Rapport BIPM-2003/10

Bureau International des Poids et Mesures

Revised comparison of the standards for air kerma of the ENEA-INMRI and the BIPM for ^{60}Co gamma rays

P J Allisy-Roberts, D T Burns
BIPM

R F Laitano, M Toni, M Bovi
ENEA-INMRI

October 2003

Pavillon de Breteuil, F-92312 SEVRES cedex

Rapport BIPM-2003/10

Revised comparison of the standards for air kerma of the ENEA-INMRI and the BIPM for ^{60}Co γ-rays

P.J. Allisy-Roberts and D.T. Burns
Bureau International des Poids et Mesures, F-92312 Sèvres Cedex, France

R.F. Laitano, M. Toni and M. Bovi
Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti,
ENEA CR Casaccia, cp 2400 – 00100 Rome, Italy

Abstract
In 1998 a comparison of the standards of air kerma of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy (ENEA-INMRI) and of the Bureau International des Poids et Mesures (BIPM) was carried out in ^{60}Co radiation. The comparison result, declared in 2003, is 1.0044 (0.0026) and demonstrates that the ENEA-INMRI and BIPM standards are in agreement within the expanded uncertainty (k = 2).

1. Introduction

A comparison of the standards for air kerma of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy, (ENEA-INMRI), and of the Bureau International des Poids et Mesures (BIPM), was carried out at the BIPM in ^{60}Co radiation in September 1998 [1]. In this comparison the ENEA-INMRI used two standard graphite-cavity ionization chambers: the OMH type chambers, serial numbers C1 and C3, constructed at the ENEA-INMRI details of which are given in [2]. The BIPM air kerma standard is described in [3].

The original result of this comparison has been revised recently. A new determination made at the ENEA-INMRI to take account of the effects of the graphite walls of the standard cavity chamber was declared in January 2001, published in July 2002 [4] and subsequently revised in May 2003 [5]. In addition, the analysis on which the volume of the standard chamber determination was based has been revised. A new determination of this volume was made at the ENEA-INMRI and was declared in May 2003 [6]. Furthermore, the volume determinations obtained for both the chambers C1 and C3 were compared at the ENEA-INMRI with those obtained for six new chambers of the same type for which the volumes have been determined precisely. The results of this analysis showed that the value of the chamber volume determined for the chamber C3 is not consistent with that of the other similar chambers [6]. Consequently, the ENEA-INMRI decided to reject the chamber C3 as a standard and to consider only the comparison measurements made with the C1 chamber at the

BIPM in 1998 as being valid. Details of chamber C1 are given in section 2 of this report. The present report supersedes the report describing the previous results[1].

An earlier comparison between the ENEA-INMRI and the BIPM took place in 1983 [7] and a bilateral comparison with the NIST (USA) and the ENEA-INMRI was conducted in 1994 [8]. The results of these comparisons are consistent when the various changes are taken into account, as discussed later in this report.

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 in air,
$(\mu_{\text{en}}/\rho)_{\text{a,c}}$	is the ratio of the mean massenergy-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 ENEA-INMRI primary standard are given in Table 1.

3. Experimental results

The air kerma is determined at the BIPM under the following conditions :
- the distance from source to reference plane is 1 m;
- the field size in air at the reference plane is 10 cm × 10 cm, the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre of the square.

Data concerning the various factors entering in the determination of air kerma in the ^{60}Co beam using the two standards are shown in Table 2. They include the physical constants [9], 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 [10]. Also shown in Table 2 are the relative uncertainties in the ratio $R_K = \dot{K}_{\text{ENEA-INMRI}} / \dot{K}_{\text{BIPM}}$.

Table 1. Characteristics of the ENEA-INMRI standard for air kerma

Type	C-ENEA standard chamber	Nominal values
Chamber	Outer height / mm	19
	Outer diameter / mm	19
	Inner height / mm	11
	Inner diameter / mm	11
	Wall thickness / mm	4
Electrode	Diameter / mm	2
	Height / mm	10
Volume	Air cavity / cm^3	1.0312
	relative uncertainty / cm^3	0.0020
Wall	Material	ultrapure graphite
	Density / $g \cdot cm^{-3}$	1.75
	Impurity fraction	$< 1.5 \times 10^{-4}$
Applied tension (both polarities)	Voltage / V	300

The correction factors for the ENEA-INMRI standard were determined at the ENEA-INMRI. The polarity effect was about 1.0023 (2), but as all measurements were made with both polarities no corrections were applied. Some measurements concerning the effect of ion recombination and the effect of attenuation and scatter in the chamber walls were repeated in the BIPM beam.

The ratio of the ionization currents obtained with applied voltages of 300 V and 150 V (both polarities) was the same (with a difference smaller than than 4×10^{-4}) for the ENEA-INMRI standard in the ENEA-INMRI beam as it was in the BIPM beam. This gave a simple estimate of ion recombination loss k_s = 1.0024 at the BIPM. However, on measuring the ratio I_V / $I_{V/4}$ [11] in the BIPM beam for a series of different ionization currents, a more precise value of k_s was derived. This value was also equivalent to that for the BIPM transfer chamber of the same size and shape (CC01 serial 122) for an applied voltage of 300 V. Consequently, the correction k_s = 1.0018 (0.0005) as measured at the BIPM was applied to the ENEA-INMRI standard in the BIPM beam.

Table 2. Physical constants and correction factors entering in the determination of air kerma and their estimated relative uncertainties in the BIPM ^{60}Co beam

	BIPM values	Relative [a] uncertainty		ENEA-INMRI values	Relative [a] uncertainty		R_K relative [a] uncertainty	
		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} [b]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05	0.9985	-	0.05	-	-
$\bar{s}_{c,a}$	1.0010	-	0.11[c]	1.0007	-	0.11[c]	-	-
W/e	33.97	-		33.97	-		-	-
$\bar{g}$	0.0032	-	0.02	0.0032	-	0.02	-	-
Correction factors								
k_s recombination loss	1.0016	0.01	0.01	1.0018	-	0.05	0.01	0.05
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	1.0000	0.01	-	1.0000	-	0.03	0.01	0.03
k_{att} wall attenuation	1.0402	0.01	0.04				0.01	0.04
k_{sc} wall scattering	0.9716	0.01	0.07	1.0220	-	0.10	0.01	0.12
k_{CEP} mean origin of electrons	0.9922	-	0.01				-	0.01
k_{an} axial non-uniformity	0.9964	-	0.07	1.0001	-	0.01	-	0.07
k_{rn} radial non-uniformity	1.0016	0.01	0.02	1.0003	-	0.01	0.01	0.02
Measurement of ***I/Vρ***								
V volume / cm^3	6.8116	0.01	0.03	1.0312	-	0.20	0.01	0.20
I ionization current / pA [b]		0.01	0.02	155.947	0.01	0.06	0.01	0.07
Uncertainty								
quadratic summation		0.03	0.17		0.01	0.27	0.03	0.26
combined uncertainty		0.17			0.27		0.26	

[a] Expressed as one standard deviation.
s_i represents the relative uncertainty estimated by statistical methods, type A,
u_i represents the relative uncertainty estimated by other means, type B.

[b] At 101.325 kPa and 273.15 K.

[c] Combined uncertainty for the product of stopping power ratio and W/e

The effect of attenuation and scatter in the graphite walls of the ENEA-INMRI chamber has been determined conventionally by adding graphite caps of thickness up to 16 mm to the chamber wall (4 mm) and extrapolating to zero thickness. This experiment was repeated in the BIPM beam and the result is similar in both the BIPM and the ENEA-INMRI beams (Table 3). Consequently, the correction factor $k_{att.sc}$ = 1.0159 (0.0010) deduced from the measurements made at the BIPM would have been used until recently in the determination of air kerma at the BIPM. This value, together with the correction k_{CEP}, would have given a total correction for wall effects of k_{wall} 1.0131 (0.0022) for the ENEA-INMRI standard.

Table 3. Check measurements with C1-ENEA-INMRI for $k_{att.sc}$ by extrapolation

Number of caps added	0	1	2	3	4
Total wall thickness / mm ρ = 1.75 g cm^{-3}	4.00	8.05	12.10	16.15	20.20
Fractional current decrease in the BIPM beam and in the	1	0.9838	0.9681	0.9518	0.9356
ENEA-INMRI beam	1	0.9846	0.9690	0.9535	0.9368

However, improvements to replace the traditional extrapolation method have been made recently by the ENEA-INMRI using a technique that involves measurement and analytical calculation [4, 5]. The result of this determination produces a value for the total wall correction ($k_{att}k_{sc}k_{CEP}$) that agrees within the stated uncertainties with the value calculated at the ENEA-INMRI using the Monte Carlo code EGSnrc [12]. This latest value of 1.0220 with a combined standard uncertainty u = 0.0010 (statistical uncertainty s = 0.0002) is now used for the total wall correction. This value is 8.9×10^{-3} higher that the previous experimental value. The new value for k_{wall} agrees well with the value of 1.0219 (s = 0.0001) calculated for the same chamber at the NRC (Canada) [13] using the Monte Carlo code EGSnrc.

The volume determined for the ENEA-INMRI standard chamber, about twenty years ago, has been used in all international comparisons performed so far with this standard. After the comparison measurements were carried out at the BIPM in 1998, the analysis on which that volume determination was based was re-examined. This demonstrated a need to include in the chamber volume a small region near the base of the central electrode surrounded by an insulator. This region was not included originally as the contribution of that volume to the collected charge was assumed to be negligible. As this assumption was identified as an error through a subsequent thorough analysis [6], the incorrect original value of the chamber volume had to be increased by about 0.9 %. In addition, the original uncertainty assigned to the volume determination needed to be increased from 0.14 % to 0.2 %. The revised values for the chamber volume and its uncertainty are as given in Table 2.

An additional correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the ENEA-INMRI standard has been estimated from [14]; its numerical value is 1.0003.

Two series of measurements at the BIPM were made with a 180° orientation of the chamber. The effect of this orientation was 5×10^{-4}. The measured correction factor at the ENEA-INMRI is 1.0006 (1) and this was applied to correct the current measured at the BIPM to that measured at an angle of 0°. The corrected result is given in the final column of Table 4.

The evaluation of the air kerma rate at the BIPM measured with the ENEA-INMRI standard is obtained from (1) in section 2 using the data in Table 1 and the mean measured ionization current given in Table 4.

Table 4. Measurements made with the ENEA-INMRI C1 standard at the BIPM

Date	I / pA at +300 V	I / pA at -300 V	orientation	Corr. mean I / pA
98-9-14	156.062	155.685	180°	155.968
98-9-15	156.040	155.681	180°	155.953
98-9-17	156.084	155.737	0°	155.910
98-9-21	156.127	155.764	0°	155.946
98-9-25	156.139	155.781	0°	155.960
Mean, corrected				**155.947**

The result of the comparison $R_K = \dot{K}_{\text{ENEA-INMRI}} / \dot{K}_{\text{BIPM}}$ is given in Table 5.

Table 5. Result of the ENEA-INMRI/BIPM comparison of standards of air kerma

$\dot{K}_{\text{ENEA-INMRI}}$ / mGy s^{-1}	$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	R_K	u_c
4.0669	4.0489	1.0044	0.0026

The $\dot{K}_{\text{BIPM}}$ value is the mean of measurements that were performed over a period of one month before and after the present comparison. The $\dot{K}$ values refer to an evacuated path length between source and standard and are given at the reference date of 1998-01-01, 0 h UTC where the half-life of ^{60}Co is taken as 1925.5 days (u = 0.5 days) [15]. The ratio of the values of the air kerma rate determined by the ENEA-INMRI and the BIPM standards is 1.0044 with a combined standard uncertainty, u_c, of 0.0026. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the ENEA-INMRI 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 given in Table 2.

4. Discussion

4.1 Previous ENEA-INMRI comparisons

In 1983, for the earlier air kerma comparison, the ENEA-INMRI standard used was the same chamber C1. The ionization current produced by the standard chamber C1 in the BIPM beam in 1998 was used to determine a calibration coefficient that was then compared with one derived from the original data of 1983. The calibration coefficient of 1983 has been updated to account for the correct value for Δ and then for changes in stopping power ratios in 1985. The results are given in Table 6 and show a relative difference of 1.3×10^{-3} that could be in part due to the change in the ^{60}Co source (and source housing) used for air kerma comparisons at the BIPM during the intervening fifteen years. Taking note of this, it would appear that the ENEA-INMRI C1 chamber has not changed significantly with time.

Table 6. BIPM calibration coefficient for the C1-ENEA chamber.

Year	**1983/5**	**1998**
Calibration coefficient[(a)] N_K /(Gy/μC)	25.99_7	25.96_4
Combined standard uncertainty of N_K/(Gy/μC)	0.04	0.04

[(a)] at 273.15 K

An indirect comparison between the ENEA-INMRI and the NIST held in 1994, using two transfer chambers of the NIST, produced a mean comparison result for the ratio ENEA-INMRI/NIST of 1.0004 (0.0051) [6]. The NIST compared their standard with the BIPM in 1996, using the same two transfer chambers, and this gave a result for the ratio NIST/BIPM of 0.9980 (0.0040) [16]. Using these two values, a comparison result between the ENEA-INMRI and the BIPM can be deduced as 0.9984. As shown in Table 7, this agrees within one standard uncertainty (0.0040) with the result of the updated 1983 comparison (0.9994). It also agrees with the original result of the 1998 direct comparison (1.0016) obtained before the recent revisions in the corrections for beam (axial and radial) non-uniformity and wall effects together with that for the chamber volume [1, 5, 17].

Table 7. Previous comparison results for the ENEA-INMRI/BIPM

Year	1983	1983 corrected for Δ	1985 update using ICRU $\bar{s}_{c,a}$	1996 inferred from the ENEA-INMRI/NIST	1998 result with unrevised parameters
ENEA-INMRI/BIPM	0.9982	0.9985	0.9994	0.9984	1.0016
Uncertainty u_c	0.0040	0.0040	0.0040	0.0051	0.0026

4.2 Discussion regarding k_{wall} effects

For more than 10 years there have been intensive discussions on wall correction factors for cavity ionization chambers determined with an experimental extrapolation method versus those calculated using Monte Carlo methods [18, 19, 13]. There has also been considerable debate over the corrections for non-uniformity and the point of measurement [20, 21].

The majority of the national metrology institutes (NMIs) currently use wall correction factors that have been determined by the linear extrapolation method. Both experimental and theoretical results have been provided in recent years which strongly support the validity of calculated wall correction factors and these calculated values may differ significantly from those obtained by linear extrapolation of experimental data to zero wall thickness. This is particularly the case for the cylindrical cavity chambers that are used as primary air kerma standards by some NMIs. In some cases, the differences amount to 50 % of the correction itself [22].

During the 14th CCRI(I) meeting in 1999, the various approaches for determining wall and axial non-uniformity correction factors for graphite-cavity standards were discussed in detail [23]. It became apparent that several NMIs were actively re-evaluating their correction factors for ^{60}Co air kerma standards including their uncertainties. It was agreed to set up a working group (WG) to study the implications of using correction factors for ^{60}Co air kerma standards based on Monte Carlo methods. The members of the WG include the BNM-LNHB (France), NIST, NMi (The Netherlands), NPL (UK) and the BIPM. The NRC agreed to act as a consultant and submit to the working group a paper that it intended to publish on this topic. Furthermore, it was decided that before publishing results in the key comparison database (KCDB), which shows the degrees of equivalence between the NMIs, the BIPM would ask the NMIs to review their uncertainty budgets for air kerma standards in ^{60}Co gamma radiation. It was further suggested that the method of determining the correction factors (e.g. Monte Carlo or experimental, particularly linear extrapolation) should be identified in the KCDB, together with a statement on the implications of differences between the two methods with respect to the uncertainty [23].

The debate continued during the 15th CCRI(I) meeting in 2001 and several NMIs produced documents [22, 24-26] describing the work undertaken since the 1999 meeting. Significant contributions were made to the debate on wall correction factors for cavity chambers. During the 16th CCRI(I) meeting in 2003, it was recognized that electron-photon Monte Carlo calculations are a robust method of determining k_{wall} correction factors for air kerma cavity chamber standards in ^{60}Co fields [26].

The results of comparisons at the BIPM are currently being re-evaluated, taking into account the effect of changes being made in national standards. The OMH (Hungary) has already declared a new value for its air kerma standard [24], as has the PTB (Germany) [27]. The SZMDM (Yugoslavia) and the NCM (Bulgaria), both of which have made comparisons recently with the BIPM [28, 29], have also changed their method of k_{wall} determination, using Monte Carlo calculations. The BIPM is also making calculations of the equivalent factors for its standard to verify its determination of air kerma [30]. 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).

Once the evaluations have been completed and the results approved by the CCRI(I), they will be published in the KCDB.

5. Conclusion

The ENEA-INMRI standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air kerma standard gives a comparison result of 1.0044 (0.0026). The difference between this result and that obtained in 1983 is consistent with the changes to the ENEA-INMRI C1 standard.The result is also consistent with the indirect comparison via the NIST standard.

In principle, all the comparison results of the national metrology institutes and designated laboratories will be used as the basis of the entries in Appendix B of the KCDB set up under the Mutual Recognition Arrangement [31]. The NMIs that have previously used experimental extrapolation methods to determine wall correction factors are currently checking their factors, using various Monte Carlo codes or other methods. It may be several months before all the NMIs will be ready for their results to be entered into the BIPM key comparison database (KCDB). In the meantime, the BIPM is also reviewing its experimental and calculated results for the wall corrections of its primary standard.

References

[1] Allisy-Roberts P.J., Toni M., Bovi M., Comparison of the standards for air kerma of the ENEA-INMRI and the BIPM for ^{60}Co γ rays, 2002, *Rapport BIPM-2002/09*, 10 pp.

[2] Laitano R. F. and Toni M. P., The primary exposure standard of ENEA for Co-60 gamma radiation: characteristics and measurement procedures, 1983, *ENEA report*, RT/PROT(83)28.

[3] Boutillon M. and Niatel M.-T., A study of a graphite cavity chamber for absolute measurements of ^{60}Co gamma rays, 1973, *Metrologia*, **9**, 139-146.

[4] Laitano R.F., Toni M.P., Pimpinella M. and Bovi M. determination of the k_{wall} correction factor for a cylindrical ionization chamber to measure air kerma in a Co-60 gamma beam, 2002, *Phys.Med.Biol.*, **47**, No.14, 2411-2431.

[5] Laitano R. F., Pimpinella M., Toni M. P.and Tricomi G. Determination of the K_{wall} correction factor for cylindrical ionisation chambers of various dimensions, 2003, *CCRI(I) 16th meeting document* CCRI(I)/03-27, 4 pp.

[6] Laitano R. F., Pimpinella M., Toni M. P., Quini M., Bovi M., Re-determination of the air-cavity volume for the Co-60 gamma-ray air-kerma standard at the ENEA-INMRI, 2003, *CCRI(I) 16th meeting document* CCRI(I)/03-26, 6 pp.

[7] Allisy A. Comparison of standards of exposure, *Comité Consultatif pour les Étalons de Mesures des Rayonnements Ionisants*, *Section (I)*, 1983, **7**, p. R(I) 30-31.

[8] Laitano R.F., Lamperti P.J. and Toni M.P. Comparison of the NIST and ENEA air kerma standards, 1994, *ENEA Internal Report,* 33 pp.

[9] *Comité Consultatif pour les Étalons de Mesures des Rayonnements Ionisants*, Constantes physiques pour les étalons de mesure de rayonnement, 1985, *CCEMRI Section (I)*, **11**, R45.

[10] Boutillon M., Allisy-Roberts P.J. and Burns D.T. Measuring conditions used for the calibration of ionization chambers at the BIPM, 2001, *Rapport BIPM-01/04*, 19 pp.

[11] Boutillon M. Volume recombination parameter in ionization chambers, 1998, *Phys.Med.Biol.*, **43**, 2061-2072.

[12] Rogers D.W.O, Kawrakow I., Seuntjens J.P. and Walters B.R.B. User codes for EGSnrc, 2000, *NRCC Report PIRS-702*, (Otawa) NRC.

[13] Rogers D.W.O. and Treurniet J. Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, 1999, *NRCC Report PIRS–663*, and *CCRI 14th meeting document* CCRI(I)/99-26, 25 pp.

[14] Boutillon M. and Perroche A.-M., Radial non-uniformity of the BIPM ^{60}Co beam, 1989, *Rapport BIPM-89/2*, 9 pp.

[15] IAEA, X- and gamma-ray standards for detector calibration, 1991, *IAEA TECDOC-619*.

[16] Allisy-Roberts P.J., Boutillon M., Lamperti P., Comparison of the standards of air kerma of the NIST and the BIPM for ^{60}Co gamma rays, 1996, *Rapport BIPM-1996/09*, 8 pp.

[17] Laitano R. F., Physical parameters, correction factors and comparison results for the ENEA air kerma standard for Co-60 gamma rays, 2001*, CCRI(I) 15th meeting document*, CCRI(I)/03-40, 1 p.

[18] Rogers D.W.O., Bielajew A.F. and Nahum A.E. Ion chamber response and A_{wall} correction factors in a ^{60}Co beam by Monte Carlo simulation, 1985, *Phys. Med. Biol.*, **30**, 429–443.

[19] Bielajew A.F. and Rogers D.W.O. Implications of new correction factors on primary air kerma standards in ^{60}Co beams, 1992, *Phys. Med. Biol.*, **37**, 1283–1291.

[20] Kondo S. and Randolph M.L. Effect of finite size of ionization chambers on measurements of small photon sources, 1960, *Radiat. Res*., **13**, 37–60.

[21] Bielajew A.F. Correction factors for thick-walled ionisation chambers in point-source photon beams, 1990, *Phys. Med. Biol*., **35**, 501–516.

[22] Büermann L., Kramer H.-M. Csete I., Results supporting calculated wall correction factors for cavity chambers, 2003, *Phys. Med. Biol*. (In press).

[23] *Comité Consultatif des Rayonnements Ionisants*, The estimation of k_{att}, k_{sc} k_{CEP} and their uncertainties, 1999, CCRI, **16,** 145-146.

[24] Csete I., New correction factors for the OMH air kerma standard for ^{137}Cs and ^{60}Co radiation, 2001, *CCRI(I) 15th meeting document* CCRI(I)/01-03, 2 pp.

[25] Csete I., Büermann L., Kramer H.-M., Comparison of the PTB and OMH air kerma standards for ^{60}Co and 1^{37}Cs gamma radiation, 2002, *Report PTB-Dos-40*, Physikalisch-Technische Bundesanstalt, Braunschweig.

[26] Comité Consultatif des Rayonnements Ionisants, 2003, *Report of the 18th meeting*, CCRI **18** to be published.

[27] Kramer H.-M., Büermann L. and Ambrosi P. Change in the realization of the gray at the PTB, 2002, *Metrologia*, **39**, 111-112.

[28] Allisy-Roberts P.J., Burns D.T., Kessler C. and Spasić-Jokić V. Comparison of the standards of air kerma of the SZMDM Yugoslavia and the BIPM for ^{60}Co γ rays, 2002, *Rapport BIPM-02/01*, 9 pp.

[29] Allisy-Roberts P.J., Burns D.T., Kessler C., Ivanov R.N., Comparison of the standards of air kerma of the NCM Bulgaria and the BIPM for ^{60}Co γ rays, 2002, *Rapport BIPM-02/03*, 9 pp.

[30] Burns D.T., Calculation of k_{wall} for ^{60}Co air-kerma standards using PENELOPE, 2003, *CCRI (I) 16th meeting document*, CCRI(I)/03-40, 3 pp.

[31] MRA: *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 1999, 45 pp. http://www.bipm.org/pdf/mra.pdf.

October 2003