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THE NPL AIR KERMA PRIMARY STANDARD FREE AIR CHAMBER FOR MEDIUM ENERGY X-RAYS: SUMMARY OF FACTORS

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1 INTRODUCTION

The National Physical Laboratory (NPL) air kerma primary standard for x-rays generated at kilovoltages from 40 kV up to 300 kV is a parallel plate, guarded field free-air ionisation chamber that covers the range of x-ray qualities from approximately 1.0 mm Al HVL to 20.0 mm Al HVL for therapy level qualities and from 0.085 mm Cu to 6.2 mm Cu for protection level qualities. The usable air kerma rate range is from about 0.2 mGy min^{-1} to 90 mGy min^{-1}. This standard has been in use at NPL as the national primary standard since the spring of 1998.

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

Since 1998 many of the measured factors have been reassessed by Monte Carlo simulations; in all cases the calculated values have confirmed that the original measurement-derived factors in use are reasonable. For consistency, the original factors are still in use.

2 300 KV PRIMARY STANDARD FREE AIR CHAMBER METROLOGY

Table **1** contains metrology information for the primary standard and Figure **1** shows the features of the free air chamber.

Table 1 Results of free air chamber metrology

Measurement	Value
Collecting electrode length	100.258 mm
Beam-defining aperture E7 diameter	10.014 mm
Air path length	493 mm
HT-collecting electrode plate separation	264 mm
Collecting volume	7896.3 mm^3
Collecting electrode insulation resistance	at least 10^{14} Ω

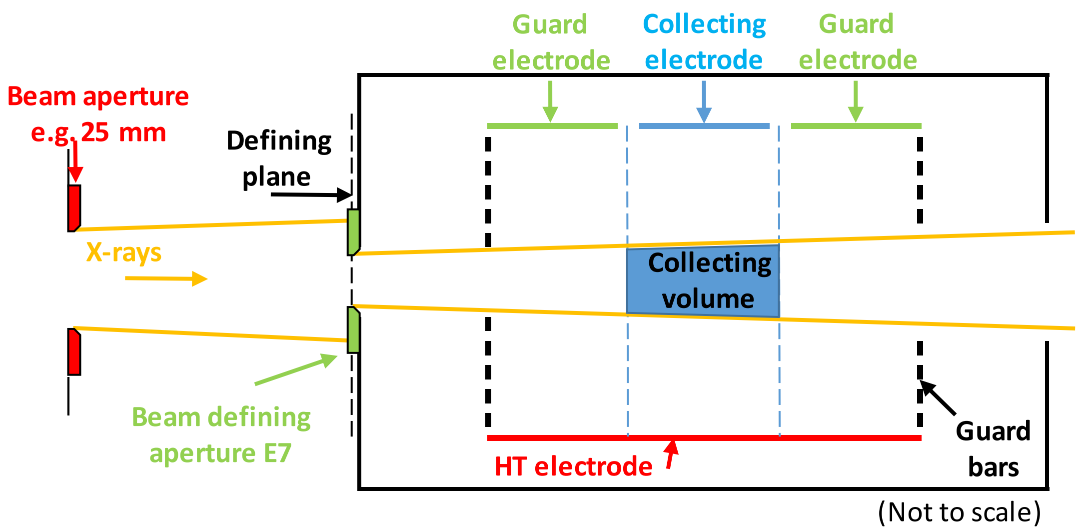

Figure 1 Schematic of the 300 kV primary standard free air chamber (not to scale)

3 SET UP CONDITIONS

3.1 THERAPY LEVEL (TL) X-RAYS

- 25 mm beam-limiting aperture used
- Beam-defining aperture diameter 10 mm (nominal, serial number E7) fit to the chamber
- Reference point (defining plane) of the chamber is 4.68 mm from the external face of aperture E7
- 75 cm source to chamber reference point
- -3000 V polarising potential applied to chamber HT electrode in normal use, such that negative ionisation current is generated.

3.2 PROTECTION LEVEL (PL) X-RAYS

- 35 mm beam-limiting aperture used
- Beam-defining aperture diameter 10 mm (nominal, serial number E7) fit to the chamber
- Reference point of the FAC is 4.68 mm from the external face of aperture E7
- 100 cm source to chamber reference point
- -3000 V polarising potential applied to chamber HT electrode in normal use, such that negative ionisation current is generated.

4 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:

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

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

and

$$\Pi = k_a \cdot k_d \cdot k_e \cdot k_l \cdot k_{pol} \cdot k_{sc} \cdot k_{fl} \cdot k_s \qquad (2)$$

where k_a is the correction for air attenuation between the aperture and the collecting electrode, necessary because the reference point of the chamber is taken to be the defining plane of the aperture and not the centre of the collector,
k_d is the field distortion correction, necessary because the electric field inside the free air chamber is not perfectly perpendicular to the electrodes at all points,
k_e is the electron loss correction, necessary at higher energies when the range of the secondary electrons in air is greater than the plate separation in the free air chamber,
k_l is the front face penetration correction, necessary if the front face of the free air chamber is not thick enough to attenuate the x-ray beam,
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,

k_{sc} is the scattered photon correction that accounts for photons scattered from the main beam through the chamber and which produce ionisation in the space between the electrodes not defined by the ionisation volume,

k_{fl} is the fluorescence correction which accounts for the re-absorption of fluorescence photons generated by argon in the air of the free air chamber,

k_s is the ion recombination correction that must be applied to the measured response of the chamber, 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).

5 THERAPY LEVEL BEAM QUALITIES

5.1 SUMMARY OF THE MEASURED FACTORS FOR THERAPY LEVEL BEAM QUALITIES

Table 2 300 kV Primary standard correction factors determined from measurement for therapy level beam qualities

Nominal generating potential (kV)	Beam quality, HVL		Factor					
	mm Cu	mm Al	k_s	k_a	k_{sc}	k_d	k_{pol}	k_l
50	0.030	1.0	1.0007	1.0419	0.9908	1.0003	1.0000	1.0000
70	0.062	2.0	1.0007	1.0258	0.9920	1.0003	1.0000	1.0000
100	0.150	4.0	1.0007	1.0168	0.9932	1.0003	1.0000	1.0000
105	0.20	5.0	1.0007	1.0150	0.9935	1.0003	1.0000	1.0000
135	0.50	8.8	1.0007	1.0116	0.9945	1.0003	1.0000	1.0000
180	1.00	12.3	1.0007	1.0097	0.9952	1.0003	1.0000	1.0000
220	2.00	16.1	1.0007	1.0089	0.9960	1.0003	1.0000	1.0000
280	4.00	20.0	1.0007	1.0073	0.9968	1.0003	1.0000	1.0000

5.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR THERAPY LEVEL BEAM QUALITIES

Table 3 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for therapy level beam qualities

Nominal generating potential (kV)	Beam quality, HVL		Factor or quantity				
	mm Cu	mm Al	W_{air}/e (J/C)	$(1\text{-}g)^{-1}$	k_h	ρ (g·cm^{-3})	V (cm^3)
50	0.030	1.0	33.97	1.000	0.998	1.2045	7.8963
70	0.062	2.0					
100	0.150	4.0					
105	0.20	5.0					
135	0.50	8.8					
180	1.00	12.3					
220	2.00	16.1					
280	4.00	20.0					

5.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR THERAPY LEVEL BEAM QUALITIES

Table 4 Primary standard air kerma sensitivity N_k in grays per coulomb (Gy/C) $\times 10^6$ for therapy level beam qualities

Nominal generating potential (kV)	Beam quality, HVL		Air kerma sensitivity N_k Gy/C $\times 10^6$
	mm Cu	mm Al	
50	0.030	1.0	3.6837
70	0.062	2.0	3.6309
100	0.150	4.0	3.6036
105	0.20	5.0	3.5981
135	0.50	8.8	3.5897
180	1.00	12.3	3.5857
220	2.00	16.1	3.5885
280	4.00	20.0	3.5897

6 PROTECTION LEVEL BEAM QUALITIES (ISO 4037 NARROW SPECTRUM SERIES)

6.1 SUMMARY OF THE MEASURED FACTORS FOR PROTECTION LEVEL BEAM QUALITIES (ISO 4037 NARROW SPECTRUM SERIES)

Table 5 300 kV Primary standard correction factors determined from measurement for protection level beam qualities

Nominal generating potential (kV)	Beam quality, HVL	Factor					
	mm Cu	k_s	k_a	k_{sc}	k_d	k_{pol}	k_l
40	0.085	1.0000	1.0201	0.9924	1.0003	1.0000	1.0000
60	0.234	1.0000	1.0133	0.9935	1.0003	1.0000	1.0000
80	0.581	1.0000	1.0109	0.9945	1.0003	1.0000	1.0000
100	1.12	1.0000	1.0094	0.9954	1.0003	1.0000	1.0000
120	1.73	1.0000	1.0088	0.9958	1.0003	1.0000	1.0000
150	2.42	1.0000	1.0069	0.9962	1.0003	1.0000	1.0000
200	4.10	1.0000	1.0059	0.9968	1.0003	1.0000	1.0000
250	5.33	1.0000	1.0072	0.9972	1.0003	1.0000	1.0000
300	6.26	1.0000	1.0061	0.9975	1.0003	1.0000	1.0000

6.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR PROTECTION LEVEL BEAM QUALITIES (ISO 4037 NARROW SPECTRUM SERIES)

Table 6 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for protection level beam qualities

Nominal generating potential (kV)	Beam quality, HVL	Factor or quantity				
	mm Cu	W_{air}/e (J/C)	$(1\text{-}g)^{-1}$	k_h	ρ (g·cm^{-3})	V (cm^3)
40	0.085	33.97	1.000	0.998	1.2045	7.8963
60	0.234					
80	0.581					
100	1.12					
120	1.73					
150	2.42					
200	4.10					
250	5.33					
300	6.26					

6.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR PROTECTION LEVEL BEAM QUALITIES

Table 7 300 kV primary standard air kerma sensitivity N_k in grays per coulomb (Gy/C) $\times 10^6$ for protection level beam qualities (ISO 4037 Narrow Spectrum Series)

Nominal generating potential (kV)	Beam quality, HVL mm Cu	Air kerma sensitivity N_k Gy/C $\times 10^6$
40	0.085	3.6098
60	0.234	3.5896
80	0.581	3.5849
100	1.12	3.5828
120	1.73	3.5821
150	2.42	3.5783
200	4.10	3.5826
250	5.33	3.5908
300	6.26	3.6006

7 MEASUREMENT EQUATION FOR AIR KERMA RATE

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

$$\dot{K} = \left(I_{raw} - I_{leakage}\right) \cdot k_{elec} \cdot k_{ion} \cdot k_{TP} \cdot N_k \qquad (3)$$

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

$$k_{TP} = \frac{T}{293.15} \cdot \frac{101.325}{p} \qquad (4)$$

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

8 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 ionisation chamber, derived from measurements using the secondary standard bracketed by measurements with the primary standard (calibration by substitution), is given by

$$N_{k,ss} = \frac{\dot{K}}{\left(I_{raw,ss} - I_{leak,ss}\right) \cdot k_{elec,ss} \cdot k_{ion,ss} \cdot k_{TP,ss}} \qquad (5)$$

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 mGyh^{-1}). Initial recombination loss will also be small (around 0.1%) for therapy and protection level chambers at the recommended polarising voltage and can be ignored.

9 SUMMARY OF UNCERTAINTY ANALYSIS

Table 8 and Table 9 and summarise the uncertainties associated with the 300 kV primary standard correction factor and the primary standard measurement of air kerma. Table 10 summarises the uncertainty in the calibration of an NPL2611 secondary standard ionisation chamber for therapy level medium energy x-rays.

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

Table 8 Uncertainties in the primary standard correction Π applicable to therapy level qualities (estimated values for protection level qualities in brackets)

Symbol	Quantity, source of uncertainty	Type A	Type B
k_a	Air attenuation correction	0.13	-
k_d	Field distortion correction	0.01	-
k_e	Electron loss correction	-	0.05
k_l	Front face penetration correction	0.03	-
k_{pol}	Polarity correction	0.04	-
k_{sc}	Scattered photon correction	0.10	-
k_{fl}	Fluorescence correction	-	0.05
k_s	Ion recombination correction	0.03	-
$u_c(\Pi)$	Combined standard uncertainty	0.18 (0.18)	

Table 9 Uncertainties in the 300 kV primary standard measurement of air kerma rate $\dot{K}$ for therapy level beam qualities (estimated values for protection level qualities in brackets)

Symbol	Quantity, source of uncertainty	Type A	Type B
Π	Total primary standard correction	-	0.18
k_{elec}	Electrometer current calibration (pA/'pA')	-	0.10 (0.25)
k_{res}	Electrometer resolution (pA)	-	0.05
$I_{leakage}$	Leakage current (A)	0.05 (0.30)	-
(W_{air}/e)	Energy per ion pair (J/C)	-	0.15
g	Fraction of energy lost by bremsstrahlung	-	0.02
ρ_{air}	Density of dry air (kg/m^3)	-	0.01
k_h	Humidity correction	-	0.05
T	Temperature (K)	0.04	-
p	Pressure (kPa)	0.02	-
V	Collecting volume (cm^3)	-	0.01
R	Repeatability	0.10 (0.30)	-
$u_c(\dot{K})$	Combined standard uncertainty	0.28 (0.53)	

Table 10 Uncertainties in the air kerma calibration $N_{k,ss}$ of an NPL2611 secondary standard ionisation chamber for therapy level beam qualities

Symbol	Quantity, source of uncertainty	Type A	Type B
$\dot{K}$	Air kerma rate	-	0.28
$k_{elec,ss}$	Electrometer current calibration (nA/'nA')	-	0.05
$k_{res,ss}$	Electrometer resolution (nA)	-	0.03
$k_{ion,ss}$	Ion recombination correction	0.10	-
$I_{leakage,ss}$	Leakage current (A)	0.05	-
T_{ss}	Temperature (K)	0.04	-
p_{ss}	Pressure (kPa)	0.02	-
k_{dist}	Distance from source	-	0.05
k_{orient}	Orientation of chamber	-	0.01
R	Repeatability	0.10	-
$u_c(N_{k,ss})$	Combined standard uncertainty	0.33	
U	Expanded uncertainty (k=2)	0.64	

10 ACKNOWLEDGEMENTS

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