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of the LNE-LNHB and the BIPM for ^{60}Co gamma radiation

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Abstract
A direct comparison of the standards for air kerma of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in December 2003. The results, expressed as ratios of the LNE-LNHB and the BIPM standards for air kerma, indicate a relative difference of 3.5×10^{-3} with a combined standard uncertainty of 2.7×10^{-3}. The earlier direct comparison in ^{60}Co γ rays, made in 1993, resulted in an agreement of the two standards within 2.5×10^{-3}.

1. Introduction

The last direct comparison of the air kerma standards of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France and the Bureau International des Poids et Mesures (BIPM) for ^{60}Co gamma radiation was made in 1993 [1].

The air kerma standard of the LNE-LNHB for ^{60}Co is a graphite cavity ionization chamber, referenced as GCS-10-1, constructed by the LNE-LNHB. It is of cylindrical shape with hemispherical ends and has a volume of about 9.5 cm^3. The LNE-LNHB standard is described in [2]. Some details regarding the LNE-LNHB primary standard are given in Table 1.

The BIPM standard is a parallel-plate graphite cavity ionization chamber with a volume of about 6.8 cm^3 as described in [3].

Table 1. The main dimensions and characteristics of the LNE-LNHB cavity standard

LNE-LNHB standard	**GCS-10-1**
shape	cylinder with hemispherical ends
Dimensions /mm	
outer height	39
outer diameter	28
inner height	33
inner diameter	22
minimum wall thickness	3
wall material / graphite density	1.81 g cm^{-3}
electrode diameter	2
electrode height	23
volume of air cavity /cm^3	9.4771
applied voltage (both polarities)	800 V

2. Determination of the air kerma

For the BIPM and LNE-LNHB standards, the air kerma rate is determined from

$$\dot{K} = (I/m)(W/e)(1-\bar{g})^{-1}(\bar{\mu}_{en}/\rho)_{a,c}\,\bar{s}_{c,a}\,\Pi k_i \qquad (1)$$

where

I is the ionization current measured for the mass m of air in the cavity,

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

$\bar{g}$ is the average fraction of electron energy lost to radiative processes,

$(\bar{\mu}_{en}/\rho)_{a,c}$ 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, k_s k_h k_{st} k_{sc} k_{at} k_{CEP} k_{an} k_{rn}, to be applied.

The values for the physical data used in (1) are consistent with the CCEMRI(I) 1985 recommendations [4] and the values for the correction factors needed for ^{60}Co radiation are shown in Table 2 for both the LNE-LNHB and BIPM standards, together with their associated uncertainties.

The stopping power ratio for the LNE-LNHB is taken from Table 4 in [5]. Correcting for the graphite density, results in a value of 1.0020 for $\bar{s}_{c,a}$.

At the LNE-LNHB, the correction factor for recombination losses, k_s, was determined by applying different polarizing voltages at each of several different air kerma rates. The method and the uncertainties in the measurements are described in [6].

The wall correction factor was calculated by the LNE-LNHB [7]. While this value is not in agreement with a first evaluation by the NRC using the Monte Carlo code EGSnrc for a cylindrical and a spherical virtual ionization chamber [8], the LNE-LNHB calculation takes better account of the detailed geometry of their primary standard.

The correction factors for the radial non-uniformity of the beam, designated as k_{rn}, were calculated from measured BIPM beam profiles in the radial direction [9].

Table 2. Physical constants and correction factors with their estimated relative uncertainties of the BIPM and LNE-LNHB standards for the Picker ^{60}Co gamma radiation beam at the BIPM

		BIPM			LNE-LNHB		
		values	uncertainty[(1)]		values	uncertainty[(1)]	
			100 s_i	100 u_i		100 s_i	100 u_i
Physical Constants							
ρ_0	dry air density[(2)] /kg m^{-3}	1.2930		0.01	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985		0.05	0.9988		0.07
$\bar{s}_{c,a}$		1.0010		0.11[(3)]	1.0020		0.27
W/e	J/C	33.97			33.97		
$\bar{g}$	bremsstrahlung loss	0.0032		0.02	0.0031		0.02
Correction factors:							
k_s	recombination losses	1.0015	0.01	0.01	1.0008	0.03	0.02
k_h	humidity	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	1.0000	0.01		0.9986		0.05
k_{at}	wall attenuation	1.0398	0.01	0.04			
k_{sc}	wall scattering	0.97205	0.01	0.07	1.0142		0.21
k_{cep}	mean origin of electrons	0.9922		0.01			
k_{an}	axial non-uniformity	0.9964		0.07	1.0000		0.03
k_{rn}	radial non-uniformity	1.0016	0.01	0.02	1.0005	0.01	0.02
V	chamber volume /cm^3	6.8028	0.01	0.03	9.4771	0.01	0.03
I	ionization current / pA		0.01	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.03	0.17		0.03	0.36
combined uncertainty			**0.17**			**0.36**	
Relative standard uncertainty neglecting contributions from physical constants and k_h							
quadratic summation			0.03	0.13		0.03	0.23
combined uncertainty			**0.13**			**0.24**	

(1) Expressed as one standard deviation
s_i represents the relative standard uncertainty estimated by statistical methods, type A
u_i represents the relative standard uncertainty estimated by other means, type B

(2) At 101 325 Pa and 273.15 K; the LNE-LNHB normally uses 293.15 K.

(3) Combined uncertainty for the product of $\bar{s}_{c,a}$ and W/e [10].

3. Experimental conditions

The LNE-LNHB primary standard and two NE 2571 transfer standards (serial numbers 642 and 2343) were placed in the BIPM Picker radiation beam. The reference conditions of measurement used at the BIPM [11] and the LNE-LNHB are given in Table 3.

At the BIPM, an insulating cabin was used to minimize temperature fluctuations and during a series of measurements in the ^{60}Co beam the air temperature was stable to better than 0.005 °C.

Table 3. Measurement conditions for ^{60}Co at the BIPM and the LNE-LNHB

Parameter	BIPM	LNE-LNHB
Position of the centre of the standard chamber	1 m from the source	1 m from the source
Beam cross-section	10 cm × 10 cm	16 cm ϕ
Nominal $\dot{K}$	2 mGy s^{-1}	13 mGy s^{-1}
Incident scatter in terms of energy fluence	14 %	21 %
Humidity range /%	50 ± 5	29 to 56
Temperature / °C	19.7 to 20.0	19.5 to 20.1
Pressure / kPa	99.7 to 101.3	97.4 to 101.4
Measurement of charge	Keithley electrometer	Keithley electrometer

The ionization current measured by the LNE-LNHB standard was corrected for the leakage current. The relative correction was less than 10^{-4} in the BIPM ^{60}Co beam.

Some measurements were made to confirm the LNE-LNHB correction of 1.0011 (11) for ion recombination at the BIPM. Using the Niatel method [12], the value obtained and applied at the BIPM is 1.0008 (3), which is in agreement within the uncertainty with the LNE-LNHB evaluation. Figure 1 shows the BIPM experimental results for this measurement, which produces an initial recombination of 5.4×10^{-4} and a volume recombination coefficient of 3.7×10^{-7} pA^{-1}. At the LNE-LNHB, the corresponding values are 7.6×10^{-4} and 3.2×10^{-7} pA^{-1}.

No measurements were made at the BIPM to confirm the effect of the supporting stem. Measurements made at the LNE-LNHB at different distances in their ^{60}Co beam indicate that there should be no significant difference at the BIPM.

In addition to the direct comparison, two transfer standards of the LNE-LNHB were calibrated at the BIPM. The calibration coefficients of the LNE-LNHB were referred to the same measurement conditions as at the BIPM (Table 4) to enable this indirect comparison to be made. The NE 2571-642 transfer standard is normally used in a graphite phantom at the LNE-LNHB, locating on axis to a groove marked on the chamber stem. This orientation is rotated about 30° from the normal position used at the BIPM where the engraved black line on the stem is used to locate the chamber on axis with the reference beam. An orientation correction factor for the groove position of this chamber was measured at the BIPM as 0.9991 (2).

The stability of the three LNE-LNHB standards was confirmed by measurements made at the LNHB after their return. Agreement for each standard was within 2×10^{-4} of its pre-BIPM value.

Figure 1. Recombination measurements made at the BIPM for the LNE-LNHB GCS-10-1 primary standard

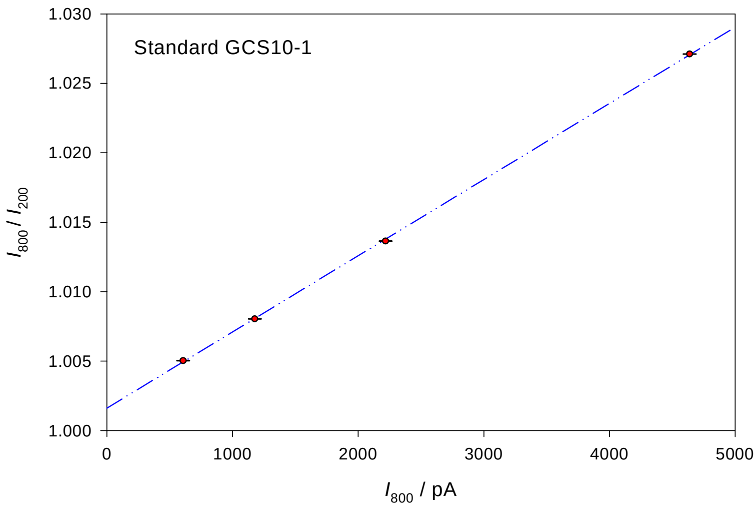

Table 4. Normalized conditions for transfer standard calibration

Normalization	BIPM	LNE-LNHB	
Humidity	50 %	0 %	
Temperature	20 °C	20 °C	
Pressure	101.325 kPa	101.325 kPa	
Correction factors		NE2571-642	NE2571-2343
k_{pol}	---	0.9991	0.9990
k_s	---	1.0011	1.0011
k_{rn}	1.0001	1.0001	1.0001
$k_{orientation}$	---	0.9991*	---

* multiplying factor measured at the BIPM for the difference in chamber orientation in the two laboratories.

4. Results

The values of the ionization currents measured at the BIPM for each standard are given in Table 5. These values are corrected for leakage and for decay from the measurement date to the reference date, and normalized to the reference conditions of air temperature 273.15 K and pressure 101.325 kPa. No humidity correction has been applied; the BIPM laboratory is controlled at 50 % relative humidity.

Table 5. Ionization currents measured with the LNE-LNHB standards at the BIPM

^{60}Co radiation, Picker beam, values are given in pA				Mean values	100 s*
GCS-10-1	748.284	747.941	747.983	748.069	0.01
NE 2571-642	55.121	55.114	–	55.118	0.01
NE 2571-2343	54.583	54.571	–	54.577	0.01

* relative statistical uncertainties in the measurements

The comparison results are given by,

$$R_{\dot{K}} = \dot{K}_{\text{LNE-LNHB}} / \dot{K}_{\text{BIPM}} \,, \tag{2}$$

where $\dot{K}$ is the value of the air kerma rate at the BIPM measured by the LNE-LNHB and BIPM standards, respectively. The results are given in Table 6 together with their uncertainties. As some constants (such as air density, *W/e*, $\overline{\mu}_{\text{en}}/\rho$, $\overline{g}$, $\overline{s}_{c,a}$ and k_h) are derived from the same basic data in both laboratories, the uncertainty in R_K is due only to the uncertainties in the correction factors, the volumes of the standards, the ionization currents measured and the distance to the source, the values of which are also given in Table 2. The relative uncertainty in the position of each chamber at the BIPM is less than 0.01 %.

The air kerma value for the LNE-LNHB standard is derived from the mean of the current measurement series in Table 5 and applying the physical constants and correction factors given in Table 2 in accordance with (1). The BIPM air kerma value is the mean of measurements made over several months before and after the comparison.

Table 6. Results of the direct comparison of standards for air kerma

Beam	LNE-LNHB	$\dot{K}_{\text{LNE-LNHB}}$ /mGy s^{-1}	$\dot{K}_{\text{BIPM}}$ /mGy s^{-1}	R_K	100 u_c
Picker	GCS-10-1	2.1048	2.0974	1.0035	0.27

The values for $\dot{K}$ refer to an evacuated path length between source and standard. They are given at the reference date of 2003-01-01: 0 h UT (the half life of ^{60}Co is taken as 1925.5 (0.5) days [13]).

Compared to the last comparison of air kerma in ^{60}Co gamma radiation [1] R_K has increased by about 0.1 %.

The result of the indirect comparison, R'_K, is expressed in the form

$$R'_K = N_{K,\text{NMI}} / N_{K,\text{BIPM}} \,, \tag{3}$$

where N_K is the calibration coefficient of the transfer chamber determined at each laboratory, referenced to the BIPM conditions in Table 4. The relevant $\dot{K}$, I and N_K values obtained are shown in Table 7 together with R'_K and its relative combined standard uncertainty u_c.

Table 7. Results of the indirect comparison of standards for air kerma

LNE-LNHB	$N_{K\,\text{LNE-LNHB}}$ /Gy μC^{-1}	$N_{K\,\text{BIPM}}$ / Gy μC^{-1}	R'_K	100 u_c
NE 2571-642	41.003	40.844	1.0039	0.28
NE 2571-2343	41.408	41.248	1.0039	0.28
Mean value			1.0039	0.28

5. Discussion and analysis of the BIPM ongoing ^{60}Co air kerma comparisons

In the last two years, the BIPM has made new Monte Carlo calculations of the wall corrections and other factors for its ^{60}Co standard to verify its determination of air kerma [14]. The effect that this would have on the present comparison result is shown in Table 8. The changes due to the re-evaluation of k_{an} are more significant for the BIPM standard than the changes due to the calculated k_{wall} correction factors. However, any new result needs to be approved and implemented at a date to be confirmed by the CCRI, probably in 2007.

Table 8. Changes to the LNE-LNHB comparison results if the Monte Carlo calculated correction factors are used for the BIPM standard

Correction factor	^{60}Co		
	present	new [14]	ratio
k_{wall}	1.0028 (8)	1.0012 (2)	0.9984
k_{an}	0.9964 (7)	1.0027 (3)	1.0063
total difference*			1.0046
R_K **(new)**	**0.9989 (27)**		

*including other small changes [14]

Recent calculations by the LNE-LNHB, BIPM [15] and the NRC [16] for the LNE-LNHB standard indicate that the wall correction factor for the present standard will increase by a factor of about 1.0026. However, the LNE-LNHB is planning to produce a new air kerma reference standard based on three cavity ionization chambers. The wall corrections for these chambers will then be based on MC calculations.

The results of air kerma comparisons in ^{60}Co at the BIPM are currently being re-evaluated, taking into account the effect of changes being made in many national standards following the recommendations of the Consultative Committee for Ionizing Radiation (CCRI) [17]. The NRC (Canada), OMH (Hungary), PTB (Germany) and the BEV (Austria) have already declared new values for their air kerma standard [18, 19, 20, 21]. The SZMDM (Serbia and Montenegro), NCM (Bulgaria) and the ENEA (Italy), all of which have made comparisons recently with the BIPM [22, 23, 24], have also changed their previous method of k_{wall} determination, now using Monte Carlo calculations. The NMi and the LNMRI/IRD have recently confirmed their earlier comparison results [25, 26] but are in the process of publishing or recalculating wall effects for their primary standard.

In the meantime, the other comparisons that have been made are being reviewed, such as for the NIST (USA) [27], and once the evaluations have been updated and the results approved by the CCRI(I), they will be published in the BIPM key comparison database (KCDB) that was set up under the CIPM Mutual Recognition Arrangement [28]. In this database, BIPM air kerma comparisons for ^{60}Co are identified as BIPM.RI(I)-K1.

6. Conclusion

The LNE-LNHB standard for air kerma in ^{60}Co gamma radiation compared with the present BIPM air kerma standard gives a comparison result, expressed as a ratio, of 1.0035 (27). An indirect comparison made at the same time using transfer standards gives a comparison result of 1.0039 (28), which agrees with the direct comparison within the uncertainties of the measurements.

In principle, all the comparison results of the national metrology institutes (NMIs) and designated laboratories will be used as the basis of the entries in Appendix B of the KCDB set up under the CIPM MRA. The NMIs that have previously used experimental extrapolation methods to determine wall correction factors are currently checking their factors, using various Monte Carlo codes or other methods. The LNE-LNHB is working towards a new set of primary standards for air kerma that will include Monte Carlo calculated wall correction factors. It is expected that all the NMIs will be ready for their results to be entered into the BIPM KCDB by the summer of 2006. In the meantime, the BIPM has also reviewed its experimental and calculated results for the wall and other correction factors for its primary standard. This re-evaluation of the BIPM primary standard has been published in the open literature and is awaiting formal adoption by the CCRI.

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