Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the SCK•CEN, Belgium and the BIPM in ^{60}Co gamma radiation

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Abstract

A first key comparison of the standards for air kerma of the Laboratory for Nuclear Calibrations (LNK) from the Studiecentrum voor Kernenergie - Centre d'Etude de l'Energie Nucleaire (SCK•CEN), Belgium and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in September 2016. The comparison result, evaluated as a ratio of the SCK•CEN and the BIPM standards for air kerma, is 1.0021 with a combined standard uncertainty of 2.6×10^{-3}. The results for an indirect comparison made at the same time are consistent with the direct results at the level of 7 parts in 10^4. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

The Laboratory for Nuclear Calibrations (LNK) from the Studiecentrum voor Kernenergie - Centre d'Etude de l'Energie Nucleaire (SCK•CEN), Belgium, is the Designated Institute for ionising radiation in Belgium since 2012. The LNK, currently traceable to the Dutch Metrology Institute (VSL), is in the process of adopting its own primary standard for ^{60}Co air kerma. As part of this process, a first comparison of the standards of the SCK•CEN and of the Bureau International des Poids et Mesures (BIPM) was carried out in September 2016 in the ^{60}Co radiation beam at the BIPM. An indirect comparison was also made using a thimble ionization chamber as a transfer instrument. The final results were supplied by the SCK•CEN in October 2016.

2. Details of the standards

The SCK•CEN standard CC01 serial number 104 for air kerma is a cylindrical graphite-walled cavity ionization chamber constructed by the Österreichisches Forschungszentrum (ÖFS), Austria. The details of the SCK•CEN standard and the transfer chamber are given in Table 1.

The BIPM primary standard is a parallel-plate graphite cavity ionization chamber with a volume of about 6.8 cm^3 (Boutillon *et al* 1973, Burns *et al* 2007).

Table 1. Characteristics of the SCK•CEN standard for air kerma and the transfer chamber

SCK•CEN chambers		CCO1-104	NE 2571-3588 [(1)]
Chamber	Outer height / mm	19	26.5
	Outer diameter / mm	19	7.0
	Wall thickness / mm	4	0.35
Electrode	Diameter / mm	2	1.0
	Height / mm	10	21.0
Volume	Air cavity / cm^3	1.022 [(2)]	0.7
Wall	Materials	Ultra pure graphite (EK51 Ringsdorf)	
	Density	1.71 $g\cdot cm^{-3}$	
	Impurity	$< 1.5 \times 10^{-4}$	
Insulator		PTFE Teflon	
Applied voltage	Polarity	250 V [(3)]	250 V [(4)]

(1) Purchased in 2009 from Thermo Fischer Scientific

(2) measured by the Bundesamt für Eich-und Vermessungswesen (BEV), Austria

(3) both polarities applied at the BIPM; measurements at the SCK•CEN are made using negative polarity with an applied correction k_{pol} = 1.0010 (6)

(4) positive polarity applied to the outer electrode at both laboratories

3. Determination of the air kerma

For a cavity chamber with measuring volume V, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{air} V} \frac{W}{e} \frac{1}{1-\bar{g}} \left(\frac{\mu_{en}}{\rho}\right)_{a,c} \bar{s}_{c,a} \prod k_i \qquad (1)$$

where

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

I is the ionization current under the same conditions,

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

$\bar{g}$ is the fraction of electron energy lost by bremsstrahlung production in air,

$(\mu_{en}/\rho)_{a,c}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,

$\bar{s}_{c,a}$ is the ratio of the mean stopping powers of graphite and air,

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

Physical data and correction factors

The values used for the physical constants, recommended by the Consultative Committee for Ionizing Radiation (CCEMRI 1985) are given in Table 2. The correction factors entering in equation (1), the volume of the primary standards and the associated uncertainties for the BIPM (Allisy-Roberts *et al* 2011) and the SCK•CEN standards are also included in Table 2.

Table 2. Physical constants and correction factors with their relative standard uncertainties of the BIPM and SCK•CEN standards for the ^{60}Co radiation beam at the BIPM

		BIPM	**CH 6.1**		**SCK•CEN**	**CC01-104**	
		values	uncertainty (1)		values	uncertainty (1)	
			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Physical Constants							
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.01	1.2930	–	0.01
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9989	–	0.05
$s_{\mathrm{c,a}}$	ratio of mass stopping powers	1.0010	–	0.11 (3)	1.0007	–	0.11
W/e	mean energy per charge / J C^{-1}	33.97	–		33.97	–	
g_{a}	fraction of energy lost in radiative processes	0.0031	–	0.02	0.0032	–	0.02
Correction factors:							
k_{g}	re-absorption of radiative loss	0.9996	–	0.01	–	–	–
k_{s}	recombination losses	1.0022	0.01	0.02	1.0025 (4)	0.01	0.02
k_{h}	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–	0.9999	–	0.04
k_{wall}	wall attenuation and scattering	1.0011	–	– (5)	1.0209	–	0.10
k_{an}	axial non-uniformity	1.0020	–	– (5)	1.0000	–	0.10
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0002	–	0.02
k_{pol}	polarity	–	–	–	– (6)	–	–
Measurement of I / V							
V	chamber volume / cm^3	6.8855	–	0.08 (5)	1.0220	–	0.20 (7)
I	ionization current / pA		0.01	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.15		0.01	0.28
combined uncertainty			**0.15**			**0.28**	

(1) Expressed as one standard deviation

$u_{i\mathrm{A}}$ represents the type A relative standard uncertainty estimated by statistical methods,

$u_{i\mathrm{B}}$ represents the type B relative standard uncertainty estimated by other means

(2) At 101 325 Pa and 273.15 K

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

(4) Determined at the BIPM

(5) The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al* 2007)

(6) At the SCK•CEN, k_{pol} = 1.0010(6)

(7) As determined through dimensional measurements by the BEV

The correction factor k_{wall} that accounts for photon attenuation and scattering in the wall of the chamber was calculated using the Monte Carlo code Penelope. The geometries of the chamber and the ^{60}Co source, shielding, and collimation were simulated using the Pengeom code. The correction factor k_{wall} was calculated using the regeneration technique (Bielajew 1990). The result agrees with that obtained by Burns (2003) when scaled for the SCK-CEN graphite wall density of 1.71 g cm^{-3}. The axial non-uniformity correction was taken from Rogers *et at* (1999) as being very close to unity.

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Allisy-Roberts *et al* (2011):

- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 10 cm × 10 cm, defined by 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 conditions at the SCK•CEN are the same to those at the BIPM.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\mathrm{BIPM}}$ values refer to an evacuated path length between source and standard corrected to the reference date of 2016-01-01, 0 h UTC. The half-life of ^{60}Co was taken as 1925.19 days (u = 0.29 days) (Bé *et al* 2006).

The $\dot{K}_{\mathrm{SCK \bullet CEN}}$ value is the mean of four measurements made over a period of about 3 weeks around the period of the comparison. By convention it is given at the reference date of 2016-01-01 T 0 h UTC using the same half-life value for ^{60}Co.

Beam characteristics

The characteristics of the BIPM and SCK•CEN beams are given in Table 3. The Theratron 780C sn 178 irradiation unit was installed in 2008 at the Laboratory for Nuclear Calibrations at the working site at Ghent. The source type C-146 was provided by MDS Nordion and contained 276.8 TBq (reference date 2003-10-17) of ^{60}Co. This source is a double encapsulated cylinder with a stainless steel outer capsule. The inner and outer diameter of the double-encapsulation is 2.0 cm and 2.34 cm, respectively. The inner and outer cylinder height is 3.05 cm and 3.67 cm, respectively. The radioactive content is in the form of plated ^{60}Co pellets.

The PENELOPE 2011 code (Salvat *et al* 2011) was used at the SCK•CEN to simulate the scattered photons from the Theratron. Scatter contribution in terms of energy fluence represents 28% of the total number of photons at the detector. The source, source capsule and the Pb shielding generate the majority of the scattered photons, 2.7 times more than the collimator.

Table 3. Characteristics of the ^{60}Co beams at the SCK•CEN and the BIPM

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
SCK•CEN source	4.2	20	30.5[a]	28%	10 cm × 10 cm
BIPM source	2.9	20	14	21 %	10 cm × 10 cm

[a] inner length of the encapsulation

4. Experimental method

The experimental method for measurements at the BIPM is described by Allisy-Roberts *et al* (2011); the essential details of the measurements at each laboratory 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 facing the source.

Applied voltage and polarity

CC01-104

At the BIPM a collecting voltage of 250 V (both polarities) was applied to the outer electrode of the standard at least 30 min before any measurements were made; no correction for polarity was applied. At the SCK•CEN, the same collecting voltage (negative polarity) was applied to the outer electrode of the standard and a correction of 1.0010 (6) is applied to account for the polarity effect. A value of 1.0007 (1) was determined at the BIPM for this chamber.

NE2571

At both laboratories a collecting voltage of 250 V (positive polarity) was applied to the outer electrode of the chamber; no correction was applied for polarity at either laboratory.

Volume recombination

CC01-104

The correction factor for the SCK•CEN standard for losses due to ion recombination was determined at the BIPM during the present comparison using the method described by Boutillon (1998). The recombination correction k_s can be expressed as

$$k_s = 1 + k_{init} + k_{vol} I_V \qquad (2)$$

where k_{init} is the initial recombination, k_{vol} is the volume recombination coefficient and I_V is the current measured for the applied voltage V. The current, I_V, is the current as measured by the chamber, not corrected for decay and not normalized for temperature and pressure. Table 4 gives the values for k_{init} and k_{vol} and the uncertainty for k_s calculated for the BIPM radiation beam.

Table 4. Ion recombination for the SCK•CEN standard

Standard CC01-104	BIPM values
Initial recombination and diffusion, k_{init}	2.3×10^{-3}
Volume recombination coefficient, k_{vol} / pA^{-1}	1.4×10^{-6}
k_s in the BIPM beam	1.0025
Standard uncertainty	2×10^{-4}

The ion recombination correction factor k_s for the CC01-104 is consistent with the mean of the values obtained for similar chambers at the level of 4 parts in 10^4.

The SCK•CEN adopted the BIPM determination for k_s. Thus, a correction factor of 1.0025 was applied to the measured current at the BIPM.

NE2571
Volume recombination is negligible at a kerma rate of less than 15 mGy s^{-1} for this chamber type at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories. No correction for recombination was applied and a relative uncertainty component of 2×10^{-4} is included in Table 9.

Radial non-uniformity correction

CC01-104
The applied correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the SCK•CEN standard is 1.0002 (2).

NE2571
For the transfer chamber, this correction is less than 2×10^{-4} at the BIPM; at the SCK•CEN, this correction would be less than 4×10^{-4}. No radial non-uniformity correction was applied for the indirect comparison and a relative uncertainty component of 2×10^{-4} is included in Table 9.

Charge and leakage measurements
The charge Q collected for the transfer chamber was measured at the SCK•CEN using a Keithley electrometer, model 6517 A; at the BIPM, the charge is measured using a Keithley electrometer, model 642. The chambers were pre-irradiated for at least 30 min at both laboratories before any measurements were made. The ionization current measured for each chamber was corrected for the leakage current; at both laboratories, this correction was less than 2×10^{-4} in relative value.

Ambient conditions
During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.03 °C at the BIPM. At the SCK•CEN, the air temperature was stable to better than 0.2 °C. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories.
Relative humidity is controlled at (50 ± 5) % at the BIPM. At the SCK•CEN, relative humidity is not adjusted, but calibrations are done only in the range 20-80%.

5. Results of the comparison

The SCK•CEN primary standard was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 1×10^{-4}. The values of the ionization currents measured at the BIPM for the SCK•CEN standard are given in Table 5. They have been normalized to standard temperature and pressure and corrected to the reference date for the decay of the ^{60}Co source.

Table 5. The experimental results from the SCK•CEN standards in the BIPM beam

SCK•CEN standard	I_+ *and* I_- /pA		I_{mean} / pA
CC01-104	111.07	-110.92	110.995
	111.06	-110.91	110.989
Mean current			110.992

The result of the comparison, R_K, is expressed in the form

$$R_K = \dot{K}_{\text{SCK•CEN}} / \dot{K}_{\text{BIPM}} \qquad (3)$$

and is presented in Table 6.

Table 6. Final result of the SCK•CEN/BIPM comparison of standards for ^{60}Co air kerma

	$\dot{K}_{\text{SCK•CEN}}$ / mGy s^{-1}	$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	R_K	u_c
CC01-104	2.9197	2.9137	1.0021	0.0026

The combined standard uncertainty u_c for the comparison result R_K is presented in Table 7.

Table 7. Uncertainties associated with the comparison result

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
$\dot{K}_{\text{SCK•CEN}} / \dot{K}_{\text{BIPM}}$	0.02	0.26[a]
Relative standard uncertainty of R_K	0.02	0.26
	u_c = 0.0026	

[a] Takes account of correlation in type B uncertainties.

The ratio of the air kerma rate values determined by the SCK•CEN and the BIPM standards taken from Table 6 is 1.0021 with a combined standard uncertainty, u_c, of 0.0026. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the SCK•CEN determinations (such as air density, *W/e*, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel each other when evaluating the uncertainty of R_K.

For the transfer chamber the comparison result is evaluated as the ratio of the calibration coefficients $N_{K,\text{lab}}$ determined at each laboratory. The calibration coefficient is given by

$$N_{K,\text{lab}} = \dot{K}_{\text{lab}} / I_{\text{lab}} \qquad (3)$$

where $\dot{K}_{\text{lab}}$ is the air kerma rate at each lab and I_{lab} is the ionization current of a transfer chamber measured at the SCK•CEN or at the BIPM. Table 8 lists the relevant values of N_K at the stated reference conditions (293.15 K and 101.325 kPa) and the final results of the indirect comparison. The uncertainties associated with the calibration of the transfer chambers are presented in Table 9.

Table 8. Results of the indirect comparison

Transfer chamber	$N_{K,\text{SCK•CEN}}$ / Gy µC^{-1}			$N_{K,\text{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
NE2571-3588	41.773	41.747	41.760	41.643	1.0028	0.0032

The result of the indirect comparison taken from Table 8 is 1.0028 with a combined standard uncertainty, u_c, of 0.0032. This result is in agreement with the direct comparison at the level of 7 parts in 10^4. The result of the direct comparison is used to evaluate the degrees of equivalence for entry in the key comparison database (KCDB).

Table 9. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		SCK•CEN	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air kerma rate	0.02	0.15	0.02	0.30
Ionization current for the transfer chambers	0.01	0.02	0.03	0.02
Distance	0.01	–	–	0.01
Reproducibility	0.01	–	0.04	–
Electrometer	–	–		0.10
Time	–	–		0.10
Temperature and pressure	–	–	–	0.02
$N_{K,\text{lab}}$	0.03	0.15	0.05	0.33
Indirect comparison result	100 u_{iA}		100 u_{iB}	
$N_{K,\text{SCK•CEN}}$ / $N_{K,\text{BIPM}}$ (1)	0.06		0.32	
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
$N_{K,\text{SCK•CEN}}$ / $N_{K,\text{BIPM}}$	u_c = 0.0032			

(1) The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

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 K_{BIPM}, is taken as the key comparison reference value (KCRV) (Allisy-Roberts *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 $D_i = (K_i - K_{\text{BIPM},i}) / K_{\text{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 10 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 10, 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 10. 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)-K1 - COOMET.RI(I)-K1 (2006) - EURAMET.RI(I)-K1 (2005 to 2008) – APMP.RI(I)-K1 (2004 to 2006) - APMP.RI(I)-K1.1 (2009 to 2012)

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
DMDM	2.5	3.6
VSL	-1.5	4.4
MKEH	5.5	4.4
GUM	2.3	4.8
NPL	1.1	7.6
NRC	3.2	5.6
BEV	3.4	4.2
VNIIM	0.8	3.6
KRISS	-0.5	3.2
ARPANSA	0.9	6.2
NIST	3.9	6.4
NMIJ	1.2	4.4
ININ	3.6	4.2
LNE-LNHB	-0.6	3.6
PTB	3.6	3.4
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
SCK•CEN	2.1	5.2

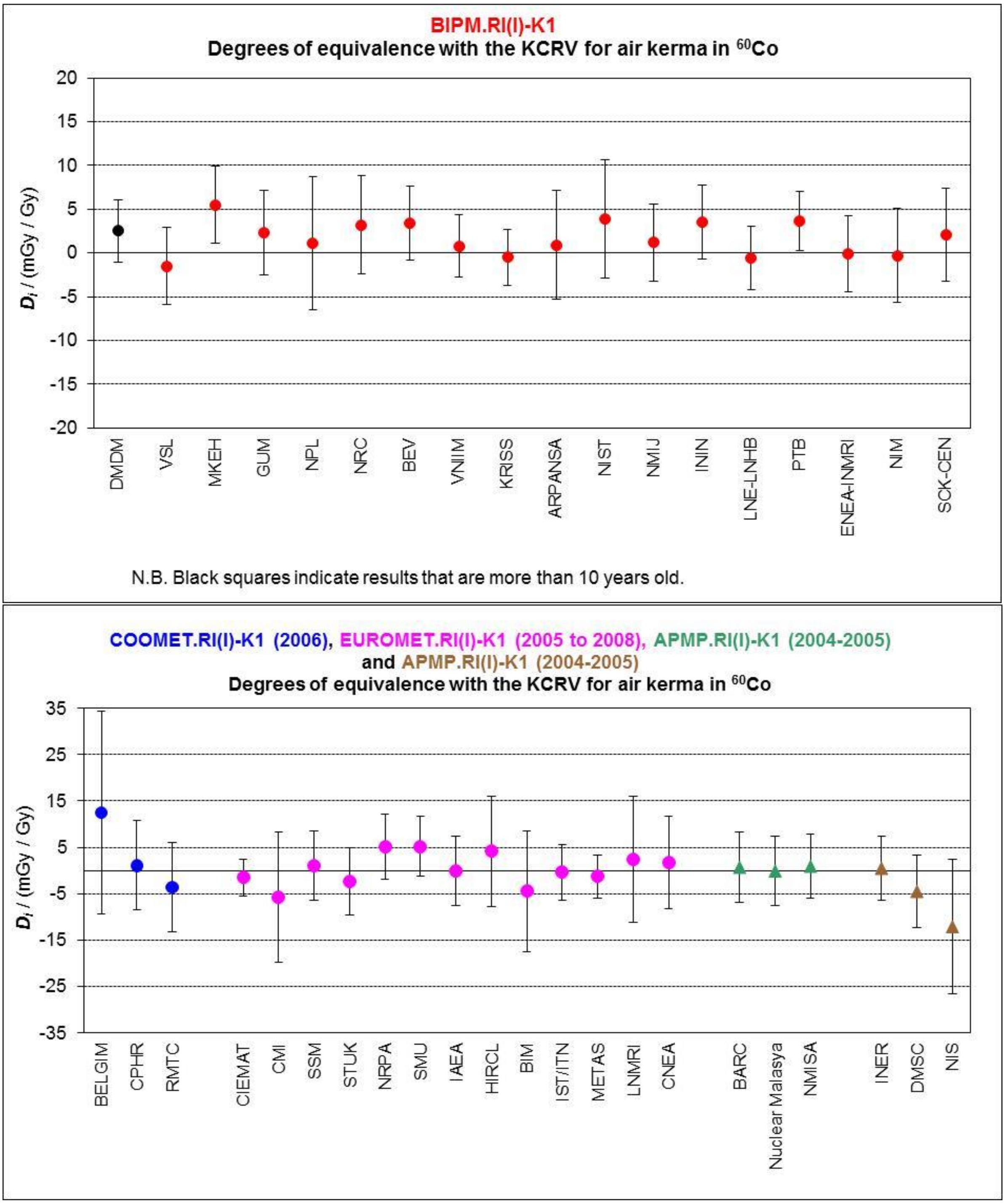
Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
BARC	0.7	7.6
Nuclear Malasya	-0.1	7.4
NMISA	0.9	6.9

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
CIEMAT	-1.5	3.9
CMI	-5.8	14.1
SSM	1.0	7.5
STUK	-2.3	7.3
NRPA	5.1	7.1
SMU	5.2	6.5
IAEA	0.0	7.5
HIRCL	4.2	11.9
BIM	-4.5	13.0
METAS	-1.3	4.6
LNMRI	2.4	13.7
CNEA	1.8	10.0

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
BelGIM	12.5	21.8
CPHR	1.1	9.7
RMTC	-3.6	9.7

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
INER	0.5	6.9
DMSC	-4.5	7.8
NIS	-12.1	14.6

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



7. Conclusion

The SCK•CEN standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0021 (26). The indirect and direct comparison results are in agreement at the level of 7 parts in 10^4, which is within the standard uncertainty of the calibration procedure.

The SCK•CEN is in agreement within the expanded uncertainty with all the NMIs that took part in the BIPM.RI(I)-K1 ongoing key comparison for air kerma standards in ^{60}Co gamma-ray beam.

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