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Abstract
A first comparison of the standards of air kerma of the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{137}Cs radiation. The comparison result is 1.0005 with a relative standard uncertainty of 2.8×10^{-3}. This result indicates that the NMIJ and BIPM standards are in agreement within one standard uncertainty.

1. Introduction

A comparison of the standards of air kerma of the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{137}Cs radiation. The NMIJ standard of air kerma [1] is comprised of two cylindrical graphite cavity ionization chambers of different size constructed at the NMIJ (C-110G No. 766 and C-110G No. 764), dimensional details of which are given in [2]. The BIPM air kerma standard is described in [3, 4]. The comparison of the standards took place at the BIPM in January 2001.

2. Determination of the air kerma rate

The air kerma rate is determined using the relation

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

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

3. Experimental method

The air kerma is determined at the BIPM under the following conditions [4]:
- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is normally10 cm in diameter, the photon fluence rate at the field edge being 50 % of the photon fluence rate on the central axis. However, a larger field size (20 cm diameter) was used for this comparison to provide a more uniform beam profile for the size of the NMIJ standards.

Each NMIJ/AIST chamber was placed so that its centre was in the reference plane of the gamma ray field but angled at 45° to the direction of the gamma ray beam as shown in Figure 1.

Data concerning the various factors entering in the determination of air kerma in the ^{137}Cs beam using the two standards are shown in Tables 1 and 2. They include the physical constants [5], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties [1, 4]. Also shown are the relative standard uncertainties in the ratio R_K that represents the comparison result;

$$R_K = \dot{K}_{\text{NMIJ}} / \dot{K}_{\text{BIPM}} \ . \tag{2}$$

The correction factors for the NMIJ standard were determined at the NMIJ. Some correction factors were reassessed at the BIPM as described in the following paragraphs.

k_s : correction factor for losses due to ion recombination

Values for the parameters describing ion recombination losses were obtained for the two chambers from measurements at the BIPM [2]. The ionization currents measured in the ^{137}Cs beam are quite small (between 4 pA and 45 pA) and consequently there is no significant volume recombination for either of the NMIJ primary standards.

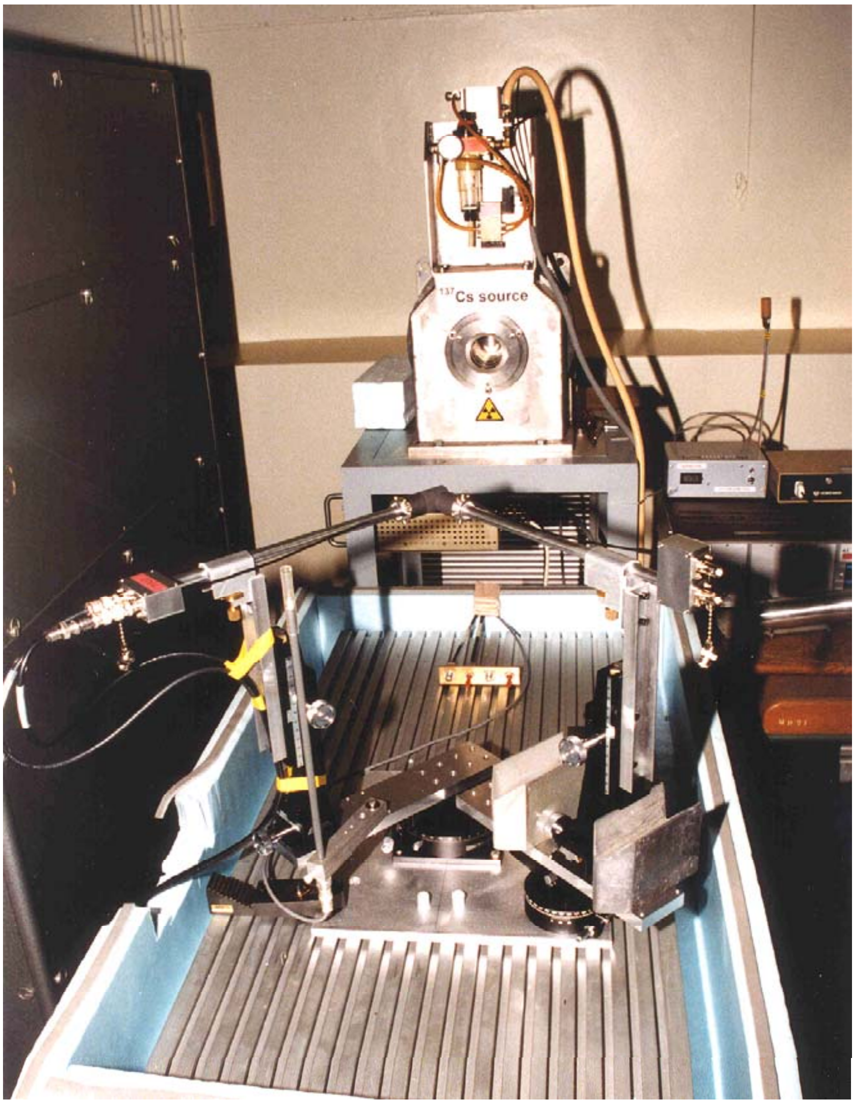


Figure 1. The NMIJ chamber (C-110G-764) at the reference position in the ^{137}Cs beam, together with a dummy stem (on the right) to measure the stem scatter correction.

k_h: correction factor for humidity

The relative humidity for all the measurements at the BIPM was within the range 49 % to 51 %. Although common uncertainties associated with k_h are removed in the comparison value, the uncertainty in the reference data used for k_h gives rise to an uncertainty in the air kerma determination; this is taken to be 0.03 % [6].

k_{wall}: correction factor for wall attenuation and scattering

Although at the time of the comparison in January 2001, the values for k_{wall} were measured by the linear extrapolation method, this method is not recommended [7] and so the values for k_{wall} actually used were obtained by the Monte Carlo method, using the EGS4 code [8]. In the calculations, the chamber wall thickness is taken as 2 mm for ^{137}Cs gamma rays. The stem of the chamber was neglected in the calculation for k_{wall} because the scattering effects of the stem were obtained by measurement and accounted for using the correction factor k_{st}. The scatter component of the incident gamma ray spectrum was also neglected.

Table 1. Physical constants and correction factors entering in the determination of air kerma and their estimated relative standard uncertainties in the BIPM ^{137}Cs beam for NMIJ standard C-110G-766

	BIPM values	100 × relative [(a)] uncertainty s_i	u_i	NMIJ values C-110G-766	100 × relative [(a)] uncertainty s_i	u_i	100 × relative [(a)] uncertainty of R_K s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9990	-	0.05	0.9990	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0104	-	0.11	1.0104	-	0.11	-	-
W/e /(J C^{-1})	33.97			33.97				
$\bar{g}$ fraction of energy lost to bremsstrahlung	0.0012	-	0.02	0.0012	-	0.02	-	-
Correction factors								
k_s recombination losses	1.0014	0.01	0.01	1.0012	0.02	0.01	0.02	0.01
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	0.9998	0.01	-	0.9939	0.01	0.10	0.01	0.10
k_{att} wall attenuation	1.0540	0.01	0.04					
k_{sc} wall scattering	0.9535	0.01	0.15	1.0192	0.06	0.10	0.06	0.18
k_{CEP} mean origin of electrons	0.9972	-	0.01					
k_{an} axial non-uniformity	0.9981	-	0.07	0.9982	0.10	0.05	0.10	0.09
k_{rn} radial non-uniformity[(c)]	1.0011	0.01	0.03					
k_p position	1.0000	-	0.01	1.0000	-	0.06	-	0.06
Measurement of $I/v\rho$								
v volume / cm^3	6.8344	0.01	0.10	62.701	0.01	0.03	0.01	0.10
I ionization current		0.03	0.02		0.05	0.02	0.06	0.03
Uncertainty								
quadratic summation		0.04	0.24		0.13	0.21	0.13	0.26
combined uncertainty		0.24			0.25		0.29	

[(a)] 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.

[(b)] At 101 325 Pa and 273.15 K.

[(c)] For the 20 cm diameter beam.

k_{st}: correction factor for stem scattering

For each chamber the ratio was determined of signal currents measured in the BIPM beam with and without a dummy stem placed at the chamber side (Figure 1). However, a dummy stem placed at the end of the chamber fixed in a beam would seem to represent more realistically the effects of the actual stem [2]. Consequently, the correction factor corresponding to this geometry was obtained by measuring the ratios of signal currents with and without the dummy stem in both cases for gamma ray fields at the NMIJ and correcting the measurements made at the BIPM.

Table 2. Physical constants and correction factors entering in the determination of air kerma and their estimated relative standard uncertainties in the BIPM ^{137}Cs beam for NMIJ standard C-110G-764

	BIPM values	100 × relative [(a)] uncertainty		NMIJ values	100 × relative [(a)] uncertainty		100 × relative [(a)] uncertainty of R_K	
		s_i	u_i	C-110G-764	s_i	u_i	s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9990	-	0.05	0.9990	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0104	-	0.11	1.0104	-	0.11	-	-
W/e /(J C^{-1})	33.97			33.97				
$\bar{g}$ fraction of energy lost to bremsstrahlung	0.00132	-	0.02	0.0012	-	0.02	-	-
Correction factors								
k_s recombination losses	1.0014	0.01	0.01	1.0015	0.01	0.01	0.01	0.01
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	0.9998	0.01	-	0.9958	0.01	0.10	0.01	0.10
k_{att} wall attenuation	1.0540	0.01	0.04	1.0166	0.06	0.10	0.06	0.13
k_{sc} wall scattering	0.9535	0.01	0.15					
k_{CEP} mean origin of electrons	0.9972	-	0.01					
k_{an} axial non-uniformity	0.9981	-	0.07	0.9990	0.06	0.05	0.06	0.09
k_{rn} radial non-uniformity[(c)]	1.0011	0.01	0.03					
k_p position				1.0000	-	0.06	-	0.06
Measurement of $I/v\rho$								
v volume / cm^3	6.8344	0.01	0.10	6.0547	0.01	0.03	0.01	0.10
I ionization current		0.03	0.02		0.10	0.02	0.11	0.03
Uncertainty								
quadratic summation		0.04	0.24		0.13	0.21	0.14	0.22
combined uncertainty		0.24			0.25		0.26	

(a) 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.

(b) At 101 325 Pa and 273.15 K.

(c) For the 20 cm diameter beam.

k_{nu}: correction factor for axial and radial non-uniformity

Values of k_{nu} for the NMIJ chambers are obtained by the Monte Carlo method. The correction is taken as the ratio between the deposition energies in the air of the chamber when it is placed in a uniform parallel gamma ray field and when it is placed 1 m from a gamma ray point source [9]. The gamma ray field of a point source was assumed to have the same radial non-uniformity as the profile measured by the BIPM [3]. The profile was calculated from

$$F = 1 - 0.00037 \times r^2 - 1.3863\text{E} - 7 \times r^3 \qquad (3)$$

where F is the fluence of gamma rays and r the radius (cm) from the beam axis on the plane perpendicular to the beam and passing a point 1 m from the gamma ray source [10].

k_p: correction factor for position error

The correction factor k_p is included to account for the uncertainty in positioning the NMIJ chambers which, because of the unusual 45° geometry, are more difficult to set up. The value for k_p was taken to be 1.0000 with a type B relative standard uncertainty estimated to be 0.0006. The value was obtained for 1 m from a gamma ray source assuming that the sum of the position uncertainty in setting the chamber for measurement and that of the mark for the centre of the chamber was 0.3 mm.

4. Comparison results

The result of the comparison $R_K = \dot{K}_{\mathrm{NMIJ}} / \dot{K}_{\mathrm{BIPM}}$ is given in Table 3. Four independent measurements were made over ten days using the NMIJ standards. The relative combined uncertainty associated with the measurements for each standard is better than 10^{-3}. The $\dot{K}_{\mathrm{BIPM}}$ value of 19.311 (s = 0.001) μGy·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 NMIJ and the BIPM standards is 1.0005 with a relative combined standard uncertainty, u_c, of 0.0028. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and the NMIJ 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 Tables 1 and 2.

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

Standard C-110G	I_{NMIJ} / pA	$\dot{K}_{\mathrm{NMIJ}}$ $^{(1)}$ / mGy·s^{-1}	R_K	u_c
766	45.150_7	19.297_9	0.9993_2	0.0029
764	4.3685_2	19.344_3	1.0017_2	0.0026

(1) The $\dot{K}$ values measured at the BIPM 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 ^{137}Cs is taken as 11 050 days (u = 40 days) [11].

5. Discussion regarding k_{wall} effects

A detailed discussion of the determination of the effects of the walls of cylindrical cavity chambers is given in [2].

The present comparison with the NMIJ used two cylindrical ionization chambers with different sizes. In calculating k_{wall} and k_{nu}, the gamma ray field is assumed to have no scattered radiation and the dependence of the mass energy absorption ratio and stopping power ratio on the size of the chamber is not taken into account. The difference in the air kerma rate determination between the two NMIJ primary standards is 2.4×10^{-3} in relative terms. This difference, although within the comparison uncertainties, is greater than was obtained in the ^{60}Co comparison undertaken at the same time [2] and may indicate some inconsistencies in the calculated values for k_{wall} for the two chambers. At the NMIJ/AIST, the ^{137}Cs air kerma standard has been disseminated on the basis of the calculated correction factors k_{wall} rather than measured values since April 2002.

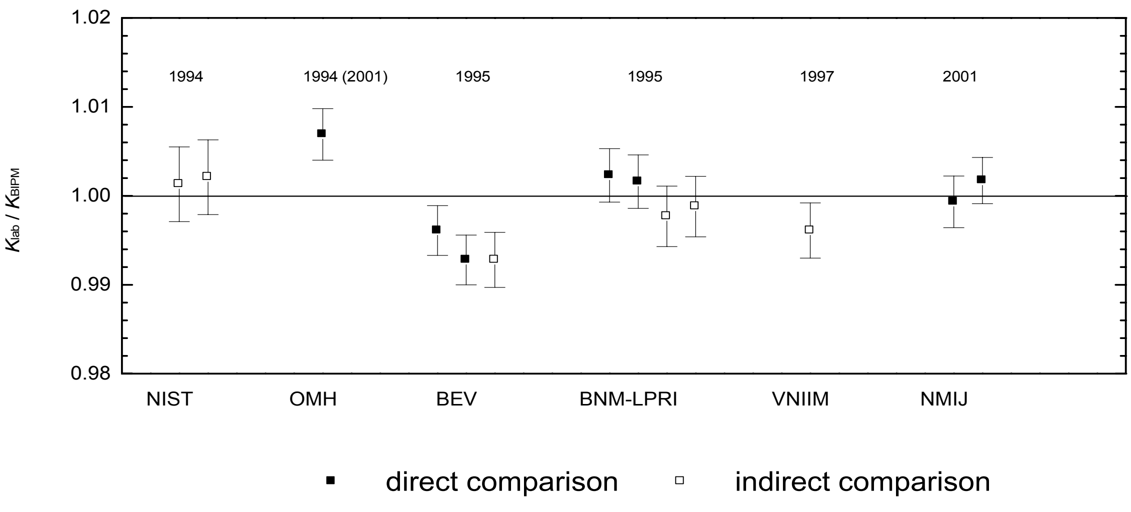
Several other NMIs have also changed their method of k_{wall} determination, using Monte Carlo calculations, and each NMI has declared these results. The NMIs concerned are the OMH (Hungary) [12], the PTB (Germany) [13] and the ENEA-INMRI (Italy) [14]. The BIPM is also reviewing its experimental and calculated results for the wall correction of its primary standard to verify the international standard of air kerma. Any future new result will need to be approved and implemented at a date to be confirmed by the Consultative Committee for Ionizing Radiation (CCRI)

7. Conclusion

The comparison result for the NMIJ standard for air kerma in ^{137}Cs gamma radiation is $R_K = 1.0005$ ($u_c = 0.0028$). 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. The standard deviation of the six published international comparison results is 1.8×10^{-3} with a mean value currently of 1.0003. The uncertainties in the figure are standard uncertainties.

The comparisons of air kerma standards in ^{137}Cs gamma radiation have been designated as key comparisons with the nomenclature BIPM.RI(I)-K5 by the CCRI. These results will in the future be used as the basis of the entries in Appendix B of the KCDB set up under the Mutual Recognition Arrangement [15]. Some NMIs that are still using experimental extrapolation methods to determine wall correction factors will need to check their factors, using various Monte Carlo codes or other methods, before this can be achieved.

Figure 2 International comparison of air kerma standards in ^{137}Cs γ radiation



All values for each laboratory

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