Comparison of the standards of absorbed dose of the ENEA and the BIPM for ^{60}Co γ rays

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Abstract
Indirect comparisons between the standards of absorbed dose to graphite and to water of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente and of the Bureau International des Poids et Mesures have been performed at the reference depth of 5 g·cm^{-2}. They agree to within 0,3 %.

1. Introduction

Indirect comparisons of the standards of absorbed dose to graphite and to water of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA), Roma, Italia, and the Bureau International des Poids et Mesures (BIPM), have been performed in ^{60}Co radiation, at the reference depth of 5 g·cm^{-2}.
The standard of absorbed dose to graphite of the ENEA is a calorimeter [1] constructed according to the design of S.R. Domen (NIST). The ENEA uses the scaling-theorem method to derive the absorbed dose to water from its calorimetric determination of absorbed dose to graphite [2]. The transfer is made using a thick-walled ionization chamber previously calibrated against the calorimeter in terms of absorbed dose to graphite. At the BIPM, the absorbed dose to graphite and to water is determined experimentally by the ionometric method [3].

Three cavity ionization chambers of the ENEA were used as transfer instruments. They were calibrated at the BIPM in February 1994. Calibrations at the ENEA were performed before and after the measurements at the BIPM. The results of the comparison are given in terms of the ratio of the calibration factors determined at the two laboratories.

2. Conditions of measurement

The absorbed dose is determined under conditions defined by the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) [4]:
- the distance from source to reference plane is 1 m,

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- 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 being 50 % of the photon fluence rate at the centre of the square,
- the reference depth is 5 g·cm^{-2}.

The transfer chambers are graphite cavity chambers: two of them (volume about 0,25 cm^3) were designed at the ENEA (N^{os} 14 and 19) and the third was manufactured by Nuclear Enterprises Ltd. (N° NE 2561-199). The collecting voltage applied to the transfer chambers is +200 V and +300 V for the ENEA and NE chambers, respectively.

3. Indirect comparison of standards of absorbed dose to graphite

The ionization chamber ENEA 14 was used as transfer instrument for this comparison. It is placed inside a graphite disc (density 1,77 g·cm^{-3}) belonging to the ENEA and its axis is positioned at a depth of 1,000 g·cm^{-2} from the front face of this disc. The calibration was performed in the BIPM graphite phantom. For this purpose the graphite disc, in which the BIPM standard is inserted, was substituted by the ENEA disc. The axis of the transfer chamber was at a depth of 5,040 g·cm^{-2} in graphite.
The calibration factors, N_C , are determined using the relations

$$(N_C)_{BIPM} = \frac{(\dot{D}_C)_{BIPM}}{(I_C)_{BIPM}}^{*} \qquad (N_C)_{ENEA} = \frac{(\dot{D}_C)_{ENEA}}{(I_C)_{ENEA}} , \qquad (1)$$

where
$(\dot{D}_C)_{BIPM}$ is the absorbed dose rate to graphite at the depth of 5,040 g·cm^{-2} in the BIPM phantom (see [5] for detailed information),
$(\dot{D}_C)_{ENEA}$ is the absorbed dose rate to graphite as determined in the ENEA graphite phantom [2] at the depth of 5,51 g·cm^{-2}, distance from source to surface of the phantom 100 cm, and field size 10cm x 10 cm,
$(I_C)_{BIPM}$ and $(I_C)_{ENEA}$ are the ionization currents (at 20°C and 101 325 Pa) of the transfer chamber, measured at the BIPM and the ENEA, respectively.

The ENEA and the BIPM used their own equipment for the measurement of the ionization current I_C. A comparison of the two measuring devices has been performed at the BIPM and shows a difference of 0,11 %. Thus, a factor f_e = 1,0011 is applied to the ratio of the calibration factors to take this difference into account.

The result of the comparison, R_C , can be expressed in the form

$$(R_C) = \frac{(N_C)_{ENEA}}{(N_C)_{BIPM}} f_e , \qquad (2)$$

and is given in Table 1 together with the factors entering in (1).

* The $(D_C)_{BIPM}$ and $(I_C)_{BIPM}$ values refer to an evacuated path length between source and phantom. They are given at the reference date of 1994-01-01, 0 h UT (the half life of ^{60}Co is taken as (1 925,5 ± 0,5) days [6]).

Table 1. Indirect comparison of ENEA and BIPM standards of absorbed dose to graphite

	Depth ($g \cdot cm^{-2}$)	$\dot{D}_C$ ($mGy \cdot s^{-1}$)	I_C (pA)	N_C ($Gy \cdot \mu C^{-1}$)	R_C	Relative uncertainty ($1\ \sigma$, in %)
at the BIPM	5,040	6,4678	59,056	109,52	0,9966	0,44
at the ENEA	5,510	2,8966	26,567	109,03		

The various contributions to the total uncertainty in R_C are given in Table 2. The ENEA statistical uncertainties reported in tables 2 and 5 refer to the reproducibility of the measurements (experimental standard deviation, 1σ) over a period of two years.

Table 2. Estimated relative uncertainty in R_C (1σ, in %)

	s_i	u_j
Determination of $(N_C)_{BIPM}$		
ionometric measurement of absorbed dose rate to graphite, at 5 $g \cdot cm^{-2}$ (see [5])	0,01	0,26
interpolation on BIPM depth dose curve, $(\dot{D}_{5,04} / \dot{D}_5)_{BIPM}$		0,01
measurement of ionization current of transfer chamber	0,01	0,02
Determination of $(N_C)_{ENEA}$		
calorimetric measurement of absorbed dose rate in graphite, $(\dot{D}_C)_{ENEA}$	0,20	0,25
measurement of ionization current of transfer chambers	0,10	0,07
Comparison conditions		
measurement of depth in ENEA disc		0,05
measurement of distance from source to chamber		0,02
difference in densities of ENEA and BIPM graphite discs		0,05
Comparison result R_C		
by quadratic summation	0,22	0,38
combined uncertainty	0,44	

* s_i = uncertainty estimated by statistical methods, type A,
u_i = uncertainty estimated by other means, type B.

4. Indirect comparison of standards of absorbed dose to water

The indirect comparison of the standards of absorbed dose to water was performed by means of three transfer chambers, each inserted in a perspex envelope made at the ENEA, which were calibrated at the BIPM in the BIPM water phantom (30 cm x 30 cm x30 cm) and at the ENEA in the ENEA water phantom which is made of a PMMA cylinder with a thin window on its front wall. The dimensions of the ENEA phantom (diameter 48 cm, height 29 cm) are scaled with respect to the standard graphite calorimeter (and the graphite phantom) as the inverse ratio of the electron concentration in the two materials.

The calibration factors in terms of absorbed dose to water, N_W, are determined using the relations

$$(N_W)_{BIPM} = \frac{(\dot{D}_W)_{BIPM}}{(I_W k_{pf})_{BIPM}}{}^{*} \;, \qquad (N_W)_{ENEA} = \frac{(\dot{D}_W)_{ENEA}}{(I_W)_{ENEA}} \;, \qquad (3)$$

where
$(\dot{D}_W)_{BIPM}$ is the absorbed dose rate to water measured by the BIPM standard at a depth d in water,
$(I_W)_{BIPM}$ is the ionization current measured by the transfer chamber, embedded in its waterproof envelope and located in the BIPM water phantom, in the reference conditions [7],
k_{pf} is a correction factor which accounts for the non-equivalence of the perspex front face of the BIPM phantom with water [7],
$(\dot{D}_W)_{ENEA}$ is the absorbed dose rate to water determined under the reference conditions,
$(I_W)_{ENEA}$ is the ionization current measured by the transfer chamber, with its waterproof sheath, under the reference calibration conditions in the ENEA water phantom.

The physical constants and correction factors entering in the determination of the absorbed dose rate to water, together with their uncertainties, are given in [3] for the BIPM and in Table 3 for the ENEA .

Table 3. Physical constants and correction factors entering in the ENEA determination of the absorbed dose rate in water at 5 g·cm^{-2}, and estimated relative uncertainties (1σ, in %)

	numerical value	uncertainty s_i	u_j
Physical constants			
$(\mu_{en}/\rho)_W$ / $(\mu_{en}/\rho)_C$	1,113		0,20
Correction factors			
β_W / β_C	1,009	0,01	0,10
Φ_W / Φ_C	1,0072	0,05	0,10

The calibration was performed at the depths of 5 g·cm^{-2} and 17 g·cm^{-2}. The $(\dot{D}_W)_{BIPM}$ values are the means of measurements performed over a period of three months, before and after the calibration at the BIPM, with $(\dot{D}_W)_{BIPM}$ = 6,859 mGy·s^{-1} and 3,791 mGy·s^{-1} at 5,000 g·cm^{-2} and 17,000 g·cm^{-2}, respectively.
The result of the comparison is given by

$$R_W = \frac{(N_W)_{ENEA}}{(N_W)_{BIPM}} f_e \;. \qquad (4)$$

Table 4 gives the result of the comparison. The various contributions to the total uncertainty in R_W are given in Table 5.

* cf. footnote on page 2.

Table 4. Indirect comparison of ENEA and BIPM standards of absorbed dose to water

Chamber	Depth ($g \cdot cm^{-2}$)	$(N_W)_{BIPM}$ ($Gy \cdot \mu C^{-1}$)	$(N_W)_{ENEA}$ ($Gy \cdot \mu C^{-1}$)	R_W	Relative uncertainty (1 σ, in %)
ENEA 14	5,000	123,90	123,40	0,997 1	0,6
ENEA 29	5,000	126,56	125,90	0,995 9	0,6
	17,000	126,63			
NE 2561-199	5,000	102,70	102,34	0,997 6	0,6
	17,000	102,90			

Table 5. Estimated relative uncertainties in the comparison result, R_W (1σ, in %)

	s_i	u_j
Determination of $(N_W)_{BIPM}$		
ionometric measurement of absorbed dose rate to water, $(\dot{D}_W)_{BIPM}$, at 5 $g \cdot cm^{-2}$ (see [3])*	0,20	0,35
measurement of ionization current of transfer chambers	0,02	0,02
measurement of depth in water		0,05
Determination of $(N_W)_{ENEA}$		
calorimetric measurement of absorbed dose rate to graphite, $(\dot{D}_C)_{ENEA}$	0,20	0,25
$(\mu_{en}/\rho)_W$ / $(\mu_{en}/\rho)_C$ and β_W/β_C	(common with BIPM)	
Φ_W/Φ_C	0,05	0,10
measurement of ionization current of the thick-walled reference chamber in graphite	0,10	0,07
in water	0,10	0,05
measurement of ionization current of transfer chambers	0,10	0,05
measurement of depth in water		0,10
Comparison result R_W		
by quadratic summation	0,34	0,47
combined uncertainty	0,58	

* Without the uncertainties in μ_{en}/ρ and β which are common to the ENEA and the BIPM.

5. Conclusion

These comparisons show a very good agreement, of order 0,3 %, between the standards of absorbed dose of the ENEA and the BIPM.
The agreement obtained for measurement in graphite is consistent with that obtained with other calorimeters of the same type [8]. It should be noted that the gap correction, measured at the ENEA for its own standard, agrees well with the calculated value of [9].
In addition, the agreement between the measurements of absorbed dose to water is consistent with that obtained with other methods based on graphite: scaling theorem at the NPL [10] and at the BIPM [11], as well as derivation from calibration of a transfer instrument in graphite [12].

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