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THE NPL AIR KERMA PRIMARY STANDARD PS5-1/PS5-2 FOR ^{137}CS AND ^{60}CO: SUMMARY OF FACTORS

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ABSTRACT

Since the 1950s the UK primary standard for the realisation of air kerma for high energies consisted of three graphite-walled cylindrical cavity ionisation chambers. These chambers have become increasingly unreliable in recent years and a project was started at the National Physical Laboratory to replace them. Spherical graphite-walled cavity ionisation chambers PS5-1 and PS5-2 have been constructed and commissioned and this report summarises the factors for the new chambers.

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1 INTRODUCTION

The National Physical Laboratory (NPL) has established two spherical graphite-walled cavity ionisation chambers of nominal volume 5 cc (serial numbers PS5-1 and PS5-2) as the UK national air kerma primary standard for the measurement of ^{137}Cs and ^{60}Co gamma rays. These two chambers replace the previous primary standard, which consisted of three cylindrical graphite-walled cavity ionisation chambers of nominal volume 1.5 cc.

This report summarises the factors applicable to the ionisation chamber response in order to realise air kerma and calibrate a secondary standard. The associated uncertainties are also presented.

2 SET UP CONDITIONS

2.1 THERAPY LEVEL (TL) ^{60}CO

- 10 cm × 10 cm field size
- 100 cm source to chamber reference point
- -500 V polarising potential applied to chamber graphite cap in normal use, such that negative ionisation current is generated
- Reference point of the chambers is taken as the geometrical centre of the graphite sphere

2.2 PROTECTION LEVEL (PL) ^{137}CS AND ^{60}CO

- 20 cm diameter field size
- 150 cm source to chamber reference point
- -500 V polarising potential applied to chamber graphite cap in normal use, such that negative ionisation current is generated
- Reference point of the chambers is taken as the geometrical centre of the graphite sphere.

3 THE AIR KERMA SENSITIVITY EQUATION

The air kerma sensitivity, N_k , in terms of grays per coulomb, of a chamber is given by the following:

$$N_k = \frac{W_{air}}{e} \cdot \frac{F}{(1-g)} \cdot k_h \cdot \frac{1}{\rho V} \tag{1}$$

where W_{air} is the energy needed to create an ion pair in dry air,
e is the electron charge,
g is the fraction of energy lost to bremsstrahlung,
k_h is the correction to 50% relative humidity,
ρ is the density of dry air,
V is the volume of the chamber, determined from measurement

and

$$F = \widetilde{F} \cdot k_{an} \cdot k_{rn} \cdot k_{stem} \cdot k_{pol} \tag{2}$$

where k_{an} is the axial non-uniformity correction, required to account for the change in the spectrum over the chamber volume in the direction of the beam axis,

k_{rn} is the radial non-uniformity correction, required to account for the change in the spectrum over the chamber volume perpendicular to the beam axis,

k_{stem} is the stem scatter correction, to correct the response of the chamber for the presence of the stem, determined experimentally for a specific field size,

k_{pol} is the polarity correction, to correct the response of the chamber for the effect of using negative and positive polarising potential, determined experimentally for a standard potential

and

$$\tilde{F} = \bar{S}_{air}^{graphite} \cdot k_{fl} \cdot (\bar{\mu}_{en}/\rho)_{graphite}^{air} \cdot k_{wall} \quad (3)$$

where $\bar{S}_{air}^{graphite}$ is the ratio of the mean stopping powers of graphite and air,

k_{fl} is the fluence perturbation correction, correcting for the perturbation of the electron fluence by the air cavity,

$(\bar{\mu}_{en}/\rho)_{graphite}^{air}$ is the ratio of the mean mass-energy absorption coefficients of air and graphite and

k_{wall} is the wall correction factor and can be expressed as $k_{wall} = \beta_{cep}^{-1} \cdot k_{att} \cdot k_{scat}$

where β_{cep}^{-1} is a correction to account for a change in the centre of electron production

k_{att} is the wall attenuation correction

k_{scat} is the wall scatter correction.

$\tilde{F}$ is the ratio of the dose to the chamber volume in the absence of the chamber, and what is actually measured, the chamber response. Monte Carlo simulations were used to determine $\tilde{F}$ (and its component factors), k_{an} and k_{rn}.

k_{ion} is the ion recombination correction that must be applied to the measured response of the chambers, to account for the incomplete collection of charge (Boag 1987, Attix 1986, Takata *et al.* 2005), determined experimentally using the Niatel/Boutillon method (Boutillon 1998). The value of the recombination correction depends on the air kerma rate and hence the ionisation current and is calculated from the following relationship:

$$k_{ion} = \mu \cdot I + c \quad (4)$$

where μ is a constant (units A^{-1})

I is the measured ionisation current in A with the standard polarising potential applied to the chamber

c is a dimensionless constant.

1.1 SUMMARY OF THE MEASURED FACTORS

Table 1 Primary standard correction factors determined from measurement

Factor	PS5-1			PS5-2		
	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co
k_{stem}, stem scatter correction	0.9951	0.9987	0.9978	0.9951	0.9987	0.9978
k_{pol}, polarity correction	1.0001	1.0001	1.0001	1.0001	1.0001	1.0001
V, sensitive volume (cm^3)	4.9164			4.9123		
μ, A^{-1}	1.3847×10^6			9.2751×10^5		
c	1.000			1.001		

1.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS

Table 2 Primary standard correction factors determined from calculation and standard values of physical quantities

Factor	PS5-1			PS5-2		
	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co
W_{air}/e (J/C)	33.97					
$\bar{S}_{air}^{graphite} \cdot k_{fl}$	1.0070	0.9976	0.9976	1.0088	1.0001	1.0001
$(\bar{\mu}_{en}/\rho)_{graphite}^{air}$	0.9993	0.9996	0.9996	0.9973	1.0000	1.0000
k_{wall}	1.0327	1.0256	1.0256	1.0311	1.0233	1.0233
$\widetilde{F}$	1.0392	1.0227	1.0227	1.0373	1.0233	1.0233
$k_{an} \times k_{rn}$	0.9996	1.0008	1.0008	0.9996	1.0008	1.0008
$(1-g)^{-1}$	1.0016	1.0032	1.0032	1.0016	1.0032	1.0032
ρ (g·cm^{-3})	1.2046					
k_h	0.9970					

1.3 PRIMARY STANDARD AIR KERMA SENSITIVITY

Table 3 Primary standard air kerma sensitivity N_k in grays per coulomb (Gy/C) ×10^6

Air kerma sensitivity (Gy/C ×10^6)	PS5-1			PS5-2		
	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co
N_k	5.9215	5.8649	5.8598	5.9158	5.8733	5.8682

2 MEASUREMENT EQUATION FOR AIR KERMA RATE

Air kerma rate $\dot{K}$ in Gy/s is determined with a primary standard from the measured ionisation current using the following equation:

$$\dot{K} = \left(I_{raw} - I_{leakage}\right) \cdot k_{elec} \cdot k_{ion} \cdot k_{TP} \cdot N_k \qquad (5)$$

where I_{raw} is the displayed ionisation current (A) on the electrometer,
$I_{leakage}$ is the leakage current (A),
k_{elec} is the electrometer correction factor,
k_{ion} is the ion recombination correction,
N_k is the air kerma sensitivity (Gy/C),
k_{TP} is the factor to correct from ambient temperature and pressure to standard temperature and pressure given by

$$k_{TP} = \frac{T}{293.15} \cdot \frac{101.325}{p} \tag{6}$$

where T is the ambient temperature (K) and
P is the ambient atmospheric pressure (kPa).

3 MEASUREMENT EQUATION FOR CALIBRATION OF SECONDARY STANDARD IN TERMS OF AIR KERMA

The air kerma calibration coefficient $N_{k,ss}$ in Grays per coulomb (Gy/C) for a secondary standard type 2611 ionisation chamber operated at +200 V polarising voltage applied to the collecting electrode, derived from measurements using the secondary standard bracketed by measurements with the primary standard (calibration by substitution), is given by

$$N_{k,ss} = \frac{\dot{K}}{\left(I_{raw,ss} - I_{leak,ss}\right) \cdot k_{elec,ss} \cdot k_{ion,ss} \cdot k_{TP,ss}} \tag{7}$$

where $\dot{K}$ is the air kerma rate (Gy/s) measured by the primary standard,
$I_{raw,ss}$ is the secondary standard ionisation current (A) displayed on the electrometer,
$I_{leak,ss}$ is the secondary standard leakage current (A),
$k_{elec,ss}$ is the secondary standard electrometer correction factor,
$k_{TP,ss}$ is the factor to correct from ambient temperature T and pressure p to standard temperature and pressure and
$k_{ion,ss}$ is the ion recombination correction for the secondary standard. Volume recombination is negligible at air kerma rates used here (~15 mGys^{-1}). Initial recombination loss will also be small (around 0.1%) for this type of chamber at the recommended polarising voltage and can be ignored.

4 SUMMARY OF UNCERTAINTY ANALYSIS

Table 4 and Table 5 and summarise the uncertainties associated with the primary standard correction factor and the primary standard measurement of air kerma, applicable to all beam qualities unless stated otherwise. Table 6 summarises the uncertainty in the calibration of an NPL2611 secondary standard ionisation chamber for therapy level Co-60.

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

Table 4 Uncertainties in the primary standard correction F, $\widetilde{F}$ and air kerma sensitivity N_k applicable to PS5-1 and PS5-2 for therapy level ^{60}Co (estimated values for protection level qualities in brackets)

Symbol	Quantity, source of uncertainty	Type A	Type B
$\bar{S}_{air}^{graphite} \cdot k_{fl}$	Mass stopping power ratio (graphite to air) x fluence perturbation correction	-	0.11
$(\bar{\mu}_{en}/\rho)_{graphite}^{air}$	Mass energy absorption coefficient ratio (air to graphite)	-	0.10
k_{wall}	Wall correction	-	0.10
$\widetilde{F}$	Standard uncertainty	0.11 (0.14)	0.18
$u_c(\widetilde{F})$	Combined standard uncertainty	0.21 (0.23)	
k_{an} x k_{rn}	Product of axial non-uniformity correction and radial non-uniformity correction	0.14 (0.17)	0.10
k_{stem}	Stem scatter correction	0.01	0.05
k_{pol}	Polarity correction	0.01	-
$u_c(F)$	Combined standard uncertainty	0.28 (0.31)	
(W_{air}/e)*	Energy per ion pair (J/C)	-	0.15
g	Fraction of energy lost by bremsstrahlung	-	0.02
k_h	Humidity correction	-	0.05
ρ_{air}	Density of dry air (kg/m^3)	-	0.01
V	Volume of cavity (cm^3)	-	0.01
$u_c(N_k)$	Combined standard uncertainty	0.28 (0.31)	

*Due to correlated uncertainties between the stopping power ratio and W_{air}/e, the uncertainty in W_{air}/e has been included in the combined uncertainty for the product $\bar{S}_{air}^{graphite} \cdot k_{fl}$

Table 5 Uncertainties in the primary standard measurement of air kerma rate $\dot{K}$ applicable to PS5-1 and PS5-2 for therapy level ^{60}Co (estimated values for protection level qualities in brackets)

Symbol	Quantity, source of uncertainty	Type A	Type B
N_k	Primary standard air kerma sensitivity	-	0.28 (0.31)
k_{elec}	Electrometer current calibration (nA/'nA')	-	0.05 (0.25)
k_{res}	Electrometer resolution (nA)	-	0.03
k_{ion}	Ion recombination correction	0.05	-
$I_{leakage}$	Leakage current (A)	0.05 (0.30)	-
p	Pressure (kPa)	0.02	
T	Temperature (K)	0.04	-
$R_{angular}$	Angular response change	0.03	-
R	Repeatability	0.05 (0.30)	-
$u_c(\dot{K})$	Combined standard uncertainty	0.30 (0.59)	

Table 6 Uncertainties in the air kerma calibration coefficient $N_{k,ss}$ of an NPL2611 secondary standard ionisation chamber for therapy level Co-60 (estimated values for protection level transfer standard in brackets)

Symbol	Quantity, source of uncertainty	Type A	Type B
$\dot{K}$	Air kerma rate	-	0.30 (0.59)
$k_{elec,ss}$	Electrometer current calibration (nA/'nA')	-	0.05
$k_{res,ss}$	Electrometer resolution (nA)	-	0.03
$k_{ion,ss}$	Ion recombination correction	0.05	-
$I_{leakage,ss}$	Leakage current (A)	0.05	-
p_{ss}	Pressure (kPa)	0.02	-
T_{ss}	Temperature (K)	0.04	-
k_{dist}	Distance from source	-	0.05
k_{orient}	Orientation of chamber	-	0.01
R	Repeatability	0.05 (0.15)	-
$u_c(N_{k,ss})$	Combined standard uncertainty	0.33 (0.62)	
U	Expanded uncertainty (k=2)	0.65 (1.22)	

5 ACKNOWLEDGEMENTS

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7 APPENDIX

7.1 SENSITIVE VOLUMES OF PRIMARY STANDARD CAVITY CHAMBERS

The sensitive volumes of the primary standards were calculated from NPL certificates reference E07100095/1A/CMM183 and E07100095/2/CMM183.