Comparisons between IRD and BIPM exposure and air-kerma standards for cobalt-60 gamma rays

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Abstract

Comparisons for cobalt-60 gamma rays between the exposure and air-kerma standards of the Bureau International des Poids et Mesures (BIPM) and the Instituto de Radioproteçao e Dosimetria (IRD) are reported. The measurements were performed for the assessment of the correction factors needed to derive the absolute value of exposure with the IRD chambers under the BIPM irradiation and measurement conditions. The results indicate that the difference between the average value of the two IRD standards and the BIPM standard is of the order of 0,1 % when the same physical data are used. This difference is consistent with the estimated uncertainties associated with the experimental conditions. Finally, the results of the IRD standards are in excellent agreement with the values obtained from previous comparisons of standards from several national laboratories with the BIPM standard.

1. Introduction

The standard instrument which, at present, is best suited for absolute measurements of exposure in air is a cavity ionization chamber. In the past, high-pressure free-air chambers have been successfully used, but are no longer available [1, 2].

The exposure, $\dot{X}$, as defined by the International Commission on Radiation Units and Measurements (ICRU) [3], is the quotient of dQ by dm, where dQ is the absolute value of the total charge of the ions of one sign produced in air when all electrons (negatrons and positrons) liberated by photons in air of mass dm are completely stopped in air. The SI unit is the coulomb per kilogram, but the special unit, the roentgen, which is equal to $2{,}58 \cdot 10^{-4}$ C kg^{-1}, is still in use temporarily.

The cavity ionization chambers are constructed from highly pure graphite and require good insulator materials in order to minimize the leakage and polarization effects and to provide an acceptable long-term stability.

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The reliability of a cavity-chamber determination of exposure has to be periodically verified by comparing it with other standards of comparable accuracy [4].

Exposure measurements of ^{60}Co radiation are of particular importance because they still largely form the basis for absorbed dose calibrations of high-energy electrons and X rays used for the treatment of cancer patients, for radiobiological studies as well as for radiation protection measurements.

In 1970 the Section I (Rayons X et γ, électrons) of the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) [5] expressly recommended direct comparisons of exposure standards for ^{60}Co γ rays.

This report deals with the comparisons between the cavity chamber standards of IRD and the BIPM standard. It has been performed during a period of seven months under the BIPM irradiation and measurement conditions.

For the correction factors needed to derive the absolute value of exposure with the IRD chambers, numerical values have been obtained at the BIPM. In addition, the results of several comparisons between IRD and BIPM standards are included. Finally, a comparison is made between the average value of the two IRD chambers, for all measurements taken, with the values obtained from previous comparisons involving the standards of several national laboratories with the BIPM standard. The new values of the physical constants recommended by CCEMRI [6] are used throughout this report.

2. Description of the standard chambers

The cavity chambers involved in the present work have the same wall and electrode material (graphite), but are different in shape, size and sensitive volume.

The BIPM standard is a flat cylindrical chamber (pill-box type); it has been described elsewhere [7].

The IRD standards are two identical cylindrical chambers (thimble type) constructed at the Österreichisches Forschungszentrum Seibersdorf (OFS), with slightly different sensitive volumes. The study of the wall effect of those chambers was made possible by using a series of close-fitting graphite caps in order to increase the thickness of the wall, as shown in Figure 1.

The essential dimensions of the BIPM standard are summarized in Table 1 and the complete set of characteristics and dimensions of the IRD standards are given in Table 2 and shown in Figure 2.

3. Measurement conditions

The measurements have been carried out in the BIPM cobalt-60 γ-ray facility which was originally designed to minimize the contribution of scattered radiation. Nevertheless, the scattered component in the beam, primarily coming from the source itself in addition to its environment, is still of the order of 8 %.

The experimental conditions are summarized in Table 3. The chambers were mounted on the slide rest of a lathe machine, and its displacement has been measured with a specially mounted micrometric scale. The irradiation room is thermally isolated from the rest of the climatized irradiation hall in order to damp the air temperature fluctuations to about ± 0,01 °C during the measurements. The center of the chamber was placed at the reference plane and the ionization currents were measured using a Townsend method with an automatic device described elsewhere [8]. As a normal procedure, the currents were measured for the two polarities of collecting potential and averaged to eliminate possible "extracameral" effects on the chamber current. The leakage currents were measured before and after each set of measurements and their relative values were normally found to be less than 0.01 %.

Since the chambers are provided with a ventilation hole, the environmental conditions were measured using near the chamber a calibrated thermistor surrounded by a polystyrene cap and a pressure transducer. Temperature and pressure were read for each measurement.

A lead shutter was used to maintain the source in a fixed position during the exchange of chambers in order to avoid any source mispositioning.

The measurements were initially done with the IRD chamber and later on with the BIPM chamber. This method seems to be appropriate since no trend for measurements taken in a same day could be observed.

4. Exposure and air kerma determination from cavity chamber measurements

The formalism required for the determination of exposure has been treated by Allisy [9] and extended by Boutillon and Niatel [7] for the case where the dimensions of the cavity and the presence of the collecting electrode inside the cavity has been taken into account.

However, several correction factors must be derived empirically and introduced in order to account for the presence of the chamber wall in the beam, the chamber design, as well as the environmental and measuring beam conditions.

By taking those facts into consideration and applying the Bragg-Gray principle to the measurement of ionization in the cavity, the exposure rate in air, $\dot{X}$, which would exist at the reference plane in the absence of the chamber, is given by

$$\dot{X} = \frac{I}{v\rho} \bar{s}_{C,a} \frac{(\mu_{en}/\rho)_{air}}{(\mu_{en}/\rho)_C} \Pi k_j ,$$

where $\dot{X}$ is the exposure rate,

I is the ionization current resulting from the collection of the ions produced in the air of the cavity,

v is the sensitive volume of the chamber in which the charge is collected,

ρ is the air density under the measurement conditions,

$\bar{s}_{C,a}$ is the mean ratio of the restricted mass stopping power of graphite to that of air, taking into account the spectra of the incident radiation for the BIPM cobalt-60 source. The cut-off energies are 14 keV and 17,5 keV for BIPM and IRD chambers, respectively,

$\frac{(\mu_{en}/\rho)_{air}}{(\mu_{en}/\rho)_C}$ is the ratio of the mass energy absorption coefficients for air and graphite,

Πk_j is the product of several correction factors such as

k_l correction for leakage current,
k_s correction for loss of ionization due to recombination,
k_H correction for water vapor in air since the exposure is defined for dry air,
k_{st} correction for scattering from the chamber stem,
k_{rn} correction for radial non-uniformity of the beam,
k_{an} correction for axial non-uniformity of the beam,
k_w correction for chamber wall attenuation.

The sensitive volume of the IRD chambers has been estimated by subtracting from the volume of the cylindrical cavity (determined by the Austrian Federal Office of Metrology with an uncertainty of 0,1 %) the volume of the electrode (carefully mechanically measured) and the additive sensitive volume (estimated by geometrical considerations), as shown in Figure 3.

The methods used for the determination of the correction factors for both chambers are described elsewhere [7, 10] and the experimental results obtained for k_j under the BIPM measuring conditions are given in Table 4. The values of $\bar{s}_{C,a}$ were calculated by Boutillon [11] on the basis of the Spencer-Attix theory [12] which takes into account the cavity size and uses a mean value for the Compton electron spectrum.

The values of the restricted mass stopping powers of air and carbon were calculated from an ICRU report [13], which contains the most recent data on mean excitation energies, namely 78 eV for carbon and 85,7 eV for air, and the mass-energy absorption coefficients are taken from Hubbell [14]. For the measurement of the ionization current the air attenuation between the source and the chamber was also considered, as well as the air compressibility factor due to the fact that air does not behave exactly like an ideal gas.

The determination of air kerma rate from the measurements of exposure rate is obtained by the equation

$$\dot{K}_{air} = \frac{\dot{X}}{1 - \bar{g}} \frac{W}{e} ,$$

where
$\dot{X}$ is the exposure rate,
$\bar{g}$ is the fraction of electron energy lost by bremsstrahlung,
W is the mean energy necessary to produce an ion pair,
e is the electrical charge of an electron.

The value of the average energy required to produce an ion pair in dry air, W, was taken from [15] and the fraction of energy of secondary charged particles produced in interaction that is lost to bremsstrahlung, g, has been calculated by Boutillon [16].

5. Determination of the correction factors for the IRD chambers

The correction factors for both IRD chambers have been determined for the BIPM measuring conditions.

A dependence of the ion collection efficiency upon the ionization current has been observed, which indicates a contribution of volume recombination. Therefore, the correction for lack of saturation can be determined by the following method. It is assumed that

$$\frac{I_s - I_v}{I_s} = P(I_s, V) = \frac{a}{V} + b \frac{I_s}{V^2} ,$$

where
I_v is the average measured current for both polarities,

I_s is the saturation current,

$\frac{a}{V}$ is the initial recombination,

$b \frac{I_s}{V^2}$ is the volume recombination.

By comparing the measurements done for two voltages V_o and V_o/α, one obtains

$$P(I_s, V_o) = \frac{a}{V_o} + b\,\frac{I_s}{V_o^2} ,$$

$$P(I_s, V_o/\alpha) = \frac{\alpha a}{V_o} + \frac{\alpha^2\, b\, I_s}{V_o^2} ,$$

and the difference is the quantity measured, m. The coefficients a and b used in the above equations can be obtained by a least-squares method from a set of equations (n) which are of the form

$$C_i\, a + D_i\, b = m_i ,$$

where $C_i = (\alpha_i - 1)/V_o$ and $D_i = (\alpha_i^2 - 1)(I_o)_i/V_o^2$.

The measurements at eight different voltages have been carried out in air with a cobalt source of 6 TBq, giving a current of 4,11 pA, and in water (5 $g\cdot cm^{-2}$) with a source of 170 TBq giving a current about 30 times higher (129,5 pA). The values obtained for the corrections at 250 V are 1,002 17 ± 0,000 03 and 1,002 34 ± 0,000 04 respectively for the measurements in air and in water (for the chamber CC-01-110). In the first case, the volume recombination is negligible; in the second case, this type of recombination amounts to 0,017 %.

The correction for chamber wall attenuation, k_w, has been measured by adding successively several graphite caps to each of the IRD chambers. The measured current was plotted versus the chamber wall thickness and the value of k_w was determined by extrapolation, taking into account the mean center of electron production in the wall. This last point was assumed to be at 0,78 mm from the inner cavity wall [17].

The stem-scatter correction, k_{st}, was also measured using a dummy stem of identical size and composition, placed on the side opposite to the chamber stem.

The correction for humidity is the one recommended by CCEMRI [18]. This correction is needed since the exposure is a quantity defined for the ionization of air free of water vapour, which modifies the measured current.

The numerical values for the correction factors and the physical data adopted in the present work are given in Table 4.

6. Statistical procedure

The normal procedure adopted for all the chambers consisted in performing a series of measurements for both polarities of the collecting potential. Each series was subdivided into at least five groups, which, in turn, contain five measurements of ionization current.

The statistical evaluations have been performed in the following way:

- The short-term standard deviation for the mean of a group is given by the mean relative standard deviation of individual readings within a group divided by the square root of the number of readings (currently 5).

- The medium-term standard deviation for the mean of a group is given by the relative standard deviation of the average value of current of each group. In this case the mean values of the various groups are treated as if they were individual values.

- The medium-term standard deviation for the mean of a series is given by the ratio of the medium-term standard deviation for the mean of a group to the square root of the number of groups.

When in comparing the short-term and medium-term standard deviations of a group no significant difference is observed, one may conclude that there has been no trend within the series.

As an example, for a mean current value of 4,616 1 pA measured with an IRD chamber, typical relative statistical characteristics are:

- short-term standard deviation for the mean of a group = $2{,}9 \cdot 10^{-4}$
- medium-term standard deviation for the mean of a group = $2{,}7 \cdot 10^{-4}$
- medium-term standard deviation for the mean of a series (with seven groups) = $1{,}0 \cdot 10^{-4}$.

7. Results and conclusions

The final results of the comparison of exposure and air kerma between the two IRD ionization chambers and the BIPM standard are shown in Figure 3. The maximum relative deviation between the IRD chambers for the entire period of study is less than 0,1 %. The comparison between the average value of the two IRD chambers with the average value of the BIPM standard shows a deviation smaller than 0,1 %.

The overall experimental uncertainties involved in the BIPM-IRD comparison are shown in Table 5.

The results shown in Figure 4 indicate that, provided that the same physical data and experimental conditions are used, the agreement between the IRD and BIPM standards for exposure in air is consistent with the estimated experimental uncertainties.

It is also shown in Figure 5 that there is an excellent agreement between the average taken from the eight months of study of the two IRD standards and the values based on previous comparisons of the standards from several national laboratories with the BIPM standard.

Therefore, it may be concluded that, during the period of this study, the two IRD standards have demonstrated to have an appropriate design, as well as physical characteristics and a stability as required for a primary standard of exposure in air for cobalt-60 gamma rays.

It is envisaged to continue this work under the IRD irradiation and measuring conditions in order to assess the long-term stability and the metrological consistency between the two IRD standards. In the future it will be appropriate to perform another intercomparison with the BIPM standard.

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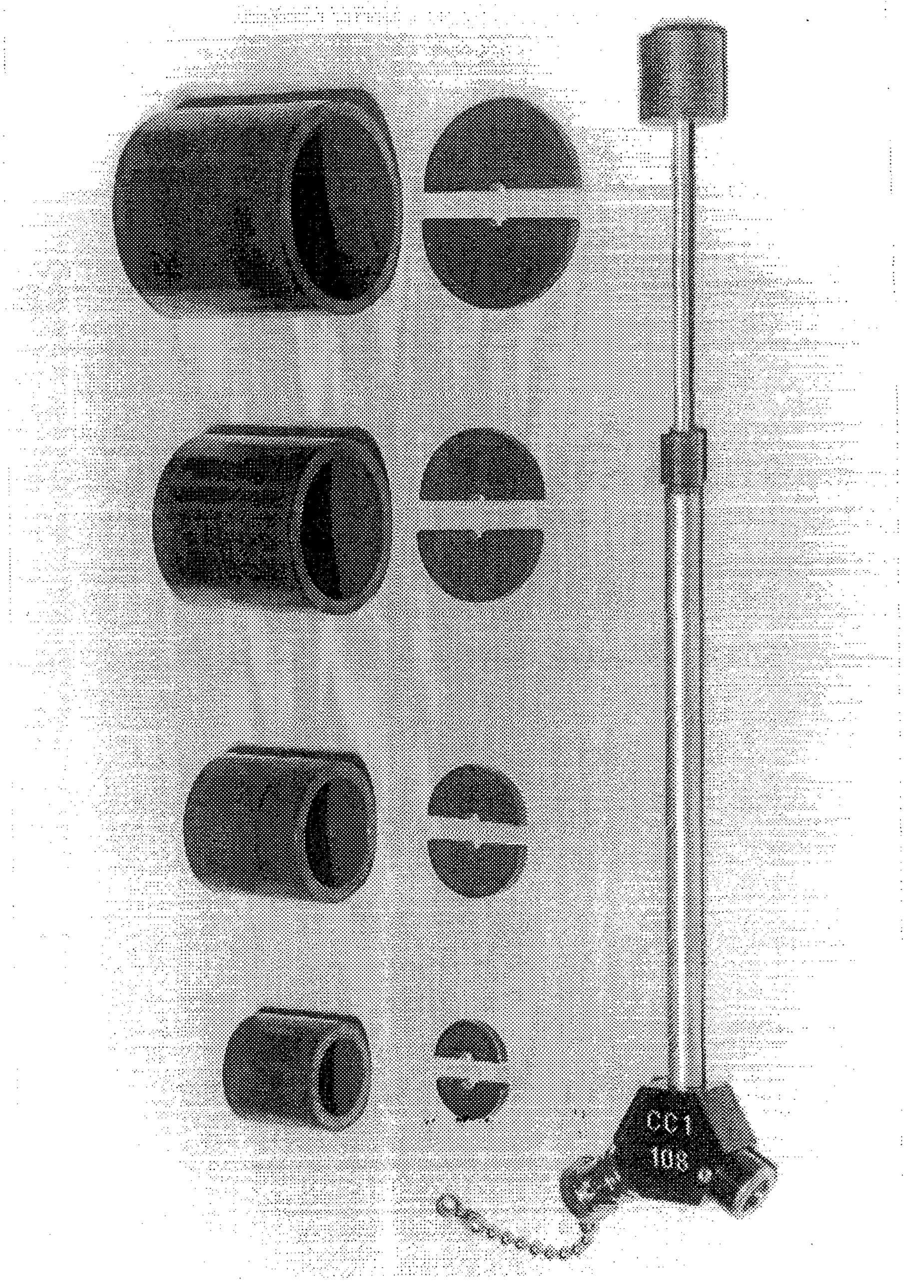

Fig. 1 - A picture of chamber n° 108 with the graphite caps and the lower base used to ensure a symmetrical scattering geometry with respect to the cavity.

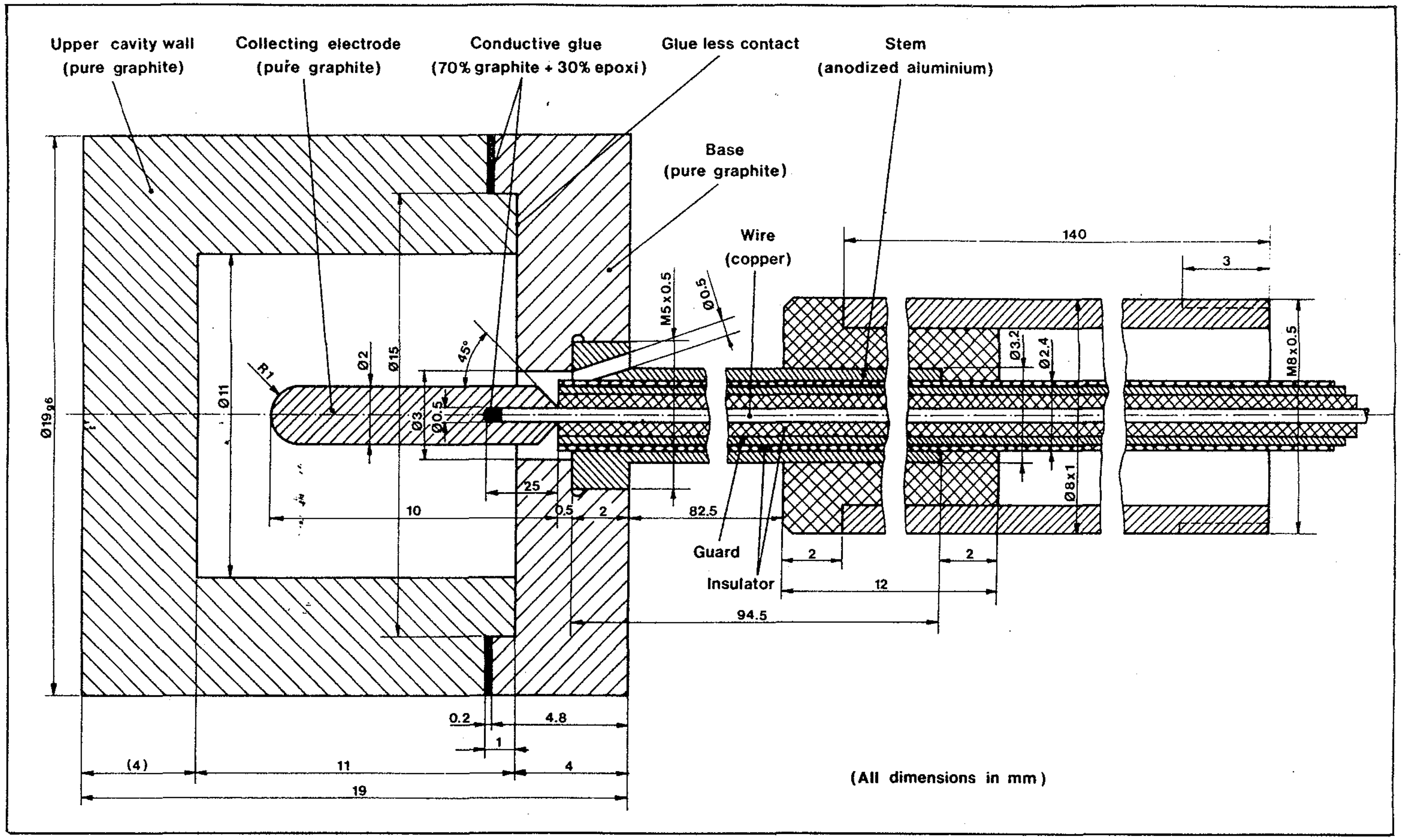

Fig. 2 - Schematic diagram of the IRD graphite cavity chamber, including its dimensions and material specification.

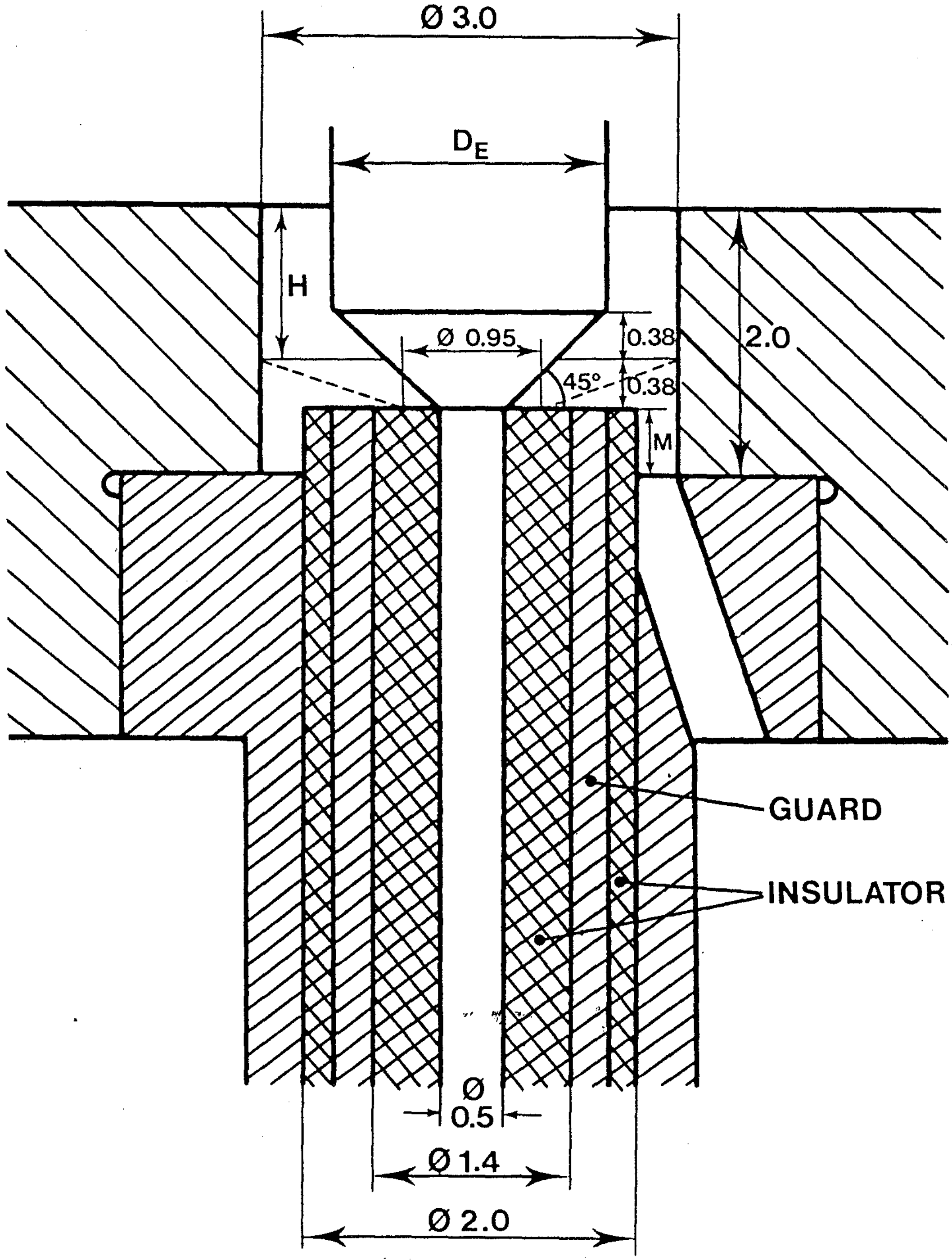

Fig. 3 - Diagram of the lower part of the interior of the chamber used to estimate the electrode volume and the additive sensitive volume.

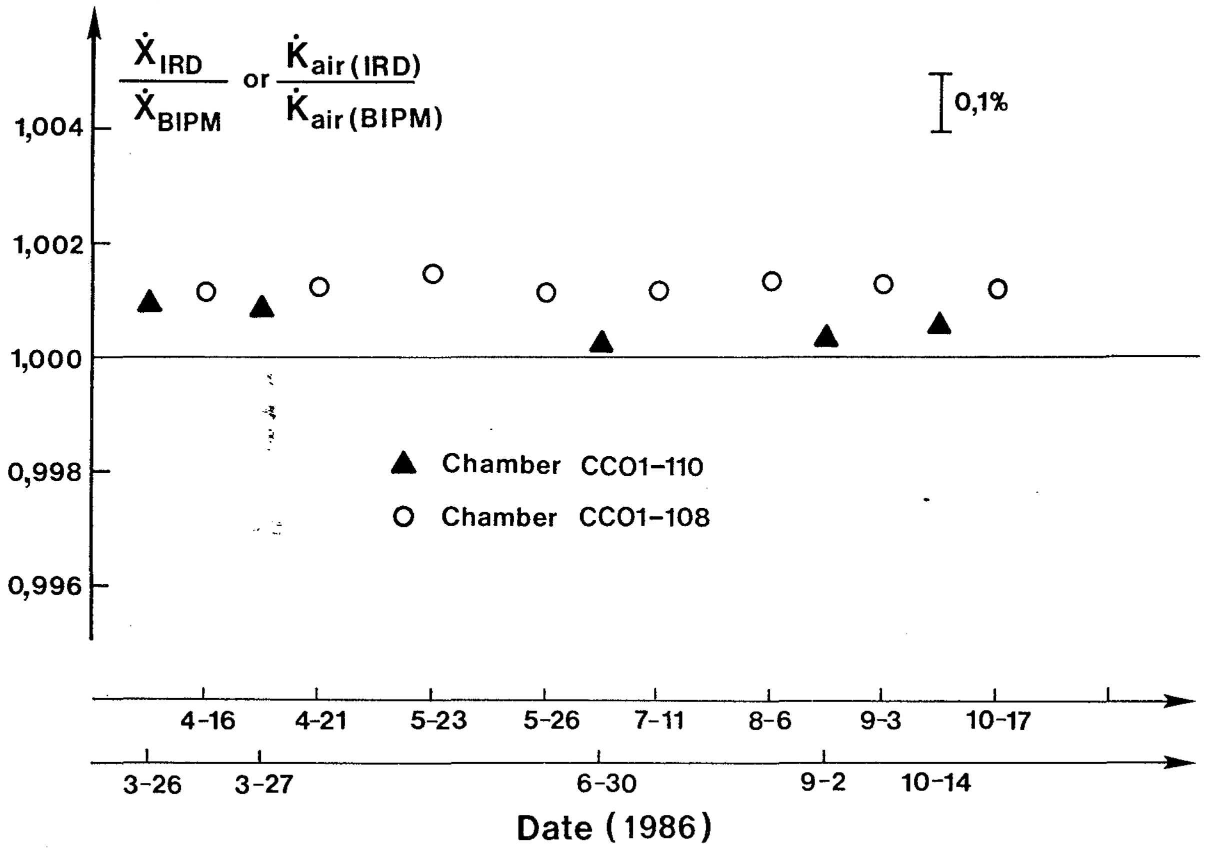

Fig. 4 - Long-term stability of the two IRD standards of exposure and air kerma normalized to the BIPM standard.

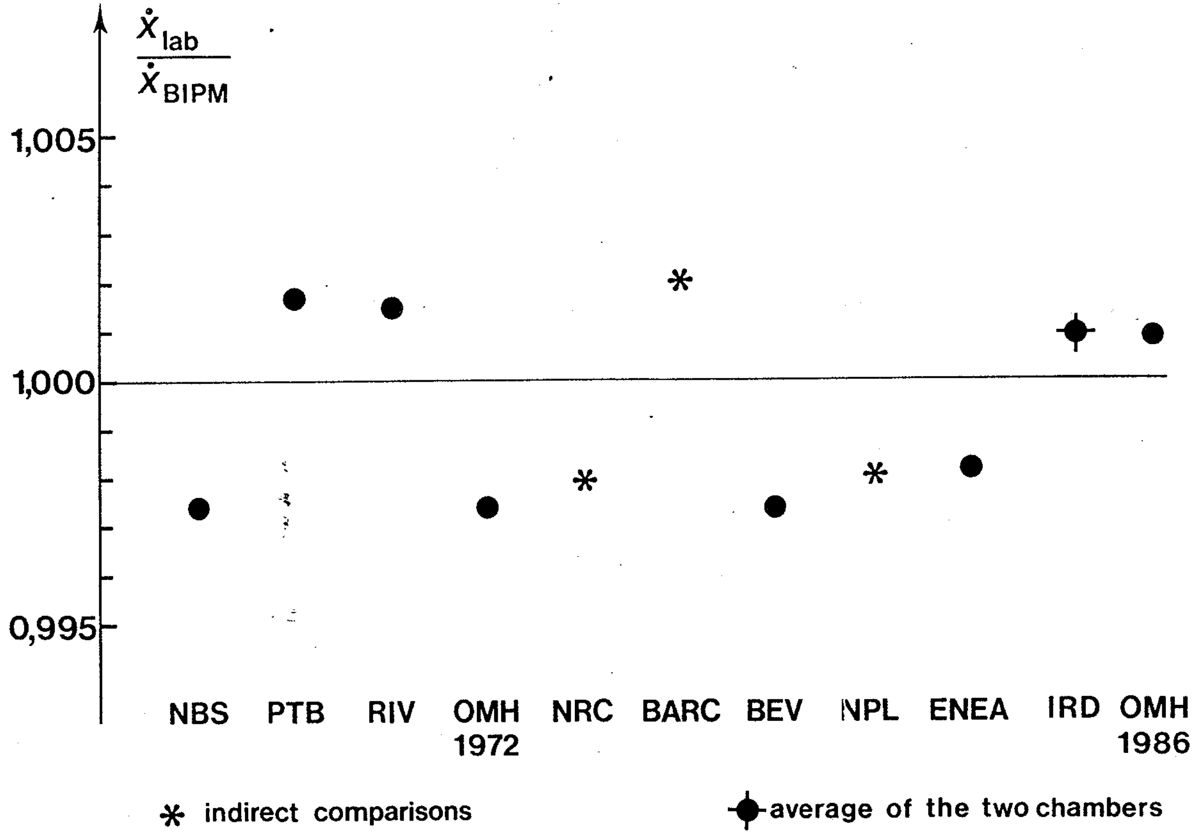

Fig. 5 - Exposure comparison between several national standards with the BIPM standard, including the average value of thirteen measurements taken with the two IRD standards.

Table 1 - Characteristics and dimensions of the BIPM standard*
(pill-box type)

Dimensions of the chamber

Diameter		
	outside	5,05 cm
	inside	4,50 cm
Height		
	outside	1,08 cm
	inside	0,51 cm
Sensitive volume		6,811 6 cm^3
Wall thickness		0,520 g/cm^2
Wall material		graphite
	density	1,84 g/cm^3
	impurities	$<$ 10 ppm

* For further details see [4] and [7]

Table 2 - Characteristics and dimensions of the IRD standard*
(thimble type)

Dimensions			n° 108	n° 110
Chamber				
nominal outer height		(mm)	19	19
nominal outer diameter		(mm)	19	19
nominal inner height		(mm)	11	11
nominal inner diameter		(mm)	11	11
volume of cylindrical* cavity		(cm^3)	1,030	1,039
volume of the electrode		(cm^3)	0,030 8	0,029 2
additive sensitive** volume		(cm^3)	0,008 2	0,007 8
sensitive volume***		(cm^3)	1,007 4	1,017 6
Electrode				
nominal diameter		(mm)	2	2
nominal length			10	10
Wall and absorption caps				
wall thickness		(mm)	4	4
outer diameter	cap 1	(mm)	27	27
	cap 2	(mm)	35	35
	cap 3	(mm)	43	43
	cap 4	(mm)	51	51
material	ultra pure graphite EK51 Ringsdorf			
	density*** 1,71 g/cm^3			
	impurities <150 ppm of ash content			
Insulator	polyethylene			

* Measured by the Austrian Federal Office of Metrology
** See Fig. 3
*** Provided by the OFS

Table 3 - Measurement conditions

Source activity		1,8 TBq (48 Ci) on 1st January 1986
Source size		
diameter	(mm)	5,6
height	(mm)	4,9
Distance between source center and chamber center	(mm)	112,0
Beam diameter at reference plane	(cm)	≃ 10,0
Exposure rate		3,546 μA/kg = 0,8246 R/min on 1st January 1986
Relative humidity		≃ 50 % at 21 °C

		BIPM	IRD n° 108	IRD n° 110
Capacitance (nominal)	(nF)	2	1	
ΔV (nominal values)	(mV)	300	100	
Δt	(s)	≃ 22	≃ 25	
Collection potential	(V)	± 80	± 250	
Ratio I_+/I_- of the currents measured		1,000 2	1,0015	

Table 4

a) Correction factors

		BIPM*	IRD n° 108 and n° 110
k_s		1,001 5	1,002 2
k_{st}		1,000 0	1,000 0
k_{rn}		1,001 3	-
k_{an}		0,996 8	-
k_w		1,003 7	1,012 5
k_H		0,997	0,997

b) Physical data

Air density	1,293 03 $kg \cdot m^{-3}$		
$\bar{s}_{C,a}$**		1,000 3	1,000 7
I_{air}	85,7 eV		
I_C	78,0 eV		
s		14 keV	17,5 keV
$\frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_C}$	0,998 5		
W/e***	33,97 J/C		
μ_{air}	0,007 530 m^{-1}		
g	$3,2 \cdot 10^{-3}$		

* See details in [7] and [4]
** ICRU, [13]
*** CCEMRI [16], and Boutillon and Perroche [15]

Table 5

Uncertainties in IRD-BIPM comparison

Exposure rate and kerma rate

	Estimated uncertainties* (1σ) in %					
	type A – statistical (degrees of freedom) s_i (ν_i)			type B u_j		
	IRD	BIPM	IRD/BIPM	IRD	BIPM	IRD/BIPM
Physical data						
air density at STP						–
$\bar{s}_{C,a}$						0,03
$(\mu_{en}/\rho)_a/(\mu_{en}/\rho)_C$						–
1 – g (for kerma rate)						–
W/e (for kerma rate)						–
Correction factors						
K_s	0,003(7)	0,007(7)	0,008	< 0,01	< 0,01	< 0,01
K_h						–
K_{st}			0,01	0,01	0,01	
$K_{W,BIPM}$: K_{at}					0,04	
$K_{W,BIPM}$: K_{CEP}					0,01	0,11
$K_{W,BIPM}$: K_{sc}					0,07	
$K_{W,cyl}$	0,01(3)		0,01	0,08		
K_{an}				0,07	0,07	0,10
K_{rn}				0,02	0,02	0,03
Measurement of I/vp						
v		0,011(18)	0,011	0,03**	0,03	0,04
I						
corrections concerning ρ: pressure			0,012(7)			
corrections concerning ρ: temperature						
Measurement of distance						< 0,01
quadratic sum			0,02			0,16

combined uncertainty: $\sqrt{\Sigma s_i^2 + \Sigma u_j^2} = 0,16$

* The uncertainties for IRD and BIPM which cancel out in the $\dot{X}_{IRD}/\dot{X}_{BIPM}$ ratio are not quoted here.

** Refers to the total uncertainty (types A and B) provided by the Austrian Federal Office of Metrology.

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