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Key comparison BIPM.RI(I)-K5 of the air-kerma standards of the KRISS, Korea and the BIPM in ^{137}Cs gamma radiation

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Abstract

A new indirect comparison of the standards for air kerma of the Korea Research Institute of Standards and Science (KRISS), Korea, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{137}Cs radiation beam using the radiation protection facility of the International Atomic Energy Agency (IAEA) in Seibersdorf, Austria, in June 2025[a]. The comparison result, based on the calibration coefficients for two transfer chambers and expressed as a ratio of the KRISS and the BIPM standards for air kerma, is 0.9992 with a combined standard uncertainty of 2.0 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database, to update the 2010 comparison result.

1. Introduction

A new comparison of the standards for air kerma of the Korea Research Institute of Standards and Science (KRISS), Korea, and of the Bureau International des Poids et Mesures (BIPM) was carried out in June 2025 in the ^{137}Cs radiation beam at the International Atomic Energy Agency (IAEA)[a] in Seibersdorf, Austria, to update the previous comparison result of 2010 (Kessler *et al*. 2010).

The comparison result is published in the BIPM key comparison database (KCDB 2025) under the reference BIPM.RI(I)-K5. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The comparison was undertaken using two ionization chambers of similar type as transfer instruments, both chambers belonging to the KRISS.

2. Details of the standards and the transfer chambers

The air-kerma standard of the KRISS for ^{137}Cs is a graphite-walled cavity ionization chamber of cylindrical shape constructed by the KRISS, referenced as Y19-01. The KRISS standard is described in Yi (2010) and Kim *et al*. (2021).

The BIPM standard, identified as CH6.3, is a parallel-plate graphite-walled cavity ionization chamber with a volume of about 6.8 cm^3 (Boutillon and Niatel 1973, Burns *et al.* 2007, Kessler *et al.* 2009, Burns and Kessler 2018).

[a] Since 2018, the BIPM no longer maintains reference radiation protection beams for ^{137}Cs and ^{60}Co. To continue the services of calibration and comparison (BIPM.RI(I)-K5) in ^{137}Cs beams, in 2022 the BIPM has installed the primary standard together with a BIPM measurement and data acquisition system at the IAEA laboratories in Seibersdorf, Austria.

Details of the BIPM and KRISS primary standards are given in Table 1; details of the KRISS transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM and the KRISS standards

Dimensions		BIPM CH6.3 (paralell-plate)	KRISS Y19-01 (cylindrical)
Cavity	Diameter / mm	45.01	13.006
	Thickness / mm	5.16	–
	Height / mm	--	13.011
	Measuring volume / cm^3	6.8313	1.6689
Electrode	Diameter / mm	41.03	3.024
	Thickness / mm	0.96	–
	Height / mm	–	10.047
Wall	Thickness / mm	2.98	2.998
	Material	Graphite	Graphite
	Density / g cm^{-3}	1.85	1.84
Voltage applied to outer electrode / V		± 80	± 250

Table 2. Characteristics of the KRISS transfer chambers

Dimensions (nominal values)		Exradin A4 (spherical)
Chamber	Outer diameter / mm	44
Electrode	Diameter / mm	4
	Length / mm	25
Cavity	Volume / cm^3	30
Wall	Thickness / mm	2.5
	Material	air equivalent plastic
Voltage applied to outer electrode / V		-500

3. Determination of the air kerma

For a cavity chamber with measuring volume *V*, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W}{e} \frac{1}{1-\bar{g}} \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{a,c}} \bar{s}_{\mathrm{c,a}} \prod k_i \tag{1}$$

where

ρ_{air} is the density of air under reference conditions,

I is the ionization current under the same conditions,

W is the average energy spent by an electron of charge e to produce an ion pair in dry air,

$\bar{g}$ is the fraction of electron energy lost by radiative processes in air,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,

$\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean mass electronic stopping powers for electrons in graphite and air,

$\prod k_i$ is the product of the correction factors to be applied to the standard.

Physical data and correction factors

The values used for the physical constants, the correction factors, the volume of the primary standards entering in equation (1), and the associated uncertainties for the ^{137}Cs radiation beams at the IAEA and at the KRISS are given in Table 3.

Table 3. Physical constants and correction factors with their relative standard uncertainties of the BIPM and KRISS standards for the ^{137}Cs radiation beams

		BIPM	**CH 6.3**		**KRISS**	**Y19-01**	
		values	uncertainty [(1)]		values	uncertainty [(1)]	
			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Physical Constants							
ρ_{air}	dry air density [(2)] / kg m^{-3}	1.2930	–	0.01	1.2930	–	0.01
$s_{\mathrm{c,a}}$	ratio of mass stopping powers	1.0023	–	0.12[(3)]	1.0030	–	0.12[(3)]
W/e	mean energy per charge / J C^{-1}	33.97	–		33.97		
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	ratio of mass energy-absorption coefficients	0.9990	0.01	0.04	0.9992	–	0.06
g_{a}	fraction of energy lost in radiative processes	0.0012	–	0.02	0.0012	–	0.02
Correction factors							
k_{s}	recombination losses	1.0013	0.01	0.02	1.0020	0.01	0.02
k_{h}	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	0.9998	0.01	–	0.9928	0.04	–
k_{wall}	wall attenuation and scattering	1.0002	0.01	– [(4)]	1.0265	0.01	0.03
k_{an}	axial non-uniformity	1.0018	–	0.04	1.0000	0.01	0.05
k_{rn}	radial non-uniformity	1.0009	–	0.05	1.0002	0.01	0.02
k_{or}	orientation	0.9997	0.01	0.01	–	–	–
k_{co}	insulator compound scattering	–	–	–	0.9951	0.01	0.11
Measurement of I / V							
V	chamber volume / cm^3	6.8313	–	0.08	1.6689	–	0.05
k_{vol}	volume correction	1.0004	–		–	–	–
I	ionization current / pA	–	0.02	0.02	–	0.01	0.02
	reproducibility		0.03	–		0.01[(5)]	–
Relative standard uncertainty							
quadratic summation			0.04	0.17		0.05	0.20
combined uncertainty			**0.17**			**0.20**	
Removing correlations			0.04	0.11		0.05	0.14

(1) Expressed as one standard deviation
$u_{i\mathrm{A}}$ represents the type A relative standard uncertainty estimated by statistical methods
$u_{i\mathrm{B}}$ represents the type B relative standard uncertainty estimated by other means

(2) At 101 325 Pa and 273.15 K

(3) Combined uncertainty for the product of $s_{\mathrm{c,a}}$ and W/e (for the BIPM standard, see Burns and Kessler 2018)

(4) The uncertainty for k_{wall} is included in the determination of the effective volume (Burns *et al* 2007)

(5) Evaluated from the measurements made during the comparison period

The correction factors for the KRISS standard are described in the previous comparison report (Kessler *et al*. 2010).

The air-kerma rate determination and measurement conditions at each laboratory are explained in the following paragraphs.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\text{BIPM}}$ is taken as the mean of four measurements made during September 2024 and June 2025. The $\dot{K}_{\text{BIPM}}$ value refers to an evacuated path length between source and standard corrected to the reference date of 2025-01-01, 0 h UTC. The half-life of ^{137}Cs was taken as 10 976 days (u = 30 days) (Bé *et al.* 2006). The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air attenuation coefficient 0.010 m^{-1} for ^{137}Cs.

At the KRISS, the $\dot{K}_{\text{KRISS}}$ value was determined using the Y19-01 primary standard and is the mean of the measurements made during the period of the comparison (May-June 2025 before BIPM measurements and June-July 2025 after BIPM measurements). The long-term stability of the reference value is estimated to be better than 5 parts in 10^4. By convention it is given at the reference date of 2025-01-01, 0 h UTC using the same half-life value for the decay correction as the BIPM. Measurements are corrected for air attenuation between source and standard using the ambient air density at the time of the measurement and the average mass energy attenuation coefficient of 0.0778 cm^2 g^{-1} (Yi *et al*. 2024).

Reference conditions and beam characteristics

The characteristics of the IAEA and KRISS beams are given in Table 4. The distance from source to reference plane is 1 m at both laboratories.

Table 4. Characteristics of the ^{137}Cs beams at the KRISS and the IAEA

^{137}Cs beam	Source dimensions / mm		Nominal $\dot{K}$/ µGy s^{-1}	Field diameter at 1 m / mm
	diameter	length		
KRISS source	32.2	57.0	815.7	115
IAEA source	14.3	19.9	16.7	230

4. Comparison procedure

The comparison of the KRISS and BIPM standards was made indirectly using the calibration coefficients for two transfer chambers given by

$$N_{K,\text{lab}} = \dot{K}_{\text{lab}}/I_{\text{lab}} \tag{2}$$

where $\dot{K}_{\text{lab}}$ is the air-kerma rate and I_{lab} is the corrected ionization current of a transfer chamber measured by each laboratory.

Two Exradin A4 ionization chambers, serial numbers XP021342 and XP130212, belonging to the KRISS, are the transfer instruments used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the KRISS before and after the measurements made by the BIPM.

The BIPM and the KRISS experimental method for measurements and the correction factors applied to the current I_{lab} are described in the following paragraphs.

Positioning

At each laboratory the transfer chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source. At the IAEA, the transfer chambers identified as XP021342 and XP130212 were set-up and measured by the BIPM on two and three separate occasions, respectively, after being repositioned each time.

Applied voltage and polarity

At both laboratories, the collecting voltage and polarity indicated in Table 2 were applied to the outer electrode of the KRISS transfer chambers at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the KRISS chambers was measured by the BIPM at the IAEA using a Keithley electrometer, model 6517B. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements. The measurements were corrected by the mean leakage current measured before and after each series of measurements. The measured leakage values for both chambers were around 4 fA, 2 parts in 10^4 in relative terms of the ionization current.

At the KRISS, the charge Q collected by the transfer chambers was measured in the same way as the BIPM using a Keithley electrometer, model 6517B. A pre-irradiation of at least 30 min was made for each chamber before any measurements. The measurements were corrected for the leakage current measured after each series of measurements. The measured leakage values for both chambers were around 1 fA, less than 1 part in 10^4 in relative terms of the ionization current.

Radial and axial non-uniformity correction

The correction for the radial non-uniformity of the beam for the transfer chambers at both laboratories is less than 5 parts in 10^4. No correction was applied to the measured current for the radial non-uniformity of the beam and a relative uncertainty component of 2 parts in 10^4 is included in Table 8.

The KRISS calculated the correction factor for the axial non-uniformity of the beam using Monte Carlo techniques for different spherical chambers. For the Exradin A4 this correction is 0.9997(2); as this effect is likely to be similar for the IAEA beam, no correction was applied.

Thermal expansion correction

The calibration coefficients provided by the KRISS included a thermal expansion correction k_{ex} calculated using the expression

$$k_{\mathrm{ex}} = 1/[1 + \alpha_{v}(T - 20^{\circ}\mathrm{C})] \qquad (3)$$

where α_{v} is the thermal expansion coefficient and T is the ambient temperature in °C (Yi and Kim 2013).

The KRISS correction for thermal expansion is 0.9989, corresponding to a temperature of 22.8 °C measured at the time of the calibration. The effect is likely to be similar for the IAEA temperature of 22.4 °C. For consistency, no correction for thermal expansion was applied for the present comparison; a relative standard uncertainty of 2 parts in 10^4 is included in Table 8.

Ion recombination

The KRISS results were corrected for losses due to ion recombination determined using the method of Niatel as described in Boutillon (1998). Initial and volume recombination were determined for both Exradin A4 chambers, and the average values were used. Ion recombination was also determined by the BIPM using the same method. The results determined at each laboratory are presented in Table 5, including the ion recombination correction calculated for the currents measured at each laboratory using both determinations.

Table 5. Ion recombination correction for the Exradin A4 ionization chambers

Ion recombination determined at each laboratory	KRISS	BIPM	
Exradin A4	Both chambers	XP021342	XP130212
Initial recombination and diffusion, k_{init}	1.65×10^{-3}	9.87×10^{-4}	1.93×10^{-3}
Volume recombination factor, k_{vol} / pA	1.29×10^{-6}	1.62×10^{-6}	1.28×10^{-6}
k_s for I = 16 pA (IAEA beam)	1.0017	1.0010	1.0019
k_s for I = 800 pA (KRISS beam)	1.0027	1.0023	1.0030
Relative standard uncertainty	2×10^{-4}	2×10^{-4}	

Considering the k_s mean value determined by the KRISS and the mean of the values determined by the BIPM for each of the two chambers, the ion recombination correction factors are in agreement at the level of 2 parts in 10^4 for both the IAEA and KRISS ^{137}Cs radiation beams. The BIPM results are corrected by the values determined for each chamber. The corresponding relative standard uncertainties are included in Table 7.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.2 °C at the IAEA. At the KRISS, the air temperature was stable to better than 0.2 °C during each series of measurements. At both laboratories, the current measured using the transfer chambers is normalized to the reference conditions of 293.15 K and 101.325 kPa.

Relative humidity is controlled, and it was between 45 % and 55 % at the IAEA and between 46 % and 60 % at the KRISS.

5. Results of the comparison

The result of the comparison R_K is expressed in the form

$$R_K = N_{K,\mathrm{KRISS}}/N_{K,\mathrm{BIPM}} \quad (4)$$

in which the average value of measurements made at the KRISS before and after those made at the IAEA by the BIPM is compared with the mean of the measurements made by the BIPM.

Table 6 lists the relevant values of N_K at the stated reference conditions (293.15 K and 101.325 kPa) and the final results of the indirect comparison.

Table 6. Result of the KRISS/BIPM comparison of the ^{137}Cs air kerma standards

Transfer chambers Exradin A4	$N_{K,\mathrm{KRISS}}$/ Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
XP021342	0.9969	0.9970	0.9970	0.9981	0.9988	0.0020
XP130212	1.0086	1.0084	1.0085	1.0090	0.9995	0.0020
				Mean value	0.9992	0.0020

The uncertainties associated with the calibration of the transfer chambers at each laboratory and with the indirect comparison are presented in Table 7 and Table 8, respectively. The reproducibility at the IAEA and at the KRISS are estimated to be 1 and 2 parts in 10^4, respectively; these values are included in Table 7.

The values $N_{K,\mathrm{KRISS}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose root mean squared (rms) value is taken as a representation of the stability of the transfer instruments. The short-term stability thus evaluated is included in Table 8 and it was estimated to be 1 part in 10^4. Table 8 includes a component of 4 parts in 10^4 for the difference in the comparison result between the two transfer chambers.

Table 7. Uncertainties associated with the transfer chamber calibration

Relative standard uncertainty	BIPM		KRISS	
	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air-kerma rate	0.04	0.17	0.05	0.20
Ionization current for the transfer chambers	0.01	0.02	0.01	0.02
Distance	0.01	–	0.01	–
Reproducibility	0.01	–	0.02	–
Ion recombination k_s	0.01	0.02	0.01	0.02
Air attenuation k_{att}	–	–	0.01	–
$N_{K,\mathrm{lab}}$	0.05	0.17	0.06	0.20

Table 8. Uncertainties associated with the indirect comparison

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
$N_{K,\mathrm{KRISS}}$ / $N_{K,\mathrm{BIPM}}$	0.07	0.18(1)
Thermal expansion	–	0.02
Radial non-uniformity	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.04	–
$R_{K,\mathrm{KRISS}}$	u_c = 0.0020	

(1) The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

Some uncertainties in $\dot{K}_{\mathrm{air}}$ that appear in both the BIPM and the KRISS determinations (namely air density, W/e, $(\mu_{en}/\rho)_{a,c}$, $\bar{g}$, $s_{c,a}$ and k_h) cancel when evaluating the uncertainty of the ratio R_K of the KRISS and BIPM calibration coefficients.

The mean ratio of the air-kerma calibration coefficients of the transfer chambers determined by the KRISS and the BIPM taken from Table 6 is 0.9992 with a combined standard uncertainty, u_c, of 0.0020.

6. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here K_{BIPM}, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each NMI i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{BIPM,i}) / K_{BIPM,i} = x_i - 1$ and its expanded uncertainty $U_i = 2\ u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 9 gives the values for D_i and U_i for each NMI, i, taken from the KCDB of the CIPM MRA (1999) and this report. These data are presented graphically in Figure 1.

Note that the data presented in Table 9, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. In addition, revised validity rules for comparison data have been agreed by the CCRI(I) so that any results older than 15 years are no longer considered valid and have been removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database.

Table 9. Degrees of equivalence

For each laboratory i, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K5

Lab i	D_i	U_i
	/ (mGy/Gy)	
NIST	-1.0	7.0
NMIJ	-2.3	5.2
PTB	2.4	5.4
NIM	-3.3	4.2
ININ	4.8	4.0
VSL	-4.8	7.6
SMU	5.1	5.4
BEV	4.3	5.4
CIEMAT	-0.8	4.4
GUM	0.5	5.6
LNE-LNHB	-3.0	4.4
KRISS	-0.8	4.0

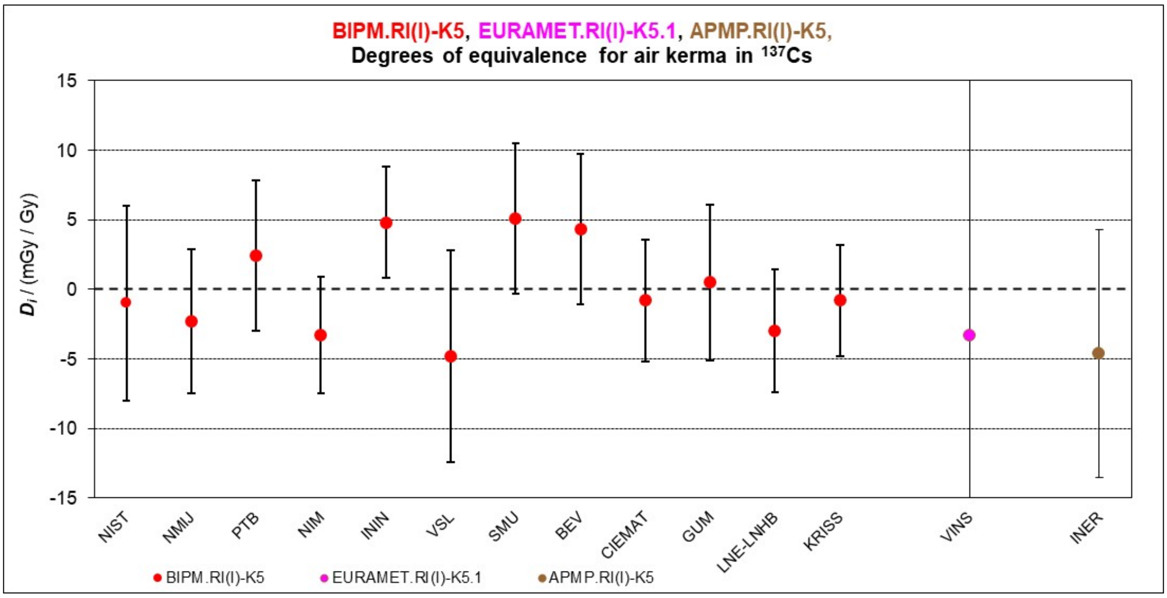
EURAMET.RI(I)-K5.1

Lab i	D_i	U_i
	/ (mGy/Gy)	
VINS	-3.3	20.2

APMP.RI(I)-K5

Lab i	D_i	U_i
	/ (mGy/Gy)	
INER	-4.6	8.9

Figure 1. **Graph of degrees of equivalence with the KCRV**



7. Conclusion

The previous comparison of the KRISS and BIPM standards for air kerma in ^{137}Cs beam was made in 2010 using the primary standards at the BIPM. The result of the direct comparison was 0.9986 (22).

Since the previous comparison, both laboratories implemented some changes in the standards following the recommendations of the ICRU 90. For the KRISS and for the BIPM, this resulted in a reduction of 6.8 parts in 10^3 and 8 parts in 10^3 in the determination of air kerma, respectively. Adopting these changes, the 2010 comparison result becomes 0.9998 (22).

The present comparison made indirectly using two transfer standards gives a result of 0.9992 (20), in agreement within the uncertainties with the 2010 result updated with the changes implemented to the standards at both laboratories.

The KRISS is in agreement within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K5 ongoing key comparison for air-kerma standards in ^{137}Cs gamma-ray beams.

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