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

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

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ABSTRACT
The NPL air kerma primary standard free-air ionisation chamber for low energy x-ray qualities was established in 1977. 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 the factors for the NPL primary standard including the two new factors, and changes to the standard up to the publication date.

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1 INTRODUCTION

The National Physical Laboratory (NPL) air kerma primary standard for x-rays generated at kilovoltages from 8 kV up to 50 kV is a parallel plate, guarded field free-air ionisation chamber that covers the range of x-ray qualities from approximately 0.024 mm Al HVL to 1.0 mm Al HVL for grenz level qualities, from 0.058 mm Cu to 0.084 mm Cu for protection level qualities and from 0.31 mm Al to 0.62 mm Al for mammographic qualities.

Two Free-Air Chambers (FAC) were constructed, measured, and characterised during the late 1970s at the NPL to replace the 1958 design chamber. Chamber ‘A’ was originally designated as the primary standard for this energy range and put into service in April 1982. During the early 1990s this chamber was affected by water damage, and the ‘B’ chamber was designated as the primary standard. NPL took the opportunity to remake the ‘A’ collector assembly at the same time as manufacturing another FAC for use at the Swiss NMI in 1994. The ‘B’ chamber remained the primary standard from 1994 onwards. Following an intercomparison with the Bureau International des Poids et Mesures (BIPM) in 2017, the insulator resistance of the ‘B’ chamber guard-collector assembly was found to have dropped to below an acceptable level, and as such it was decided to re-establish the ‘A’ chamber as the primary 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 ‘A’ chamber to realise air kerma and calibrate a secondary standard. The associated uncertainties are also presented, including the increase in the standard uncertainty of W_{air} from 0.15% to 0.35% as recommended in ICRU report 90.

2 50 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	20.0304 mm
Beam-defining aperture A1 diameter	8.0014 mm
Air path length	89.876 mm
HT-collecting electrode plate separation	62.537 mm
Collecting volume	1019.7 mm^3
Collecting electrode insulation resistance	at least $10^{14}\,\Omega$

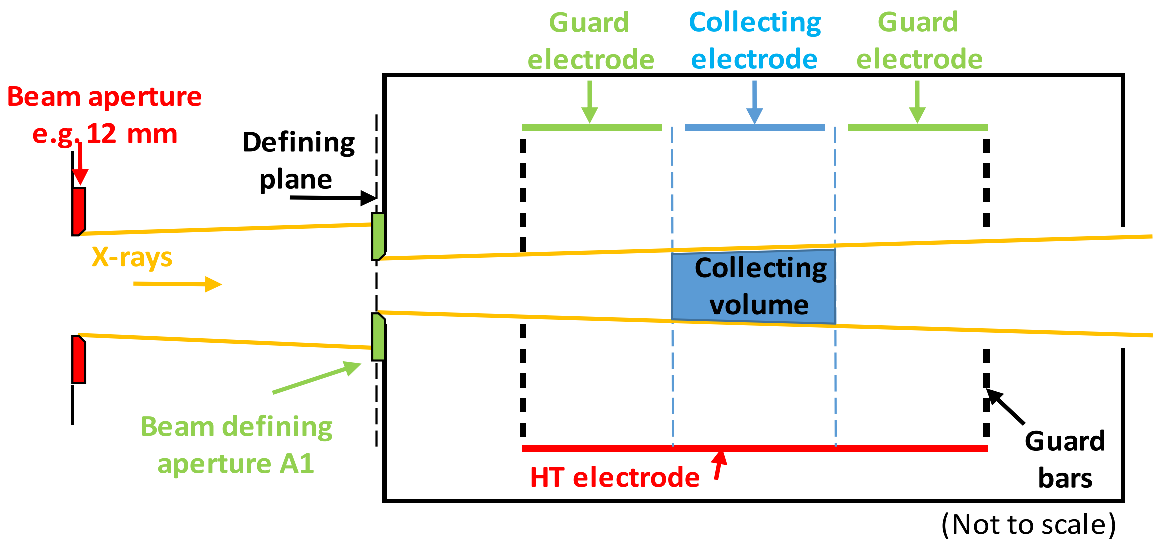

Figure 1: Schematic of the 50 kV primary standard free-air chamber (not to scale)

3 SETUP CONDITIONS

For grenz, protection and mammographic level calibrations the following setup conditions are used:

- Beam-defining aperture diameter 8 mm (nominal, serial number A1) fitted to the FAC chamber
- Reference point (defining plane) of the FAC is 0.79 mm from the external face of aperture A1
- -1500 V polarising potential applied to chamber HT electrode in normal use, such that negative ionisation current is generated.

Specific setup conditions are as given below:

3.1 GRENZ LEVEL (GL) X-RAYS

- 15 mm beam-limiting aperture used on x-ray set
- 50 cm source to chamber reference point

3.2 PROTECTION LEVEL (PL) X-RAYS

- 12 mm beam-limiting aperture used on x-ray set
- 75 cm source to chamber reference point

3.3 MAMMOGRAPHIC LEVEL (ML) X-RAYS

- 12 mm beam-limiting aperture used on x-ray set
- 60 cm source to chamber reference point

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:

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

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 collecting volume of the chamber

and

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

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 potentials, 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 Al or mm Cu HVL as appropriate from a fit to NPL/BIPM calculated factors:

$$\begin{aligned} k_{fl} &= 0.000790626 \times \ln(\text{HVL, mm Al}) + 0.997684 \\ k_{fl} &= 0.000519237 \times \ln(\text{HVL, mm Cu}) + 0.999521 \end{aligned} \tag{3}$$

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:

$$k_s = 5599361 \times I + 1.00067 \tag{4}$$

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 GRENZ LEVEL BEAM QUALITIES

5.1 SUMMARY OF THE MEASURED FACTORS FOR GRENZ LEVEL BEAM QUALITIES

Table 2: 50 kV Primary standard correction factors determined from measurement for grenz level beam qualities

Nominal generating potential (kV)	Beam quality HVL mm Al	Factor					
		k_a*	k_d	k_l	k_{pol}	k_{sc}	k_s**
8.5	0.024	-	1.0002	1.0000	1.0004	0.9944	1.0011
10	0.036	-	1.0002	1.0000	1.0004	0.9949	1.0011
11.5	0.05	-	1.0002	1.0000	1.0004	0.9954	1.0013
14	0.07	-	1.0002	1.0000	1.0004	0.9959	1.0012
16	0.10	-	1.0002	1.0000	1.0004	0.9962	1.0013
20	0.15	-	1.0002	1.0000	1.0004	0.9967	1.0014
24	0.25	-	1.0002	1.0000	1.0004	0.9971	1.0014
34	0.35	-	1.0002	1.0000	1.0004	0.9973	1.0019
41	0.50	-	1.0002	1.0000	1.0004	0.9975	1.0021
44	0.70	-	1.0002	1.0000	1.0004	0.9977	1.0020
50	1.00	-	1.0002	1.0000	1.0004	0.9979	1.0017

* Air attenuation for these qualities is measured at each occasion of use of the chamber using a specially constructed FAC.

**Values of k_s valid for 50 cm SCD, -1500 V HT and 15 mA beam current

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

Table 3: 50 kV primary standard correction factors determined from calculation and standard values of physical quantities for grenz level beam qualities

Nominal generating potential (kV)	Beam quality HVL	Factor or quantity							
	mm Al	k_e	k_{fl}	$k_{ii} \cdot k_W$	$\frac{W_{air}}{e}$ (J/C)	(1- g)$^{-1}$	k_h	ρ (kg·m^{-3})	V (cm^3)
8.5	0.024	1.0000	0.9947	0.9951	33.97	1.000	0.998	1.2046	1.0197
10	0.036	1.0000	0.9951	0.9955					
11.5	0.05	1.0000	0.9953	0.9958					
14	0.07	1.0000	0.9956	0.9961					
16	0.10	1.0000	0.9959	0.9965					
20	0.15	1.0000	0.9962	0.9969					
24	0.25	1.0000	0.9966	0.9974					
34	0.35	1.0000	0.9969	0.9977					
41	0.50	1.0000	0.9971	0.9978					
44	0.70	1.0000	0.9974	0.9979					
50	1.00	1.0000	0.9977	0.9980					

5.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR GRENZ LEVEL BEAM QUALITIES

Table 4: 50 kV primary standard air kerma sensitivity N_K in grays per coulomb (Gy/C) ×10^7 for grenz level beam qualities

Nominal generating potential (kV)	Beam quality HVL mm Al	Air kerma sensitivity N_K Gy/C ×10^7
8.5	0.024	2.7215
10	0.036	2.7249
11.5	0.05	2.7280
14	0.07	2.7309
16	0.10	2.7339
20	0.15	2.7376
24	0.25	2.7409
34	0.35	2.7446
41	0.50	2.7466
44	0.70	2.7479
50	1.00	2.7488

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: 50 kV Primary standard correction factors determined from measurement for protection level beam qualities

Nominal generating potential (kV)	Beam quality HVL		Factor					
	mm Al	mm Cu	k_a*	k_d	k_l	k_{pol}	k_{sc}	k_s**
10	0.058	-	1.1060	1.0002	1.0000	1.0004	0.9954	1.0007
15	0.17	-	1.0312	1.0002	1.0000	1.0004	0.9966	1.0008
20	0.36	-	1.0148	1.0002	1.0000	1.0004	0.9973	1.0008
25	0.69	-	1.0074	1.0002	1.0000	1.0004	0.9977	1.0007
30	1.21	-	1.0045	1.0002	1.0000	1.0004	0.9979	1.0007
40	-	0.085	1.0045	1.0002	1.0000	1.0004	0.9983	1.0007

*For protection level calibrations the air attenuation correction is entered separately into the calibration software program and therefore is not included in the total air kerma sensitivity given in Table 7 below

** Values of k_s valid for 75 cm SCD, -1500 V HT and 20 mA beam current

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

Table 6: 50 kV primary standard correction factors determined from calculation and standard values of physical quantities for protection level beam qualities (ISO 4037 Narrow Spectrum Series)

Nominal generating potential (kV)	Beam quality HVL		Factor or quantity							
	mm Al	mm Cu	k_e	k_{fl}	$k_{ii} \cdot k_W$	$\frac{W_{air}}{e}$ (J/C)	(1- g)$^{-1}$	k_h	ρ (kg·m^{-3})	V (cm^3)
10	0.058	-	1.0000	0.9954	0.9958	33.97	1.000	0.998	1.2046	1.0197
15	0.17	-	1.0000	0.9963	0.9967					
20	0.36	-	1.0000	0.9969	0.9972					
25	0.69	-	1.0000	0.9974	0.9977					
30	1.21	-	1.0000	0.9978	0.9978					
40	-	0.085	1.0000	0.9982	0.9981					

6.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR PROTECTION LEVEL BEAM QUALITIES (ISO 4037 NARROW SPECTRUM SERIES)

Table 7: 50 kV primary standard air kerma sensitivity N_K in grays per coulomb (Gy/C) $\times 10^7$ for protection level beam qualities (ISO 4037 Narrow Spectrum Series)

Nominal generating potential (kV)	Beam quality, HVL		Air kerma sensitivity N_K Gy/C $\times 10^7$
	mm Al	mm Cu	
10	0.058	-	2.7270
15	0.17	-	2.7351
20	0.36	-	2.7402
25	0.69	-	2.7441
30	1.21	-	2.7461
40	-	0.085	2.7489

7 MAMMOGRAPHIC LEVEL BEAM QUALITIES (IEC 61267 SERIES)

7.1 SUMMARY OF THE MEASURED FACTORS FOR MAMMOGRAPHIC LEVEL BEAM QUALITIES (IEC 61267 SERIES)

Table 8: 50 kV Primary standard correction factors determined from measurement for mammographic level beam qualities

Nominal generating potential (kV)	Beam quality, HVL	Factor					
	mm Al	k_a	k_d	k_l	k_{pol}	k_{sc}	k_s*
28	0.31 (RQR-M 2)	1.0218	1.0002	1.0000	1.0004	0.9972	1.0010
28	0.62 (RQB-M 2)	1.0128	1.0002	1.0000	1.0004	0.9976	1.0007

* Values of k_s valid for 150 cm SCD, -1500 V HT and 10 mA beam current

7.2 SUMMARY OF THE NON-MEASURED VALUES AND FACTORS FOR MAMMOGRAPHIC LEVEL BEAM QUALITIES (IEC 61267 SERIES)

Table 9: 50 kV primary standard correction factors determined from calculation and standard values of physical quantities for mammographic level beam qualities

Nominal generating potential (kV)	Beam quality HVL	Factor or quantity							
	mm Al	k_e	k_{fl}	$k_{ii} \cdot k_W$	$\frac{W_{air}}{e}$ (J/C)	(1- g)$^{-1}$	k_h	ρ (kg·m^{-3})	V (cm^3)
28	0.31 (RQR-M 2)	1.0000	0.9968	0.9971	33.97	1.000	0.998	1.2046	1.0197
28	0.62 (RQB-M 2)	1.0000	0.9973	0.9976					

7.3 PRIMARY STANDARD AIR KERMA SENSITIVITY FOR MAMMOGRAPHIC LEVEL BEAM QUALITIES

Table 10: 50 kV primary standard air kerma sensitivity N_K in grays per coulomb (Gy/C) ×10^7 for mammographic level beam qualities (IEC 61267 Series)

Nominal generating potential (kV)	Beam quality, HVL	Air kerma sensitivity N_K Gy/C ×10^7
	mm Al	
28	0.31 (RQR-M 2)	2.7997
28	0.62 (RQB-M 2)	2.7783

8 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:

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

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

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

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

9 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

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

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 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.

10 SUMMARY OF UNCERTAINTY ANALYSIS

Table 11 and Table 12 and summarise the uncertainties associated with the 50 kV primary standard correction factor and the primary standard measurement of air kerma. Table 13 summarises the uncertainty in the calibration of a secondary standard ionisation chamber for grenz, protection and mammographic level energy x-rays.

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

Table 11: Uncertainties in the primary standard correction Π applicable to therapy, protection, and mammographic level qualities

Symbol	Quantity, source of uncertainty	Type A	Type B
k_a	Air attenuation correction	0.20	-
k_d	Field distortion correction	0.01	-
k_e	Electron loss correction	-	0.05
k_l	Front face penetration correction	0.01	-
k_{pol}	Polarity correction	0.02	-
k_{sc}	Scattered photon correction	0.10	-
k_{fl}	Fluorescence correction	-	0.05
$k_{ii} \cdot k_W$	Initial ionisation and energy dependence of W_{air}	-	0.12
k_s	Ion recombination correction	0.05	-
$u_c\,(\Pi)$	Combined standard uncertainty	0.27	

Table 12: Uncertainties in the 50 kV primary standard measurement of air kerma rate $\dot{K}$ for therapy, protection, and mammographic level qualities.

Symbol	Quantity, source of uncertainty	Type A	Type B
Π	Total primary standard correction	-	0.27
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)	-	0.10
R	Repeatability	0.10	-
$u_c(\dot{K})$	Combined standard uncertainty	0.50	

Table 13: Uncertainties in the air kerma calibration $N_{K,ss}$ of a secondary standard ionisation chamber for therapy and mammographic level beam qualities (protection level qualities in brackets are higher due to the use of a transfer chamber)

Symbol	Quantity, source of uncertainty	Type A	Type B
$\dot{K}$	Air kerma rate	-	0.50 (0.62)
$k_{elec,ss}$	Electrometer current calibration (nA/'nA')	-	0.15
$k_{res,ss}$	Electrometer resolution (nA)	-	0.05
$k_{ion,ss}$	Ion recombination correction	0.05	-
$I_{leakage,ss}$	Leakage current (A)	0.10	-
T_{ss}	Temperature (K)	0.02	-
p_{ss}	Pressure (kPa)	0.04	-
k_{dist}	Distance from source	-	0.02
k_{orient}	Orientation of chamber	-	0.10
R	Repeatability	0.30	-
$u_c(N_{K,ss})$	Combined standard uncertainty	0.62 (0.72)	
U	Expanded uncertainty (k = 2)	1.25 (1.43)	

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