Comparisons of the standards of air kerma of the VNIIM and the BIPM for ^{137}Cs and ^{60}Co γ rays

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Abstract

Comparisons of the standards of air kerma of the D.I. Mendeleyev Institute for Metrology (VNIIM) and of the Bureau International des Poids et Mesures (BIPM) have been carried out for the first time in ^{137}Cs and ^{60}Co radiation beams. The results show that the VNIIM and the BIPM standards for air kerma agree very well to within 0.2 % for ^{60}Co and to within 0.4 % for ^{137}Cs.

1. Introduction

For the first time, comparisons of the standards of air kerma held by the D.I. Mendeleyev Institute for Metrology (VNIIM), St. Petersburg, Russian Federation and of the Bureau International des Poids et Mesures (BIPM), have been carried out in ^{137}Cs and ^{60}Co radiation beams. The VNIIM standards take the form of two cylindrical graphite cavity ionization chambers of volumes 1 cm^3 and 30 cm^3 and were constructed at the VNIIM (type C1 and C30): they are described in Section 2 and compared with an earlier VNIIM standard in [1]. At the BIPM, the standards are graphite cavity ionization chambers of pancake form as described in [2,3].

The comparisons were made using a VNIIM transfer chamber made by the Physicalisch-Technische Werkstatten in Germany and took place at the BIPM in April 1997.

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2. Determination of the air kerma

The air kerma rate is determined from

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

where

I/m is the mass 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,

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

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

$\bar{s}_{\text{c,a}}$ 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 VNIIM standards of air kerma are listed in Table 1. The large volume standard (C30) is used because the air kerma rate of the ^{60}Co beam at the VNIIM is small (see Table 5).

Table 1. Characteristics of the VNIIM standards of air kerma

Chamber type		C1	C30
Shape		cylinder	cylinder
Dimensions	Inner height / mm	11.06	37.00
	Inner diameter / mm	11.07	32.10
Electrode	Diameter / mm	1.98	2.00
	Height / mm	7.95	25.9
Volume	Air cavity / cm^3	1.040	29.86
Wall	Wall thickness / mm	4	2 + 2 (cap)
	Material	ultrapure graphite	ultrapure graphite
	Density / g·cm^{-3}	1.634	1.634
Insulator		polyethylene	PPFE (teflon)
Applied voltage	Both polarities	250 V	400 V

The two standards agree with each other to within 0.08 % in the ^{137}Cs and to within 0.11 % in the ^{60}Co radiation beams at the VNIIM.

The values of the physical constants [4], the correction factors used in (1) and associated uncertainties for ^{137}Cs radiation are shown in Table 2 for both the VNIIM and the BIPM standards.

Table 2. Physical constants, correction factors and associated uncertainties used in the determination of air kerma in ^{137}Cs radiation

	BIPM values	BIPM relative uncertainty[1] 100 s_i	100 u_i	VNIIM values	VNIIM relative uncertainty[1] 100 s_i	100 u_i	$R_{\dot{K}}$ relative uncertainty[1] 100 s_i	100 u_i
Physical constants								
dry air density / $kg \cdot m^{-3}$ [2]	1.293 0	-	0.01	1.293 0	-	0.01	-	-
$(\bar{\mu}_{en}/\rho)_{a,c}$	0.999 0	-	0.05	0.999 0	-	0.05	-	-
$\bar{s}_{c,a}$	1.010 4	-	0.30	1.010 1	-	0.30	-	-
W/e / $(J \cdot C^{-1})$	33.97	-	0.15	33.97	-	0.15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0.001 2	-	0.02	0.001 2	-	0.02	-	-
Correction factors								
k_s recombination losses	1.001 4	0.01	0.01	1.001 5[3]	0.03	0.03	0.03	0.03[3]
				1.002 3[4]	0.04	0.03	0.04	0.03[4]
k_h humidity	0.997 0	-	0.03	0.997 1	-	0.03	-	-
k_{st} stem scattering	0.999 8	0.01	-	0.997 0[3]	0.02	0.02	0.02	0.02[3]
				0.999 7[4]	0.02	0.02	0.02	0.02[4]
k_{at} wall attenuation	1.054 0	0.01	0.04					
k_{sc} wall scattering	0.953 5	0.01	0.07	1.024 0[3,5]	0.03	0.15	0.03	0.17[3,5]
				1.022 0[4,5]	0.03	0.15	0.03	0.17[4,5]
k_{CEP} mean origin of electrons	0.997 2	-	0.01	0.998 0[6]	-	0.10	-	0.10
k_{an} axial non-uniformity	0.998 1	-	0.07	0.999 8[3]	-	0.05	-	0.09[3]
				0.999 6[4]	-	0.05	-	0.09[4]
k_{rn} radial non-uniformity	1.007 0	0.01	0.03	1.000 4[3]	0.02	0.05	0.02	0.06[3]
				1.000 8[4]	0.02	0.05	0.02	0.06[4]
Measurement of $I/V\rho$								
V volume / cm^3	6.834 4	0.01	0.10	1.040[3]	-	0.12	0.01	0.16[3]
				29.86[4]	-	0.10	0.01	0.14[4]
I ionization current / pA		0.03	0.02		0.03	0.03	0.04	0.04
Relative standard uncertainty								
quadratic summation		0.04	0.37		0.06	0.41[3]	0.07	0.28[3]
					0.06	0.41[4]	0.07	0.27[4]
combined uncertainty		0.38			0.41[3]		0.29[3]	
					0.41[4]		0.28[4]	

(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.
(3) Values for the C1 standard.
(4) Values for the C30 standard.
(5) The wall attenuation and scattering corrections are combined.
(6) Determined using reference [5].

The corresponding values for ^{60}Co radiation are shown in Table 3.

Table 3. Physical constants, correction factors and associated uncertainties

used in the determination of air kerma in ^{60}Co radiation

	BIPM values	BIPM relative uncertainty[1]		VNIIM values	VNIIM relative uncertainty[1]		$R_{\dot{K}}$ relative uncertainty[1]	
		100 s_i	100 u_i		100 s_i	100 u_i	100 s_i	100 u_i
Physical constants								
dry air density / kg·m^{-3} [2]	1.293 0	-	0.01	1.293 0	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.998 5	-	0.05	0.998 5	-	0.05	-	-
$\bar{s}_{c,a}$	1.001 0	-	0.30	1.001 0	-	0.30	-	-
W/e / (J·C^{-1})	33.97	-	0.15	33.97	-	0.15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0.003 2	-	0.02	0.003 2	-	0.02	-	-
Correction factors								
k_s recombination losses	1.001 6	0.01	0.01	1.002 3[3]	0.03	0.03	0.03	0.03[3]
				1.008 7[4]	0.04	0.03	0.04	0.03[4]
k_h humidity	0.997 0	-	0.03	0.997 1	-	0.03	-	-
k_{st} stem scattering	1.000 0	0.01	-	0.999 4[3]	0.02	0.02	0.02	0.02[3]
				1.000 0[4]	0.02	0.02	0.02	0.02[4]
k_{at} wall attenuation	1.040 2	0.01	0.04					
k_{sc} wall scattering	0.971 6	0.01	0.07	1.012[3,5]	0.03	0.15	0.03	0.17[3,5]
				1.019[4,5]	0.03	0.15	0.03	0.17[4,5]
k_{CEP} mean origin	0.992 2	-	0.01	0.997 0[3,6]	-	0.10	-	0.10[3]
of electrons				0.996 5[4,6]	-	0.10	-	0.10[4]
k_{an} axial non-uniformity	0.996 4	-	0.07	0.999 8[3]	-	0.05	-	0.09[3]
				0.999 6[4]	-	0.05	-	0.09[4]
k_{rn} radial non-uniformity	1.001 6	0.01	0.02	1.000 4[3]	0.02	0.05	0.02	0.05[3]
				1.000 8[4]	0.02	0.05	0.02	0.05[4]
Measurement of *I*/*Vρ*								
V volume / cm^3	6.811 6	0.01	0.03	1.040[3]	-	0.12	0.01	0.12[3]
				29.86[4]	-	0.10	0.01	0.10[4]
I ionization current / pA		0.01	0.02		0.03	0.03	0.03	0.04
Relative standard uncertainty								
quadratic summation		0.02	0.36		0.06	0.41[3]	0.06	0.26[3]
					0.06	0.41[4]	0.07	0.25[4]
combined uncertainty		0.36			0.41[3]		0.27[3]	
					0.41[4]		0.26[4]	

(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.
(3) Values for the C1 standard.
(4) Values for the C30 standard.
(5) The wall attenuation and scattering corrections are combined.
(6) Determined using reference [5].

The Tables also list the relative uncertainties of the kerma ratio expressed as $R_{\dot{K}} = \dot{K}_{\mathrm{Lab}} / \dot{K}_{\mathrm{BIPM}}$. As the physical constants are derived from the same basic data in both laboratories, the relative uncertainty in $R_{\dot{K}}$ is due only to the relative uncertainties in the correction factors, the volumes of the standards and the ionization currents measured.

3. Air kerma calibration factor

The air kerma calibration factor N_K for a transfer chamber measured at a given laboratory is given by

$$N_{K\,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \quad , \qquad (2)$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate and I_{lab} is the ionization current of the transfer chamber. The experimental method for calibrations at the VNIIM is outlined in Section 3.1 and that for the BIPM in [6]. The main characteristics of the VNIIM transfer chamber are given in Table 4. This transfer chamber was calibrated at the VNIIM for the first time in March 1997 and again during the six months following the comparison. The calibrations are consistent to within about 0.1 %.

Table 4. Characteristics of the VNIIM transfer chamber

Transfer chamber	M30001	Serial Number 0109
Shape	cylinder	
Dimensions	Inner height / mm	23.0
	Inner diameter / mm	6.1
	Wall thickness / mm	0.425
Electrode	Diameter / mm	1.0
	Height / mm	21.2
Volume	Air cavity / cm^3	0.6
Wall	Material	PMMA with graphite
	Density / $g \cdot cm^{-2}$	1.18
Build-up cap	Material and density	PMMA and 1.18 $g \cdot cm^{-3}$
	Thickness / mm	4.55
Applied voltage	Positive polarity	350 V

3.1 Conditions of measurement at the VNIIM and the BIPM

At the VNIIM, two sources of ^{137}Cs and one of ^{60}Co are used. Their parameters are compared with those of the BIPM in Table 5. In other respects the conditions of measurement at the two laboratories were similar throughout the comparison.

- *Position of the transfer chamber*. The axis of the transfer chamber was located in the centre of the field at the reference plane at 1 m or 0.8 m from the source at the VNIIM and at 1 m at the BIPM. The photon fluence rate at the edge of the field is 50 % of the photon fluence rate at the centre. The position of the chamber was verified without the build-up cap, the black line on the stem being placed so as to face the source. These conditions result in an uncertainty in positioning of 0.1 mm at the VNIIM and 0.04 mm at the BIPM.

Table 5. Source characteristics of the VNIIM and the BIPM

Source	**Cs-137**			**Co-60**	
Location	**VNIIM**		**BIPM**	**VNIIM**	**BIPM**
Nominal activity / GBq	140	1 200	1 000	32	50 000
Reference distance / m	1	0.8	1	1	1
Beam diameter or size / cm	20	11 x 11	11	20	10 x 10
Kerma rate / μGy·s^{-1}	3	42	21	2.7	4 600

- *Build-up cap.* The transfer chamber was supplied with a build-up cap for use in these radiation beams. This was screwed into place for all measurements of ionization current.

- *Humidity, temperature and pressure*. During calibration, the relative humidity was in the range 40 % to 60 % at the VNIIM. At the BIPM it was 20 % to 30 % for the measurement in ^{137}Cs and 45 % to 50 % for the measurement in ^{60}Co. No correction for humidity was applied to the current measured by the chamber. The air temperature was between 18 °C and 22 °C at the VNIIM; at the BIPM it was about 20 °C in the ^{137}Cs beam and 21 °C in the ^{60}Co beam. During each series of measurements, the air temperature was stable to better than 0.05 °C at the VNIIM and to 0.03 °C at the BIPM. The ambient air pressure varied between 95 kPa and 105 kPa at the VNIIM and between 100 kPa and 102 kPa at the BIPM. The measured ionization current was normalized to 293.15 K and 101.325 kPa.

- *Collecting voltage*. A collecting voltage of 350 V (positive polarity) was applied to the chamber in each laboratory

- *Measurement of charge.* The charge Q collected by the chamber was measured using the BIPM or the VNIIM electrometer as appropriate. The VNIIM standard electrometer, type B7-45 of Russian manufacture, was compared at the VNIIM with a UNIDOS (PTW-Freiburg) measuring system. A systematic charge difference of almost 0.5 % was measured. Subsequently all the transfer chamber measurements were made at the VNIIM using the standard electrometer; earlier measurements were corrected to allow for this difference.

- *Reproducibility of measurements*. The short-term relative standard deviation of the mean ionization current, measured with the transfer chamber, was estimated at the VNIIM to be 0.03 % in the 1200 GBq ^{137}Cs beam, 0.09 % in the 140 GBq ^{137}Cs beam and 0.1 % in the ^{60}Co beam (7 series of 10 measurements). At the BIPM the corresponding values are 0.03 % in the ^{137}Cs beam and 0.02 % in the ^{60}Co beam (4 series of 30 measurements).

3.2 Other Factors

- *Recombination.* No correction was applied for incomplete ion collection: the volume recombination is negligible for this type of chamber for air kerma rates near 5 mGy·s^{-1} and the initial recombination is the same in the two laboratories.

- *Leakage current.* The measured current was corrected for the leakage current of the transfer chamber. At the BIPM this was less than 0.01 % for ^{60}Co and up to 0.1 % for ^{137}Cs for which the air kerma rate is smaller by a factor of 100 than that in the ^{60}Co beam.

- *Stem scattering effect.* No correction for the stem scattering effect was applied at either laboratory.

- *Radial non-uniformity of the beam*. No correction for radial non-uniformity over the section of the transfer chamber was made to the results obtained at either laboratory. (In the BIPM beams, this effect is less than 0.01 % for this type of chamber.)

4. Results of the comparison

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

$$R'_K = N_{K_{\mathrm{VNIIM}}} / N_{K_{\mathrm{BIPM}}} \quad , \qquad (3)$$

where N_K is the calibration factor of the transfer chamber determined at each laboratory. The relevant $\dot{K}$, I and N_K values obtained are shown in Table 6 together with R'_K and its relative combined standard uncertainty u_c.

The chamber was calibrated at the BIPM in April 1997. At the VNIIM it was calibrated in March 1997 before the comparison and in May to October 1997 after the comparison. The values quoted for the VNIIM are the mean of the results obtained before and after the comparison.

Table 6. Results of the air kerma comparisons using the VNIIM transfer chamber

Source	Laboratory	$\dot{K}_{lab}$ (1) / µGy·s^{-1}	I_{lab} (1) / pA	N_K / Gy·µC^{-1}	100 u_c	R'_K	100 u_c
^{137}Cs (1)	VNIIM	2.916	0.059 34	49.14 (3)	0.42	0.996 1 (4)	0.31
	VNIIM	41.76	0.849 1	49.18 (3)			
	BIPM	21.175	0.429 1	49.35	0.37		
^{60}Co (2)	VNIIM	2.644	0.054 08	48.89 (3)	0.43	1.002 0	0.28
	BIPM	4618.1	94.657	48.79	0.36		

(1) The half life of ^{137}Cs is taken as (11 050 d, u = 40 d) [7]. The BIPM values are referenced to 1997-01-01, 0h UT.
(2) The half life of ^{60}Co is taken as (1 925,5 d, u = 0,5 d) [8]. The BIPM values are referenced to 1997-01-01, 0h UT.
(3) The result is the mean of the calibration factors measured at the VNIIM before and after the measurements at the BIPM.
(4) The result uses the mean of the calibration factors in both ^{137}Cs beams at the VNIIM.

Contributions to the relative standard uncertainty in N_K and in the comparison result R'_K are shown in Table 7a for ^{137}Cs and Table 7b for ^{60}Co.

Table 7a. Estimated relative standard uncertainties in the calibration factor, N_K, of the transfer chamber and the comparison result, R'_K in ^{137}Cs

	Uncertainty in $N_{K_{VNIIM}}$		Uncertainty in $N_{K_{BIPM}}$		Uncertainty in R'_K (1)	
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	0.06	0.41	0.04	0.37	0.07	0.28
Ionization current of transfer chamber	0.09 (2)	-	0.03	-	0.09	-
Chamber position	0.02	0.02	0.01	0.02	0.02	0.03
Beam spectra difference	-	-	-	-	-	0.03
Humidity difference	-	-	-	-	-	0.03
Relative standard uncertainty						
quadratic summation	0.11	0.41	0.05	0.37	0.12	0.28
combined uncertainty	0.42		0.37		0.31	

(1) The uncertainty for the ratio of air kerma rate is taken from Table 2.
(2) This value relates to the smaller source. Using the larger activity source reduces this uncertainty value to 0.03 %.

Table 7b. Estimated relative standard uncertainties in the calibration factor, N_K, of the transfer chamber and the comparison result, R'_K in ^{60}Co

	Uncertainty in $N_{K_{\text{VNIIM}}}$		Uncertainty in $N_{K_{\text{BIPM}}}$		Uncertainty in R'_K (3)	
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	0.06	0.41	0.02	0.36	0.07	0.25
Ionization current of transfer chamber	0.10	-	0.02	-	0.10	-
Chamber position	0.02	0.02	0.01	0.02	0.02	0.03
Beam spectra difference	-	-	-	-	-	0.03
Relative standard uncertainty						
quadratic summation	0.12	0.41	0.03	0.36	0.12	0.25
combined uncertainty	0.43		0.36		0.28	

(3) The uncertainty for the ratio of air kerma rate is taken from Table 3.

5. Conclusion

The same VNIIM standards are used for air kerma determinations in both ^{137}Cs and ^{60}Co radiation beams. Two standards are used and these agree to 0.08 % and 0.11 % respectively in the two VNIIM radiation beams. For the comparisons with the BIPM standards, a single VNIIM transfer standard, of small volume was used in both radiation beams. The result for the ^{137}Cs comparison, R_K (^{137}Cs) = 0.996 1, is compatible with the standard uncertainty for the comparison while the result for ^{60}Co radiation, R_K (^{60}Co) = 1.002 0, is in good agreement and lies within the uncertainty.

Four other national laboratories have made ^{137}Cs comparisons with the BIPM standard: the results are shown in Table 8 together with those for ^{60}Co comparisons with the same laboratories.

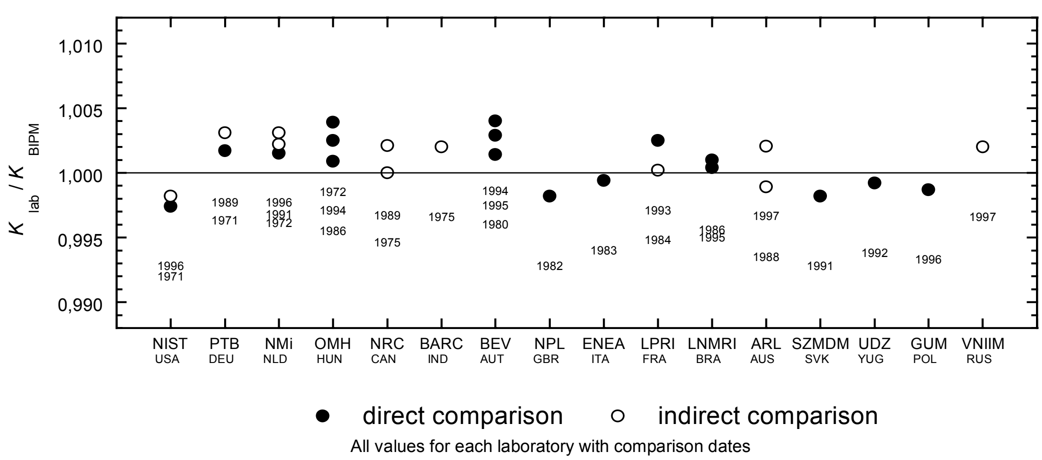
Table 8. Comparison of national laboratory results for air kerma

Laboratory	$R_K = K_{\text{Lab}} / K_{\text{BIPM}}$			
	^{137}Cs		^{60}Co	
	R_K	100 σ_{RK}	R_K	100 σ_{RK}
BEV [9]	0.994 5	0.28	1.002 9	0.25
OMH [10]	0.995 4	0.30	1.002 5	0.24
NIST [11, 12]	1.001 7	0.42	0.998 9	0.40
BNM-LPRI [13, 14]	1.001 9	0.30	1.002 5	0.26
VNIIM	0.996 1	0.31	1.002 0	0.28

Table 8 shows that the spread of the results for ^{137}Cs is almost twice as large as that for ^{60}Co. This suggests that some correction factors related to air kerma measurements in a ^{137}Cs beam are difficult to evaluate. Of particular importance is the determination of the correction for attenuation and scattering in the chamber wall. When this correction is obtained by extrapolation from measurements made with a wall thickness far in excess of the maximum range of the electrons, it may well be underestimated [15].

Figure 1 shows the results of all air kerma comparisons made at the BIPM in ^{60}Co radiation. The standard deviation of the comparisons with the sixteen national primary laboratories is 0.17 %. The values relating to recent comparisons are given in [16].

Figure 1 International comparison of AIR KERMA standards in ^{60}Co γ radiation



Although the result for the comparison of air kerma in ^{60}Co radiation is very satisfactory, it may be possible to improve that for the air kerma determination in a ^{137}Cs beam.

Prior to 1992, the VNIIM used a different air kerma standard. This was a cylindrical cavity ionization chamber, C40/4, and was used for international comparisons within the framework of the COMECON treaty (now called COOMET). Since the results of comparisons made in 1990 between the OMH, UDZ, ASMW, NIM and the VNIIM are linked to those of the BIPM through the OMH/BIPM comparison, they provide indirect values of the ratio $K_{\mathrm{VNIIM}}/K_{\mathrm{BIPM}}$ for ^{60}Co of 0.994 and for ^{137}Cs of 0.985. The uncertainties of these values are in the range 0.4 % to 0.5 %. The direct values obtained in the current comparison are a better link to the BIPM, but the indirect results agree with the direct ones to within two combined standard uncertainties.

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June 1998