Comparison of the air kerma standards of the ARL and the BIPM for ^{60}Co γ rays

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Abstract
A comparison between the standards of air kerma of the Australian Radiation Laboratory and those of the Bureau International des Poids et Mesures has been carried out in ^{60}Co gamma radiation. It shows good agreement between the standards for which the ratio of the air kerma values is 1.002 8 with a relative standard uncertainty of $3.2 \cdot 10^{-3}$.

1. Introduction

A comparison of the standards of air kerma held by the Australian Radiation Laboratory (ARL), Victoria, Australia, and the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co gamma radiation. The Australian standard is a graphite double-pancake cavity ionization chamber constructed at the ARL following the design of a similar chamber at the BIPM described in [1].

The comparison took place at the BIPM in April 1997 using two ARL transfer chambers. The results of the comparison are given in terms of the ratio of the calibration factors of the transfer standards as determined at the two laboratories.

The results of the present air kerma comparison are in agreement, within the uncertainties, with those obtained in the previous comparison of air kerma standards conducted in 1988 [2].

2. Determination of air kerma

Air kerma is determined under the following reference conditions:

- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 10 cm x 10 cm,
- the photon fluence rate at the centre of each side of the square is 50 % of the photon fluence rate at the centre of the square.

The air kerma rate is determined from

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

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 energy lost by bremsstrahlung,
$\left(\bar{\mu}_{\text{en}}/\rho\right)_{\text{a,c}}$	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 values of the physical constants [3] and the correction factors used in (1) are listed in Table 1 for both standards together with their associated uncertainties. The uncertainties of the kerma ratio, expressed as $R_K = K_{\text{ARL}}/K_{\text{BIPM}}$, are also listed in the table. As some constants (such as air density, W/e, $\left(\bar{\mu}_{\text{en}}/\rho\right)_{\text{a,c}}$, $\bar{g}$, $\bar{s}_{\text{c,a}}$ and k_{h},) are derived from the same basic data in both laboratories, the uncertainty in R_K is due only to the uncertainties in the correction factors, the volumes of the standards , the ionization currents measured and the distance to the source. It should be noted that the definition of air kerma applies to conditions in which the air is dry, that is conditions in which the relative humidity is zero.

3. Changes made at the two laboratories since 1988

Changes have been made at both laboratories since the last comparison in 1988 so all correction factors and relevant physical constants have been reassessed.

The primary chamber at the ARL is that used in 1988 to determine the air kerma, however the volume has been re-evaluated to provide a better estimate.

The ^{60}Co source was last renewed at the ARL in 1995 and, although the source housing and collimator are the same, it has been necessary to apply new correction factors to the standard. These factors have been determined experimentally or by calculation following the methods described in [1]. The mass energy absorption ratio has been re-calculated using a Monte-Carlo simulation of the spectrum of the ARL source rather than assuming the source to be mono-energetic. The other major difference since 1988, is that the ARL has developed its own current integrator system to replace the commercial system used in 1988. Using this the leakage current is smaller as is the standard deviation in the measured current.

The 1997 ARL values used in (1) are listed in Table 1. The overall change since 1988 is an increase of 0.09 % in the measured value of air kerma at the ARL.

Table 1. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{\mathrm{BIPM}}$ and $\dot{K}_{\mathrm{ARL}}$, and their estimated relative uncertainties

	BIPM values	BIPM relative uncertainty[(1)]		ARL values	ARL 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[(2)] / kg·m^{-3}	1.293 0	-	0.01	1.293 0	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.998 5	-	0.05	0.999 3	-	0.05	-	-
$\bar{s}_{c,a}$	1.001 0	-	0.11[(3)]	1.000 4	0.04	0.09[(3)]	-	-
W/e / (J·C^{-1})	33.97			33.97			-	-
$\bar{g}$ 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	1.001 2	0.01	0.01	0.01	0.01
k_h humidity	0.997 0	-	0.03	0.997 1	-	0.01	-	-
k_{st} stem scattering	1.000 0	0.01	-	0.998 6	-	0.02	0.01	0.02
k_{at} wall attenuation	1.040 2	0.01	0.04	1.037 4	-	0.15	0.01	0.16
k_{sc} wall scattering	0.971 6	0.01	0.07	0.970 3	-	0.10	0.01	0.12
k_{CEP} mean origin of electrons	0.992 2	-	0.01	0.992 2	-	0.05	-	0.05
k_{an} axial non-uniformity	0.996 4	-	0.07	0.996 3	-	0.20	-	0.21
k_{rn} radial non-uniformity	1.001 6	0.01	0.02	1.004 0	-	0.03	0.01	0.04
V volume / cm^3	6.811 6	0.01	0.03	6.845 7	0.02	0.05	0.02	0.06
I ionization current / pA		0.01	0.02		0.03	0.03	0.03	0.04
Relative standard uncertainty								
quadratic summation		0.02	0.17		0.05	0.30	0.04	0.31
combined uncertainty		0.17			0.31		0.31	

(1) s_i represents the relative standard uncertainty $u(x_i)/x_i$ estimated by statistical methods, type A,
u_i represents the relative standard uncertainty $u(x_i)/x_i$ estimated by other means, type B.

(2) at 0 °C and 101.325 kPa.

(3) combined uncertainty for the product ($\bar{s}_{c,a} \cdot W/e$)

Since the 1988 comparison, the BIPM has installed a second experimental set up, a new source and a different standard for the determination of air kerma in ^{60}Co radiation. This new set up became operational in 1991 when all the correction factors for the standard had been evaluated. There are slight changes in k_{sc}, k_{at}, k_{cep}, $s_{c,a}$ and μ_{en}/ρ due to the change of the beam energy spectrum (from 8 % scatter to 18 % scatter). The recombination loss and k_{rn} have different values in the two set ups, corresponding to the different beams. The volumes of the original and later standards have been compared accurately by ionometry in the same beam. If the factors appropriate to each beam are used in (1), the two standards produce the same value for the air kerma. The BIPM values appropriate to the 1997 conditions are listed in Table 1 together with their uncertainties.

4. Comparison of air kerma standards

The comparison of the ARL and BIPM standards was made indirectly by comparing the calibration factors N_K of the two ARL transfer chambers as determined in the individual laboratories. The calibration factor is given by

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

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate measured with the standard and I_{lab} is the ionization current of the transfer chamber corrected for the effects described in Section 5.

The two ARL transfer chambers are graphite cavity chambers manufactured by Nuclear Enterprises (Type NE 2561 serial numbers 070 and 328). Their main characteristics are listed in Table 2. Details concerning the calibration, pertinent corrections to the ionization current of the transfer chambers and estimations of the uncertainties on N_K are described in Section 5 of this report.

Table 2. Characteristics of the ARL transfer chambers

Chamber	NE 2561	070 and 328
Dimensions	Inner diameter / mm	7.35
	Wall thickness / mm	0.5
	Cavity length / mm	9.22
Electrode	Diameter / mm	1.00
Volume	Air cavity / cm^3	0.325
Wall	Materials	graphite < 0.01 % impurity
	Density / $g \cdot cm^{-3}$	1.80
Build-up cap	Material	Delrin
	Thickness / mm	3.87
Applied voltage	Negative polarity / V	210

5. Experimental conditions

The method of calibration used at the ARL is described in [4] and that for the BIPM in [5].

5.1. Conditions of Measurement

- *Positioning of the transfer chamber*. The axis of the transfer chamber is located in the reference plane, 1 m from the source at the BIPM and 0.993 m at the ARL. At the BIPM the position is measured without the build-up cap in place. At the ARL, the chamber position is aligned using lasers without the build-up cap. Its position is then measured with the build-up cap in place. In both cases, the uncertainty in the measurement of the position by micrometer is less than 0.01 mm. The chambers are positioned so that the serial number on the stem faces the source.

- *Build-up cap.* Each transfer chamber was supplied with a build-up cap for use in ^{60}Co radiation. These were in place for all measurements of ionization current and were oriented so the writing on the build-up cap faced the source.

- *Humidity and temperature*. During calibration, the relative humidity at the BIPM is controlled in the range 45 % to 55 %. The relative humidity at the ARL is usually between 40 % and 60 %, but can range from 30 % to 90 %. In this case corrections are made (see section 5.2). At the BIPM, the air temperature was around 21 °C and, during each series of measurements, it was stable to within ± 0.01 °C. At the ARL, the air temperature was around 23 °C and during each series of measurements was stable to within ± 0.02 °C.

- *Collecting voltage*. A collecting voltage of 210 V (negative polarity), was applied to the chambers at least 30 minutes before any measurement was made at either laboratory.

- *Measurement of charge.* The charge Q collected by the chambers was measured using the BIPM or the ARL current integrator as relevant. The chambers were pre-irradiated for at least 30 minutes before measurements began. To detect any gross changes in the transfer chambers during transport, and any differences between the current measurement systems at the ARL and the BIPM, a check source of ^{90}Sr belonging to the ARL (NE 2562-024) was used to irradiate the transfer chambers in a constant geometry. The currents measured using the ^{90}Sr source were normalized where necessary to 50 % relative humidity, 20 °C and 101.325 kPa. Corrections for the radioactive decay were made to a common reference date, 1997/03/15 using a half life of 28.8 years. The results are given in Table 3.

Table 3. ^{90}Sr check source results in 1997

Chamber	ARL (Mar) I / pA	BIPM (April) I / pA	ARL (May) I / pA	I_{ARL}(Mar)/ I_{ARL}(May)	$R_I = I_{ARL}/I_{BIPM}$
070	23.678 6	23.630 5	23.705 6	0.998 86	1.002 6
328	22.642 7	22.670 9	22.668 1	0.998 88	0.999 3
070/328	1.045 8	1.042 3	1.045 8	1.000 0	1.003 3

That the 070/328 ratio was the same at the ARL before and after the measurements at the BIPM, but the BIPM ratio was about 0.3 % different, suggests that there may have been a problem with one of the chambers regarding these measurements. Indeed, chamber 070 exhibited a leakage current of about 100 fA (0.4 % of the measured current) when used with the ^{90}Sr source at the BIPM. This was so both before and after the measurements in the ^{60}Co beam during which time the leakage current was only 10 fA. Previous values of R_I for chamber 070 were 1.000 4 in 1979 and 0.999 8 in 1988 [2]. Short term variations within a range of 0.3 % have been noted by the ARL for measurements using the check source over the period since 1976 [4]. Consequently, no significance should be attached to the differences between the currents measured by the two laboratory systems as the differences lie within this uncertainty.

- *Reproducibility of measurements*. The short-term relative standard deviation of the mean ionization current, measured with each transfer chamber, was estimated to be 0.03 % (3 series each of 50 measurements for each chamber) at the ARL and 0.02 % for both chambers (4 series each of 30 measurements for each chamber) at the BIPM. The differences in calibration factors measured by the ARL for each chamber before and after calibration at the BIPM are consistent with the short-term standard deviations.

5.2. Corrections applicable to the ionization current of the ARL chambers

At each laboratory the corrections applicable to the transfer chambers are performed automatically by the computer associated with the current measuring device.

- *Leakage current.* The leakage current of the transfer chambers was negligible, being less than 0.001 %.

- *Recombination.* A recombination correction, k_s = 1.001 7 for incomplete ion collection was applied to the ionization current measured at each laboratory, based on measurements made at the ARL [4]. The corresponding value, 1.001 4, measured at the BIPM for other chambers of the same type is slightly different. The air kerma rates observed at the two laboratories are similar.

- *Temperature and pressure normalization.* At both laboratories, the measured ionization current of the transfer chambers was normalized to a temperature of 293.15 K and a pressure of 101.325 kPa.

- *Humidity.* During calibration, the relative humidity at the BIPM is in the range from 48 % to 52 % and, as agreed, no correction is made. The range of humidity is much greater at the ARL and appropriate corrections from 0.02 % to 0.09 % are made to normalize the results to 50 % humidity. These corrections are calculated from an empirical fit to the data given in reference [6].

- *Other factors.* The stem scattering effect has not been checked at either the BIPM or the ARL. No allowance for the radial non-uniformity of the beam over the section of the transfer chamber has been made in the results. In the BIPM beam, this effect is about 0.02% for these chambers [7] and at the ARL the value is zero with an uncertainty of 0.01 % [4].

6. Results and discussion

The results of the comparison, R_K , are expressed in the form

$$R_K = N_{K_{\text{ARL}}} / N_{K_{\text{BIPM}}} \quad . \qquad (3)$$

The values measured for the comparison are shown in Table 4. Contributions to the relative standard uncertainty in N_K are given in Table 5. Taking the mean value for the two chambers used in the present comparison gives R_K = 1.002 8 with a combined standard uncertainty $u_c(R_K)$ = 0.003 2.

Table 4. Results of the air kerma standards comparison

Lab.	Transf. chamb.	$\dot{K}_{lab}$ / mGy·s^{-1}	I_{lab} / pA	N_K / Gy·µC^{-1}	R_K	mean value R_K	Relative standard uncertainty u_c
ARL		5.242 5	-	-	1.002 9 for 070 and 1.002 6 for 328	1.002 8	0.003 2
	070	-	55.854	93.861			
	328	-	55.404	94.623			
BIPM		4.617 3	-	-			
	070	-	49.335	93.591			
	328	-	48.925	94.375			

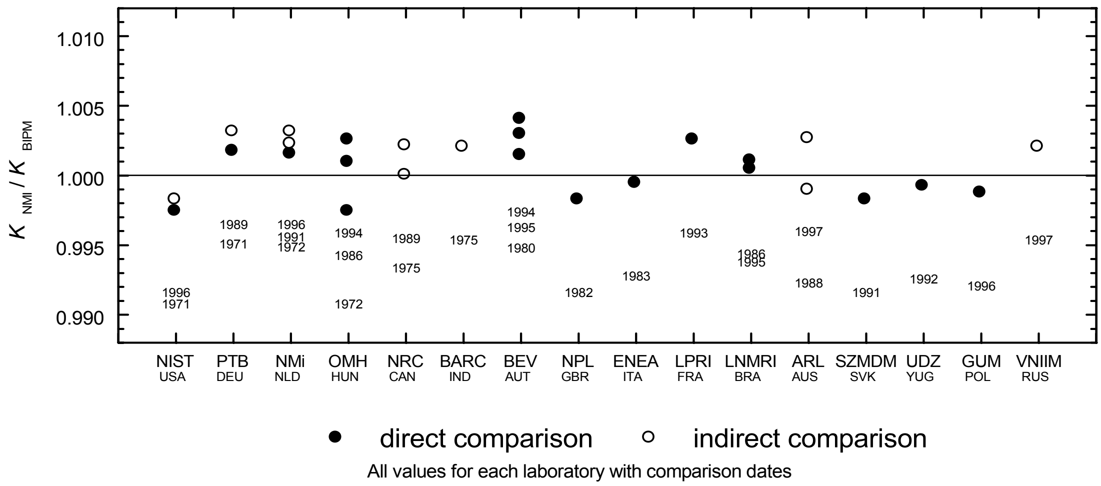
The values obtained at the ARL are the means of measurements before and after the comparison corrected to 1997-03-15, 1200h AEST (the half life of ^{60}Co is taken as (1 925.5 d, σ = 0.5 d) [8]). The $\dot{K}_{BIPM}$ value is the mean of measurements which were performed over a period of three months before and after the comparison at the BIPM. It is given at the reference date of 1997-01-01, 0h UT as is each value of I_{BIPM}.

Table 5. Estimated relative standard uncertainties in the calibration factors, N_K, and their ratio, R_K.

	N_K ARL		N_K BIPM		R_K ARL/BIPM	
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	0.05	0.30	0.02	0.17	0.04	0.31
Ionization current of each transfer chamber	0.03	0.03	0.02	0.02	0.04	0.04
Distance	0.01	0.01	0.01	0.02	0.01	0.02
Relative standard uncertainty						
quadratic summation	0.06	0.30	0.03	0.17	0.06	0.31
combined uncertainty	0.31		0.17		0.32	

The value for R_K is within the range obtained in the comparisons of the air kerma standards of other national metrology institutes (NMIs) with the BIPM, as shown in Figure 1. The present mean value of R_K for all the NMIs shown, is 1.000 8 with a statistical uncertainty of $5\cdot10^{-4}$. The values relating to recent comparisons are given in [9, 10, 11, 12, 13 and 14].

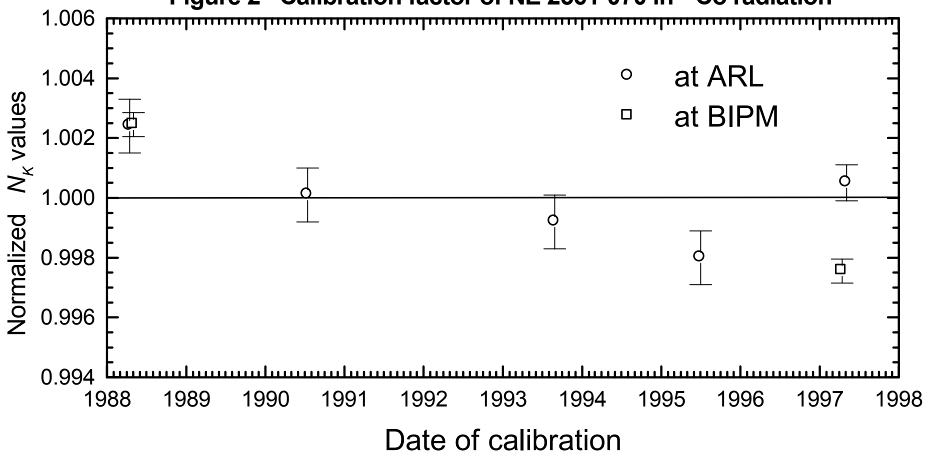
Figure 1 International comparison of air kerma standards in ^{60}Co γ radiation



The previous air kerma comparison between the BIPM and the ARL for ^{60}Co radiation was made in 1988 [2]. The result, R_K = 0.998 1 (u_c = 0.003 2) is in fair agreement with the present result. However, an inspection of the 1988 results shows that one of the transfer chambers (NE 2561-194) behaved in an unstable fashion when at the BIPM and for some time after its return to the ARL. The other chamber used in 1988, NE 2561-070, was also used in 1997 and it appears to have been stable when exposed to the ^{60}Co beams at both the laboratories on both occasions. Its value in 1988 was R_K = 1.000 6, which is in closer agreement with the value of 1.002 9 obtained in 1997. However, the measurement of air kerma has changed by 0.09 % at the ARL over the same period. If this change is taken into account, the value of R_K for 1988 becomes 1.001 5, which is within about 0.1 % of the 1997 value and is compatible with the statistical uncertainties of 0.06 %. This indicates that the relationship between the two air kerma standards, as expressed by a comparison of calibration factors, is stable.

Data on the stability of the transfer chamber 070 over the period from 1988 to 1997 is shown in Figure 2. The values of N_K at the ARL were obtained using the standard chamber response and the correction factors applied in 1997.

Figure 2 Calibration factor of NE 2561-070 in ^{60}Co radiation



The expected variation of the chamber over a short period of time (from ARL calibration to BIPM calibration) can be considered negligible. It is interesting to note however, that over the period of 10 years the chamber's response has a relative standard deviation of $1.5 \cdot 10^{-3}$.

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Table 4 expanded. Results of the air kerma standards comparison

Lab.	Transf. chamb.	$\dot{K}_{\text{lab}}$ / mGy·s^{-1}	$\dot{X}_{\text{lab}}$ / µA·kg^{-1}	I_{lab}* / pA	$N_{\dot{K}}$ / Gy·µC^{-1}	$N_{\dot{X}}$ / mg^{-1}	$R_{\dot{K}}$	Relative standard uncertainty 100 u_c
ARL 1988 values		5.242 0	153.82	-	-	-		
	070	-	-	55.871	93.824	2.753 1		
	328	-	-	55.435	94.562	2.774 8		
BIPM		4.618 1	135.51	-	-	-		
	070	-	-	49.335	93.607	2.746 7	1.002 3	0.31
	328	-	-	48.925	94.391	2.7697	1.001 8	0.31
ARL 1997 values		5.240 5	153.77	-	-	-		
	070	-	-	55.856	93.822	2.753 1		
	328	-	-	55.419	94.561	2.774 7		

The values at the ARL are the means of measurements before and after the comparison corrected to 1997-03-15, 0h UT (the half life of ^{60}Co is taken as (1 925.5 d, σ = 0.5 d) [9]). The $\dot{K}_{\text{BIPM}}$ value is the mean of measurements which were performed over a period of three months before and after the comparison at the BIPM. It is given at the reference date of 1997-01-01, 0h UT as is the value of I_{BIPM}.

* The current has been corrected for recombination losses in each laboratory by a factor of 1.001 7.