Rapport BIPM–02/01

Bureau International des Poids et Mesures

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January 2002

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Abstract
A comparison of the standards of air kerma of the Savezni Zavod za Mere i Dragocene Metale (SZMDM) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. It shows that the SZMDM and BIPM standards differ by 0.79 % with a relative standard uncertainty of 1.8×10^{-3}. This result is compatible with the previous comparison of 1991 when the changes in the corrections for the wall effect and for axial non-uniformity of the SZMDM standard are taken into account.

1. Introduction

A comparison of the standards of air kerma of the Savezni Zavod za Mere i Dragocene Metale, (SZMDM), Belgrade, Yugoslavia, and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co radiation. The SZMDM standard of air kerma is a graphite cavity ionization chamber constructed at the Orszagos Mérésügyi Hivatal (OMH), Budapest, Hungary (type ND1005/A, serial number 8304), details of which are given in section 3 of this report. The BIPM air kerma standard is described in [1]. The standards of the SZMDM and the BIPM were last compared in 1991 [2] and the present comparison took place at the BIPM in November 2001.

2. Conditions of measurement

The air kerma is determined at the BIPM under the following conditions [3]:
- 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 SZMDM primary standard are given in Table 1.

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

Standard Type		Primary ND1005/A - 8304 Nominal values
Chamber	Outer height / mm Outer diameter / mm Inner height / mm Inner diameter / mm Wall thickness / mm	19 19 11 11 4
Electrode	Diameter / mm Height / mm	2 10
Volume	Air cavity / cm^3 relative uncertainty / cm^3	1.0126 0.0003
Wall	Material Density / $g \cdot cm^{-3}$ Impurity fraction	ultrapure graphite 1.75 $< 1.5 \times 10^{-4}$
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 [4], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties [3]. Also shown are the relative uncertainties in the ratio $R_K = \dot{K}_{\mathrm{SZMDM}} / \dot{K}_{\mathrm{BIPM}}$.

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

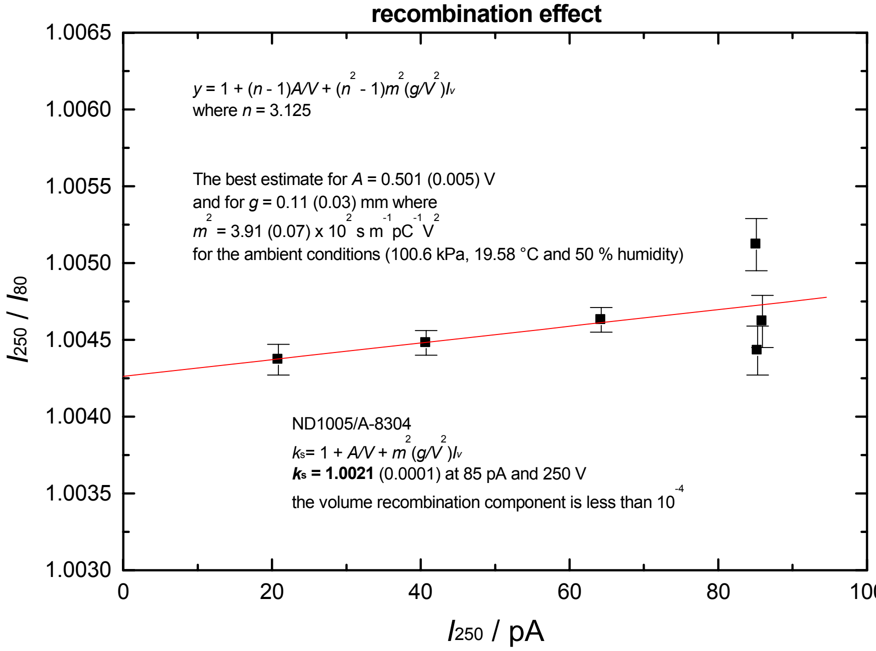
	BIPM values	100 × Relative [(1)] uncertainty		SZMDM values	100 × Relative [(1)] uncertainty		100 × Relative [(1)] uncertainty of R_K	
		s_i	u_i		s_i	u_i	s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(2)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05	0.9985	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0010	-	0.11	1.0009	-	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	1.0021	0.01	0.03	0.01	0.03
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	1.0000	0.01	-	0.9998	0.01	0.01	0.01	0.01
k_{att} wall attenuation	1.0398	0.01	0.04	1.0231				
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	0.9966				
k_{an} axial non-uniformity	0.9964	-	0.07	0.9998	-	0.10	-	0.12
k_{rn} radial non-uniformity	1.0016	0.01	0.02	1.0003	0.01	0.02	0.01	0.03
Measurement of *I*/vρ								
v volume / cm^3	6.8028	0.01	0.03	1.0126	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		0.04	0.19	0.04	0.18
combined uncertainty		0.17			0.19		0.18	

(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 SZMDM standard were determined at the SZMDM. 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 SZMDM standard with applied voltages of 250 V and 80 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 identical to that previously determined at the BIPM for this chamber type. Consequently, the correction factor k_s of 1.0021 (0.0001) for ion recombination at 250 V and 85 pA was applied to the SZMDM 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 SZMDM as a larger correction would only be appropriate for an air kerma rate in excess of 5 mGy s^{-1}.

Figure 1 SZMDM primary standard for Co-60 air kerma recombination effect



The procedure of adding graphite to the walls of the cavity chamber has been used in the past to determine the attenuation in the walls and the scatter correction at the SZMDM [2]. The value thus obtained of $k_{att}k_{sc}$ = 1.0173 (0.0010) for this standard agrees with that measured by the SZMDM method at the BIPM for a transfer standard of the same shape and size. Combined with the value k_{CEP} = 0.9966, this gives the total wall correction 1.0138. However, improvements to replace the extrapolation method have been made recently using the Monte Carlo code EGS4 plus the FOTELP extension developed at the Technical Institute in Belgrade according to the Los Alamos design. The result of these calculations produces a value for the total wall correction ($k_{att}k_{sc}k_{CEP}$) of 1.0196 with a statistical uncertainty s = 0.0003. This value is slightly lower than the value of 1.0211 (s = 0.0001) calculated for the same 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 to the value of 1.0219 (s = 0.0001) calculated at the NRC for this OMH chamber.

The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the section of the SZMDM standard had been estimated previously [7]; its numerical value is 1.0003. The correction factor for axial non-uniformity was taken as 0.997 (0.001) in 1991 and since 1996 has been taken as 0.9998 (0.0007) for this chamber type.

The result of the comparison $R_K = \dot{K}_{\mathrm{SZMDM}} / \dot{K}_{\mathrm{BIPM}}$ is given in Table 3. Five independent measurements were made over eight days using the SZMDM standard. The relative combined uncertainty associated with these measurements is 4×10^{-4}. The $\dot{K}_{\mathrm{BIPM}}$ value of 2.7293 (s = 0.0003) $\mathrm{mGy \cdot s^{-1}}$ is the mean of measurements that were 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 SZMDM and the BIPM standards is 1.0079 with a combined standard uncertainty, u_c of 0.0018. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and the SZMDM 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 SZMDM-BIPM comparison of primary standards of air kerma

I_{SZMDM} / pA	u_I / pA	$\dot{K}_{\mathrm{SZMDM}}$ (1) / $\mathrm{mGy \cdot s^{-1}}$	R_K	u_c
103.826	0.037	2.7510	1.0079	0.0018

(1) The $\dot{K}$ values refer to an evacuated path length between source and standard and are given at the reference date of 2001-01-01, 0h UT where the half life of ^{60}Co is taken as 1 925.5 days (u = 0.5 days) [8].

6. Discussion

The standards of the SZMDM and the BIPM were last compared in 1991 [2]. At that time the experimental method was used to determine the correction factor for the wall effect. The comparison result was 0.9982 (0.0019). In comparing this with the present comparison result of 1.0079 (0.0018) one must take into account changes in the values used for the wall effect and the axial non-uniformity correction for the SZMDM standard. The total wall correction factor $k_{att}k_{sc}k_{CEP}$ (measured) is 1.0138 and by calculation is 1.0196, a ratio of 1.0057 (0.0009). The axial non-uniformity correction has changed from 0.997 to 0.9998, a ratio of 1.0028.

The SZMDM has recently (1999) made a comparison directly against the OMH primary standard, at the OMH [9]. This direct bilateral comparison result is $R_{\mathrm{SZMDM / OMH}}$ = 0.9999 (0.0025), with both laboratories using the experimental value for the wall correction. Comparing the previous comparisons of 1991 and 1994 that the two NMIs made with the BIPM gives an indirect result for $R_{\mathrm{SZMDM / OMH}}$ of 1.0007, which agrees with the 1999 result within the uncertainties. The OMH has recently declared a new value for its air kerma standard [6]. Using this value to correct the 1994 OMH / BIPM comparison and taking the result of the present SZMDM / BIPM comparison, the new ratio of the indirect comparison $R_{\mathrm{SZMDM / OMH}}$ through the BIPM is 0.9970 (0.0027). The difference (1.0037) between this value and that of the previous indirect comparison can be attributed to the differences in the newly applied correction factors, although this value also agrees with the 1999 direct bilateral comparison within the overall uncertainties.

The results of comparisons at the BIPM with standards of the same type as that of the SZMDM are given in Table 4 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 has re-evaluated its wall correction factor using MC calculations. However, some of the other NMIs with standards of different shapes have also used MC calculations but their results match the lower group.

It is anticipated that it will be a further thirteen 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.

Table 4. Comparison of the ND1005-type standards belonging to national laboratories with the BIPM standard

Laboratory and year	$\dot{K}_{\text{Lab}} / \dot{K}_{\text{BIPM}}$ ^{60}Co	100 × Relative standard uncertainty u_c
UDZ 1992 [10]	0.9992	0.2
OMH 1972 [11]	1.0039	0.5
1986 [12]	1.0009	0.3
1994 [13] [6]	1.0109	0.2
BEV 1980, 1989 [14,15]	1.0014	0.3
1994 [16]	1.0040	0.2
1995 [17]	1.0029	0.3
LNMRI 1986 [18]	1.0010	0.3
1995 [19]	1.0004	0.2
GUM 1996 [20]	0.9987	0.3
ENEA 1998 [21]*	1.0103	0.3
SMU 2000 [22]*	1.0033	0.3
SZMDM [this work]	1.0079	0.2

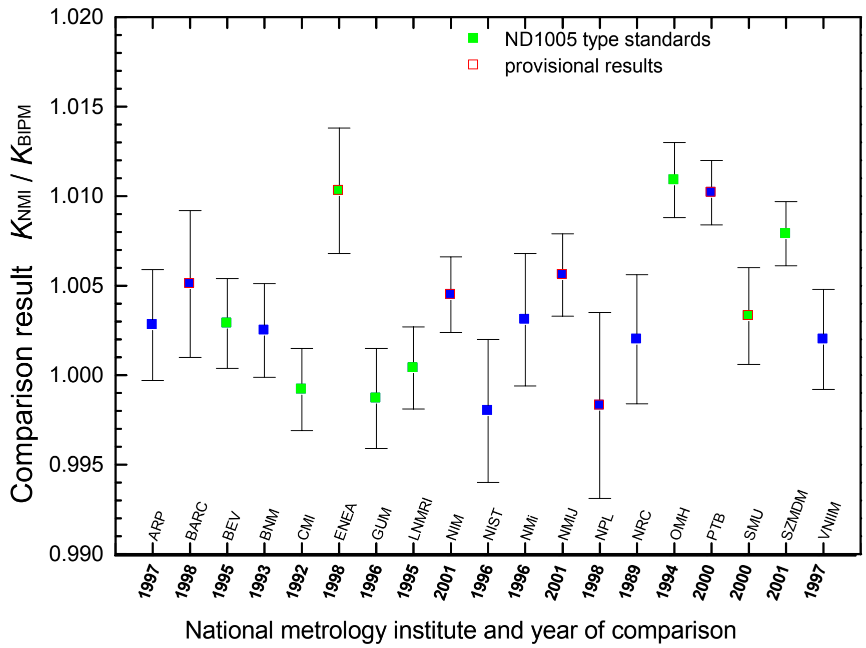
* Provisional results

7. Conclusion

The comparison result for the SZMDM standard for air kerma in ^{60}Co gamma radiation is R_K = 1.0079 (0.0018). The result is in agreement with the previous comparison when the new method of calculating the correction factors (a difference of 1.0057 for the wall effect and a difference of 1.0028 for the axial non-uniformity) for the SZMDM standard are taken into account.

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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January 2002