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

by A.-M. Perroche* and M. Boutillon
Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

T.W.M. Grimbergen and E. Van Dijk
Nederlands Meetinstituut, NL-Utrecht

Abstract
A comparison between the standards of absorbed dose to graphite of the Nederlands Meetinstituut and of the Bureau International des Poids et Mesures has been carried out around the reference depth of 5 g · cm^{-2} in the ^{60}Co radiation. This shows agreement to within 0,23 %. This direct comparison was followed by an indirect one, using two NMi transfer chambers, which gave similar results.

1. Introduction

The standard of absorbed dose to graphite of the Nederlands Meetinstituut (NMi), Utrecht, The Netherlands, is a graphite heat-loss compensated three-body calorimeter [1], of the type developed by S. R. Domen (National Institute of Standards and Technology , USA).

An earlier version of the calorimeter was compared with the ionometric standard of absorbed dose to graphite of the Bureau International des Poids et Mesures (BIPM) in 1979 and the standards were found to be in good agreement. In 1984 this calorimeter was replaced by a new one. A new comparison in 1985 showed an unexpected discrepancy of 1 %. So, it was repeated in September 1993. As a check, an indirect comparison was also carried out using two transfer cavity chambers belonging to the NMi.

2. Conditions of measurement

The absorbed dose to graphite is determined under following conditions defined by the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) [2]:
- the graphite phantom (Φ = 30 cm) is homogeneous. Its thickness is sufficient to provide full backscatter,
- 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 being 50 % of the photon fluence rate at the centre of the square,

* Service Central de Protection contre les Rayonnements Ionisants, F-78110 Le Vésinet.

- the reference depth in graphite is 5 g $\cdot$ cm^{-2}.

The centres of the NMi and BIPM detectors (calorimeter core and ionization chamber) are placed in the reference plane.

3. BIPM ionometric determination of absorbed dose to graphite

The BIPM standard is a flat ionization cavity chamber in graphite which has been described elsewhere [3].

The BIPM reference absorbed dose rate, $(\dot{D}_5)_{\mathrm{BIPM}}$, at the depth (5,00 g $\cdot$ cm^{-2}), is given by

$$(\dot{D}_5)_{\mathrm{BIPM}} = \frac{I}{m}\frac{W}{e}\bar{s}_{\mathrm{c,a}}k_{\mathrm{p}}k_{\mathrm{rn}}k_{\mathrm{dist}} \ , \tag{1}$$

where

- I is the ionization current measured in the mass m of the air of the chamber cavity. The middle plane of the cavity is located at 5,018 6 g $\cdot$ cm^{-2} in the graphite. I is corrected for humidity (k_{h}) and for ion recombination (k_{s}). The I values refer to an evacuated path length between source and phantom, and are given at the reference date of 1993-01-01, 0 h UT (the half life of ^{60}Co is (1 925,5 ± 0,5) days [4]),
- W is the average energy spent by an electron of charge e to produce an ion pair in dry air [5],
- $\bar{s}_{\mathrm{c,a}}$ is the weighted mean ratio of the stopping powers for carbon and air [5],
- k_{p} is the perturbation correction factor of the BIPM standard [6],
- k_{rn} is the correction factor for the radial non-uniformity of the ^{60}Co beam over the section of the BIPM standard [7],
- k_{dist} is the ratio of the absorbed dose rates in graphite at 5,00 g $\cdot$ cm^{-2} and 5,018 6 g $\cdot$ cm^{-2}, determined previously from the BIPM experimental curve, $(\dot{D}_{\mathrm{d}} / \dot{D}_5)_{\mathrm{BIPM}}$ of absorbed dose versus depth d.

The absorbed dose rate to graphite, at another depth in the BIPM phantom, is given by the relation

$$(\dot{D}_{\mathrm{d}})_{\mathrm{BIPM}} = (\dot{D}_5)_{\mathrm{BIPM}}\left(\frac{\dot{D}_{\mathrm{d}}}{\dot{D}_5}\right)_{\mathrm{BIPM}}. \tag{2}$$

The physical constants and the correction factors entering in the ionometric determination of the absorbed dose rate to graphite at 5,00 g $\cdot$ cm^{-2}, together with their uncertainties, are given in Table 1. The values of $(\dot{D}_{\mathrm{d}} / \dot{D}_5)_{\mathrm{BIPM}}$ for the depths used in the present comparison are given in Table 4.

Table 1. Physical constants and correction factors entering in the BIPM ionometric determination of the absorbed dose rate in graphite at 5,00 g $\cdot$ cm^{-2}, and estimated relative uncertainties* (1σ, in %)

			numerical value	uncertainty s_i	u_j
Physical constants					
air density at STP		(kg m^{-3})	1,293 0		0,01
$\bar{s}_{c,a}$			1,003 0		0,20
W/e		(J C^{-1})	33,97		0,15
Corrections factors					
k_{rn}	radial non-uniformity		1,003 2		0,03
k_p	perturbation correction		0,989 6		0,05
k_{dist}	depth in graphite		1,000 6		0,01
k_z	air compressibility		1,000 2		
k_s	recombination losses		1,001 6	0,004	0,01
k_h	humidity		0,997 0		0,03
Measurement of $I/v\rho$					
v	volume	(cm^3)	6,787 3		0,03
I	ionization current			0,01	0,02
Uncertainty in $(\dot{D}_5)_{BIPM}$					
	by quadratic summation			0,01	0,26
	combined uncertainty			0,26	

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

4. NMi calorimetric determination of absorbed dose to graphite

The main characteristics of the NMi calorimeter are given in Table 2.
The absorbed dose rate $(\dot{D}_d)_{NMi}$ at depth d is given by the relation

$$(\dot{D}_d)_{NMi} = \frac{(M_c)_d}{m} N_E k_{gap} k_m k_{an} \ , \qquad (3)$$

where

$(M_c)_d$ is the calorimeter reading at depth d; the values refer to an evacuated path length between source and phantom and to the reference date 1993-01-01 0h UT,

N_E is the electrical calibration factor,

m is the mass of the core,

k_{gap} is the correction factor for the effect of vacuum and air gaps,

k_m is the correction factor for radial non-uniformity of the BIPM ^{60}Co beam, over the section of the core of the calorimeter,

k_{an} is the correction factor for axial non-uniformity.

Table 2. Characteristics of the NMi graphite calorimeter

Core	diameter	(mm)	20,022
	length	(mm)	2,744
	mass	(g)	1,568 93
	graphite density	($g \cdot cm^{-3}$)	1,82
Gap widths	gap 1	(mm)	0,644
	gap 2	(mm)	0,812
	gap 3	(mm)	0,914
	gap 4	(mm)	0,5
Distance from the entrance window to the middle plane of the core		(mm)	7,61
Depth of point of measurement		($g \cdot cm^{-2}$)	0,944
Phantom	diameter	(mm)	300
	length	(mm)	260
	graphite density	($g \cdot cm^{-3}$)	1,85

The numerical values of the terms entering in (3) are given in Table 3, together with their uncertainties.

Table 3. Quantities and correction factors entering in the NMi calorimetric measurement of the absorbed dose rate in graphite at 5,00 g $\cdot$ cm^{-2}, and estimated relative uncertainties (1σ, in %)

		numerical value	uncertainty s_i	uncertainty u_j
Measured quantity				
M_c	($W \cdot s^{-1}$) for 34 calorimetric runs		0,06	
N_E	($mJ \cdot \Omega^{-1}$)	1,500 6	0,25	0,30
m	(g)	1,568 93	0,002	0,03
Correction factors				
	depth of point of measurement			0,05
k_{gap}	vacuum and air gaps	1,003 9		0,07
k_{an}	axial non-uniformity	1,000 0		
k_{rn}	radial non-uniformity	1,000 2		0,01
Uncertainty in $(\dot{D}_5)_{NMi}$				
	by quadratic summation		0,26	0,31
	combined uncertainty		0,41	

5. Results of the direct comparison of standards

The value of $(\dot{D}_5)_{\mathrm{BIPM}}$ is a mean of measurements done over a period of three months before and after the NMi calorimetric measurements at the BIPM, with $(\dot{D}_5)_{\mathrm{BIPM}} = 7{,}3850\ \mathrm{mGy \cdot s^{-1}}$.

The calorimetric measurements of absorbed dose to graphite were carried out at the BIPM at three depths between 4,29 $\mathrm{g \cdot cm^{-2}}$ and 5,58 $\mathrm{g \cdot cm^{-2}}$. The corresponding values for the BIPM standard (see Table 4) are obtained from (2).

The density of the NMi discs (1,85 $\mathrm{g \cdot cm^{-3}}$) in front of the calorimeter is different from that of the BIPM disc (1,77 $\mathrm{g \cdot cm^{-3}}$). The variation between the absorbed doses at the same depth in the NMi and BIPM phantoms, which is due to this difference, is deduced from previous experiments made at the BIPM [8] and is estimated to be 0,1 %. Thus, a conversion factor $f_\rho = 0{,}999$ is applied to the experimental ratio of the absorbed doses measured by the two methods.

The result of the comparison, at a depth *d*, is thus given by

$$R_d = \frac{(\dot{D}_\mathrm{d})_{\mathrm{NMi}}}{(\dot{D}_\mathrm{d})_{\mathrm{BIPM}}} f_\rho \ . \tag{4}$$

The values of R_d are listed in Table 4 and their uncertainties in Table 5. The results are given in chronological order. May note that the standard deviation of a series of calorimetric measurements decreases with time of run because the measurements began one day after installation and before the calorimeter had reached a stable condition. This effect had already been observed with another calorimeter [9].

Table 4. Direct comparison of NMi and BIPM absorbed dose rates to graphite

Depth d ($\mathrm{g \cdot cm^{-2}}$)	Number of calorimetric runs	$(\dot{D}_\mathrm{d})_{\mathrm{NMi}}$ ($\mathrm{mGy \cdot s^{-1}}$)	σ* (%)	$(\dot{D}_\mathrm{d} / \dot{D}_5)_{\mathrm{BIPM}}$	$(\dot{D}_\mathrm{d})_{\mathrm{BIPM}}$ ($\mathrm{mGy \cdot s^{-1}}$)	R_d
5,000	10	7,388	0,18	1,000 0	7,385	0,999 4
5,000	11	7,378	0,12	1,000 0	7,385	0,998 1
4,291	6	7,526	0,13	1,021 0	7,540	0,997 1
5,577	7	7,241	0,08	0,982 4	7,255	0,997 1
				weighted mean value		0,997 5

* Statistical uncertainty.

The weighted mean value of R_d in the vicinity of 5 g $\cdot$ cm^{-2} is 0,997 5 ± 0,000 4. This value indicates that the two standards are in very good agreement, within their uncertainties. Note that it also agrees very well with the value obtained during the 1979 comparison (R_5 = 0,999 8 [10]) which was performed with the BIPM discs in front of the NMi calorimeter, thus avoiding the introduction of the factor f_ρ.

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

	s_i	u_j
Determination of $(\dot{D}_d)_{\mathrm{BIPM}}$		
ionometric measurement of absorbed dose rate in graphite, at 5,00 g cm^{-2} (see Table 1)	0,01	0,26
interpolation on BIPM depth dose curve, $(\dot{D}_d / \dot{D}_5)_{\mathrm{BIPM}}$		0,01
Determination of $(\dot{D}_d)_{\mathrm{NMI}}$		
calorimetric measurement of absorbed dose rate in graphite, $(\dot{D}_d)_{\mathrm{NMI}}$ (see Table 3)	0,26	0,31
Comparison conditions		
difference in densities of NMI and BIPM graphite discs	-	0,05
measurement of distance from source to detectors	-	0,03
Comparison result R_d		
by quadratic summation	0,26	0,41
combined uncertainty	0,48	

6. Results of the indirect comparison

Two transfer cavity chambers (type NEL 2561) belonging to the NMi were calibrated at both the NMi and the BIPM for an indirect comparison. The measurements were performed inside an NMi graphite phantom, especially designed for calibration, and the same measuring system was used [11] at the two laboratories. The collecting voltage applied to the transfer chambers was -200 V. The chambers were positioned with their axes in the reference plane, at a depth d in the graphite of about 5 g $\cdot$ cm^{-2}. The calibration factor was determined using the relation

$$(N_c)_d = \frac{(\dot{D}_d)_{\mathrm{BIPM}} / f_\rho}{(L_c)_d / R(e)} \quad , \qquad (5)$$

where

$(\dot{D}_d)$ is the absorbed dose rate to graphite measured by the BIPM standard in the BIPM phantom,

f_ρ is the conversion factor to take into account the difference in the graphite densities of the two phantoms, as said before,

$(L_c)_d$ is the reading of the NMi electrometer output,

$R(e)$ is the calibration factor of the NMi electrometer: $R(e)$ = 100,02 V/µC.

The transfer chambers were calibrated at several depths between 4,2 g · cm^{-2} and 6,1 g · cm^{-2} (Table 6). The calibration factors determined at the BIPM and at the NMi agree to within 0,25 %, which confirms the results of the direct comparison.

Table 6. Indirect comparison of NMi and BIPM absorbed dose rates to graphite

Chamber	depth (g · cm^{-2})	L_C (mV · s^{-1})	$\sigma(L_C)$* (%)	$(N_C)_{BIPM}$ (Gy · µC^{-1})	$(N_C)_{NMi}$ (Gy · µC^{-1})	$(N_C)_{NMi}/(N_C)_{BIPM}$
NE 2561-183	4,232	8,285	0,08	91,27		
	4,934	8,133	0,06	91,09		
	6,076	7,859	0,08	90,97		
	5,000	interpolated		91,05	90,85	0,997 8
NE 2561-246	4,232	8,382	0,01	90,21		
	4,572	8,306	0,02	90,15		
	4,934	8,222	0,01	90,10		
	6,076	7,945	0,01	89,99		
	5,000	interpolated		90,04	89,81	0,997 4
	Relative uncertainty (1 σ, in %)			0,30	0,45	0,54

* Statistical uncertainty

7. Conclusion

The present comparisons, direct and indirect, confirm the excellent agreement between the standards of absorbed dose to graphite of the NMi and the BIPM obtained in 1979. Thus, it is thought that the results obtained in 1985 are in error, but the reason remains unknown.

References

[1] GRIMBERGEN T.W.M. and DIJK E. Van , The NMi calorimeter, *NMi report* (in preparation).

[2] BIPM, Comparaisons d'étalons de dose absorbée, *BIPM Com. Cons. Etalons Mes. Ray. Ionisants*, Section (I) **5**, 1979, p. R(I) 5 (Paris: Offilib).

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

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

[5] BIPM, Constantes physiques pour les étalons de mesure de rayonnement, *BIPM Com. Cons. Etalons Mes. Ray. Ionisants*, (Section I) 11, 1985, p. R45 (Paris: Offilib).

[6] BOUTILLON M., Perturbation correction in the ionometric determination of absorbed dose in a graphite phantom for ^{60}Co gamma rays, *Phys. Med. Biol.*, 1983, **28**, 375-388.

[7] BOUTILLON M. and PERROCHE A.-M., Radial non-uniformity of the BIPM ^{60}Co beam, *Rapport BIPM-89/2*, 1989, 9 pages.

[8] NIATEL M.-T. Mesure de la dose absorbée dans le graphite, *BIPM Proc.-Verbaux Com. Int. Poids et Mesures*, 1979, **47**, 49-51 and 1980, **48**, 63-64.

[9] PERROCHE A.-M. and GARDEL P., Comparison of the standards of absorbed dose to graphite of the IRA and the BIPM for ^{60}Co γ rays, *Rapport BIPM-90/9*, 1990, 14 pages.

[10] BOUTILLON M., Revision of the results of international comparisons of absorbed dose in graphite, in a ^{60}Co beam, *Rapport BIPM-90/4*, 1990, 7 pages.

[11] Van DIJK E. and GRIMBERGEN T.W.M., Report of the indirect comparison of Kerma standards of BIPM and NMI December 1991, *NMi report* 15-01-1993, 9 pages.

(March 1994)