CIPM MRA
Comparison reports

EURAMET.RI(I)-K5.2

Air kerma in Cs-137 radiation protection beams

KEY COMPARISON

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Key comparison of air kerma standards in ^{137}Cs radiation beams for radiation protection, EURAMET.RI(I)-K5.2

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Abstract

A key comparison of air kerma standards of five participating laboratories was carried out in ^{137}Cs radiation beams at radiation protection level, from June 2024 to January 2025. Three of the participating laboratories are secondary standards laboratories (DSA, STUK, and SSM) and NPL and CIEMAT are primary standards laboratories, with CIEMAT acting as the linking laboratory to the BIPM key comparison, BIPM.RI(I)-K5. The comparison results are published in the BIPM key comparison database (KCDB) under the reference EURAMET.RI(I)-K5.2. The comparison was made indirectly using one ionization chamber as transfer instrument. The results are analysed and presented in terms of degrees of equivalence suitable for entry in the BIPM key comparison database.

1. Introduction

The National Metrology Laboratories for dosimetry quantities of Finland (STUK, Radiation and Nuclear Safety Authority), Norway (DSA, Norwegian Radiation and Nuclear Safety Authority), Spain (CIEMAT, Spanish National Metrology Institute for Ionising Radiation), Sweden (SSM, Swedish Radiation Safety Authority) and the United Kingdom of Great Britain and Northern Ireland (NPL, National Physical Laboratory) have performed a comparison in terms of air kerma/rate in ^{137}Cs radiation fields. NPL and CIEMAT are primary standards laboratories (PSDLs), with CIEMAT acting as the linking laboratory to BIPM.RI(I)-K5. The other participating laboratories are secondary standards laboratories (SSDLs). STUK acted as the measuring pilot laboratory and SSM as the reporting pilot laboratory.

Two transfer chambers, spherical Exradin A6 ionisation chambers, were circulated among the participants, and each laboratory reported calibration coefficients and uncertainty budgets for those chambers in terms of air kerma. During the circulation of the chambers, one chamber was found to be defective, XQ152602. The defect expressed itself as a high and unstable leakage (between 10 -100 times normal leakage). Therefore, the results from XQ152602 have not been taken into consideration and results are presented only for one A6 chamber (XQ200282).

The objective of the comparison is to support the ionising radiation CMCs of SSM, DSA, STUK, and NPL in the dosimetry branch for the quantity air kerma/rate from a ^{137}Cs source at radiation protection levels.

The detailed technical protocol is available in the KCDB under the reference EURAMET.RI(I)-K5.2.

2. Comparison procedure

2.1 Participants and measurement schedule

Five participants, listed in table 1, were included in the comparison. CIEMAT acted as the linking laboratory to the CCRI(I) key comparison reference value. STUK and SSM shared responsibilities as pilot laboratories: STUK acting as measuring pilot laboratory and SSM acting as reporting laboratory. STUK performed measurements at the beginning, in the middle and at the end of the comparison to confirm the stability of the transfer chamber.

Table1. Participants of the comparison, their traceability and the measurement schedule.

Institute, country	Contact person	Comment	Traceability, type of standard	Measuring period
STUK	Jussi Huikari	Pilot, measurements	PTB, secondary	June-August 2024
DSA	Per Otto Hetland		IAEA, secondary	August-September 2024
NPL	Martin Kelly		NPL, primary	October 2024
STUK, stability check				October 2024
SSM	Linda Persson	Pilot, reporting	BIPM, secondary	October 2024
CIEMAT	Néstor Armando Cornejo Díaz	Linking lab	CIEMAT, primary	December 2024
STUK, stability check				13-17 January 2025

2.2 Transfer instrument

The transfer chamber is the property of STUK and had not been calibrated outside STUK before this comparison. The laboratories used their own electrometers and cables for performing the measurements during the comparison. The technical details of the transfer chamber are presented below (table 2).

Table 2. Technical details of the transfer chamber

Chamber type	EXRADIN A6 Ref. 92716
Serial number	XQ200282
Geometry	spherical
Wall material	C552
Wall thickness [mm]	3.0
External diameter / mm	120

Nominal volume / cm^3	800
Reference point for the air kerma measurements	Geometric centre of the chamber
Polarising voltage of the chamber	+400 V on collector (central) electrode, 0 V on chamber wall (collecting negative charge) (if +400 V on collector is not available: -400 V on chamber wall, 0 V on collector electrode)
Connector type	Triax BNC (male) (2 lug)

2.3 Radiation quality and reference conditions

The radiation quality used in the comparison is ^{137}Cs at radiation protection level. The quantity used for the comparison is the air kerma defined according to ICRU85a. The relevant data from ICRU90 has been used for the primary standards from participants in the comparison and for primary standards against which the secondary standards have been calibrated.

Radiation fields for ^{137}Cs radiation protection fields fulfil ISO 4037-1:2019 and ISO 4037-2:2019. The reference point for the chamber is its geometric centre. The chamber was placed free in air with the marking on the stem oriented towards the radiation source. The diameter of the radiation field at each participating laboratory can be found in Appendix 1.

The calibration coefficients for the transfer chamber were corrected to standard conditions of air temperature and pressure; T = 293.15 K and P = 101.325 kPa. The measurements were performed with relative humidity between 40 % and 67 %; therefore, they were not corrected to the reference condition of 50 % RH. Each laboratory was using its own equipment to measure environmental conditions and ensuring traceability for those measurements.

2.4 Reference value

The comparison reference value is the reference value of the BIPM.RI(I)-K5 comparison, with the CIEMAT acting as linking laboratory. The primary standard, the measurement method equation, and the physical constants and correction factors used by the CIEMAT in order to obtain the air kerma rate are the same as in the latest BIPM comparison (Kessler C *et al.*, 2024).

2.5 Determination of the calibration coefficient of the transfer chamber

CIEMAT and NPL determined the calibration coefficients in the same way as the SSDLs (i.e. using equation 2), except that the realization of the quantity air kerma is based on their primary air kerma standards, based on graphite-walled cavity ionisation chambers, as described in Cornejo Díaz N. A., 2022 and in the comparison report BIPM.RI(I)-K5 (Kessler C *et al.*, 2024) for CIEMAT, and in Bass GA *et al.*, 2019 for NPL.

Each laboratory used their own procedure referring to international practices/guidance followed when performing the calibration.

Typically, for air kerma, the laboratories establish a reference air kerma rate $\dot{K}_{air,lab}$ at their facilities in accordance with their own procedure following an equation such as:

$$\dot{K}_{air,lab} = N_{K,PSDL} \cdot I_{lab} \qquad (1)$$

where $N_{K,\mathrm{PSDL}}$ is the calibration coefficient used by a given laboratory in order to reach traceability to a primary standards laboratory for air kerma in ^{137}Cs beams, and where I_{lab} is the ionisation current measured for the different setups used by the participants. I_{lab} is corrected to standard conditions of air temperature and pressure, and, if needed, for relative humidity. For the other corrections to I_{lab}, the laboratory proceeded according to their own procedure and may have included e.g. the electrometer correction factor, correction for leakage, correction for distance, correction for volume etc. All corrections used by the participants are reported in Appendix 1.

Each laboratory positioned the transfer chamber at the reference point (see table 2), and the calibration coefficient for the transfer chamber $N_{K,lab}$ was calculated as:

$$N_{K,lab} = \frac{\dot{K}_{air,lab}}{I_{M,lab}} \qquad (2)$$

where $\dot{K}_{air,lab}$ is the reference air kerma rate from equation (1), and $I_{M,lab}$ is the ionization current measured by the laboratory with the transfer chamber. Like I_{lab}, $I_{M,lab}$ was corrected to standard conditions of air temperature and atmospheric pressure. The correction for the air relative humidity was not required, according to Section 2.3.

2.6 Degrees of equivalence

Since one of the transfer chambers got broken, the results were analysed for only a single chamber. Degrees of equivalence were calculated using the comparison results provided by the participants (calibration coefficients and uncertainty budgets) according to CCRI(I)/17-09 instructions. The degree of equivalence of each laboratory, with respect to the key comparison reference value, was evaluated as follows in terms of air kerma:

$$R_{lab} = \frac{N_{K,lab}}{N_{K,\mathrm{CIEMAT}}} R_{\mathrm{CIEMAT,BIPM}} \qquad (3)$$

where R_{lab} is the ratio of the calibration coefficient reported by the participating laboratory, $N_{K,lab}$, to the KCRV, i.e. $N_{K,\mathrm{CIEMAT}}$, and $R_{\mathrm{CIEMAT,BIPM}}$ represents the results of CIEMAT in BIPM comparison BIPM.RI(I)-K5 (Kessler C *et al.*, 2024).

The variance of R_{lab} is:

$$u_{\mathrm{R},lab}^2 = \left(u_{lab}^2 + u_{\mathrm{BIPM}}^2 - \textstyle\sum_j f_j^2 (u_{lab,j}^2 + u_{\mathrm{BIPM},j}^2)\right) + u_{\mathrm{tr}}^2 + u_{\mathrm{CIEMAT}}^2 \qquad (4)$$

where u_{lab} is the combined standard uncertainty of the calibration coefficient reported by the i-th participating laboratory; u_{BIPM} is the combined standard uncertainty of the BIPM's air kerma rate standard (K_{BIPM}) as described in the BIPM.RI(I)-K5; u_{tr} is the uncertainty arising from the transfer chamber; u_{CIEMAT} represents the uncertainty arising from the linking mechanism (the components to be considered in u_{CIEMAT} are indicated in table 1 of the report CCRI(I)/17-09 for the case of a direct BIPM comparison) and f_j are correlation factors related to correlated components between the participating laboratory and the BIPM, which in case of a secondary standards laboratory are the correlated components of the primary standard of the primary standards laboratory against which the secondary standards laboratory has calibrated their secondary standard (e.g. the W/e and the stopping power ratio graphite to air).

In equation (4), u_{tr} combines the stability of the transfer chambers over the period of the comparison. The measuring pilot laboratory STUK has performed several measurements for the transfer chamber. u_{CIEMAT} in equation (4) includes the uncertainty of non-statistical components, which are not cancelled out via the linking mechanism. To ease estimation of

u_{CIEMAT}, CIEMAT's measurement conditions in this comparison were as close as possible to those used in the CIEMAT-BIPM comparison, BIPM.RI(I)-K5. The non-statistical uncertainty component of the primary standard of CIEMAT in the comparison with the BIPM and in this comparison is 0.5 % ($k = 2$) (Kessler C *et al.*, 2024). Therefore, the uncertainty adopted for the linking mechanism is 1.02 % ($k = 2$).
The degree of equivalence for every laboratory was calculated as follows:

$$D_{lab} = R_{lab} - 1 \tag{5}$$

and its expanded uncertainty is $U_{lab} = 2\ u_{\mathrm{R},lab}$.

2.7 Correlated uncertainties for degrees of equivalence

Correlated uncertainties were analysed and excluded from the calculation of expanded uncertainties for degrees of equivalence. SSM are directly traceable to BIPM, and DSA is traceable to BIPM trough IAEA for air kerma, while STUK is traceable to PTB, and NPL is traceable to NPL. The type B component from BIPM calibrations was removed for the calculation of expanded uncertainties for degrees of equivalence in all cases, where the laboratory is traceable to BIPM, i.e. SSM and DSA. For NPL and STUK, correlated components related to physical constants were removed.

3. Results

3.1 Transfer chamber stability and recombination

The transfer chamber was calibrated in terms of air kerma in a ^{137}Cs field by STUK at the beginning, in the middle and at the end of the measurement rounds. In total, there were 10 stability check measurements for the transfer chamber. The standard uncertainty of the mean for the transfer chamber, u_{tr}, was found to be 0.033 % which shows that the chamber was stable during the measurement round.
The pilot laboratory did not apply corrections for lack of saturation of the circulated transfer chamber, using the information provided by the participating laboratories. Nevertheless, in the specific case of this comparison, the volume of the transfer chamber is 800 cm^3 (spherical) and the polarizing voltage is 400 V. For this kind of chamber, to achieve 99% saturation at 400 V, the maximum air kerma rate should not be greater than 420 mGy/h (this nominal value corresponds to a 99 % saturation current for a 1000 cm^3 spherical ionization chamber according to the PTW manual for chamber types 32002, 32003 and 32005 D466.131.0/3). This value of air kerma rate is much higher than the maximum value reported by the participants. Moreover, taking into account previous studies done with the CIEMAT secondary standard ionisation chambers, the corrections for lack of saturation varied between 1.0015 and 1.0019 (with a standard uncertainty of 0.05 %). The initial recombination is constant for a given type of chamber and polarizing potential. The volumetric component of the ion recombination, which depends on the measured current, has a negligible impact on the correction, in this case. An uncertainty component to account for this effect was included in the CIEMAT, NPL and SSM uncertainty budget, for the transfer chamber. STUK and DSA consider the effect negligible.

3.2 Calibration coefficient and uncertainties

The calibration coefficients and their uncertainties are given in table 3 below. Detailed uncertainty budgets for each laboratory are given in Appendix 1.

Table 3. Reported calibration coefficients for transfer chamber EXRADIN A6 (Ref. 92716, serial number XQ200282) in terms of ^{137}Cs air kerma and their relative expanded uncertainties.

Institute	$N_{K,lab}$ **(Gy/C)**	U **(%),** $k = 2$
STUK	37777	1.44
DSA	37365	0.93
NPL	37540	1.46
SSM	37400	1.10
CIEMAT	37293	1.14

3.3 Degrees of equivalence

The degrees of equivalence (D_i) and expanded uncertainties (U_i) were calculated according to equations 3-5. The values are expressed in mGy/Gy. The following table summarizes D_i and U_i obtained in this comparison. The result for CIEMAT was taken from BIPM.RI(I)-K5 (Kessler C *et al.*, 2024) and is presented in table 4 just for comparison.

Table 4. Degrees of equivalence (D_i) with respect to the key comparison reference value and their expanded uncertainties (U_i) as mGy/Gy for participating laboratories in terms of air kerma.

Institute	D_i ***[mGy/Gy]***	U_i ***[mGy/Gy]***
STUK	12.16	18
DSA	1.13	14
NPL	5.81	18
SSM	2.07	15
*CIEMAT**	-0.8	4.4

*for CIEMAT the same value as in BIPM.RI(I)-K5 (Kessler C *et al.*, 2024).

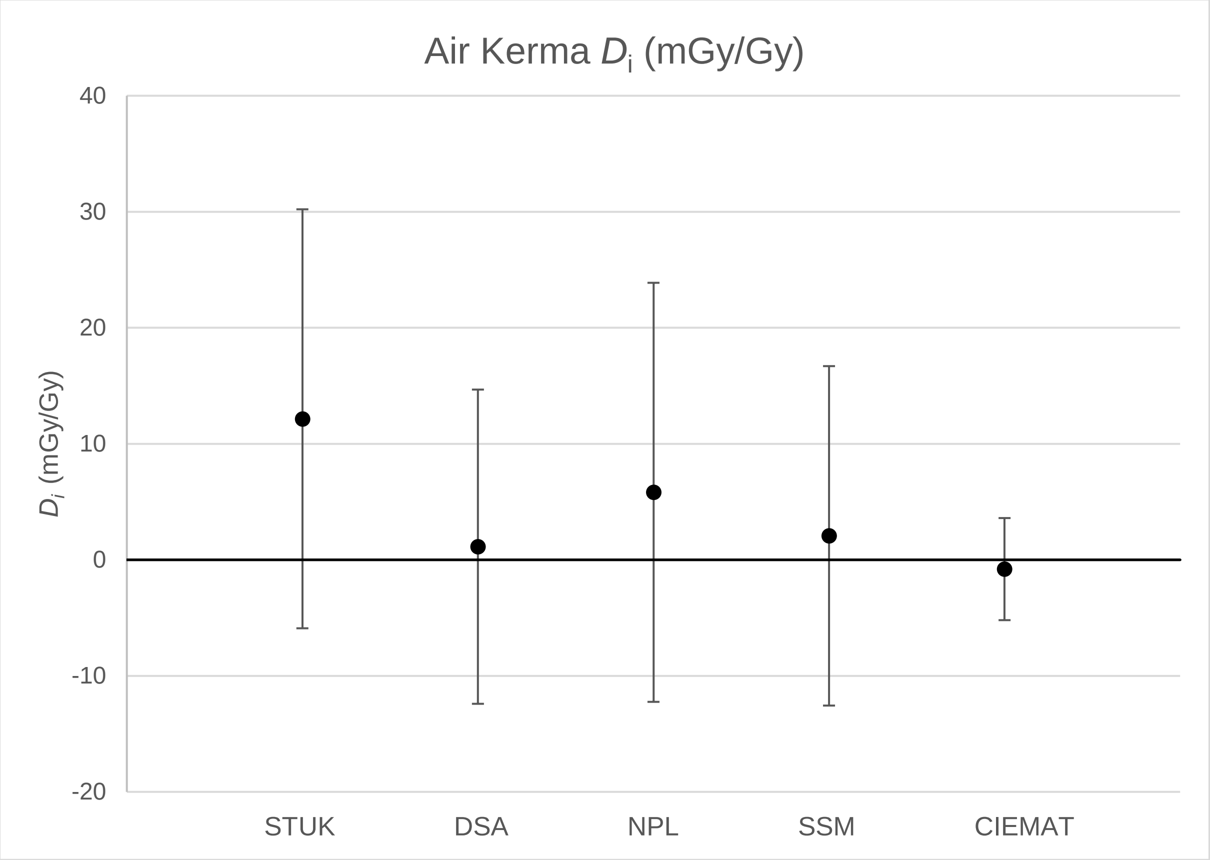

Figure 1. Graphical presentation of the results in table 4; Degrees of equivalence (D_i) with respect to the key comparison reference value and their expanded uncertainties (U_i), expressed as mGy/Gy, for participating laboratories in terms of air kerma.

4. Discussion and conclusions

A key comparison in terms of air kerma for ^{137}Cs radiation has been carried out between five laboratories. The comparison started with two transfer chambers, but one transfer chamber was excluded due to excessive and unpredictable leakage currents. The comparison results of all participating laboratories are in agreement with each other within the expanded uncertainties and support the CMCs of the participating laboratories.

5. References

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KCDB, technical protocol
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6. Appendix 1

Measurement results, uncertainty budgets and additional information for participating laboratories in the same order as the comparison measurements were performed:

STUK; page 10-10

DSA; page 12-13

NPL; page 14-16

SSM; page 17-18

CIEMAT; page 18-23

STUK

Chamber	**EXRADIN A6 (XQ200282)**
	N_{Kair}
Date of measurement	Aug 2024
Calibration coefficient [Gy/C]	*3,778E+04*
U (k = 2) [%]	**1,44**
mean ionization current [pA]	-174,29
measured leakage current [fA]	-2,00
Environmental conditions (T, p, h), is there correction for humidity?	20 °C, 100.8 kPa, 50% rh, no correction for humidity
Correction factors: k_{elec}	1,0041

Background information	**K_{air}**
Radiation source	Cs-137
Irradiator	Gemini
Field size	30 cm (98%)
Dose rate [Gy/s]	6,592E-06
SDD [cm]	200 cm
Reference standard (chamber + traceability)	PTW TM32002-0260, PTB
Electrometer (charge vs current, range + traceability)	Keithley 6517B 4132822, measuring charge, 20 nC, VTT MIKES (Finland, 11/21)

Equation/model
Computation method (analytic or MC) and program model
NK = K(air)/((Itot-Ileak)*k(kTp)*k(elec))
Analytic

Quantity Kair

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,60
Long term stability of reference standard		0,29
Spectral difference of SSDL and PSDL		0,03
Difference in radial non-uniformity of the beam and field size		0,06
Combined uncertainty of reference standard and setup	**0,00**	**0,669**
2 Use of reference standard		
Chamber positioning (distance, orientation)		
Current/charge measurement including leakage	0,05	0,12
Air temperature correction		0,057
Air pressure correction		0,007
Others (e.g. humidity of the measurement environment))		0,06
Combined uncertainty in measuring with reference standard	**0,05**	**0,149**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,05**	**0,686**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,05	0,124
Air temperature correction		0,057
Air pressure correction		0,007
Difference in radial non-uniformity of the beam and field size		
Decay of Cs-137		
Others (e.g. humidity in measurement environment)		0,06
Combined uncertainty in measuring with transfer chamber	**0,05**	**0,19**
Relative combined standard uncertainty (1+2+3)	**0,07**	**0,712**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,715**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,44**	
Confidence level (%)	95,3	

DSA

Chamber	**EXRADIN A6 (XQ200282)**
	N_{Kair}
Date of measurement	04.09.2024 to 05.09.2024
Calibration coefficient [Gy/C]	*37365*
***U* (*k* = 2) [%]**	0,93
mean ionization current [A]	*-1,596E-11*
measured leakage current [A]	*-1,2E-14*
Environmental conditions (T, p, h), is there correction for humidity?	04.09: T=294.60 K, P=100.81 kPa, h=65%, no correction for humidity
Environmental conditions (T, p, h), is there correction for humidity?	05.09: T=293.95 K, P=101.44 kPa, h=67%, no correction for humidity
Correction factors: k_{elec}	Ref: 1.0009, UUT: 1.001
Correction factors: kTP	04.09: Mean 1.010
Correction factors: kTP	05.09: Mean 1.002

Background information	**K_{air}**
Radiation source	**Cs-137**
Irradiator	DIR101, Veenstra
Field size	24 cm diameter
Kerma rate [mGy/h]	2,15
SDD [cm]	100,0
Reference standard (chamber + traceability)	Exradin A6 XQ102232, IAEA 2021, for S-Cs and S-Co
Electrometer (charge vs current, range + traceability)	Keithley 6517A 0863876 and Keithley 6517A 0925329, measuring current, calibrated in-house and traceable to Justervesenet
other remarks	All currents and dose rates are referenced to 01.09.2024

Quantity	Kair	
Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,40
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,05
Difference in radial non-uniformity of the beam and field size		0,10
Combined uncertainty of reference standard and setup	**0,00**	**0,43**
2 Use of reference standard		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,02	
Air temperature correction		0,06
Air pressure correction		0,02
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,10**	**0,07**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,10**	**0,43**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,02	
Air temperature correction		0,06
Air pressure correction		0,02
Difference in radial non-uniformity of the beam and field size		
Decay of Cs-137		0,00
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,10**	**0,07**
Relative combined standard uncertainty (1+2+3)	**0,14**	**0,44**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,461**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**0,93**	
Confidence level (%)	95,3	

NPL

Chamber	**EXRADIN A6 (XQ200282)**
	N_{Kair}
Date of measurement	04-Oct-24
Calibration coefficient [Gy/C]	*3,754E+04*
U **(*k* = 2) [%]**	**1,46**
mean ionization current [pA]	-318,52
measured leakage current [fA]	39
Environmental conditions (T, p, h), is there correction for humidity?	T= 292.27 K (19.12 C), p= 102.085 kPa, rh=51.7%, no correction for humidity applied
Correction factors: k_{elec}	1,00
Background information	**K_{air}**
Radiation source	Cs-137
Irradiator	Mainance
Field size (cm)	48,9
Dose rate [mGy/h]	42,54
SDD [cm]	300,00
Reference standard (chamber + traceability)	NPL primary standard via a specially constructed graphite-walled transfer standard chamber
Electrometer (charge vs current, range + traceability)	Keithley 6517B measuring current, 2nA range, internal UKAS calibration.

Table 1	**Uncertainties in the primary standard factor**		
Symbol	Quantity, source of uncertainty	Type A	Type B
$\overline{S}_{air}^{graphite} \cdot k_{fl}$	Mass stopping power ratio (graphite to air) x fluence perturbation correction	-	0,08
$\left(\mu_{en}/\rho\right)_{graphite}^{air}$	Mass energy absorption coefficient ratio (air to graphite)	-	0,10
k_{wall}	Wall correction	-	0,10
$u_c(\widetilde{F})$	Standard uncertainty	0,11	0,16
$u_c(\widetilde{F})$	Combined standard uncertainty	0,20	
k_{an} x k_{rn}	Product of axial uniformity and radial uniformity correction factors	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	0,28	
(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_{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	

*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 $\overline{S}_{air}^{graphite} \cdot k_{fl}$

Table 2	**Uncertainties in the primary standard measurement**		
Symbol	Quantity, source of uncertainty	Type A	Type B
N_k	Total primary standard correction	-	0,28
k_{elec}	Electrometer current calibration (pA/'pA')	-	0,30
k_{res}	Electrometer resolution (nA)	-	0,03
k_{ion}	Ion recombination correction	0,05	-
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
$R_{angular}$	Angular response change	0,03	-
R	Repeatability	0,30	-
$u_c(K_a)$	Combined standard uncertainty	0,53	

Table 3 Uncertainties in the calibration of the NPL transfer standard

Symbol	Quantity, source of uncertainty	Type A	Type B
K_a	Air kerma rate	-	0,53
k_{elec}	Electrometer current calibration (nA/'nA')	-	0,15
k_{res}	Electrometer resolution (nA)	-	0,03
k_{ion}	Ion recombination correction	0,05	-
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
k_{dist}	Distance from source	-	0,05
k_{orient}	Orientation of chamber	-	0,01
R	Repeatability	0,30	-
$u_c(N_k)$	Combined standard uncertainty	0,64	
U	Expanded uncertainty (k =2)	1,28	

Table 4 Uncertainties in calibration of a secondary standard

Symbol	Quantity, source of uncertainty	Type A	Type B
K_a	Air kerma rate	-	0,64
k_{elec}	Electrometer current calibration (nA/'nA')	-	0,15
k_{res}	Electrometer resolution (nA)	-	0,03
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
k_{dist}	Distance from source	-	0,05
k_{orient}	Orientation of chamber	-	0,01
R	Repeatability	0,30	-
$u_c(K_a)$	Combined standard uncertainty	0,73	
U	Expanded uncertainty (k =2)	1,46	

SSM

Chamber	**EXRADIN A6 (XQ200282)**
	N_{Kair}
Date of measurement	2024-11-15
Calibration coefficient [Gy/C]	37400
U (k = 2) [%]	1,1
mean ionization current [pA]	-403,05
measured leakage current [fA]	-4,79
Environmental conditions (T, p, h), is there correction for humidity?	T=21,45°C, p=101,55 kPa, rh=43% no correction for humidity
Correction factors: k_{elec}	1,00

Background information	**K_{air}**
Radiation source	Cs-137
Irradiator	Veenstra DIR101
Field size	FWHM= 40 cm
Dose rate [mGy/s]	1,526E-02
SDD [cm]	100
Reference standard (chamber + traceability)	Exradin A6 XQ040063, BIPM 2016
Electrometer (charge vs current, range + traceability)	Keysight B2987A-MY54321271, current measurements, 2E-9 range, RISE 04/24

Equation/model

$$\Delta K_{1m}=\delta N_{k,\text{PSDL}}*\Delta I*\Delta k_{T,p}*\delta T*\delta k_{\text{pos.jonk.1m,inmätning}}*\delta k_{\text{rek,1m}}*\delta E_{\text{PSDL}}*\delta T_{1/2}*\delta k_{\text{spridd}}*\delta k_{\text{fält}}*\delta k_{\text{stab}}*\delta k_{\text{spek}}$$

$$\Delta N_{k,1m}=\Delta K_{1m}*\delta k_{\text{fält,instr,1m}}*\delta k_{\text{pos.instr,1m}}*\Delta I\text{Trans}*\Delta k_{T,p}*\delta T*\delta A*\delta RH*\delta k_{\text{pos.källa}}*\delta M_{1m}*\delta T_{1/2}$$

Computation method (analytic or MC) and program model analytic

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL	0,10	0,19
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,06
Combined uncertainty of reference standard and setup	**0,10**	**0,30**
2 Use of reference standard		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,201	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life Cs-137		0,00
Recombination		0,01
Temperature gradients		0,06
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,20**	**0,17**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,22**	**0,346**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,01	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life Cs-137		0,00
Temperature gradients		0,06
Difference in radial non-uniformity of the beam and field size		0,30
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,01**	**0,35**
Relative combined standard uncertainty (1+2+3)	**0,22**	**0,49**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,538**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,08**	
Confidence level (%)	95,3	

CIEMAT

Chamber	**EXRADIN A6 (XQ200282)**
Quantity	$N_{K\mathrm{air}}$
Date of measurement	27/11/2024 - 13/12/2024
Calibration coefficient [Gy/C]	**3,7293E+04**
U (k = 2) [%]	**1,14**
mean ionization current [pA]	-52,03
measured leakage current [fA]	4,00
Environmental conditions (T, p, h), is there correction for humidity?	T = 293,75 K (20,6 °C); P = 94,84 kP; h = 40 %, No correction for humidity
Correction factors: k_{elec}	1,001 (HIGH, uncertainty included)
Background information	K_{air}
Radiation source	Cs-137
Irradiator	NI-646 (Nuclear Ibérica)
Field size	Diameter: 42,0 cm
Air Kerma rate [mGy/s]	1,9403E-03
SDD [cm]	300 cm
Reference standard (chamber + traceability)	Graphite chambers CS-001 and SP-001 and secondary standards: 1-PTW 32005 (00047)and 2-PTW 32002 (00345). Traceability: CIEMAT
Electrometer (charge vs current, range + traceability)	PTW UNIDOS - T10002-20641 (Charge mode, range HIGH (22 nC), VSL (Nederlands 05/2024))

Equation/model: Primary Reference (Measurement. Volume 188, 110374 (2022))

$$\dot{K}_{\mathrm{air}} = \frac{I}{\rho_0 \cdot V_{\mathrm{col}}} \cdot \left(\frac{\bar{W}}{e}\right)_{\mathrm{air}} \cdot \left(\frac{\bar{S}_{\mathrm{el}}}{\rho}\right)_{\mathrm{c,air}} \cdot \left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{air,c}} \cdot \frac{1}{(1-\bar{g}_{\mathrm{air}})} \cdot \prod_i k_i$$

$$\left\{\prod_i k_i = k_{PT} \cdot k_{\mathrm{h}} \cdot k_{\mathrm{dec}} \cdot k_{\mathrm{att}} \cdot k_{\mathrm{pos}} \cdot k_{\mathrm{pol}} \cdot k_{\mathrm{s}} \cdot k_{\mathrm{st}} \cdot k_{\mathrm{wall}} \cdot k_{\mathrm{an}} \cdot k_{\mathrm{rn}} \cdot k_{\mathrm{SA}}\right\}$$

Table 1: Laboratory reference

Quantity: Air Kerma rate

Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Physical constants		
ρ_0 (dry air density)	-	0,01
$(\bar{W}/e)_{\mathrm{air}} \cdot (\bar{S}_{\mathrm{el}}/\rho)_{\mathrm{c,air}}$	-	0,13
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{air,c}}$ / $(1-\bar{g}_{\mathrm{air}})$	-	0,10
Quadratic summation	**0,00**	**0,16**
Chamber volume and Correction factors		
V_{col} (Chamber collection volume)	-	0,10
k_{PT} (air pressure and temperature)	-	0,07
k_{h} (humidity)	-	0,03
k_{dec} (source decay)	-	0,01
k_{att} (air attenuation)	-	0,03
k_{pos} (chamber positioning)	-	0,06
k_{pol} (effect of the polarizing voltage)	-	0,01
k_{s} (recombination losses)	0,01	0,02
k_{st} (stem scattering)	0,03	-
k_{wall} (wall effect)	0,01	0,10
k_{an} (axial non-uniformity)	0,05	0,03
k_{rn} (radial non-uniformity)	0,06	0,08
k_{SA} (Spencer-Attix theory)	-	0,10
Quadratic summation	**0,08**	**0,22**
Ionization current measurements		
Electrometer resolution	-	0,01
Leakage current	-	0,03
N_{el} (Electrometer calibration factor)	-	0,10
$f_{\mathrm{non\text{-}lin}}$ (Linearity correction of the electrometer response)	-	
f_{tem} (rate of the electrometer timer)	-	0,10
Repeatability	0,02	-
Quadratic summation	**0,02**	**0,14**
Reference Air Kerma rate		
Quadratic summation	**0,09**	**0,31**
Relative combined standard uncertainty, $u(\dot{K}_{\mathrm{air}})$	**0,32**	

Table 2: Uncertainties in the calibration of the CIEMAT secondary standard 1 (30 cm^3)		
Quantity: N_k (Gy/C)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Reference air kerma rate	0,09	0,31
Measured current (including leakage correction)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,03	-
Quadratic summation	**0,09**	**0,36**
Relative combined standard uncertainty, $u(N_K)$	**0,37**	

Table 3: Uncertainties in the calibration of the CIEMAT secondary standard 2 (1000 cm^3)

Quantity: Air Kerma rate (Obtained with the secondary standard 1)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 1, N_K	0,09	0,36
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,02	-
Quadratic summation	**0,10**	**0,40**
Relative combined standard uncertainty, $u(\dot{K}_{\mathrm{air}})$	**0,41**	
Quantity: N_k (Gy/C)		
Air kerma rate	0,10	0,40
Measured current (including leakage correction)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,09	-
Quadratic summation	**0,13**	**0,44**
Relative combined standard uncertainty, $u(N_K)$	**0,46**	

Table 4: Uncertainties in the calibration of the transfer chamber (EXRADIN A6 (XQ200282))		
Quantity: Air Kerma rate (Obtained with the secondary standard 2)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 2, N_K	0,13	0,44
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,04
Radial non-uniformity correction	-	0,10
Repeatability	0,15	-
Quadratic summation	**0,20**	**0,47**
Relative combined standard uncertainty, $u(\dot{K}_{\text{air}})$	**0,51**	
Quantity: N_k (Gy/C)		
Air kerma rate	0,20	0,47
Measured current (including leakage correction)	0,01	0,12
Ion recombination		0,10
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,04
Radial non-uniformity	-	0,15
Repeatability	0,09	-
Quadratic summation	**0,22**	**0,52**
Relative combined standard uncertainty (1σ), $u(N_K)$	**0,57**	
Relative expanded uncertainty ($k = 2$), $U(N_K)$	**1,14**	
Coverage probability (%)	**95**	