

NPL REPORT IR 54

**THE NPL AIR KERMA PRIMARY STANDARD FREE-AIR CHAMBER
FOR MEDIUM ENERGY X-RAYS: SUMMARY OF FACTORS
INCORPORATING ICRU REPORT 90 RECOMMENDATIONS**

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

AUGUST 2019

The NPL air kerma primary standard free-air chamber
for medium energy x-rays: summary of factors
incorporating ICRU Report 90 recommendations

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

ABSTRACT

The NPL air kerma primary standard free-air ionisation chamber for medium energy x-ray qualities was established in 1998. The International Commission for Radiation Measurements and Units Report 90 proposes the introduction of two new correction factors applicable to free air ionisation chambers in this energy range. This report summarises all of the factors for the NPL primary standard including the two new factors.

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ISSN 1754-2952

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) 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, from 0.085 mm Cu to 6.2 mm Cu for protection level qualities and from 1.42 mm Al to 13.3 mm Al for diagnostic 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.

NPL Report IR 42 (Bass et al. 2017) summarises the factors applicable to the chamber response in order to realise air kerma and calibrate a secondary standard.

The International Commission for Radiation Measurements and Units (ICRU) Report 90 proposes two new factors for free-air ionisation chambers, k_{ii} and k_W , both related to the mean energy expended in dry air per ion formed, W_{air} . The initial ionisation correction factor k_{ii} accounts for the fact that the definition of W_{air} does not include the charge of the initial charged particle, while the correction factor k_W accounts for the rapid increase in the value of W_{air} at electron energies below around 10 keV. It is noted that, individually, these two factors have large effects but fortuitously cancel each other out. Calculations of their combined effect have been performed and ICRU Report 90 presents values for the product of the correction factors $k_{ii} \cdot k_W$ as a function of photon energy from which the factors contained in this report were derived.

This report summarises the factors applicable to the NPL free-air chamber similarly to the previous report but with updated factors where appropriate to incorporate the ICRU Report 90 recommendations.

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.

2 300 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

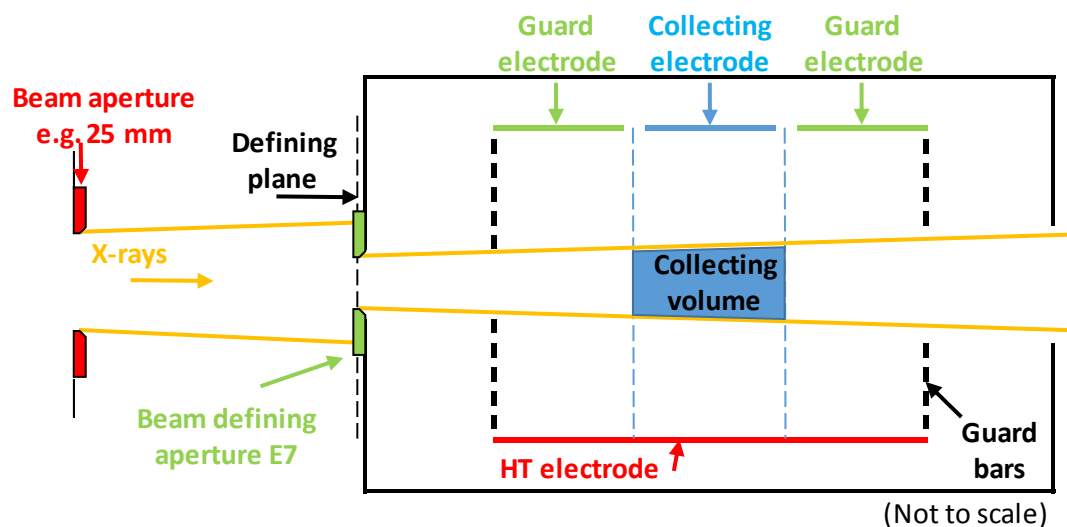


Figure 1: Schematic of the 300 kV primary standard free-air chamber (not to scale)

3 SETUP CONDITIONS

3.1 THERAPY LEVEL (TL) X-RAYS

- 25 mm beam-limiting aperture used
- Beam-defining aperture diameter 10 mm (nominal, serial number E7) fitted to the chamber
- Reference point (defining plane) of the free-air 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) fitted to the chamber
- Reference point of the free-air chamber 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.

3.3 DIAGNOSTIC LEVEL (DL) X-RAYS

- 25 mm beam-limiting aperture used
- Beam-defining aperture diameter 10 mm (nominal, serial number E7) fitted to the chamber
- Reference point (defining plane) of the free-air chamber is 4.68 mm from the external face of aperture E7
- 150 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:

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

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 collecting volume of the chamber

And

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

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, calculated for each beam quality in mm Cu HVL from a fit to NPL/BIPM calculated factors:

$$k_{fl} = 0.000519237 \times \ln(\text{HVL}) + 0.999521 \quad (3)$$

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), calculated from the measured ionisation current I in A:

$$k_s = 6029526 \times I + 1.00029 \quad (4)$$

k_{ii} is the initial ionisation correction factor accounting for the fact that the definition of W_{air} does not include the charge of the initial charged particle,
 k_W accounts for the rapid increase in the value of W_{air} at electron energies below around 10 keV.

5 THERAPY LEVEL BEAM QUALITIES

5.1 SUMMARY OF 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	1.0024	1.0419	0.9908	1.0003	1.0000	1.0000
70	0.062	2.0	1.0025	1.0258	0.9920	1.0003	1.0000	1.0000
100	0.150	4.0	1.0028	1.0168	0.9932	1.0003	1.0000	1.0000
105	0.20	5.0	1.0028	1.0150	0.9935	1.0003	1.0000	1.0000
135	0.50	8.8	1.0029	1.0116	0.9945	1.0003	1.0000	1.0000
180	1.00	12.3	1.0040	1.0097	0.9952	1.0003	1.0000	1.0000
220	2.00	16.1	1.0039	1.0089	0.9960	1.0003	1.0000	1.0000
280	4.00	20.0	1.0039	1.0073	0.9968	1.0003	1.0000	1.0000

*Values of k_s valid for 75 cm SCD, -3000 V HT and 10 mA beam current

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	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_W$	ρ (kg·m ⁻³)	V (cm ³)
50	0.030	1.0	33.97	1.000	1.0000	0.9977	0.998	0.9980	1.2046	7.8963
70	0.062	2.0			1.0000	0.9981		0.9982		
100	0.150	4.0			1.0000	0.9985		0.9979		
105	0.20	5.0			1.0000	0.9987		0.9979		
135	0.50	8.8			1.0000	0.9992		0.9978		
180	1.00	12.3			1.0000	0.9995		0.9979		
220	2.00	16.1			1.0008	0.9999		0.9983		
280	4.00	20.0			1.0019	1.0000		0.9988		

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	3.6738
70	0.062	2.0	3.6239
100	0.150	4.0	3.5980
105	0.20	5.0	3.5930
135	0.50	8.8	3.5863
180	1.00	12.3	3.5882
220	2.00	16.1	3.5931
280	4.00	20.0	3.5962

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	1.0003	1.0201	0.9924	1.0003	1.0000	1.0000
60	0.234	1.0003	1.0133	0.9935	1.0003	1.0000	1.0000
80	0.581	1.0003	1.0109	0.9945	1.0003	1.0000	1.0000
100	1.12	1.0003	1.0094	0.9954	1.0003	1.0000	1.0000
120	1.73	1.0003	1.0088	0.9958	1.0003	1.0000	1.0000
150	2.42	1.0004	1.0069	0.9962	1.0003	1.0000	1.0000
200	4.10	1.0003	1.0059	0.9968	1.0003	1.0000	1.0000
250	5.33	1.0003	1.0072	0.9972	1.0003	1.0000	1.0000
300	6.26	1.0003	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	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_w$	ρ (kg·m ⁻³)	V (cm ³)
40	0.085	33.97	1.000	1.0000	0.9982	0.998	0.9981	1.2046	7.8963
60	0.234			1.0000	0.9988		0.9980		
80	0.581			1.0000	0.9992		0.9987		
100	1.12			1.0000	0.9996		0.9979		
120	1.73			1.0000	0.9998		0.9982		
150	2.42			1.0004	1.0000		0.9984		
200	4.10			1.0020	1.0000		0.9988		
250	5.33			1.0026	1.0000		0.9990		
300	6.26			1.0061	1.0000		0.9993		

6.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR PROTECTION LEVEL BEAM QUALITIES

Table 7: 300 kV primary standard air kerma sensitivity N_{KK} 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	Air kerma sensitivity N_k Gy/C $\times 10^6$
	mm Cu	
40	0.085	3.5974
60	0.234	3.5789
80	0.581	3.5783
100	1.12	3.5747
120	1.73	3.5756
150	2.42	3.5735
200	4.10	3.5790
250	5.33	3.5882
300	6.26	3.5988

7 DIAGNOSTIC (ENTRANCE) LEVEL RQR SERIES BEAM QUALITIES

7.1 SUMMARY OF THE MEASURED FACTORS FOR DIAGNOSTIC (ENTRANCE) LEVEL RQR SERIES BEAM QUALITIES

Table 8: 300 kV Primary standard correction factors determined from measurement for diagnostic (entrance) level RQR series beam qualities

Nominal generating potential (kV)	RQR beam quality	Beam quality HVL	Factor					
		mm Al	k_s^*	k_a	k_{sc}	k_d	k_{pol}	k_l
40	RQR2	1.42	1.0005	1.0419	0.9908	1.0003	1.0000	1.0000
50	RQR3	1.78	1.0006	1.0314	0.9916	1.0003	1.0000	1.0000
60	RQR4	2.19	1.0007	1.0258	0.9921	1.0003	1.0000	1.0000
70	RQR5	2.58	1.0008	1.0222	0.9924	1.0003	1.0000	1.0000
80	RQR6	3.01	1.0010	1.0202	0.9927	1.0003	1.0000	1.0000
90	RQR7	3.48	1.0011	1.0187	0.9928	1.0003	1.0000	1.0000
100	RQR8	3.97	1.0013	1.0175	0.9930	1.0003	1.0000	1.0000
120	RQR9	5.00	1.0016	1.0155	0.9933	1.0003	1.0000	1.0000
150	RQR10	6.57	1.0020	1.0140	0.9937	1.0003	1.0000	1.0000

*Values of k_s valid for 150 cm SCD, -3000 V HT and 15 mA beam current

7.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR DIAGNOSTIC (ENTRANCE) LEVEL RQR SERIES BEAM QUALITIES

Table 9: 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for diagnostic (entrance) level RQR series beam qualities

Nominal generating potential (kV)	RQR beam quality	Beam quality HVL	Factor or quantity							
		mm Al	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_w$	ρ (kg·m ⁻³)	V (cm ³)
40	RQR2	1.42	33.97	1.000	1.0000	0.9980	0.998	0.9979	1.2046	7.8963
50	RQR3	1.78			1.0000	0.9981		0.9981		
60	RQR4	2.19			1.0000	0.9983		0.9982		
70	RQR5	2.58			1.0000	0.9984		0.9983		
80	RQR6	3.01			1.0000	0.9986		0.9981		
90	RQR7	3.48			1.0000	0.9987		0.9980		
100	RQR8	3.97			1.0000	0.9988		0.9979		
120	RQR9	5.00			1.0000	0.9990		0.9978		
150	RQR10	6.57			1.0000	0.9992		0.9978		

7.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR DIAGNOSTIC (ENTRANCE) LEVEL RQR SERIES BEAM QUALITIES

Table 10: 300 kV primary standard air kerma sensitivity N_K in grays per coulomb (Gy/C) $\times 10^6$ for diagnostic (entrance) level RQR series beam qualities

Nominal generating potential (kV)	RQR beam quality	Beam quality HVL	Air kerma sensitivity N_K Gy/C $\times 10^6$
		mm Al	
40	RQR2	1.42	3.6674
50	RQR3	1.78	3.6348
60	RQR4	2.19	3.6179
70	RQR5	2.58	3.6074
80	RQR6	3.01	3.6006
90	RQR7	3.48	3.5959
100	RQR8	3.97	3.5924
120	RQR9	5.00	3.5866
150	RQR10	6.57	3.5840

8 DIAGNOSTIC (EXIT) LEVEL RQA SERIES BEAM QUALITIES

8.1 SUMMARY OF THE MEASURED FACTORS FOR DIAGNOSTIC (EXIT) LEVEL RQA SERIES BEAM QUALITIES

Table 11: 300 kV Primary standard correction factors determined from measurement for diagnostic (exit) level RQA series beam qualities

Nominal generating potential (kV)	RQA beam quality	Beam quality HVL	Factor					
		mm Al	k_s^*	k_a	k_{sc}	k_d	k_{pol}	k_l
40	RQA2	2.2	1.0003	1.0228	0.9924	1.0003	1.0000	1.0000
50	RQA3	3.8	1.0003	1.0167	0.9932	1.0003	1.0000	1.0000
60	RQA4	5.4	1.0003	1.0140	0.9937	1.0003	1.0000	1.0000
70	RQA5	6.8	1.0003	1.0126	0.9941	1.0003	1.0000	1.0000
80	RQA6	8.2	1.0003	1.0117	0.9945	1.0003	1.0000	1.0000
90	RQA7	9.2	1.0003	1.0113	0.9946	1.0003	1.0000	1.0000
100	RQA8	10.1	1.0003	1.0109	0.9947	1.0003	1.0000	1.0000
120	RQA9	11.6	1.0003	1.0103	0.9951	1.0003	1.0000	1.0000
150	RQA10	13.3	1.0004	1.0098	0.9954	1.0003	1.0000	1.0000

*Values of k_s valid for 150 cm SCD, -3000 V HT and 15 mA beam current

8.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR DIAGNOSTIC (EXIT) LEVEL RQA SERIES BEAM QUALITIES

Table 12: 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for diagnostic (exit) level RQA series beam qualities

Nominal generating potential (kV)	RQA beam quality	Beam quality HVL	Factor or quantity							
		mm Al	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_w$	ρ (kg·m ⁻³)	V (cm ³)
40	RQA2	2.2	33.97	1.000	1.0000	0.9983	0.998	0.9980	1.2046	7.8963
50	RQA3	3.8			1.0000	0.9987		0.9982		
60	RQA4	5.4			1.0000	0.9990		0.9980		
70	RQA5	6.8			1.0000	0.9992		0.9979		
80	RQA6	8.2			1.0000	0.9993		0.9978		
90	RQA7	9.2			1.0000	0.9994		0.9978		
100	RQA8	10.1			1.0000	0.9995		0.9978		
120	RQA9	11.6			1.0000	0.9996		0.9978		
150	RQA10	13.3			1.0000	0.9997		0.9978		

8.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR DIAGNOSTIC (EXIT) LEVEL RQA SERIES BEAM QUALITIES

Table 13: 300 kV primary standard air kerma sensitivity N_K in grays per coulomb (Gy/C) $\times 10^6$ for diagnostic (exit) level RQA series beam qualities

Nominal generating potential (kV)	RQA beam quality	Beam quality HVL	Air kerma sensitivity N_K Gy/C $\times 10^6$
		mm Al	
40	RQA2	2.2	3.6071
50	RQA3	3.8	3.5907
60	RQA4	5.4	3.5831
70	RQA5	6.8	3.5799
80	RQA6	8.2	3.5781
90	RQA7	9.2	3.5775
100	RQA8	10.1	3.5768
120	RQA9	11.6	3.5767
150	RQA10	13.3	3.5764

9 DIAGNOSTIC (FLUOROSCOPY) LEVEL RQC SERIES BEAM QUALITIES

9.1 SUMMARY OF THE MEASURED FACTORS FOR DIAGNOSTIC (FLUOROSCOPY) LEVEL RQC SERIES BEAM QUALITIES

Table 14: 300 kV Primary standard correction factors determined from measurement for diagnostic (fluoroscopy) level RQC series beam qualities

Nominal generating potential (kV)	RQC beam quality	Beam quality HVL	Factor					
		mm Al	k_s^*	k_a	k_{sc}	k_d	k_{pol}	k_l
50	RQC3	4.5	1.0003	1.0157	0.9927	1.0003	1.0000	1.0000
70	RQC5	8.4	1.0003	1.0118	0.9940	1.0003	1.0000	1.0000
100	RQC8	11.5	1.0003	1.0140	0.9949	1.0003	1.0000	1.0000

*Values of k_s valid for 150 cm SCD, -3000 V HT and 15 mA beam current

9.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR DIAGNOSTIC (FLUOROSCOPY) LEVEL RQC SERIES BEAM QUALITIES

Table 15: 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for diagnostic (fluoroscopy) level RQC series beam qualities

Nominal generating potential (kV)	RQC beam quality	Beam quality HVL	Factor or quantity							
		mm Al	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_w$	ρ (kg·m ⁻³)	V (cm ³)
50	RQC3	4.5	33.97	1.000	1.0000	0.9983	0.998	0.9981	1.2046	7.8963
70	RQC5	8.4			1.0000	0.9987		0.9978		
100	RQC8	11.5			1.0000	0.9990		0.9978		

9.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR DIAGNOSTIC (FLUOROSCOPY) LEVEL RQC SERIES BEAM QUALITIES

Table 16: 300 kV primary standard air kerma sensitivity N_{KK} in grays per coulomb (Gy/C) $\times 10^6$ for diagnostic (fluoroscopy) level RQC series beam qualities

Nominal generating potential (kV)	RQC beam quality	Beam quality, HVL	Air kerma sensitivity N_K Gy/C $\times 10^6$
		mm Al	
50	RQC3	4.5	3.5854
70	RQC5	8.4	3.5769
100	RQC8	11.5	3.5761

10 DIAGNOSTIC (CT) LEVEL RQT SERIES BEAM QUALITIES

10.1 SUMMARY OF THE MEASURED FACTORS FOR DIAGNOSTIC (CT) LEVEL RQT SERIES BEAM QUALITIES

Table 17: 300 kV Primary standard correction factors determined from measurement for diagnostic (CT) level RQT series beam qualities

Nominal generating potential (kV)	RQT beam quality	Beam quality HVL	Factor					
		mm Al	k_s^*	k_a	k_{sc}	k_d	k_{pol}	k_l
100	RQT8	6.9	1.0007	1.0133	0.9937	1.0003	1.0000	1.0000
120	RQT9	8.4	1.0009	1.0121	0.9942	1.0003	1.0000	1.0000
150	RQT10	10.1	1.0012	1.0111	0.9946	1.0003	1.0000	1.0000

*Values of k_s valid for 150 cm SCD, -3000 V HT and 15 mA beam current

10.2 SUMMARY OF NON-MEASURED VALUES AND FACTORS FOR DIAGNOSTIC (CT) LEVEL RQT SERIES BEAM QUALITIES

Table 18: 300 kV primary standard correction factors determined from calculation and standard values of physical quantities for diagnostic (CT) level RQT series beam qualities

Nominal generating potential (kV)	RQT beam quality	Beam quality HVL	Factor or quantity							
		mm Al	$\frac{W_{air}}{e}$ (J/C)	$(1-g)^{-1}$	k_e	k_{fl}	k_h	$k_{ii} \cdot k_w$	ρ (kg·m ⁻³)	V (cm ³)
100	RQT8	6.9	33.97	1.000	1.0000	0.9992	0.998	0.9978	1.2046	7.8963
120	RQT9	8.4			1.0000	0.9994		0.9978		
150	RQT10	10.1			1.0000	0.9995		0.9978		

10.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR DIAGNOSTIC (CT) LEVEL RQT SERIES BEAM QUALITIES

Table 19: 300 kV primary standard air kerma sensitivity N_{kK} in grays per coulomb (Gy/C) $\times 10^6$ for diagnostic (CT) level RQT series beam qualities

Nominal generating potential (kV)	RQC beam quality	Beam quality HVL	Air kerma sensitivity N_{kK} Gy/C $\times 10^6$
		mm Al	
100	RQT8	6.9	3.5819
120	RQT9	8.4	3.5807
150	RQT10	10.1	3.5802

11 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:

$$\dot{K} = (I_{raw} - I_{leakage}) \cdot k_{elec} \cdot k_{ion} \cdot k_{Tp} \cdot N_K \quad (5)$$

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 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

$$k_{Tp} = \frac{T}{293.15} \cdot \frac{101.325}{p} \quad (6)$$

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

12 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

$$N_{K,ss} = \frac{\dot{K}}{(I_{raw,ss} - I_{leak,ss}) \cdot k_{elec,ss} \cdot k_{ion,ss} \cdot k_{Tp,ss}} \quad (7)$$

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 mGy h⁻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.

13 SUMMARY OF UNCERTAINTY ANALYSIS

Table 20 and Table 21 summarise the uncertainties associated with the 300 kV primary standard correction factor and the primary standard measurement of air kerma. Table 22 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 20: Uncertainties in the primary standard correction Π applicable to all qualities

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	0.02	-
$k_{ii} \cdot k_W$	Initial ionisation and energy dependence of W_{air}	-	0.12
$u_c(\Pi)$	Combined standard uncertainty	0.22	

Table 21: Uncertainties in the 300 kV primary standard measurement of air kerma rate $\dot{K}$ for all qualities

Symbol	Quantity, source of uncertainty	Type A	Type B
Π	Total primary standard correction	-	0.22
k_{elec}	Electrometer current calibration (pA/pA)	-	0.15
k_{res}	Electrometer resolution (pA)	-	0.05
$I_{leakage}$	Leakage current (A)	0.10	-
$\frac{W_{air}}{e}$	Energy per ion pair (J/C)	-	0.35
g	Fraction of energy lost by bremsstrahlung	-	0.02
ρ	Density of dry air (kg/m ³)	-	0.01
k_h	Humidity correction	-	0.05
T	Temperature (K)	0.02	-
p	Pressure (kPa)	0.04	-
V	Collecting volume (cm ³)	-	0.01
R	Repeatability	0.30	-
$u_c(\dot{K})$	Combined standard uncertainty	0.55	

Table 22: 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	-	0.55
$k_{elec,ss}$	Electrometer current calibration (nA/nA)	-	0.15
$k_{res,ss}$	Electrometer resolution (nA)	-	0.05
$k_{ion,ss}$	Ion recombination correction	0.10	-
$I_{leakage,ss}$	Leakage current (A)	0.10	-
T_{ss}	Temperature (K)	0.02	-
p_{ss}	Pressure (kPa)	0.04	-
k_{dist}	Distance from source	-	0.001
k_{orient}	Orientation of chamber	-	0.05
R	Repeatability	0.30	-
$u_c(N_{K,ss})$	Combined standard uncertainty	0.66	
U	Expanded uncertainty ($k = 2$)	1.32	

14 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Measurement System Policy Unit of the UK Department for Business, Energy and Industrial Strategy.

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