Key comparison BIPM.RI(I)-K5 of the air-kerma standards of the SMU, Slovakia and the BIPM in ^{137}Cs gamma radiation

C. Kessler[1], D. Burns[1], N. Durný [2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
[2] Slovak Institute of Metrology/Slovenský Metrologický Ústav (SMU)
Karloveská 63, 842 55 Bratislava, Slovakia

Abstract

The first direct comparison of the standards for air kerma of the Slovak Institute of Metrology (SMU), Slovakia and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{137}Cs radiation beam of the BIPM in June 2017. The comparison result, evaluated as a ratio of the SMU and the BIPM standards for air kerma, is 1.0051 with a combined standard uncertainty of 2.7×10^{-3}. The results for an indirect comparison made at the same time are consistent with the direct results at the level of 2 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

A first comparison of the standards for air kerma of the Slovak Institute of Metrology (SMU), Slovakia, and of the Bureau International des Poids et Mesures (BIPM) was carried out in June 2017 in the ^{137}Cs radiation beam at the BIPM. The comparison result is published in the BIPM key comparison database (KCDB 2017) under the reference BIPM.RI(I)-K5. The comparison was undertaken using the primary standard of the SMU. An indirect comparison was also made using a cylindrical ionization chamber as a transfer instrument. The final results were supplied by the SMU in October 2017.

2. Details of the standards

The SMU standard ND1005/A serial number 8111 for air kerma is a cylindrical graphite-walled cavity ionization chamber constructed by the Országos Mérésügyi Hivatal (OMH), Budapest, Hungary. The details of the SMU standard and the transfer chamber are given in Table 1.
The BIPM standard is a parallel-plate graphite-walled cavity ionization chamber with a volume of about 6.8 cm^3 as described by Boutillon *et al* (1973) and Boutillon *et al* (1996);

the results of calculated correction factors and new volume estimations are described by Burns *et al* (2007) and Kessler *et al* (2009).

Table 1. Characteristics of the SMU standard for air kerma and the transfer chamber

Standard	ND1005/A-8111	PTW TW23361
Shape	Cylindrical	Cylindrical
Outer height / mm	19	65
Outer diameter / mm	19	32.9
Wall material	Ultra pure graphite	PMMA graphited
Wall thickness / mm	4	1.0
Wall density / g cm^{-3}	1.71	1.19
Electrode diameter / mm	2	14
Electrode length / mm	10.3	43.5
Air cavity volume / cm^3	1.0218 (1)	30
Applied voltage / V	300 V (2)	-300 V (3)

(1) Calculated from technical drawings provided by the Országos Mérésügyi Hivatal (OMH), Hungary
(2) Both polarities applied at the BIPM and the SMU
(3) Negative 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

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

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,
$(\mu_{\text{en}}/\rho)_{\text{a,c}}$ 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.

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 SMU standards are also included in Table 2.

Table 2. Physical constants and correction factors with their relative standard uncertainties of the BIPM and SMU standards for the ^{137}Cs radiation beam at the BIPM

		BIPM	CH 6.3		SMU	ND1005/A-8111	
		values	uncertainty [1]		values	uncertainty [1]	
			100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
Physical Constants							
ρ_{air}	dry air density [2] / kg m^{-3}	1.2930	–	0.01	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9990	–	0.05	0.9990	–	0.05
$s_{c,a}$	ratio of mass stopping powers	1.0104	–	0.11[3]	1.0101	–	0.11[3]
W/e	mean energy per charge / J C^{-1}	33.97	–		33.97	–	
g_a	fraction of energy lost in radiative processes	0.0012	–	0.02	0.0012	–	0.02
Correction factors:							
k_s	recombination losses	1.0018	0.01	0.02	1.0016	0.01	0.03
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	0.9998	0.01	–	0.9997	0.01	–
k_{wall}	wall attenuation and scattering	1.0002	0.01	[4]	1.0312	–	0.06
k_{an}	axial non-uniformity	1.0018	–	0.04	1.0013	–	0.06
k_{rn}	radial non-uniformity	1.0011	0.01	0.05	1.0003	0.01	0.03
k_{leak}	leakage	–	–	–	–	–	0.03
Measurement of I / V							
V	chamber volume / cm^3	6.8313	–	0.08	1.0218[5]	–	0.24
I	ionization current / pA	–	0.02	0.02	–	0.02	0.02
Relative standard uncertainty							
quadratic summation			0.03	0.17		0.02	0.29
combined uncertainty			**0.17**			**0.29**	

[1] Expressed as one standard deviation
u_{iA} represents the type A relative standard uncertainty estimated by statistical methods,
u_{iB} 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] The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al* 2007)

[5] Volume re-evaluated by the SMU from the dimensional measurements done by the OMH

Correction factors for the SMU primary standard

– *Recombination loss (k_s)*

The correction factor for the SMU standard for losses due to ion recombination was determined at the BIPM during the BIPM.RI(I)-K1 comparison (Allisy-Roberts *et al* 2004) 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 3 gives the values for k_{init} and k_{vol} and the uncertainty for k_s calculated for the BIPM radiation beam.

Table 3. Ion recombination for the SMU standard

Standard ND1005A-8111	BIPM values
Initial recombination and diffusion, k_{init}	1.6×10^{-3}
Volume recombination coefficient, k_{vol} / pA^{-1}	6.2×10^{-7}
k_s in the BIPM beam	1.0016
Standard uncertainty	3×10^{-4}

The SMU adopted the BIPM determination for k_s. Thus, a correction factor of 1.0016 was applied to the measured current at the BIPM.

– *Stem scattering (k_{st})*

The correction for stem scatter for the standard determined at the SMU using a dummy stem is 0.9997 with a relative standard uncertainty of 1 parts in 10^4

– *Attenuation and scattering in the chamber wall (k_{wall}) and axial non-uniformity (k_{an})*

The effect of attenuation and scatter in the graphite wall of the standards and the axial non-uniformity correction were determined by the SMU using the MCNPX Monte Carlo code.

– *Polarity effect (k_{pol})*

The polarity effect measured at the BIPM is 0.9996(2). As both polarities were applied to the standard during the measurements at the BIPM and the mean current value was used for the comparison, no k_{pol} was applied.

– *Radial non-uniformity of the beam (k_{rn})*

The corrections for the radial non-uniformity of the BIPM radiation beam for the SMU standard is estimated from the measured beam profile in the radial direction. The correction applied to the chamber is 1.0003(3).

– *Volume determination*

The volume of the chamber, calculated in 1999 at the SMU from dimensional measurements provided by the Országos Mérésügyi Hivatal (OMH), Hungary (now Budapest Főváros Kormányhivatala (BFKH)), was 1.0185 cm3 (value used for the ^{60}Co air kerma comparison in 2000 (Allisy-Roberts et al 2002)). A re-evaluation of the volume was done recently using the technical drawings and dimensions provided, resulting in a value higher by 3.2 parts in 10^3. The increase arises from considering an air gap at the bottom of the collector and the air volume located in the cavity around the stem, as reported by Laitano (2003).

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 20 cm diameter.

The following conditions are established at the SMU for the two ^{137}Cs sources:

- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 24 cm diameter.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of four measurements made around the period of the comparison. The $\dot{K}_{\mathrm{BIPM}}$ value refers to an evacuated path length between source and standard corrected to the reference date of 2017-01-01, 0 h UTC. The half-life of ^{137}Cs was taken as 10 976 days (u = 30 days) (Bé *et al* 2006). The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air attenuation coefficient 0.010 cm^2 g^{-1} for ^{137}Cs.

At the SMU, the $\dot{K}_{\mathrm{SMU}}$ value is taken as the mean of six measurements made over a period of about 2 weeks around the period of the comparison. By convention it is given at the reference date of 2017-05-26 T 0 h UTC using the half-life value taken from the ISO 4037 as 11050 days for ^{137}Cs.

Beam characteristics

The characteristics of the BIPM and SMU beams are given in Table 4.

Table 4. Characteristics of the ^{137}Cs beams at the SMU and the BIPM

^{137}Cs beam	Nominal $\dot{K}$ / µGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field diameter at 1 m / cm
		diameter	length		
SMU source IM4-2	887	32.2	57.0	not specified	24
SMU source IM4-3	101	17.5	17.6	not specified	24
BIPM source	13	8	13	30 %	20

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 using the primary standard and the transfer chamber 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

A collecting voltage of 300 V (both polarities) and 300 V (negative polarity) was applied to the outer electrode of the SMU standard and the transfer chamber, respectively, at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the SMU chambers was measured at the BIPM using a Keithley electrometer, model 642. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A preirradiation was made for at least 40 min before any measurements. Leakage current was measured before and after each series of measurements. The measured value for the standard was around 0.5 fA, 7×10^{-4} in relative terms, the air kerma rate being relatively small. An uncertainty of 3×10^{-4} is included in Table 2. The relative leakage correction for the transfer chamber was less than 1×10^{-4}. The ionization current measured for each chamber was corrected for the leakage current.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.04 °C at the BIPM. At the SMU, 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 SMU, humidity is controlled and calibrations were made in the range (60 ± 10) %.

5. Results of the comparison

Direct comparison

The SMU primary standard was set-up and measured in the BIPM ^{137}Cs beam on two separate occasions. The results were reproducible to better than 3×10^{-4}. The values of the ionization currents measured at the BIPM for the SMU 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 ^{137}Cs source.

Table 5. The experimental results from the SMU standard in the BIPM beam

SMU standard	I_+ and I_- /pA		I_{mean} / pA
ND1005A-8111	0.5023	-0.5023	0.5023
	0.5029	-0.5021	0.5025
Mean current			0.5024

The result of the comparison R_K is expressed in the form

$$R_K = \dot{K}_{\mathrm{SMU}} / \dot{K}_{\mathrm{BIPM}} \tag{3}$$

and is presented in Table 6.

Table 6. Final result of the SMU/BIPM comparison of standards for ^{137}Cs air kerma

	$\dot{K}_{\mathrm{SMU}}$ / µGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / µGy s^{-1}	R_K	u_c
ND1005A-8111	13.4557	13.3878	1.0051	0.0027

The combined standard uncertainty u_c for the comparison result R_K is presented in Table 7.
The ratio of the air kerma rate values determined by the SMU and the BIPM standards taken from Table 6 is 1.0051 with a combined standard uncertainty, u_c, of 0.0027. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the SMU 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.

Table 7. Uncertainties associated with the comparison result

Relative standard uncertainty	$100\ u_{i\mathrm{A}}$	$100\ u_{i\mathrm{B}}$
$\dot{K}_{\mathrm{SMU}} / \dot{K}_{\mathrm{BIPM}}$	0.04	0.27[a]
Relative standard uncertainty of R_K	0.04	0.27
	u_c = 0.0027	

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

Indirect comparison

The transfer chamber was set-up and measured in the BIPM ^{137}Cs beam on two separate occasions. The comparison result is evaluated as the ratio of the calibration coefficients $N_{K,\mathrm{lab}}$ determined at each laboratory. The calibration coefficient is given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \tag{4}$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate at each lab and I_{lab} is the ionization current of a transfer chamber measured at the SMU 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	$N_{K,\mathrm{SMU}}$ / Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
PTW TW23361	0.9361	0.9351	0.9356	0.9310	1.0049	0.0035

The calibration coefficients measured before and after the measurements at the BIPM give rise to the relative standard uncertainty s_{tr}, which represents the uncertainty in the N_K arising from the transfer chamber stability, included in Table 9.

The correction factor for the PTW TW23361 for losses due to ion recombination was determined at the BIPM during present comparisonusing the method described by Boutillon (1998). The values for initial k_{init} and volume k_{vol} recombination are 1.1×10^{-3} and 1.60×10^{-7} pA^{-1}, respectively. Similar values were determined at the SMU. Thus, a correction factor k_s of 1.0011 and 1.0012 was applied to the measured current at the BIPM and the SMU, respectively. A relative uncertainty component of 2×10^{-4} is included in Table 9.

No radial non-uniformity correction was applied. This correction is 6×10^{-4} at the BIPM and a similar non-uniformity exists in the reference beams at the SMU; a relative uncertainty component of 2×10^{-4} is included in Table 9.

The result of the indirect comparison taken from Table 8 is 1.0049 with a combined standard uncertainty, u_c, of 0.0035. This result is in agreement with the direct comparison at the level of 2 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		SMU	
Relative standard uncertainty	$100\,u_{iA}$	$100\,u_{iB}$	$100\,u_{iA}$	$100\,u_{iB}$
Air kerma rate	0.02	0.17	0.03	0.29
Ionization current for the transfer chambers	0.01	0.02	0.01	.
Distance	0.01	–	–	0.08
Reproducibility	0.02	–	0.02	–
Electrometer	–	–		0.17
Temperature, pressure	–	–		0.02
$N_{K,\mathrm{lab}}$	0.04	0.17	0.04	0.35
Indirect comparison result	$100\,u_{iA}$		$100\,u_{iB}$	
$N_{K,\mathrm{SMU}}$ / $N_{K,\mathrm{BIPM}}$ (1)	0.05		0.34	
Short-term stability s_{tr}	0.07			
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
$N_{K,\mathrm{SMU}}$ / $N_{K,\mathrm{BIPM}}$	$u_c = 0.0035$			

(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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ 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.

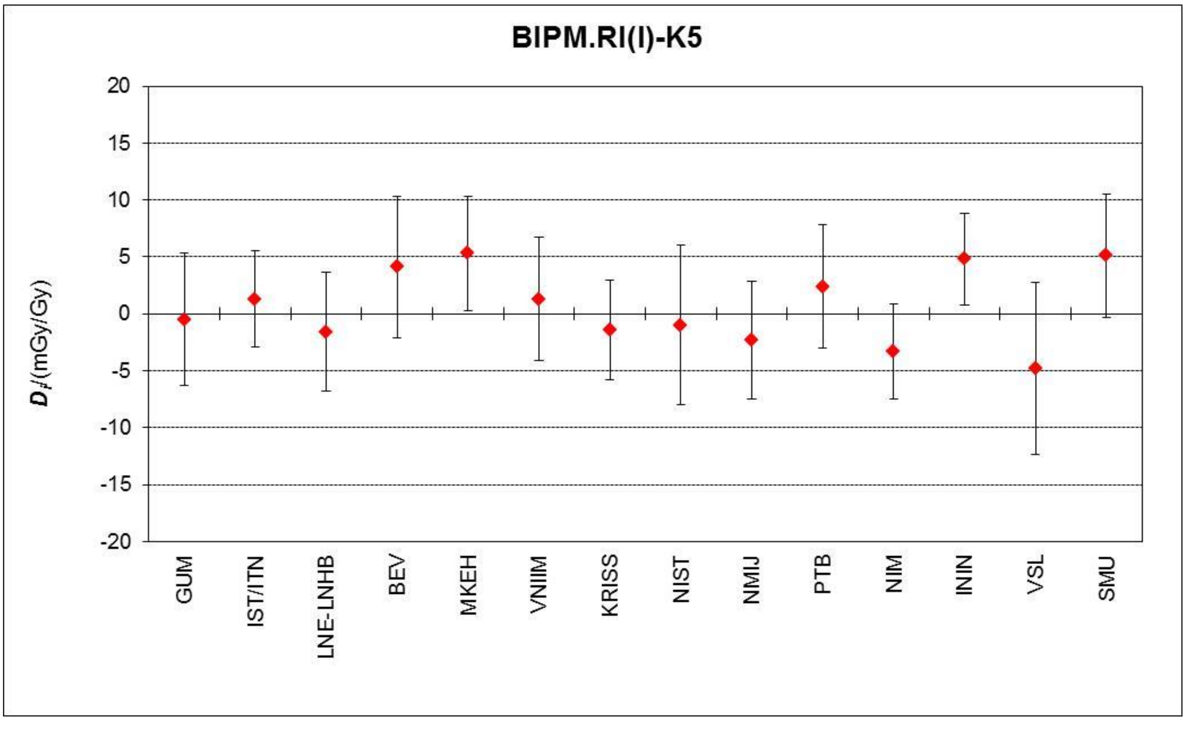
Note that the data presented in Table 10, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

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

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
GUM	-0.5	5.8
IST/ITN	1.3	4.2
LNE-LNHB	-1.6	5.2
BEV	4.1	6.2
MKEH	5.3	5.0
VNIIM	1.3	5.4
KRISS	-1.4	4.4
NIST	-1.0	7.0
NMIJ	-2.3	5.2
PTB	2.4	5.4
NIM	-3.3	4.2
ININ	4.8	4.0
VSL	-4.8	7.6
SMU	5.1	5.4

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



Comparison of any two NMIs with each other

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 the table, 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.

7. Conclusion

The SMU standard for air kerma in ^{137}Cs gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0051 (27). The indirect and direct comparison results are in agreement at the level of 2 parts in 10^4, which is within the standard uncertainty of the calibration procedure.

The SMU is in agreement within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K5 ongoing key comparison for air kerma standards in ^{137}Cs gamma-ray beam.

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