ratio	1.0037	0.01	0.07
$\beta_{\mathrm{w,g}}$	absorbed-dose-to-collision-kerma ratio	0.9998	0.01	0.01
Correction factors				
k_{env}	envelope of the chamber	0.9993	0.01	0.02
k_{win}	entrance window of the phantom	0.9997	0.01	0.01
k_{rn}	radial non-uniformity	1.0056	0.01	0.03
k_{s}	saturation	1.0021	0.01	0.02
k_{h}	humidity	0.9970	–	0.03
Measurement of I /υ				
υ	volume / cm^3	6.7928 [(4)]	–	0.08
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) [(5)]		0.02	–
Combined uncertainty of the BIPM determination of absorbed-dose rate to water				
quadratic summation			0.04	0.18
combined relative standard uncertainty			0.19	

(1) Details on the determination of absorbed dose to water are described by Boutillon and Perroche (1993) and the re-evaluation of the standard is described by Burns and Kessler (2018).

(2) $u_{i\mathrm{A}}$ represents the relative uncertainty estimated by statistical methods (Type A);
$u_{i\mathrm{B}}$ represents the relative uncertainty estimated by other methods (Type B).

(3) The uncertainty component of 0.13 represents the uncertainty of 0.08 for the product of W/e and the stopping-power ratio $s_{\mathrm{g,air}}$, as evaluated for the BIPM and other air-kerma standards for Co-60 and the uncertainty of k_{cav}

(4) Standard CH7-1.

(5) Over a period of 3 months.

At the NRC, the absorbed dose to water D_{w} is determined using

$$\dot{D}_{\mathrm{w,NRC}} = \Delta T_w c_w \prod k_i k_{HD} \quad (2)$$

where

ΔT_w is the measured temperature rise,

c_w is the specific heat capacity of water at the calorimeter operating temperature of 4 °C,

$\prod k_i$ is the product of the correction factors to be applied to the standard, and

k_{HD} is a correction factor for the heat defect of water.

The absorbed dose to water at the NRC is disseminated via a reference ^{60}Co field, the output of which is determined by the primary standard water calorimeter. A series of secondary standard ionization chambers, calibrated directly against the water calorimeter, are used to monitor the stability of the reference field. Due to the challenges of operating a water calorimeter (e.g., relatively low sensitivity) measurements with the standard in the ^{60}Co field are only performed soon after a source change, when the dose rate is the highest.

Table 4. Physical constants, correction factors and relative standard uncertainties for the NRC standard for absorbed dose to water

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty u_{iA}	u_{iB}
Determination of D_w				
$c_{w,p}$	specific heat capacity / (J g^{-1} K^{-1})	4.2048	–	<0.005
	thermistor sensitivity	–	–	0.08
k_c	heat conduction	0.9963	–	0.10
k_p	vessel perturbation	1.0021	–	0.05
k_{HD}	heat defect	1.0000	–	0.15
k_{rho}	change in density of water (4 °C to 22 °C)	1.0006	–	0.02
k_{dd}	profile non-uniformity	1.0005	–	0.01
	positioning calorimeter, probes and vessel	–	–	0.08
	reproducibility	–	0.08	–
Calibration of reference chamber				
	short term reproducibility $M_{raw,ref}$	–	0.02	–
P_{dd}	profile non-uniformity	1.0014	–	0.03
P_{ion}	ion recombination (1)	–	–	0.05
P_{pol}	polarity (1)	–	–	0.01
P_{elec}	charge calibration of electrometer	–	–	0.01
P_{TP}	air density correction	–	–	0.05
	positioning of chamber	–	–	0.05
	humidity (range 20% – 70%)	–	–	0.06
Combined uncertainty of the NRC calibration of the reference chamber $N_{D,w,ref}$				
quadratic summation			0.08	0.25
combined relative standard uncertainty			0.26	

(1) Polarity and ion recombination corrections were not applied for this comparison but are included in Table 4 for completeness. For Farmer-type reference chambers, P_{ion} and P_{pol} are typically 1.0014 and 0.9995 respectively.

Reference conditions

The reference conditions for the absorbed-dose-to-water determination at the BIPM are described by Kessler and Burns (2018):

- the distance from the source to the reference plane (centre of the detector) is 1 m;

- the beam 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; and
- the reference depth in the water phantom is 5 g cm^{-2}.

The reference conditions at the NRC are as described in the previous comparison report (Kessler *et al*. 2010). The only significant deviation from the BIPM reference conditions is that the reference depth for the calibration of ionization chambers including the transfer chambers used in this comparison is 5 cm water plus the 3 mm PMMA window of the phantom.

Reference values

The BIPM reference absorbed-dose-to-water rate $\dot{D}_{\mathrm{w,BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison, corrected to the reference date of 2020-01-01, 0 h UTC, as is the ionization current of the transfer chambers. The half-life of ^{60}Co used for the decay correction was taken as 1925.21 days (u = 0.29 days) (Bé *et al* 2006).

The value of $\dot{D}_{\mathrm{w,NRC}}$ used for the comparison is based on the reference dose rate determined following the source change and referenced to 2020-01-01, 12:00 PM EST using the half-life value of 1925.02 days (u = 0.47 days) (Rutledge *et al.* 1983); for the calibration of reference chambers, the dose rate is then corrected from the reference value to the day of measurement using the same half-life.

Beam characteristics

The characteristics of the BIPM and NRC beams are given in Table 5.

Table 5. Characteristics of the ^{60}Co beams at NRC and the BIPM

^{60}Co beam	Nominal $\dot{D}_w$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
NRC GammaBeam X-200	20.8	20	20	19 %	10 cm × 10 cm
BIPM Theratron 1000	6.5	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}}/I_{\mathrm{lab}} \tag{3}$$

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

The ionization chambers NE 2571, serial number 3694, FC65G, serial number 1233 and PTW 30013, serial number 1527, belonging to the NRC, were used as the transfer chambers for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the NRC before and after the measurements at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2018); the essential details for the determination of the calibration coefficients $N_{D,\mathrm{w,lab}}$ for the transfer chambers are reproduced here.

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem and waterproof sleeve facing the source.

Applied voltage and polarity

At the BIPM, a collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the transfer chambers at least 40 min before any measurements were made; at the NRC the same collecting voltage (negative polarity) was applied to the collector at least 20 minutes before any measurements were made at the NRC.

Charge and leakage measurements

The charge Q collected by the transfer chambers was measured at the BIPM using a Keithley electrometer, model 642. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements (~13 Gy). Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 1 part in 10^4. At the NRC, the ionization current I is measured using a Keithley electrometer, model 35617. A pre-irradiation of at least 15 min (~19 Gy) was made for each chamber before any measurements. Leakage current was measured before each series of measurements. The relative leakage correction for each chamber was less than 2 parts in 10^5.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible for continuous beams for these chamber types at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; a relative uncertainty component of 2 parts in 10^4 is included in Table 7.

Radial non-uniformity correction

At the NRC, the radial non-uniformity of the beam over the section of the transfer chambers is less than 1 part in 10^3. At the BIPM, the correction to the ionization current would only be 1.0008 for the transfer chambers. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 7.

Ambient conditions

At both laboratories, the water temperature is measured for each current measurement; it was stable to better than 0.1 °C at the BIPM and 0.2 °C at the NRC.

The ionization current is normalized to 293.15 K and 101.325 kPa at both laboratories for the purposes of this calibration (the standard reference temperature for calibrations at the NRC is 295.15 K).

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the NRC, relative humidity is controlled, but is seasonally variable, and was in the range from 20 % to 55 %; no correction for humidity is applied to the ionization current measured.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and, at the BIPM, the thickness of the PMMA front window of the phantom is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber. In addition, the BIPM applies a correction factor k_{pf} (0.9996) that accounts for the non-equivalence to water of the PMMA in terms of interaction coefficients. A waterproof sleeve of PMMA was supplied by the NRC for the transfer chambers. The same sleeve was used at both laboratories and, consequently, no correction for the influence of the sleeve was necessary at either laboratory for these chambers.

5. Results of the comparison

The transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results for each chamber were reproducible to better than 2 parts in 10^4.
The result of the comparison, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,NRC}} / N_{D,\mathrm{w,BIPM}} \tag{4}$$

in which the average value of measurements made at the NRC before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM. The results for each chamber are presented in Table 6.

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w,lab}}$ and the combined standard uncertainty u_c for the comparison result $R_{D,\mathrm{w}}$ are presented in Table 7.

The values $N_{D,\mathrm{w,NRC}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose rms value is taken as a representation of the stability of the transfer instruments. The short-term stability is estimated to be 5 parts in 10^4. Table 7 includes a component of 1 part in 10^4 for the difference in the comparison result between the three transfer chambers.

Table 6. Results of the comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D,\mathrm{w,NRC}}$/ Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2571-3694	45.08	45.10	45.09	45.12	0.9993	0.0035
FC65G-1233	48.21	48.25	48.23	48.25	0.9996	0.0035
PTW 30013-1527	53.78	53.83	53.81	53.83	0.9996	0.0035
Mean values					**0.9995**	**0.0035**

Table 7. Uncertainties associated with the indirect comparison

<table>
<tr><td rowspan="2">Relative standard uncertainty</td><td colspan="2">BIPM</td><td colspan="2">NRC</td></tr>
<tr><td>100 $u_{i\mathrm{A}}$</td><td>100 $u_{i\mathrm{B}}$</td><td>100 $u_{i\mathrm{A}}$</td><td>100 $u_{i\mathrm{B}}$</td></tr>
<tr><td>Absorbed-dose-to-water rate</td><td>0.04</td><td>0.18</td><td>0.08</td><td>0.25</td></tr>
<tr><td>Ionization current for the transfer chambers</td><td>0.01</td><td>0.02</td><td>0.02</td><td>–</td></tr>
<tr><td>Distance</td><td>0.02</td><td>–</td><td>–</td><td rowspan="2">0.05</td></tr>
<tr><td>Depth in water</td><td>0.02</td><td>0.06</td><td>–</td></tr>
<tr><td>Short-term reproducibility</td><td>0.02</td><td>–</td><td>0.02</td><td>–</td></tr>
<tr><td>Air density correction</td><td>–</td><td>–</td><td>–</td><td>0.05</td></tr>
<tr><td>Humidity</td><td>–</td><td>–</td><td>–</td><td>– (1)</td></tr>
<tr><td>Long term stability ^{60}Co field(2)</td><td>–</td><td>–</td><td>0.02</td><td>–</td></tr>
<tr><td>$N_{D,\mathrm{w,lab}}$</td><td>0.05</td><td>0.19</td><td>0.09</td><td>0.26</td></tr>
</table>

Table 7. **Uncertainties associated with the indirect comparison (cont)**

	BIPM 100 u_{iA}	NRC 100 u_{iB}
$N_{D,\mathrm{w,NRC}}/N_{D,\mathrm{w,BIPM}}$	0.10	0.32
Ion recombination	–	0.02
Radial non-uniformity	–	0.02
Stability of the chambers	0.05	
Different chambers	0.01	–
$R_{D,\mathrm{w}}$	u_c = 0.0034	

(1) This component is correlated with the correction given in Table 4

(2) Evaluated from repeat measurements using the NRC reference chambers; includes repeatability of the source position, jaw setting, *etc*.

The comparison result is taken as the unweighted mean value for the three transfer chambers, $R_{D,\mathrm{w}}$ = 0.9995 with a combined standard uncertainty for the comparison of 0.0034, demonstrating the agreement between the two standards for absorbed dose to water.

6. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

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) (Allisy *et al* 2009). It follows that for each NMI i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i})/ D_{\mathrm{w,BIPM}i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 8 gives the values for D_i and U_i for each NMI, i, taken from the KCDB of the CIPM MRA (1999) and this report. These data are presented graphically in Figure 1.

When required, the degree of equivalence between two laboratories i and j can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j. Following the advice of the CCRI(I) in 2011, results for D_{ij} and U_{ij} are no longer published in the KCDB. Note that the data presented in Table 8, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

Table 8. **Degrees of equivalence**

For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database
BIPM.RI(I)-K4 – EUROMET.RI(I)-K4 (2005 to 2008) – EURAMET.RI(I)-K4.1 – EURAMET.RI(I)-K4.2

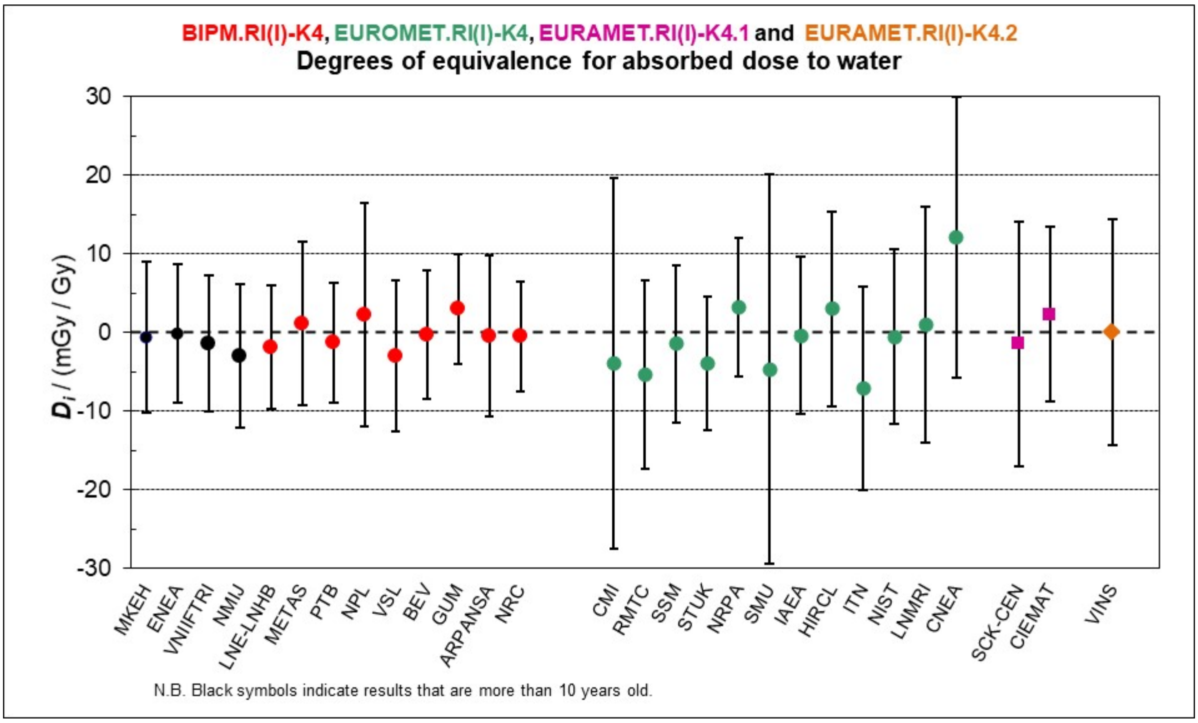
Lab *i*	D_i / (mGy / Gy)	U_i
MKEH	-0.7	9.6
ENEA	-0.1	8.8
VNIIFTRI	-1.4	8.6
NMIJ	-3.0	9.2
LNE-LNHB	-1.9	7.8
METAS	1.1	10.4
PTB	-1.3	7.6
NPL	2.3	14.2
VSL	-3.0	9.6
BEV	-0.3	8.2
GUM	3.0	7
ARPANSA	-0.5	10.2
NRC	-0.5	6.8

CMI	-4.0	23.6
RMTC	-5.3	12.0
SSM	-1.4	10.0
STUK	-3.9	8.5
NRPA	3.2	8.8
SMU	-4.7	24.7
IAEA	-0.4	10.0
HIRCL	3.0	12.4
ITN	-7.1	13.0
NIST	-0.6	11.1
LNMRI	1.0	15.0
CNEA	12.0	17.9

SCK-CEN	-1.5	15.5
CIEMAT	2.3	11.1

VINS	0.0	14.3

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



7. Conclusions

The previous comparison of the absorbed dose to water standards for ^{60}Co gamma radiation of the NRC and the BIPM was made indirectly in 2009. The comparison result was 0.9980 (52). In 2020, the BIPM adopted the changes recommended by the ICRU 90 which results in a reduction of 1 part in 10^3in the determination of absorbed dose to water; as the ICRU 90 has no impact on water calorimeters, the NRC standard remains unchanged. Considering the change adopted by the BIPM, the comparison result of 2009 becomes 0.9990.

For the present comparison, made also indirectly using transfer instruments, the NRC standard for absorbed dose to water in ^{60}Co gamma radiation compared with the BIPM absorbed dose to water standard gives a comparison result of 0.9995 (34), in agreement within the uncertainties with the previous comparison result. The NRC standard agrees within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K4 ongoing key comparison for absorbed dose to water standards in ^{60}Co gamma-ray beam.

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