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THE NPL ABSORBED DOSE PRIMARY STANDARD GRAPHITE CALORIMETER (2015 DESIGN) FOR ^{60}Co: SUMMARY OF CORRECTION AND CONVERSION FACTORS

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ABSTRACT

Since the 1980s the UK primary standard for the realisation of absorbed dose for ^{60}Co gamma rays has been a Domen-type graphite calorimeter. This calorimeter has become increasingly unreliable in recent years and a project was started at the National Physical Laboratory to replace it. A new graphite calorimeter for the measurement of therapy level photons (^{60}Co and 4 MV – 25 MV linac beams) has been constructed and commissioned and this report summarises the factors for the new photon calorimeter (2015 design). This report focuses on the ^{60}Co beam quality only.

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CONTENTS

1 INTRODUCTION

The National Physical Laboratory (NPL) has established a Domen-type absorbed dose graphite calorimeter (2015 design) as the UK national absorbed dose primary standard for the measurement of ^{60}Co gamma rays and 4 MV – 25 MV linac photon beams. This calorimeter replaces the previous primary standard graphite microcalorimeter which was designed and built in the 1980s.

The NPL uses the scaling dose ratio method to derive the absorbed dose to water from its calorimetric determination of absorbed dose to graphite (Nutbrown *et al.* 2002).

This report summarises the factors applicable to the calorimeter response in order to realise absorbed dose and calibrate a secondary standard thimble chamber. The associated uncertainties are also presented.

2 SET UP CONDITIONS FOR THERAPY LEVEL ^{60}CO ABSORBED DOSE MEASUREMENTS AT NPL

- 10 cm × 10 cm field size
- 1 m distance from the ^{60}Co source to the centre of the graphite core of the calorimeter
- The calorimeter is operated in quasi-adiabatic mode
- The reference point of the calorimeter is taken as the geometrical centre of the cylindrical graphite core at a depth which is equivalent to 5 g cm^{-2} in water
- The ^{60}Co irradiator at the NPL is a Theratron 780C. The irradiator has not been fitted with a monitor chamber because transit time variations have been found to be negligible.

3 DETERMINATION OF THE ABSORBED DOSE TO WATER

At the NPL, the absorbed dose to water is determined from measurements of absorbed dose to graphite with a graphite calorimeter and a conversion from graphite to water with a set of reference standard ionisation chambers, as explained in the following paragraphs.

3.1 MEASUREMENT OF ABSORBED DOSE TO GRAPHITE AT THE REFERENCE POINT

The NPL standard of absorbed dose is a Domen-type graphite calorimeter constructed by the NPL with the physical dimensions presented in Tables 1 and 2. The calorimeter is operated in quasi-adiabatic mode and the sensitivity of the calorimeter to ionising radiation energy absorbed in the graphite core is calculated from voltage and resistance measurements traceable to NPL standards.

The absorbed dose to graphite, $D_{\mathrm{g,\,ref}}$, at the reference point (equivalent to 5 g cm^{-2} depth in water) in a homogeneous, cylindrical, pure graphite phantom (with the shape of the calorimeter components and their sizes scaled in terms of electron density) is given by

$$D_{\mathrm{g,\,ref}} = \left(E^{\mathrm{rad}}/m_{\mathrm{core,\,eff}}\right) k_{\mathrm{imp}}\, k_{\mathrm{gap}}\, k_{\mathrm{z,\,cal}}\, k_{\mathrm{d,\,cal}}\, k_{\mathrm{rn,\,cal}}\, k_{\mathrm{an,\,cal}}\, k_{\mathrm{lead\ res,\,th}} \tag{1}$$

where

E^{rad} is the energy absorbed in the calorimeter core from ionising radiation only (Seuntjens and Duane 2009),

$m_{\mathrm{core,\,eff}}$ is the effective mass of the graphite core including all non-graphite materials,

k_{imp} is the Monte Carlo (MC) calculated impurity correction factor, calculated as the dose ratio $D_{\mathrm{core,\,gaps}}/D_{\mathrm{core,\,all}}$ where $D_{\mathrm{core,\,gaps}}$ is the dose to the core with all non-graphite materials in the calorimeter substituted with pure graphite (no impurities) with mass density of the core graphite and scaled in terms of electron density and $D_{\mathrm{core,\,all}}$ is the dose to the core in the real calorimeter,

k_{gap} is the MC calculated vacuum gap correction factor, calculated as the dose ratio $D_{\text{core, no gaps}}/D_{\text{core, gaps}}$, with all non-graphite parts in the calorimeter substituted with pure graphite (no impurities) with mass density of the core graphite and scaled in terms of electron density,

$k_{\text{z, cal}}$ is the correction factor for the reference distance from the ^{60}Co source. The decrease of absorbed dose with distance from the source obeys an inverse square law. A correction is applied for the deviation of the calorimeter measurement distance from the reference value, 1 m.

$k_{\text{d, cal}}$ is the correction factor for the reference depth in graphite. The desired reference depth is achieved with the available combination of graphite build-up plates within the measurement tolerances.

$k_{\text{rn, cal}}$ is the correction factor for the radial non-uniformity of the ^{60}Co beam over the calorimeter core. This was obtained experimentally by measuring the radial profile of the beam using a small volume thimble ionisation chamber in water.

$k_{\text{an, cal}}$ is the correction factor for the axial non-uniformity of the ^{60}Co beam over the calorimeter core. The decrease of absorbed dose with depth at 5.6 g cm^{-2} in graphite is approximately linear and as the calorimeter core extends only 5 mm along the beam axis, no correction is made for the non-uniformity of absorbed dose along the beam axis.

$k_{\text{lead res, th}}$ is the correction factor for the change in thermistor lead resistance between calibration and final assembly.

The numerical values of the correction factors in Equation 1 are shown in Table 3.

Table 1. Main dimensions of the NPL standard

Vertical dimensions / mm		Horizontal dimensions / mm	
Core diameter	19.984	Core thickness	5.005
Inner jacket inner diameter	21.484	Core/Inner jacket gap (front)	0.768
Inner jacket outer diameter	29.467	Inner jacket thickness (front)	0.762
Outer jacket inner diameter	30.950	Inner jacket/Outer jacket gap (front)	0.769
Outer jacket outer diameter	38.969	Outer jacket thickness (front)	0.750
Mantle inner diameter	40.527	Outer jacket/Mantle gap (front)	0.822
Mantle outer diameter	149.963	Mantle thickness (front)	3.005
Vacuum housing inner diameter	151.5	Vacuum housing thickness (front)	3.033
Vacuum housing outer diameter	210	Build-up plate thickness	20.788
Phantom outer diameter	320	Core/Inner jacket gap (back)	0.768
		Inner jacket thickness (back)	0.772
		Inner jacket/Outer jacket gap (back)	0.769
		Outer jacket thickness (back)	0.782
		Outer jacket/Mantle gap (back)	0.822
		Mantle thickness (back)	2.799
		Vacuum housing thickness (back)	2.940

Table 2. Characteristics of the NPL graphite calorimeter

Component	Characteristic	Value
Core	Diameter / mm	19.984
	Thickness / mm	5.005
	Effective mass / g	2.9572
	Graphite density / g cm^{-3}	1.878
Gap widths	Gap between core to inner front jacket / mm	0.768
	Gap between inner to outer front jacket / mm	0.769
	Gap between outer front jacket and outer front mantle / mm	0.822
Water-equivalent depth	Mid-plane of core to front of phantom (excl. build-up) / g cm^{-2}	1.5558
Cylindrical outer graphite phantom	Diameter / cm	32
	Height (excl. build-up) / cm	8.26
Cylindrical build-up plate	Diameter / cm	23
	Height / cm	2.08
	Graphite density (mean) / g cm^{-3}	1.841

Table 3. Correction factors and their uncertainties in the NPL calorimetric determination of the absorbed dose to graphite

Correction factors		Numerical value	Relative standard uncertainty [(1)]	
			100 s_i	100 u_i
k_{imp}	impurity	1.0030	*)	*)
k_{gap}	gaps	1.0064	*)	*)
$k_{\mathrm{z,\,cal}}$	distance	1.0000	-	0.10
$k_{\mathrm{d,\,cal}}$	depth	1.0000	-	<0.01
$k_{\mathrm{rn,\,cal}}$	radial non-uniformity	1.0008	-	0.03
$k_{\mathrm{an,\,cal}}$	axial non-uniformity	1.0000	-	0.01
$k_{\mathrm{lead\ res,\,th}}$	thermistor lead resistance	0.9991	-	0.01

(1) 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 methods, type B.
*) See uncertainty budget at the end of the report. Values calculated using stopping power data from ICRU 1984.

3.2 CALIBRATION COEFFICIENT IN TERMS OF DOSE TO GRAPHITE FOR THE NPL REFERENCE STANDARDS

The NPL uses a set of three reference standard ionisation chambers, two manufactured by Nuclear Enterprises of type NE 2611 and one manufactured by NPL of NPL 2611, respectively, to maintain and transfer absorbed dose to graphite (Pearce *et al.* 2011). The main characteristics of these standards are listed in Table 4. The reference chambers are set up in a cuboidal graphite phantom and calibrated against the calorimeter.

Table 4. Characteristics of the reference and transfer ionisation chambers type NE 2611 and NPL 2611

Characteristic		Nominal value
Dimensions	Inner diameter / mm	7.35
	Wall thickness / mm	0.5
	Cavity length / mm	9.22
	Cavity centre from tip / mm	5.00
Electrode	External diameter / mm	1.00
Volume	Air cavity / cm^3	0.325
Wall	Material	Graphite with <0.01% impurity
	Density/ g cm^{-3}	1.80
Polarising voltage	Negative polarity*) / V	200

*) Ensuring that negative charge is collected with the electrometer.

The dose to graphite at the reference point in the graphite phantom (i.e. at the centre of the thimble chamber inside the graphite phantom), D_{g}, at 5.0426 g cm^{-2} water-equivalent depth in terms of electron density is given by

$$D_{\mathrm{g}} = D_{\mathrm{g,\,ref}}\, k_{\mathrm{geom}} \tag{2}$$

where

$D_{\mathrm{g,\,ref}}$ is the absorbed dose to graphite at the reference point in the graphite core of the calorimeter (water-equivalent depth of 5 g cm^{-2}) and

k_{geom} is the MC calculated configuration correction factor for the combined effect of (a) the difference between the geometries of the cylindrical calorimeter and the cuboidal graphite phantom which is used to calibrate secondary standard thimble chambers, resulting in different scatter contributions at the reference point, and (b) the difference in depth of the reference points for the calorimeter and graphite phantom.

The reference standard calibration coefficient, $N_{\mathrm{g,\,NPL\,ref\,cham}}$, in terms of absorbed dose to graphite per unit electric charge produced in the thimble chamber inside the graphite phantom is obtained from the relation

$$N_{\mathrm{g,\,NPL\,ref\,cham}} = D_{\mathrm{g}} / \left(Q_{\mathrm{g,\,NPL\,ref\,ch}}\, k_{\mathrm{elec}}\, k_{\mathrm{ion}}\, k_{\mathrm{z,\,cham}}\, k_{\mathrm{rn,\,cham}}\, k_{Tp}\right) \tag{3}$$

where

D_{g} is the absorbed dose to graphite at the reference point in the graphite phantom (equivalent to 5.0426 g cm $^{-2}$ water-equivalent depth),

$Q_{\mathrm{g,\,NPL\,ref\,ch}}$ is the electric charge, measured at a relative humidity in the range 20% to 70%, with the reference chamber in the graphite phantom,

k_{elec} is the electrometer correction factor,

k_{ion} is the correction factor for ion recombination in the reference chamber,

$k_{\mathrm{z,\,cham}}$ is the correction factor for the different distance of the graphite phantom from the ^{60}Co source. A correction is applied for the deviation of the thimble chamber measurement distance from the reference value, 1 m.

$k_{\mathrm{rn,\,cham}}$ is the correction factor for the radial non-uniformity of the ^{60}Co beam over the reference ionisation chamber in the graphite phantom and

k_{Tp} is the factor to correct from ambient temperature T and pressure p to standard temperature and pressure given by

$$k_{Tp} = \frac{T}{293.15} \cdot \frac{101.325}{p} \tag{4}$$

where

T is the ambient temperature (K) and

p is the ambient atmospheric pressure (kPa).

The numerical values of some of the correction factors in Equation 3 are shown in Table 5.

Table 5. Correction factors and their uncertainties in the calibration coefficient in terms of absorbed dose to graphite for the NPL reference standards

Correction factors		Numerical value	Relative standard uncertainty	
			100 s_i	100 u_i
k_{geom}	geometry (configuration, scatter and depth)	0.9970	*)	*)
k_{ion}	ion recombination	1.0014	-	0.03
$k_{\mathrm{z,\,cham}}$	distance	1.0000	-	0.10
$k_{\mathrm{rn,\,cham}}$	radial non-uniformity	1.0001	-	0.01

*) See uncertainty budget at the end of the report. Value calculated using stopping power data from ICRU 1984.

An analysis of all calibrations of these three chambers against the UK primary standard over the period January to July 2017 was used as the base for the BIPM.RI(I)-K4 key comparison 2017. The relative sample standard deviation associated with those measurements is 3.0×10^{-4}.

<u>Reference conditions</u>

Absorbed dose to graphite is determined at the NPL under reference conditions defined as:

- The distance from the source to the reference plane (centre of thimble chamber) is 1 m
- The field size in air at the reference plane is 10 cm x 10 cm
- The reference depth in the graphite phantom is 5.0426 g cm^{-2} WE depth in terms of electron density ($N_{\mathrm{g,\,NPL\,ref\,cham}}$ is applicable at this depth)

3.3 CONVERSION OF ABSORBED DOSE FROM GRAPHITE TO WATER

At the NPL the reference chamber calibration coefficient, $N_{\mathrm{w,\,NPL\,ref\,cham}}$, in terms of absorbed dose to water at the reference depth of 4.991 g cm^{-2} in water (equivalent to 5.5456 g cm^{-2} in graphite) has been obtained from the reference chamber calibration coefficient, $N_{\mathrm{g,\,NPL\,ref\,cham}}$, in terms of absorbed dose to graphite at the reference point (see Equation 3) by using the scaling dose ratio method and the formalism described by Nutbrown *et al.* 2002:

$$N_{\mathrm{w,\ NPL\ ref\ cham}} = N_{\mathrm{g,\ NPL\ ref\ cham}}\ (N_{\mathrm{w}}/N_{\mathrm{c}}) \qquad (5)$$

where

$N_{\mathrm{w}}/N_{\mathrm{c}}$ is the conversion factor of the reference chamber calibration coefficient from graphite to water at the reference point.

Nutbrown *et al.* 2002 give the numerical value of the graphite to water conversion factor for the ^{60}Co beam quality as 1.1270, with a standard uncertainty of 3.2×10^{-3}.

Reference conditions

Absorbed dose to water is determined at the NPL under reference conditions defined as:

- The distance from the source to the reference plane (centre of thimble chamber) is 1 m
- The field size in air at the reference plane is 10 cm x 10 cm
- $N_{\mathrm{w,\ NPL\ ref\ cham}}$ is applicable at a depth of 5 cm (ICRU 1973), i.e. 4.991 g cm^{-2} in water at 20 °C

A summary of the components of uncertainty in the reference chamber calibration coefficient, $N_{\mathrm{g,\ NPL\ ref\ cham}}$, in terms of absorbed dose to graphite is indicated in Table 6, giving a combined relative standard uncertainty of 6.2 x 10^{-3}.

4 SUMMARY OF UNCERTAINTY ANALYSIS

Table 6 summarises the relative standard uncertainties associated with the primary standard correction factors, the primary standard measurement of absorbed dose to graphite, the conversion from dose to graphite to dose to water and the calibration of the NPL reference chambers in terms of absorbed dose to water.

The stated uncertainties were calculated following the recommendations given in the Guide to the Expression of Uncertainty in Measurement (GUM) (ISO 1995, Bentley 2005).

Table 6. Standard uncertainties for the reference ionisation chamber calibration coefficient $N_{\mathrm{w,\,NPL\,ref\,cham}}$ for therapy level ^{60}Co

Description	Relative standard uncertainty	
	100 s_i	100 u_i
Calorimeter corrections		
Effective core mass, $m_{\mathrm{core,\,eff}}$	0.01	
Total build-up material in front of the centre of the calorimeter core	<0.01	<0.01
Inverse square correction for source-to-core distance, $k_{\mathrm{z,\,cal}}$	-	0.10
Reference depth in graphite, $k_{\mathrm{d,\,cal}}$	-	<0.01
Radial non-uniformity correction for the calorimeter, $k_{\mathrm{rn,\,cal}}$	-	0.03
Axial non-uniformity correction for the calorimeter, $k_{\mathrm{an,\,cal}}$	-	0.01
Core alignment on beam axis	-	<0.01
Monte Carlo etc considerations		
Product of factors: $k_{\mathrm{gap}} \times k_{\mathrm{imp}} \times k_{\mathrm{geom}}$	0.10	0.10
Source modelling	-	0.10
MC self-consistency, transport parameters	-	0.10
Electrical calibrations		
Electronics and thermistor calibrations	0.2	0.08
Specific heat capacity of core graphite		
Measurement of effective specific heat capacity	0.28	0.21
Calorimeter measurements		
Calorimeter data analysis	-	0.16
Repeatability of calorimetry results	0.03	-
Dose to graphite at the reference point, D_{g} (combined uncertainty)	0.50	
Ion chamber measurements		
Ion chamber repeatability	0.04	-
Electrometer calibration, k_{elec}	-	0.1
Ion recombination, k_{ion}	-	0.03
Inverse square correction for source-to-chamber distance, $k_{\mathrm{z,\,cham}}$	-	0.10
Radial beam non-uniformity correction for the ion chamber, $k_{\mathrm{rn,\,cham}}$	-	0.01
Air temperature	-	0.06
Air pressure	-	0.05
Relative humidity	-	0.1
Reference chamber calibration coefficient, $N_{\mathrm{g,\,NPL\,ref\,cham}}$ (combined uncertainty)	0.54	
Conversion of absorbed dose from graphite to water	0.32	
Reference chamber calibration coefficient, $N_{\mathrm{w,\,NPL\,ref\,cham}}$ (combined uncertainty)	0.62	

5 ACKNOWLEDGEMENTS

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7 APPENDIX

7.1 MASS METROLOGY FOR THE PRIMARY STANDARD

The mass of the graphite and PEEK parts of the primary standard calorimeter after machining was measured by NPL’s Mass & Dimensional Group (Engineering Measurement Division). The measurement results have been reported in NPL certificates 2015040392-1 and 2015040392-2.

7.2 DIMENSIONAL METROLOGY FOR THE PRIMARY STANDARD

The critical dimensions of the graphite and PEEK parts of the primary standard calorimeter were measured by NPL’s Engineering Measurement Services Group (Engineering Measurement Division). The measurement results have been reported in NPL test reports 2015040411/1, 2015040411/2, 2015040411/3, 2015040411/4 and 2015040411/5, 2015040412/1, 2015040412/2, 2015040412/3 and 2015040412/4 and 2015040411/6.