Comparison of the standards for air kerma of the MKEH and the BIPM for ^{137}Cs gamma radiation

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Abstract

An indirect comparison of the standards for air kerma of the Magyar Kereskedelmi Engedélyezési Hivatal (MKEH), Hungary, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{137}Cs radiation beam of the BIPM in October 2009. The comparison result, expressed as a ratio of the MKEH and the BIPM calibration coefficients of a transfer chamber for air kerma, is 1.0053 with a combined standard uncertainty of 2.5×10^{-3}. The result of the earlier direct comparison in ^{137}Cs γ rays, made in 1994, was 0.9954(30); taking into account the changes made recently to both standards, the 1994 result becomes 1.0038 (30), in agreement with the present comparison result.

1. Introduction

The last direct comparison of the air kerma standards of the Magyar Kereskedelmi Engedélyezési Hivatal (MKEH), Hungary and the Bureau International des Poids et Mesures (BIPM) for ^{137}Cs gamma radiation was made in 1994 [1]. An indirect comparison between both laboratories was carried out in October 2009.

The air kerma standard of the MKEH for ^{137}Cs is a graphite-walled cavity ionization chamber constructed by the MKEH in 1976, referenced as ND-1005. The MKEH standard is described in [2, 3]. The transfer standard used for the indirect comparison is a spherical cavity chamber type ND1001, serial number 7815. Some details of the MKEH standards 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 [4, 5] and the results of recent evaluations of calculated correction factors and new volume estimations are presented in [6].

Table 1. Characteristics of the MKEH cavity standards for air kerma

MKEH standard		Primary standard ND 1005 - 7708	Transfer standard ND1001 - 7815
		Nominal value	
Chamber	Outer height /mm	19	–
	Outer diameter /mm	19	38
	Inner height /mm	11	–
	Inner diameter /mm	11	3
	Wall thickness /mm	4	2.5
Electrode	Diameter /mm	2	3
	Height /mm	8.970	15
Volume	Air cavity	1.0227 cm^3	20 cm^3
Wall	Materials	graphite	Delrin
	Density	1.75 g·cm^{-3}	1.39 g·cm^{-3}
	Impurity	$< 1.5 \times 10^{-4}$	Energy compensation-layer
Insulator		PTFE Teflon	PTFE Teflon
Applied voltage		250 V; both polarities	250 V; positive polarity (1)

(1) positive polarity to the outer electrode

2. Determination of the air kerma

The air kerma rate is determined by

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

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 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

Data concerning the various factors entering in the determination of air kerma in the ^{137}Cs beam using the primary standards of the MKEH and of the BIPM are shown in Table 2. They include the physical constants [7], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties. For the BIPM standard, these data are taken from [6] and [8].

Also shown in Table 2 are the relative uncertainties in the ratio

$$R_K = \dot{K}_{\mathrm{MKEH}} / \dot{K}_{\mathrm{BIPM}} \qquad (2)$$

Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the MKEH determinations (such as air density, *W/e*, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{\mathrm{c,a}}$ and k_{h}) cancel when evaluating the uncertainty of R_K are shown in Table 2.

Table 2. Physical constants and correction factors entering in the determination of air kerma and their estimated relative uncertainties in the BIPM ^{137}Cs beam

	BIPM			**MKEH**			**R_K**	
	values	uncertainty (1)		values	uncertainty (1)		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)	1.2930	–	0.01	1.2930	–	0.01	–	–
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a.c}}$	0.9990	–	0.05	0.999	–	0.05	–	–
$\bar{s}_{c,a}$	1.0104	–	0.11 (3)	1.0101	–	0.30	–	–
W/e	33.97	–		33.97	–	0.15	–	–
$\bar{g}$	0.0012	–	0.02	0.0012	–	0.02	–	–
Correction factors								
k_{s} recombination loss	1.0018	0.01	0.02	1.0020	0.04	0.05	0.04	0.05
k_{h} humidity	0.9970	–	0.03	0.997	–	0.03	–	–
k_{st} stem scattering	0.9998	0.01	–	0.9993	0.05		0.05	–
k_{wall} wall attenuation and scattering	1.0002	0.01	–	1.0278	0.01	0.08	0.01	0.08
k_{an} axial non-uniformity	1.0018	–	0.04	1.0005	0.07	0.05	0.07	0.06
k_{rn} radial non-uniformity	1.0011	0.01	0.10	1.0002	0.01	0.05	0.01	0.11
k_{p} polarity		–	–	1.000	–	0.05	–	0.05
Measurement of *I*/*Vρ*								
V volume / cm^3	6.8283 (4)	–	0.08	1.0187	0.10	0.05	0.10	0.09
I ionization current (2)		0.02	0.02		0.02	0.02	0.03	0.03
Uncertainty								
quadratic summation		0.03	0.19		0.14	0.37	0.14	0.20
combined uncertainty		**0.19**			**0.40**		**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.

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

(4) For standard CH5-2, the measured volume 6.8344 cm^3 reduced by the factor 1.0009 [6].

Reference values

The $\dot{K}_{\mathrm{BIPM}}$ value is taken from the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\mathrm{BIPM}}$ values refer to an evacuated path length between source and standard and are given at the reference date of 2009-01-01, 0 h UTC. The half-life of ^{137}Cs was taken as 10 975.53 days (u = 29 days) [9].

Beam characteristics

A comparison of the ^{137}Cs beams at the MKEH and the BIPM is given in Table 3.

Table 3. Parameters of the ^{137}Cs beams at the MKEH and the BIPM

Parameter	BIPM	MKEH
Beam cross-section	20 cm ϕ (large collimator)	26 cm
Nominal $\dot{K}$ (2009-01-01)	16 µGy s^{-1}	100 µGy s^{-1}
Incident scatter in terms of energy fluence	30 %	Not evaluated

3. The transfer standard and its calibration

The ionization chamber ND1001, serial number 7815, belonging to the MKEH, is the transfer standard used for this comparison. The main characteristics are listed in Table 1. The comparison of the MKEH and BIPM standards was made indirectly using the calibration coefficients N_K for the transfer standard given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \ , \qquad (3)$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate and I_{lab} is the ionization current of the transfer chamber measured at the MKEH or the BIPM.

The essential details of the experimental method for calibrations at the MKEH and that for the BIPM [8] are reproduced here; the current is corrected for the effects and influences described in this section.

Positioning

At each laboratory the chamber was positioned at the reference distance of 1 m from the source, with the stem perpendicular to the beam direction; the chamber was positioned with the signal connector facing the source.

Applied voltage and polarity

A collecting voltage of 250 V (positive polarity) was applied to the outer electrode of the chamber at least 30 min before any measurements were made. No polarity correction was applied at either laboratory.

Charge and leakage measurements

The charge Q collected by the transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. The source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the MKEH, the charge is measured with a Keithley electrometer type 617.

The ionization current measured for the transfer standard was corrected for the leakage current at the BIPM. This correction was less than 2×10^{-4} in relative value. At the MKEH the leakage current of the transfer chamber was less than 3 fA, consequently no leakage correction was applied.

Ambient conditions

At the BIPM, an insulating cabin was used to minimize temperature fluctuations; the air temperature is measured for each current measurement and it was stable to better than 0.02 °C. At the MKEH, the air temperature is about 22 °C, with variation of up to 1 °C. The ionization current is normalized to 293.15 K and 101.325 kPa at both laboratories.

Relative humidity is controlled at (50 ± 5) % at the BIPM and (50 ± 15) % at the MKEH. No correction for humidity is applied to the transfer chamber ionization current.

Radial non-uniformity correction (k_{rn})

The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the MKEH transfer standard is estimated to be 1.0007 (2) using the beam profile from [5]. This effect was confirmed at the BIPM by making some measurements at 3 m from the source and comparing the results, each corrected for the appropriate radial non-uniformity.

The correction factor k_{rn} for the radial non-uniformity of the MKEH beam for the transfer chamber's diameter was calculated to be 1.0003 (5).

Scatter from the stem (k_{st})

The correction for the stem scatter of the transfer chamber was measured at the MKEH to be 0.9992 (2) and 0.9993 (2) using 26 cm and 16 cm beam diameters respectively. The applied beam diameter was 20 cm at the BIPM so the stem scattering difference was negligible; consequently, no correction has been applied.

Recombination loss (k_{s})

The correction factor for the MKEH transfer standard for losses due to ion recombination was determined at the MKEH using the method of Niatel as described in [10]. The recombination correction k_{s} can be expressed as

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} I_V \qquad (4)$$

Table 4 gives the values for k_{init} and k_{vol} and the uncertainty for k_{s}. Because of the different air kerma rates at both labs, corrections for ion recombination have been applied. Consequently, correction factors of 1.0020 (3) and 1.0022 (3) for ion recombination at 250 V was applied to the transfer standard in the BIPM and MKEH ^{137}Cs beams, respectively.

Table 4. **Ion recombination for the transfer standard**

MKEH transfer standard	ND1001
Initial recombination and diffusion, k_{init}	20×10^{-4}
Volume recombination factor, k_{vol}, per measured current / pA	3.9×10^{-6}
k_{s} in the BIPM ^{137}Cs beam	1.0020
k_{s} in the MKEH ^{137}Cs beam	1.0022
Standard uncertainty	3×10^{-4}

Uncertainties

Contributions to the relative standard uncertainty of $N_{K,\mathrm{lab}}$ are listed in Table 5.

The relative standard uncertainty of the mean ionization current measured with the transfer chamber over the short period of calibration was estimated to be 2×10^{-4} (three calibrations with repositioning, in series of 30 measurements for each chamber) at the BIPM. The chamber was calibrated at the MKEH before and after the comparison at the BIPM five times in the period of three months. The relative standard uncertainty of the mean normalized ionization current measured at the MKEH over the several months required for this comparison was typically better than 2×10^{-4}.

Table 5. Estimated relative standard uncertainties of the calibration coefficient, $N_{K,\mathrm{lab}}$, of the transfer chamber and of the comparison results, R_K

Relative standard uncertainty	**BIPM**		**MKEH**	
	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma	0.03	0.19	0.14	0.37
Ionization current of the transfer chamber	0.02	0.02	0.02	0.02
Distance and orientation	0.02	–		0.02
Radial non-uniformity	–	0.02		0.05
Recombination loss	–	0.03		0.03
Temperature, pressure	–	–		0.01
Relative standard uncertainty of $N_{K,\mathrm{lab}}$				
quadratic summation	0.04	0.19	0.14	0.38
combined uncertainty	0.19		0.40	
Relative standard uncertainties of R_K [1]				
quadratic summation	0.14		0.21	
combined uncertainty	**0.25**			

[1] taking correlation into account

4. Results

Indirect comparison

The indirect comparison of the standards was made using the MKEH transfer chamber ND1001-7815. The calibration coefficient N_K for the transfer chamber is given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \,, \tag{5}$$

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 MKEH or the BIPM.

The result of the comparison, R_K, is expressed in the form

$$R_K = N_{K,\text{MKEH}} / N_{K,\text{BIPM}} \quad , \qquad (6)$$

in which the average value of measurements made at the MKEH prior to those made at the BIPM (pre-BIPM) and those made afterwards (post-BIPM) for the chamber is compared with the mean of the measurements made at the BIPM. Table 6 lists the relevant values of N_K for the chamber at the stated reference conditions.

Table 6. Result of the indirect comparison

Transfer standard	$N_{K,\text{MKEH}}$ / Gy µC^{-1} pre-BIPM	$N_{K,\text{BIPM}}$ [(a)] / Gy µC^{-1}	$N_{K,\text{MKEH}}$ / Gy µC^{-1} post-BIPM	$N_{K,\text{MKEH}}$ / Gy µC^{-1} overall mean	R_K	u_c
ND1001-7815	1.4929	1.4843	1.4914	1.4922	1.0053	0.0025

(a) Corrected by recombination loss, determined by the MKEH.

The mean value of the calibration coefficient measured before and after the comparison at the BIPM, N_K = 1.4922 (60) Gy µC^{-1}, is compared with that measured at the BIPM of 1.4843 (29) Gy µC^{-1}, to give a ratio, R_K , of 1.0053 (25). This is in agreement with the previous direct comparison result originally of 0.9954(30) and once corrected by the changes that have been applied to both primary standards to give 1.0038 (30).

6. Discussion

During the past fifteen years, significant progress has been made in applying Monte Carlo techniques to make better estimates of the various correction factors that are applied in the measurement equation for cavity chamber standards, particularly for the effects of attenuation and scattering in the graphite walls. Since 2003, each NMI has been encouraged by the Consultative Committee for Ionizing Radiation (CCRI) to verify its correction factors and to publish any change to its national standards that it feels is appropriate so that the results may be included in the KCDB. The MKEH declared the change of their standards in 2001 [3], resulting in an increase of the air kerma determination of 1.0115 using the MKEH primary cavity standard. The BIPM has recently declared the new reference value for the air-kerma ^{137}Cs standard [6], resulting in an overall increase in air kerma rate of 1.0030. All the previous results of air kerma comparisons in ^{137}Cs at the BIPM are being re-evaluated at the moment, taking into account the effect of changes being made in national standards following the recommendations of the CCRI and of the change to the BIPM standard itself.

7. 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 for each of the CCRI radiation qualities is taken as the key comparison reference value [11]. It follows that for each NMI i having a BIPM comparison result $R_{K,i}$ (denoted x_i in the KCDB) with combined standard uncertainty, u_i, the degree of equivalence with respect to the reference value for the NMI comparison, here $K_{\text{R},i}$, is given by a pair of terms:

the relative difference $D_i = (K_i - K_{\mathrm{R},i}) / K_{\mathrm{R},i})) = R_{Ki} - 1$ (7)

and the expanded uncertainty (k = 2) of this difference,

$$U_i = 2\ u_i. \tag{8}$$

The results for D_i and U_i, are expressed in mGy/Gy.

Consequently, the degree of equivalence of the MKEH with the KCRV is expressed as

	D_i	U_i
	/ (mGy/Gy)	
MKEH	**5.3**	**5.0**

Comparison of any two NMIs with each other

The degree of equivalence between any pair of national measurement standards is expressed in terms of the difference between the two comparison results and the expanded uncertainty of this difference; consequently, it is independent of the choice of key comparison reference value.

The degree of equivalence, D_{ij}, between any pair of NMIs, i and j, is thus expressed as the difference

$$D_{ij} = D_i - D_j = R_i - R_j \tag{9}$$

and the expanded uncertainty (k = 2) of this difference, $U_{ij} = 2\ u_{ij}$, where

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{10}$$

and the final two terms are used to take into account correlation between the primary standards, notably that arising from the physical constants and correction factors for similar types of standard.

The results for D_i and U_i and those for D_{ij} and U_{ij} are currently being re-evaluated for all the NMIs that have taken part in the BIPM.RI(I)-K5 ongoing comparison in the light of the recent change to the BIPM standard and the changes since original publication of the individual NMI standards. Once this has been achieved, the result for the MKEH will be included in a summary report to be published in the KCDB together with the other results.

8. Conclusion

The MKEH standard for air kerma in ^{137}Cs gamma radiation compared indirectly with the present BIPM air kerma standard gives a comparison result of 1.0053 (25). This result also agrees with the earlier 1994 result when the changes in each standard over the intervening years are taken into account. The present result compares favourably with other similar primary standards for which the wall correction factor has been calculated using Monte Carlo methods.

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