

NPL REPORT IR 53

**THE NPL AIR KERMA PRIMARY STANDARD PS5-1/PS5-2 FOR
 ^{137}CS AND ^{60}CO : SUMMARY OF FACTORS INCORPORATING
ICRU REPORT 90 RECOMMENDATIONS**

**G A BASS, S DUANE, M J HOMER, M KELLY, J W MANNING, D J
MAUGHAN, R F NUTBROWN, T SANDER, D R SHIPLEY, J A D
SNAITH**

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ICRU Report 90 recommendations

G A Bass, S Duane, M J Homer, M Kelly, J W Manning,
D J Maughan, R F Nutbrown, T Sander, D R Shipley, J A D Snaith
Medical Physics Department

ABSTRACT

The NPL air kerma primary standard ionisation chambers PS5-1 and PS5-2 for ^{137}Cs and ^{60}Co were established in 2017. Certain factors pertinent to these standards have required re-evaluation following the recommendations contained in the International Commission for Radiation Measurements and Units Report 90. This report summarises the re-evaluated factors and those unaffected by the adoption of the recommendations.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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Approved on behalf of NPLML by
Laurence Brice, Group Leader.

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1 INTRODUCTION

The National Physical Laboratory (NPL) has established two spherical graphite-walled cavity ionisation chambers of nominal volume 5 cm³ (serial numbers PS5-1 and PS5-2) as the UK national air kerma primary standard for the measurement of ¹³⁷Cs and ⁶⁰Co gamma rays.

NPL Report IR 41 (Bass *et al.* 2017) summarises the factors applicable to the ionisation chamber response in order to realise air kerma and calibrate a secondary standard.

Following the recommendations of the International Commission for Radiation Measurements and Units (ICRU) Report 90 (ICRU 2016) certain factors pertinent to these standards required re-evaluation. This report summarises the factors applicable to these chambers similarly to the previous report but with updated factors where appropriate.

ICRU Report 90 also recommends that the standard uncertainty of the value for W_{air} is increased from 0.15% to 0.35%. This change is reflected in the uncertainty analysis presented here.

2 SET UP CONDITIONS

1. THERAPY LEVEL (TL) ⁶⁰CO

- 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. PROTECTION LEVEL (PL) ¹³⁷CS AND ⁶⁰CO

- 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:

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

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

$$F = \tilde{F} \cdot k_{an} \cdot k_{rn} \cdot k_{stem} \cdot k_{pol} \quad (2)$$

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 factor, 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

$$k_{wall} = \beta_{cep}^{-1} \cdot k_{att} \cdot k_{scat} \quad (4)$$

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 factor
 k_{scat} is the wall scatter correction factor.

$\tilde{F}$ 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 factor 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:

$$k_{ion} = \mu \cdot I + c \quad (5)$$

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. The values for $\bar{S}_{air}^{graphite} \cdot k_{fl}$, $(\bar{\mu}_{en}/\rho)_{graphite}^{air}$, k_{wall} , $\tilde{F}$ and $k_{an} \cdot k_{rn}$ have been updated from the previous report IR 41.

Factor	PS5-1			PS5-2		
	PL ¹³⁷ Cs	PL ⁶⁰ Co	TL ⁶⁰ Co	PL ¹³⁷ Cs	PL ⁶⁰ Co	TL ⁶⁰ Co
$\frac{W_{air}}{e}$ (J/C)	33.97					
$\bar{S}_{air}^{graphite} \cdot k_{fl}$	1.0018	0.9936	0.9936	1.0015	0.9944	0.9944
$(\bar{\mu}_{en}/\rho)_{graphite}^{air}$	1.0008	0.9996	0.9996	0.9995	0.9995	0.9995
k_{wall}	1.0316	1.0243	1.0243	1.0321	1.0246	1.0246
$\tilde{F}$	1.0343	1.0173	1.0173	1.0331	1.0184	1.0184
$k_{an} \cdot k_{rn}$	0.9991	1.0008	1.0008	0.9991	1.0008	1.0008
$(1-g)^{-1}$	1.0016	1.0032	1.0032	1.0016	1.0032	1.0032
ρ (kg·m ⁻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) $\times 10^6$

Air kerma sensitivity (Gy/C $\times 10^6$)	PS5-1			PS5-2		
	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co
N_K	5.8901	5.8342	5.8291	5.8883	5.8449	5.8398

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:

$$\dot{K} = (I_{\text{raw}} - I_{\text{leakage}}) \cdot k_{\text{elec}} \cdot k_{\text{ion}} \cdot k_{Tp} \cdot N_K \quad (6)$$

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 factor,
 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

$$k_{Tp} = \frac{T}{293.15} \cdot \frac{101.325}{p} \quad (7)$$

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

$$N_{K,ss} = \frac{\dot{K}}{(I_{\text{raw},ss} - I_{\text{leak},ss}) \cdot k_{\text{elec},ss} \cdot k_{\text{ion},ss} \cdot k_{Tp,ss}} \quad (8)$$

where $\dot{K}$ is the air kerma rate (Gy/s) measured by the primary standard,
 $I_{\text{raw},ss}$ is the secondary standard ionisation current (A) displayed on the electrometer,
 $I_{\text{leak},ss}$ 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 ($\sim 15 \text{ mGys}^{-1}$). 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 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 ^{60}Co . The expanded uncertainties reported here are not significantly different to those reported in IR 41.

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 factor F , $\tilde{F}$ 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
$\tilde{S}_{air}^{graphite} \cdot k_{fl}$	Mass stopping power ratio (graphite to air) x fluence perturbation correction	-	0.08
$(\mu_{en}/\rho)_{graphite}^{air}$	Mass energy absorption coefficient ratio (air to graphite)	-	0.10
k_{wall}	Wall correction	-	0.10
$\tilde{F}$	Standard uncertainty	0.11 (0.12)	0.16
$u_c(\tilde{F})$	Combined standard uncertainty	0.20 (0.20)	
$k_{an} \cdot k_{rn}$	Product of axial non-uniformity correction and radial non-uniformity correction	0.14 (0.16)	0.10
k_{stem}	Stem scatter correction	0.01	0.05
k_{pol}	Polarity correction	0.01	-
$u_c(F)$	Combined standard uncertainty	0.27 (0.28)	
$\frac{W_{air}}{e}^*$	Energy per ion pair (J/C)	-	0.35
g	Fraction of energy lost by bremsstrahlung	-	0.02
k_h	Humidity correction	-	0.05
ρ	Density of dry air (kg/m^3)	-	0.01
V	Volume of cavity (cm^3)	-	0.01
$u_c(N_K)$	Combined standard uncertainty	0.27 (0.29)	

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

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	-	0.27 (0.29)
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 (0.57)	

Table 6: Uncertainties in the air kerma calibration coefficient $N_{k,ss}$ of an NPL2611 secondary standard ionisation chamber for therapy level ^{60}Co (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 (0.58)
$k_{elec,ss}$	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	0.32 (0.61)	
U	Expanded uncertainty ($k=2$)	0.64 (1.21)	

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.

7.2 CHANGE IN OVERALL FACTORS

Table 7: Changes in overall factors for each chamber for the three beam qualities, comparing the factors presented in this report to the previous factors reported in NPL Report IR 41

Air kerma sensitivity (Gy/C $\times 10^6$)	PS5-1			PS5-2		
	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co	PL ^{137}Cs	PL ^{60}Co	TL ^{60}Co
2017 N_K	5.9215	5.8649	5.8598	5.9158	5.8733	5.8682
2019 N_K	5.8901	5.8342	5.8291	5.8883	5.8449	5.8398
2019-2017 (factor)	-0.53% (0.9947)	-0.52% (0.9948)	-0.52% (0.9948)	-0.46% (0.9954)	-0.48% (0.9952)	-0.48% (0.9952)