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COMITATO NAZIONALE PER LA RICERCA E PER LO SVILUPPO DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE

The primary exposure standard for Co-60 gamma radiation: characteristics and measurements procedures

R.F. Laitano, M.P. Toni

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THE PRIMARY EXPOSURE STANDARD FOR Co-60 GAMMA RADIATION: CHARACTERISTICS AND MEASUREMENTS PROCEDURES

Riassunto – Nell'ambito dei programmi dell'Enea, il Laboratorio di Metrologia delle Radiazioni Ionizzanti ha, come compito principale, lo sviluppo dei mezzi e delle procedure sperimentali per la realizzazione dei Campioni Primari delle principali grandezze dosimetriche utilizzate in campo radioprotezionistico, industriale e sanitario.
In questo rapporto vengono descritte le caratteristiche e le procedure di misura di una camera a cavità in grafite che rappresenta uno dei Campioni Primari messi a punto nel Laboratorio e che è utilizzata per la misura assoluta dell'esposizione dovuta alla radiazione gamma del Co-60.
Sono inoltre riportati anche i risultati di alcuni confronti internazionali effettuati con alcuni laboratori metrologici europei.

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THE PRIMARY EXPOSURE STANDARD FOR Co-60 GAMMA RADIATION: CHARACTERISTICS AND MEASUREMENTS PROCEDURES

Summary – *A description is given of a cavity ionization chamber used, as a primary exposure standard, at the Laboratorio di Metrologia delle Radiazioni Ionizzanti of the Enea in Italy.*
The primary standard is designed to make absolute measurements of exposure due to the Co-60 gamma radiation. The procedures for the realization of the exposure unit are also described.
Finally the results of some international comparisons are reported.

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THE PRIMARY EXPOSURE STANDARD FOR Co-60 GAMMA RADIATION: CHARACTERISTICS AND MEASUREMENTS PROCEDURES

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1 - Introduction

To realize the exposure unit for the Co-60 gamma radiation an absolute cavity chamber is being used since 1982 at the Laboratorio di Metrologia delle Radiazioni Ionizzanti of ENEA. By this primary standard calibrations of secondary standard class dosemeters are made. The calibrations concern in particular some reference therapy level dosemeters used in radiotherapy centres in Italy.

As for the radioprotection level dosemeters, the calibrations are mostly carried out through ionization transfer chambers whose volume is in the range from 30 cm^3 to 1000 cm^3. These chambers are referred directly or indirectly (according to their volume) to the primary standard and their use as reference standards introduce an additional uncertainty not greater than $\pm$ 2%.

In this report the relevant characteristics of the absolute cavity chamber and the measurements procedures are described.

2 - Cavity chamber characteristics

The ionization chamber was built to meet the Bragg-Gray cavity theory conditions for the Co-60 gamma radiation. The chamber geometry is cylindrical and both its walls and the collecting electrode are made by high purity graphite. In Fig. 1 the chamber scheme is reported. The upper part of the chamber is fixed to its base by conductive glue so that the glue thickness does not increase the dimensions of the chamber volume as determined before mounting the chamber components.

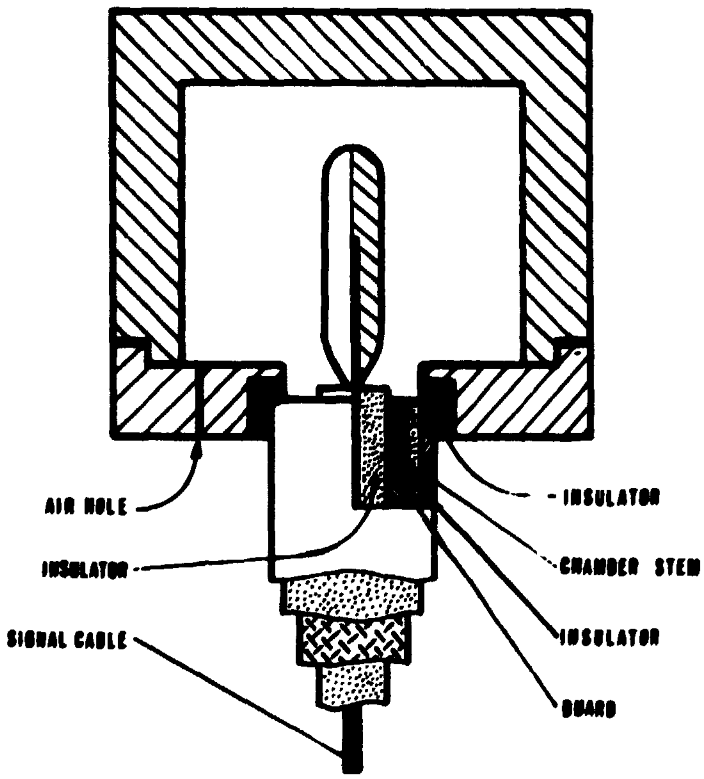


Fig. 1 - Scheme of the graphite cavity chamber.

The collecting volume was mechanically determined with an uncertainty of about 0,15%.

The aluminium chamber stem has a small diameter of about 4 mm to minimize scattered radiation.

A photograph of the spare parts of the chamber is reported in Fig. 2.

Fig. 2 - Photograph of the cavity chamber components.

In Table I some relevant data of the chamber are reported. The shape and dimensions of this chamber are similar to the standard cavity chamber existing at the hungarian primary standard laboratory (OMH).

TABLE I

Nominal dimensions of the ENEA graphite cavity chamber

Diameter of cavity (cm)		≈ 1,1
Height of cavity (cm)		≈ 1,1
Wall thickness (cm)		≈ 0,4
Collecting electrode (cm)	Diameter	≈ 0,2
	height	≈ 1
Volume of cavity (cm^3)		1,022

3 - Irradiation facilities

The chamber is usually positioned at a distance of about 111 cm from a Co-60 source whose activity is about 26 TBq (12-31-1983). At this distance the beam diameter is about 10 cm.

The source collimator is designed to minimize the electron contamination in the gamma beam. The percentage of photon scattered in the beam due to the collimator was estimated to be not greater than 3%. Actually, the largest contribution of degraded photons originates within the source itself and its amount was estimated as about 16%. Therefore the overall percentage of photons emerging from the collimator with an energy different from that characteristic of the Co-60 radiation should be not greater than 20%.

For a comparative analysis, it is worthwhile to mention the figure of 8% for the scattered photons from the Co-60 irradiator at the BIPM, but in this case the source is smaller in size and activity by a factor four than that used in our measurements.

In Table II some relevant data on the irradiating system are summarized.

TABLE II

Experimental conditions at the ENEA for exposure measurements with the cavity chamber

Co-60 source activity (TBq) (12-31-1983)		≈	26
Source diamensions	diameter (mm)	≈	20
	height (mm)	≈	20
Source-chamber distance (cm)		≈	111
Beam diameter at the reference plane (cm)		≈	10
Exposure rate (R/min) (12-31-1983)		≈	12

The beam homogeneity at the reference plane was measured by means of a small ionization chamber whose volume is 0,1 cm^3 about. In Fig. 3 one example of the homogeneity curves of the beam is reported. The beam intensity does not appreciably change within distances of 1 cm from the beam axis and decreases by about 0,2% after displacements up to 2 cm.

The reproducibility in chamber positioning at the measuring point is assured by a combined mechanical-optical system which can be partially observed in the photograph of Fig.4 where the Co-60 irradiator and the cavity chamber are also shown.

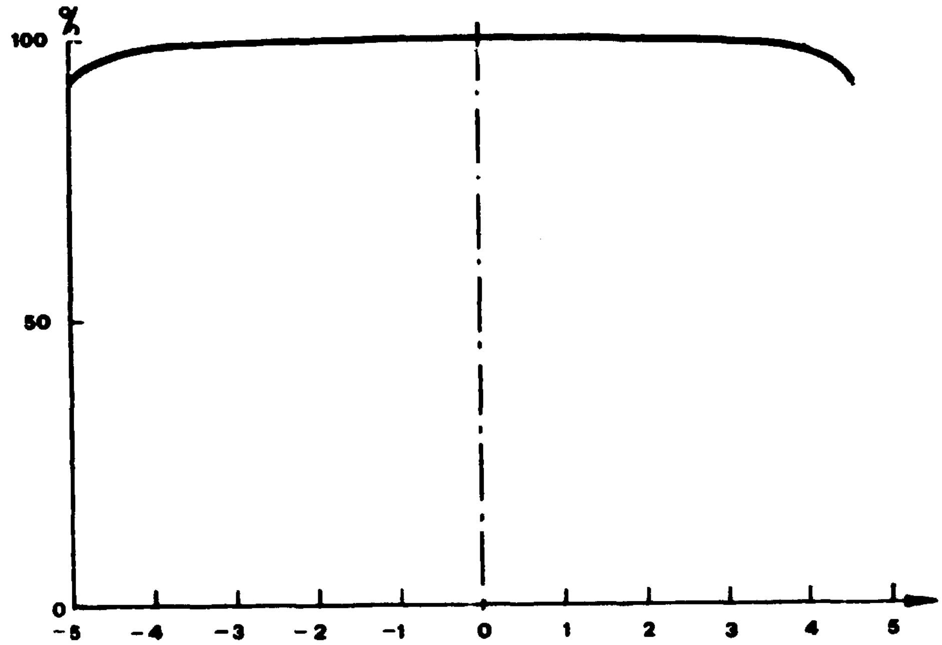


Fig. 3 - Homogeneity curve of Co-60 gamma beam along the vertical direction with respect to the beam axis.

4 - Charge measuring system

The current integrator associated to the standard cavity chamber is based on a MOSFET high gain charge amplifier ($A \approx 10^5$) with feedback interchangeable standard capacitors. The range of currents which can be measured with an accuracy of ± 0,2% is between 10^{-8} A and 10^{-14} A.

The details of this system equipped with a microcomputer will be published elsewhere.

5 - Absolute exposure determination

The exposure rate measured by a graphite cavity chamber for which the Bragg-Gray conditions are satisfied at the radiation quality of interest, can be expressed by /1/

$$\dot{X} = I \frac{1}{v\rho} \cdot \frac{1}{\bar{f}} \left(\frac{\mu_{en}}{\rho}\right)_c^a \cdot \pi K_i \quad (C \cdot kg^{-1} . s^{-1}) \qquad (1)$$

where I is the mean value of the currents I^+ and I^- measured at positive and negative chamber polarity, ρ is the air densi ty at the reference conditions and v is the chamber volume.

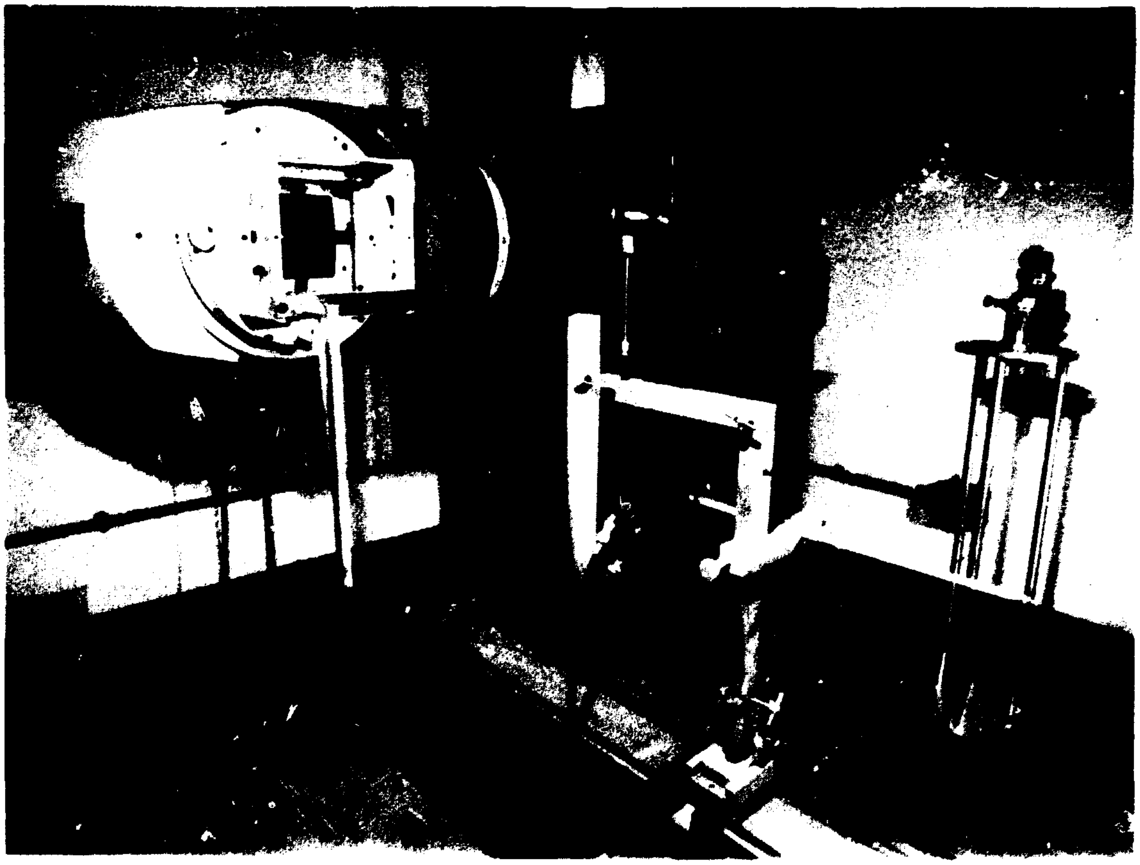


Fig. 4 - Photograph of the cavity chamber and the irradiating system.

The factor $\frac{1}{\bar{f}}$ represents the carbon-air mean mass collision stopping power ratio, and $\left(\frac{\mu_{en}}{\rho}\right)_c^a$ is the air-carbon mass energy absorbtion coefficient ratio.

The product πK_i includes all the corrective terms to be considered in an absolute exposure measurement by a cavity chamber /1/ and which will be discussed in paragraph 5.3.

The numerical values of all the physical parameters in the eq. (1), as determined in the present work, are reported in Table III. The associated uncertainties are given in Table IV.

5.1 - Stopping power ratio

The carbon-air mean mass collision stopping power ratio, $\frac{1}{f}$, was determined on the basis of the Spencer-Attix theory /2, 3/ which takes into account the cavity size. In this approach the stopping powers values are averaged on the Compton electron spectra with electron energies greater than a prefixed treshold value Δ.

The Δ value is related to the cavity size as this value corresponds to the minimum energy necessary to the electrons which exactly cross the cavity considered. Such electrons are that whose "effective range" R_p is equal to the mean chord crossing the cavity and whose lenght is given by /4/:

$$\bar{d} = 4 \frac{v}{a} \qquad (2)$$

where v and a are the volume and the internal surface of the cavity respectively.

For our chamber geometry it results:

$$\bar{d} = R_p = 0,717 \text{ cm} \qquad (3)$$

To obtain the cut-off energy Δ, we referred to the paper of Boutillon /5/ who determined the $\bar{f}$ and Δ values as a function of the electron range R.

According to Spencer /6/, the electron range R can be determined from the "effective range" R_p as:

$$R = 1{,}25\ R_p \qquad (4)$$

which from the (3) gives R = 0,896 cm for the ENEA cavity chamber.

The numerical values of $\bar{f}$ and Δ were actually determined from a further calculation of Boutillon /7/ more recent than ref. /5/, thus obtaining:

$$\Delta = 25{,}0\ \text{keV}$$

$$\bar{f} = 0{,}9930$$

For this determination the air and carbon mean excitation energies, I_{air} and I_c respectively, were taken from Berger and Seltzer /8/ as:

$$I_{air} = 86{,}8\ \text{eV}$$

$$I_c = 78{,}0\ \text{eV}$$

5.2 - Energy absorbtion coefficient ratio

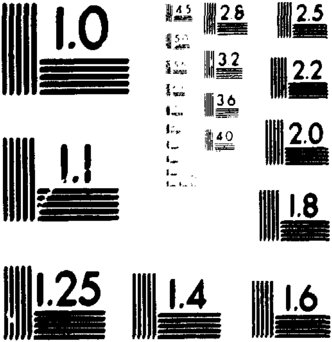
The air carbon mass energy absorbtion coefficient ratio, $\left(\frac{\mu_{en}}{\rho}\right)^a_c$ was determined from the Hubbell data /9/ for the

TABLE III

Correction factors and physical parameters for the graphite chamber

K_s^*	(saturation)	$1{,}001_9$
K_{st}^*	(radiation scattered by stem)	$1{,}000$
K_{rn}	(beam radial non-uniformity)	$1{,}000$
K_{an}	(beam axial non-uniformity)	$0{,}997$
K_c^*	(wall thickness)	$1{,}015_6$
K_{CEP}	(origin of electron production)	$0{,}997_2$
$K_W^* = K_c' \cdot K_{CEP}$	(wall effect)	$1{,}012_7$
I^+/I^- collecting voltage (V)		$1{,}003$
ρ: air density ($kg \cdot m^{-3}$) (at reference conditions)		$1{,}204_5$
$\bar{S}_a^c$: carbon air mass collision stopping power ratio		$0{,}993_0$
$(\mu_{en}/\rho)_c^a$: air-carbon mass energy absorbtion coefficient ratio		$0{,}998_5$

The values of the correction factors $K_{T,P}$ (temperature and pressure) and K_H (humidity) were determined according to ambient conditions. Reference conditions are at T = 293,15 K and P = 101,325 kPa.



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STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

TABLE IV

Uncertainties (%) associated to the parameters for exposure rate determination with the ENEA graphite cavity chamber (see Table III and eq. 1)

ΔK_s	ΔK_c	ΔK_{CEP}	ΔK_{st}	ΔK_{rn}	ΔK_{an}	ΔK_{TP}	ΔK_H	Δv	ΔI	$\Delta \bar{T}$	$\Delta \left(\frac{\mu_{en}}{\rho}\right)^a_c$
0,02	0,05	0,2	0,03	0,1	0,1	0,15	0,05	0,14	0,2	0,5	0,1

Overall uncertainty* : 0,64

*Square root of quadratic sum of the single uncertainties (95% confidence level)

Co-60 radiation and resulted:

$$\left(\frac{\mu_{en}}{\rho}\right)_a^c = 0,9985$$

5.3 - Correction factors, K_i

The correction factors, K_i, appearing in eq. (1) were evaluated taking into account the various physical effects which take place in the cavity chamber and which are briefly described below.

Lack of saturation

Part of the ionization in the cavity chamber is lost by ion recombination even at relatively high collecting voltages. The correction factor for lack of saturation is given by:

$$K_s = \frac{I_s}{I} \qquad (5)$$

where I is the ionization current at the usual collection voltage and I_s the current corresponding to the ideal conditions of full saturation.

The current I_s was determined by extrapolating the experimental curve $(\frac{1}{I}, \frac{1}{V})$ to $\frac{1}{V} = 0$. As this plot resulted to be linear with a regression coefficient of 0,9970 it was assumed that initial recombination is largely predominant /10/, in our experimental conditions, on volume recombination which varies as $\frac{1}{V^2}$ and is dependent on the exposure rate /11/. The value of K_s resulted to be 1,0019.

Wall effect

The chamber walls are made by a material (graphite) different from air and with a thickness enough to exclude the most energetic electrons produced by photons in interactions with other media. In our chamber, such thickness is also more than sufficient to realize secondary-particle transient equilibrium.

For an absolute exposure measurement, a correction for the attenuation and scattering of the radiation in the actual graphite chamber walls must be introduced.

To determine the current which would have been obtained in absence of chamber walls, the ionization corresponding to different wall thicknesses was measured. The wall thickness was increased by adding graphite caps on the chamber. Four cylindrical caps were used having identical thickness but different size in order to be exactly fitted one inside an otherone. Each cap was also provided with a lower base (Fig. 5) to assure a symmetrical scattering geometry with respect to the cavity chamber.

By extrapolating the measured current to zero wall thickness, a factor K_c was obtained such that:

$$K_c = \frac{I_o}{I_d} = 1{,}0156 \qquad (6)$$

where I_d is the current measured with the chamber without caps and I_o is the extrapolated value of the current at zero wall thickness conditions.

The factor K_c does not represent however the real correction for the wall effect as K_c does not take into account the fact that the actual ionization is due to electrons generated at some depth in the chamber wall.

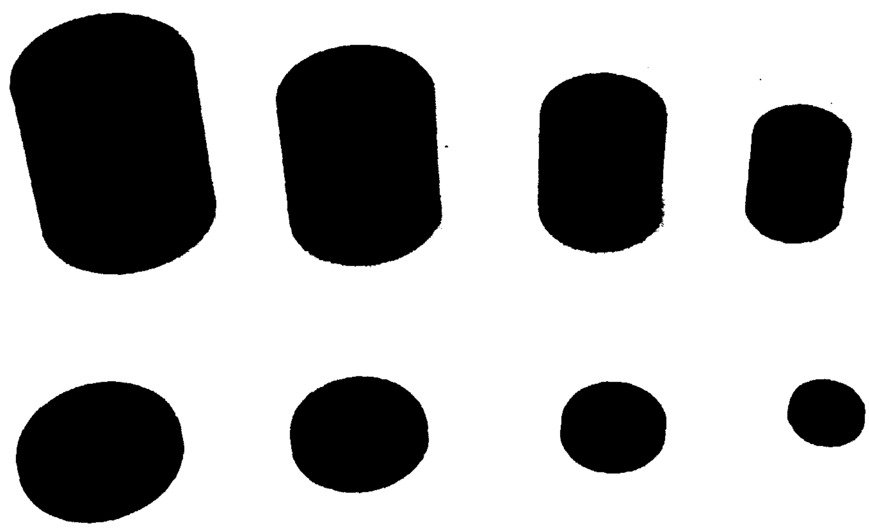

Fig. 5 - Photograph of the graphite caps for the determination of wall effect correction.

As a consequence the wall attenuation will be reduced according to the position of the mean center of electron production (CEP). Then a further correction factor, K_{CEP}, must be introduced whose role is to displace by a distance, x_c, the extrapolation point from zero wall thickness to the mean center of electron production within the chamber wall. Since the attenuation correction K_c by alone is an overestimate, the overall correction factor, K_w, for wall effect can be written as:

$$K_w = K_c \cdot K_{CEP} \tag{7}$$

and the value of K_{CEP} will be less than one.

The factor K_{CEP} is given by:

$$K_{CEP} = \frac{\phi\,(CEP)}{\phi(0)} \tag{8}$$

where ϕ (0) is the photon fluence which would occurr at zero wall thickness conditions and ϕ (CEP) is the fluence at the chamber wall thickness x_c.

The fractional fluence reduction given by eq. 8 can be also expressed as:

$$K_{CEP} = 1 - \mu x_c \tag{9}$$

where μ is the linear attenuation coefficient appropriate to our actual experimental conditions and $\mu x_c \ll 1$.

The value of μ in eq. 9 was obtained from our experimental results on K_c (eq. 6) which analogously to eq. 9 can be also written as:

$$K_c = 1 + \mu d \tag{10}$$

where d is the wall thickness of the chamber.

Therefore from eq. 10:

$$\mu = \frac{K_c - 1}{d} \tag{11}$$

and the value of μ resulted to be equal to $3,9 \cdot 10^{-2}$ cm^{-1}. This experimental value of μ considerably differs from the tabulated value of Hubbell/9/ because of the additional scattering effects existing in our experimental conditions.

The value of x_c can be determined on the basis of the works of Loftus et al. /12/, Wyckoff /13/ and Roesch /14/. In particular, x_c was calculated for our graphite chamber walls ($1,75\ g \cdot cm^{-3}$ density) from the value of the practical electron range in air for the Co-60 radiation.

The result was $x_c = 7,23 \cdot 10^{-2}$ cm and substituting in eq. 9 this value and that of μ above reported, the correction K_{CEP} was found to be 0,9972.

The overall wall effect correction then resulted:

$$K_w = K_c \cdot K_{CEP} = 1,0127$$

Chamber stem scattering

The effect on the ionization measurements due to radiation scattered on the chamber from its stem was determined by using a dummy stem of identical size placed close to the chamber on the side opposite to the fixed stem. The differences between the current readings with and without the dummy stem resulted to be within the statistical uncertainties. The correction for such effect was then considered negligible as expected because of the very small dimensions of the chamber stem (par. 2).

Therefore it is K_{st} 1,000.

Beam axial non-uniformity

The exposure measured by our cavity chamber is referred to its geometrical center. The electrons giving rise to the ionization originate in the chamber wall at the mean center of electron production which would be closer to the radiation source than the chamber geometric center since the secondary electrons are projected mainly along the forward beam direction. If the secondary electrons would arise in equal amount on the surface of the cavity, just a small correction, K_{an}, would be necessary to take into account the variation of the photon fluence along the beam axis, according the inverse square law.

The lenght which would be considered for the variation of the primary photon fluence [illegible] between the geometrical center of the chamber and the position of the mean origin of electron production. Moreover the value of K_{an} will depend on the chamber-source distance. However the conditions for a simple determination of K_{an} are not satisfied for our cavity chamber whose cylindrical geometry requires much more detailed measurements and calculations than that carried out up to present time.

The correction factor K_{an} as presently estimated is 0,997 but this value should be considered not definitive since some improvements in our experimental and theoretical procedures are foreseen for a more thorough assessment of this correction.

Beam radial non-uniformity

The photon fluence is not rigourously costant in a plane perpendicular to the beam axis since the finite size of the source and the collimating systems generally cause some reduction of fluence with increasing distance from the beam axis.

As a consequence, the exposure measured by the cavity chamber represents a value averaged over the chamber area. To obtain exposure values which are independent of the chamber size, possible radial non-uniformities of the beam must be taken into account by introducing a correction factor K_{rn}.

The radial homogeneity of our Co-60 beam was checked by a small ionization chamber (0,1 cm^3 volume) which was moved by steps of 0,5 cm along two directions normal each other and lying in the reference plane perpendicular to the beam axis. In a region of the same size as the chamber area no appreciable variation of the ionization was detected, within the statistical uncertainties. Therefore the factor K_{rn} was put equal to 1,000.

Temperature, Pressure and Humidity

The cavity chamber is provided with a vent pin hole, then corrections for ambient conditions different from the standard reference conditions (Table III) are made by the usual correcting factor $K_{T,P}$. The temperature of the irradiation room is controlled so that the largest excursions do not exceed ± 0,3°C in a day.

As far as humidity is concerned, a further correction K_H is required because water vapor is always present in ambient air while the exposure is defined from the ionization of "pure" air.

An analysis on the humidity effect on the ionization in air was carried out in the past by Barnard et al. /15/ but it resulted not completely satisfactory at the light of subsequent experiments /16/. From further studies, reported in the CCEMRI (I) Report (1977) /17/,more consistent results were obtained on this effect. The correction K_H was then determined for the cavity chamber on the basis of the data in ref. /17/.

6 - International comparisons

An international comparisons among the ENEA cavity chamber and the analogous primary standards of the BEV (Austria) and OMH (Hungary) was carried out in the early 1983. The comparison was made at the OFZS research center in Seibersdorf were the austrian BEV exposure standards are mantained. Both the ENEA and OMH standard cavity chambers were taken to the OFZS center in that occasion and the deviations in the exposure rate measurements resulted to be between 0,1% and 0,3% about.The details on this comparison are described in /18/.

After this bilateral comparison the ENEA cavity chamber was taken to Sevres where it was compared against the BIPM exposure standard for the Co-60 radiation, and the deviation in the results was about 0,2%.

The final data concerning all these comparisons are summarized in Table V.

TABLE V

Exposure rate ratios in the cavity chamber comparisons among ENEA, OMH, BEV and BIPM

$\dot{X}_{ENEA}/\dot{X}_{OMH}$	$\dot{X}_{ENEA}/\dot{X}_{BEV}$	$\dot{X}_{ENEA}/\dot{X}_{BIPM}$
1,0012	0,9970	0,9982

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