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Abstract
A comparison of the standards of air kerma of the National Center of Metrology (NCM) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. It shows that the ratio of the NCM and BIPM standards is 1.0117 with a relative standard uncertainty of 1.9×10^{-3}. This is the first comparison of air kerma standards of the NCM with the BIPM.

1. Introduction

A comparison of the standards of air kerma of the National Center of Metrology (NCM), Sofia, Bulgaria, and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co radiation. The NCM standard of air kerma is a graphite cavity ionization chamber constructed at the Országos Mérésügyi Hivatal (OMH), Budapest, Hungary (type ND1005/A, serial number 8008), details of which are given in section 3 of this report. The BIPM air kerma standard is described in [1]. This first comparison of the NCM air kerma standard took place at the BIPM in January 2002.

2. Conditions of measurement

The air kerma is determined at the BIPM under the following conditions [2]:
- the distance from source to reference plane 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.

3. Determination of the air kerma rate

The air kerma rate is determined using the relation

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

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,
$\bar{g}$	is the fraction of electron energy lost to bremsstrahlung,
$(\mu_{en}/\rho)_{a,c}$	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.

The main characteristics of the NCM primary standard are given in Table 1. The volume determination was made by the OMH and consequently the comparison result will have correlations with that of the OMH.

Table 1. Characteristics of the NCM standard for the measurement of air kerma

Standard Type		Primary ND1005/A - 8008 Nominal values
Chamber	Outer height / mm	19
	Outer diameter / mm	19
	Inner height / mm	11
	Inner diameter / mm	11
	Wall thickness / mm	4
Electrode	Diameter / mm	2
	Height / mm	10
Volume	Air cavity / cm^3	1.0267
	relative uncertainty / cm^3	0.0003
Wall	Material	ultrapure graphite
	Density / $g\cdot cm^{-3}$	1.75
	Purity	99.99 %
Applied tension	Voltage / V	250

4. Experimental results

Data concerning the various factors entering in the determination of air kerma in the ^{60}Co beam using the two standards are shown in Table 2. They include the physical constants [3], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties. Also shown are the relative uncertainties in the ratio $R_K = \dot{K}_{\mathrm{NCM}} / \dot{K}_{\mathrm{BIPM}}$.

Table 2. Physical constants and correction factors entering in the determination of air kerma and their estimated relative standard uncertainties in the BIPM ^{60}Co beam

	BIPM values	100 × Relative [(1)] uncertainty		NCM values	100 × Relative [(1)] uncertainty		100 × Relative [(1)] uncertainty of R_K	
		s_i	u_i		s_i	u_i	s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(2)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05	0.9985	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0010	-	0.11	1.0008	-	0.11	-	-
W/e /(J C^{-1})	33.97			33.97				
$\bar{g}$ fraction of energy lost to bremsstrahlung	0.0032	-	0.02	0.0032	-	0.02	-	-
Correction factors								
k_s recombination losses	1.0015	0.01	0.01	1.0022	0.01	0.01	0.01	0.03
k_h humidity	0.9970	-	0.03	0.9975	-	0.05	-	0.05
k_{st} stem scattering	1.0000	0.01	-	0.9995	0.01	0.01	0.01	0.01
k_{att} wall attenuation	1.0398	0.01	0.04	1.0237				
k_{sc} wall scattering	0.9720	0.01	0.07		0.03	0.08	0.03	0.11
k_{CEP} mean origin of electrons	0.9922	-	0.01	0.9968				
k_{an} axial non-uniformity	0.9964	-	0.07	1.0005	-	0.08	-	0.12
k_{rn} radial non-uniformity	1.0016	0.01	0.02	1.0000	0.01	0.02	0.01	0.03
Measurement of $I/v\rho$								
v volume / cm^3	6.8028	0.01	0.03	1.0267	0.01	0.03	0.01	0.04
I ionization current		0.01	0.02		0.01	0.04	0.01	0.04
Uncertainty								
quadratic summation		0.03	0.17		0.03	0.18	0.04	0.18
combined uncertainty		0.17			0.19		0.19	

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

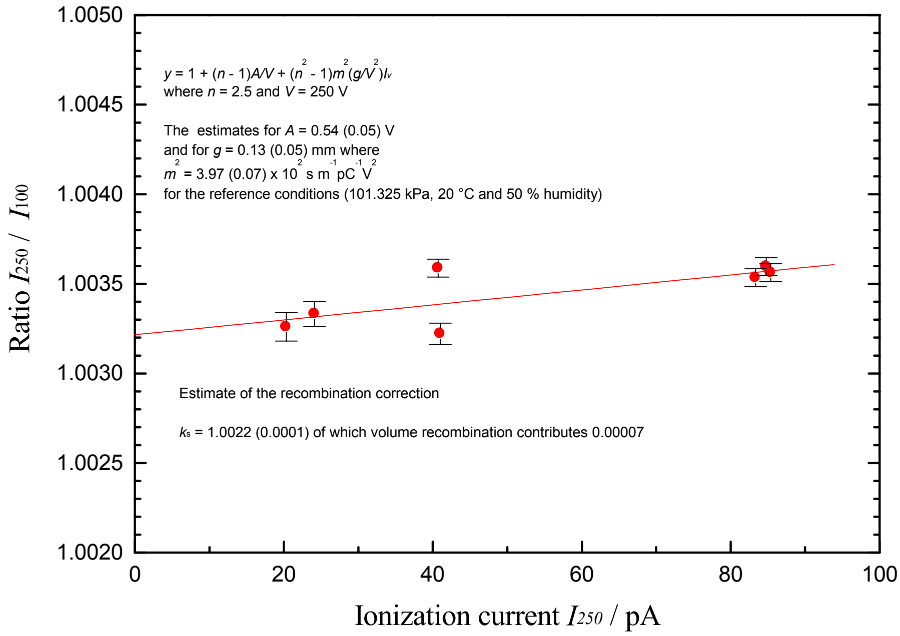
(2) At 101 325 Pa and 273.15 K.

The correction factors for the NCM standard were determined at the NCM. The results of some measurements at the BIPM of the effects of ion recombination were also used.

The ratio of the ionization currents obtained for the NCM standard with applied voltages of 250 V and 100 V (using both polarities) was measured for four different air kerma rates in the

BIPM ^{60}Co beam. A linear fit to these data identified an ion recombination effect at 250V, the same as that previously determined at the BIPM for this chamber type. Consequently, the correction factor k_s of 1.0022 (0.0001) for ion recombination at 250 V and 83 pA was applied to the NCM standard in the BIPM beam. Figure 1 shows the experimental determination. This correction is effectively for initial recombination and diffusion combined as the volume recombination is not significant at the BIPM air kerma rate. Consequently, a similar correction would be expected to apply at the NCM as a larger correction would only be appropriate for an air kerma rate in excess of 5 mGy s^{-1}.

Figure 1 Recombination correction measurement for NCM primary standard



The determination of the correction factor for the attenuation and scatter in the walls of the ionization chamber has been made using the Monte Carlo code EGS4 plus FOTELP. The value obtained for these corrections was $k_{att}k_{sc}$ = 1.0237 (0.0008). This value is significantly larger that that obtained by the experimental extrapolation method at the NCM (1.0163) which is as expected. The calculated value agrees with that computed by the SZMDM using the same MC code for a similar primary standard (1.0231) [4]. Indeed the value of $k_{att}k_{sc}k_{CEP}$ (1.0204, s = 0.0009) calculated by the NCM agrees within the uncertainties with the value of 1.0211 (s = 0.0001) calculated for a similar type of chamber at the NRC, Canada [5] using EGSnrc. The OMH has also calculated (using EGSnrc) a value of 1.0212 (s = 0.0003) for their primary standard of the same type [6], compared with the value of 1.0219 (s = 0.0001) calculated at the NRC for this OMH chamber. An equivalent preliminary calculation at the BIPM using the MC code PENELOPE yielded a result for $k_{att}k_{sc}k_{CEP}$ of 1.0208 (s = 0.0002) for the NCM chamber.

The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the section of the NCM standard had been estimated previously with a numerical value of 1.0003 [7]. However, the calculations for the non-uniformity effects made by the NCM include a component of the radial non-uniformity in their beam. Therefore, a value of unity has been used in the BIPM beam.

The result of the comparison $R_K = \dot{K}_{\text{NCM}} / \dot{K}_{\text{BIPM}}$ is given in Table 3. Five independent measurements were made over sixteen days with the NCM standard. The relative combined uncertainty associated with these measurements is 2×10^{-4}. The $\dot{K}_{\text{BIPM}}$ value of 2.3913 (s = 0.0002) mGy·s^{-1} is the mean of measurements performed over a period of several months before and after the present comparison. The ratio of the values of the air kerma rate determined by the NCM and the BIPM standards is 1.0117 with a combined standard uncertainty u_c of 0.0019. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and the NCM determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel when evaluating the uncertainty of R_K, as shown in Table 2.

Table 3. Results of the NCM-BIPM comparison of primary standards of air kerma

I_{NCM} / pA	u_I / pA	$\dot{K}_{\text{NCM}}$ (1) / mGy·s^{-1}	R_K	u_c
92.451	0.018	2.4193	1.0117	0.0019

(1) The $\dot{K}$ values refer to an evacuated path length between source and standard and are given at the reference date of 2002-01-01, 0h UT where the half life of ^{60}Co is taken as 1 925.5 days (u = 0.5 days) [8].

6. Discussion

The calibration of an NCM secondary standard (type N1001 serial number 7814) made at each institute was used to confirm the calibration capability under the reference conditions (20 °C, 101.325 kPa and 50 % humidity). The calibration coefficient at the BIPM is compared with that obtained at the NCM in Table 4. The relative uncertainties are given in Table 5.

Table 4. Calibration comparison using the NCM transfer chamber

Laboratory	$\dot{K}_{\text{lab}}$ (1) / µGy·s^{-1}	I_{lab} (1) / pA	N_K / Gy·µC^{-1}	100 u_c	R'_K	100 u_c
NCM	318.5	212.5	1.499	0.34	0.996_0	0.35
BIPM	2391	1589	1.505	0.18		

In comparing the indirect result in Table 4 and the R_K value in Table 3 (that have a difference of 1.57 %), the high level of correlation that exists between these two results should be considered. If the obvious correlations are removed, the standard uncertainty of the calibration comparison reduces to the uncertainties related to differences in the beams at the NCM and the BIPM, the positioning of the transfer chamber and the measurement of the ionization current, a total combined relative uncertainty of 3×10^{-3}. There is some evidence that a larger uncertainty should be attributed to the reproducibility of a calibration at the NCM rather than that indicated in Table 5.

The results of comparisons at the BIPM with standards of the same type as that of the NCM are given in Table 6 and shown in Figure 2 (in green). There appear to be two groups of results, each of which is self-consistent within the estimated uncertainties, but different from each other by up to 1 %. The group with the higher values its wall correction factors evaluated using MC calculations. However, some of the other NMIs with standards of different shapes have also used MC calculations but their results are consistent with the lower group's values.

Table 5. Estimated relative standard uncertainties in the calibration factor, N_K, of the transfer chamber

	Uncertainty in $N_{K_{\mathrm{NCM}}}$		Uncertainty in $N_{K_{\mathrm{BIPM}}}$		Uncertainty in R'_K	
Relative standard uncertainty in the measurement of	$100\, s_i$	$100\, u_i$	$100\, s_i$	$100\, u_i$	$100\, s_i$	$100\, u_i$
Air kerma rate (see Table 2)	0.03	0.18	0.03	0.17	0.04	0.19
Ionization current of transfer chamber	0.04	0.12	0.03	-	0.05	0.12
Chamber position / reproducibility	0.06	0.25	0.01	0.01	0.06	0.25
Beam spectra difference	-	-	-	-	-	0.03
Humidity difference	-	-	-	-	-	0.05
Relative standard uncertainty						
quadratic summation	0.08	0.33	0.04	0.17	0.09	0.34
combined uncertainty	0.34		0.18		0.35	

Table 6. Comparison of the ND1005-type standards belonging to national laboratories with the BIPM standard

Laboratory and year	$\dot{K}_{\mathrm{Lab}} / \dot{K}_{\mathrm{BIPM}}$ ^{60}Co	100 × relative standard uncertainty u_c
UDZ 1992 [9]	0.9992	0.23
OMH 1972 [10]	1.0039	0.58
1986 [11]	1.0009	0.25
1994 [12] [6]	1.0109	0.25
BEV 1980, 1989 [13,14]	1.0014	0.3
1994 [15]	1.0040	0.22
1995 [16]	1.0029	0.25
LNMRI 1986 [17]	1.0010	0.26
1995 [18]	1.0004	0.23
GUM 1996 [19]	0.9987	0.28
ENEA 1998 [20]*	1.0103	0.28
SMU 2000 [21]*	1.0033	0.27
SZMDM 2001 [5]	1.0079	0.18
NCM 2002 (this work)	1.0117	0.19

* Provisional results

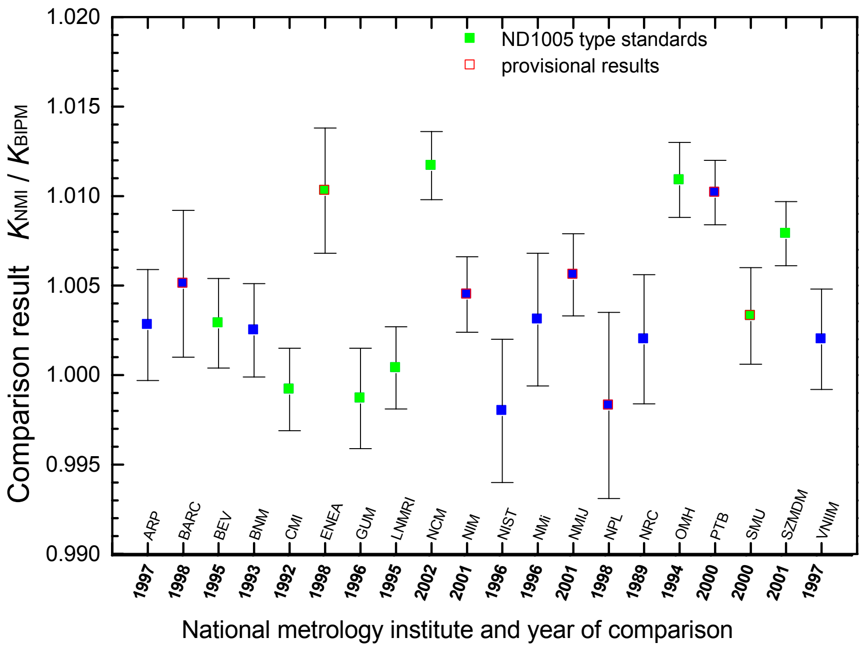
Currently, all the NMIs that have previously used experimental extrapolation methods to determine wall correction factors are checking their factors using various Monte Carlo codes. It is anticipated that it will be a further twelve months before all the NMIs are ready for their results to be entered into the BIPM key comparison database (KCDB). In the meantime, the BIPM is also reviewing its experimental and calculated results for the wall corrections of its primary standard.

7. Conclusion

The comparison result for the NCM standard for air kerma in ^{60}Co gamma radiation is R_K = 1.0117 (0.0019).

The results for all the NMIs are shown in Figure 2 where some differences between the NMIs can be attributed to the method of correction for the wall effect. All the NMIs and the BIPM are currently re-evaluating their cavity chamber wall correction factors and this may well change the overall picture for the comparison results in the future. Once agreed, these data will be used in the Appendix B of the KCDB for the BIPM key comparison of air kerma in ^{60}Co gamma radiation.

Figure 2 International air kerma comparison results



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