Comparison BIPM.RI(I)-K8 of high dose-rate Ir-192 brachytherapy standards for reference air kerma rate of the VSL and the BIPM

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Abstract

An indirect comparison of the standards for reference air kerma rate for ^{192}Ir high dose rate (HDR) brachytherapy sources of the Dutch Metrology Institute (VSL), The Netherlands, and of the Bureau International des Poids et Mesures (BIPM) was carried out at the VSL in November 2009. The comparison result, based on the calibration coefficients for a transfer standard and expressed as a ratio of the VSL and the BIPM standards for reference air kerma rate, is 0.9873 with a combined standard uncertainty of 0.0061.

1. Introduction

The Brachytherapy Standards Working Group (BSWG), created under the recommendation made by the Consultative Committee for Ionizing Radiation CCRI(I), proposed at their meeting of November 2005 to start a comparison of primary standards for reference air kerma rate (RAKR) of ^{192}Ir. To meet the needs of the National Metrology Institutes (NMIs), a new ongoing key comparison was registered in the BIPM key comparison data base (KCDB 2014) under the reference BIPM.RI(I)-K8. As no primary facility for brachytherapy is available at the BIPM, the BIPM results are based on measurements using an NE 2571 thimble-type transfer ionization chamber in the ^{60}Co reference beam at the BIPM.

The Dutch Metrology Institute (VSL) is the first NMI to participate in this new ongoing key comparison.

The comparison result is given in terms of the ratio of the calibration coefficients of the thimble chamber determined at the VSL in the ^{192}Ir radiation beam and at the BIPM in the ^{60}Co reference radiation beam, the latter corrected by a calculated factor to account for the energy dependence of the NE 2571 chamber type between ^{60}Co and ^{192}Ir (Mainegra-Hing *et al* 2006).

Measurements were also made using a well-type ionization chamber of the BIPM. The response of this chamber, connected to its own electrometer, was determined relative to the BIPM RAKR realized in the NMI ^{192}Ir beam using the NE 2571 (and the NMI electrometer system). Such a calibration of the well chamber at each NMI enables its future use in a comparison with an NMI that does not calibrate the NE2571 chamber type. The long-term stability of the well chamber is established by measurements at the BIPM using a ^{166m}Ho source.

The comparison result, approved by the CCRI, is analysed and presented in terms of degrees of equivalence for entry in the BIPM key comparison database.

2. Characteristics of the transfer instruments

Two transfer instruments, belonging to the BIPM, are used to undertake the comparisons: an NE 2571 thimble chamber and a Standard Imaging HDR1000 well chamber. The main characteristics of the transfer instruments are listed in Table 1.

Table 1. Characteristics of the BIPM transfer chambers

Characteristic/Nominal values		NE 2571-2806	Standard Imaging HDR 1000 Plus	Standard Imaging Insert 70010
Dimensions	Inner diameter / mm	6.3	102	35
	Cavity length / mm	24.0	156	121
	Wall mass thickness / g cm^{-2}	0.065	-	
	Tip to reference point / mm	13.0	-	
	Bottom to reference point / mm	-	50 (sweet-spot)	
Electrode	Length / mm	21.0	-	
	Diameter / mm	1.0	-	
Air cavity	Volume / cm^3	0.6	245	
Wall	Material	Graphite	-	
	Density / g cm^{-3}	1.7	-	
Build-up cap	Material	Delrin	-	
	Thickness / g cm^{-2}	0.551	-	
Potential of HV electrode with respect to collecting electrode		–250	–300	

3. Determination of the VSL reference value

As the VSL has no primary standard for high dose-rate (HDR) ^{192}Ir brachytherapy sources, the reference air kerma rate (RAKR) is determined using an NE 2571 ionization chamber as a transfer instrument. The determination of the calibration coefficient for ^{192}Ir is based on a linear interpolation between the air kerma calibration coefficients for a 250 kV x-ray beam, where the primary standard is a free-air chamber, and a ^{137}Cs γ-ray beam, where the primary instrument is a graphite cavity chamber, and a correction factor determined using the method described by Petersen *et al* (1994) and van Dijk *et al* (2004). In the Petersen study, the energy response of a NE 2571 was determined by calibrating the chamber against the primary standards in a series of 9 ISO narrow x-ray, ^{137}Cs and ^{60}Co beams. To obtain the air kerma calibration coefficient N_K for ^{192}Ir, each ^{192}Ir spectral line is treated individually; the air kerma calibration coefficient is obtained for each spectral line by interpolation on the energy response curve and weighting them according to the intensity of each spectral line. The ^{192}Ir spectrum was simulated using Monte Carlo techniques.

The calibration coefficient thus obtained was compared to the one obtained using a linear interpolation between 250 kV x-ray and ^{137}Cs beams. From this study, it was concluded that a correction of 1.003 has to be applied to the linear interpolation result.

The VSL standards have been compared against the BIPM primary standards in medium-energy x-rays and ^{60}Co γ-rays and their main characteristics are described in the corresponding comparison reports (Burns *et al* 2009, Allisy-Roberts *et al* 2007). For the VSL graphite cavity chamber, a new value for the wall correction factor has been determined recently (van Dijk 2007) which resulted in a decrease of 0.4 % in the air kerma determination. These modifications have been taken into account in the determination of the RAKR of the HDR ^{192}Ir source.

The main characteristics of the VSL ^{192}Ir source and the transfer instrument used to determine the RAKR are listed in Tables 2 and 3, respectively.

Table 2. Characteristics of the VSL ^{192}Ir source

After-loader unit	Nucletron NLF 01 D36B8588
Manufacturer of source	Mallinckrodt Medical BV
Apparent activity of source	386 GBq at 20/04/2010

Table 3. Characteristics of the VSL transfer chamber

Characteristic/Nominal values		NE 2571
Dimensions	Inner diameter / mm	6.4
	Wall mass thickness / g cm^{-2}	0.065
	Cavity length / mm	24.1
	Tip to reference point / mm	13.0
Electrode	Length / mm	20.6
	Diameter / mm	1.0
Air cavity	Volume / cm^3	0.6
Wall	Material	Graphite
	Density / g cm^{-3}	1.7
Voltage applied	Polarity to inner electrode / V	-250

Ambient conditions

The ionization current for each chamber is corrected to the reference conditions of 293.15 K and 101.325 kPa; relative humidity is controlled at (50 ± 5) % and no humidity correction is applied.

4. Determination of the BIPM reference values

The BIPM does not possess an ^{192}Ir source. The reference value for the thimble chamber used to evaluate the comparison result is based on measurements performed in the ^{60}Co γ-ray beam, with supporting measurements in 250 kV x-rays. The reference value for the well chamber is based on measurements made with the ^{192}Ir source of the participating labs, with supporting measurements using a reference source of ^{166m}Ho.

4.1 Reference values for the BIPM thimble chamber

The NE 2571 is calibrated periodically at the BIPM in the ^{60}Co γ-ray beam, under the reference conditions described by Allisy-Roberts *et al* (2009). The chamber is also calibrated periodically in the CCRI 250 kV x-ray beam to verify that its response at lower energies remains stable.

The calibration coefficient of the thimble chamber $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ for ^{192}Ir is derived from the calibration coefficient determined in the BIPM ^{60}Co γ-beam and a calculated correction factor k_{en} to take into account the energy dependence of this type of ionization chamber (Mainegra-Hing *et al* 2006):

$$N_{K,\mathrm{BIPM}}^{\mathrm{th}} = N_{K,\mathrm{BIPM}}^{\mathrm{th,Co\text{-}60}} \times k_{\mathrm{en}} \qquad (1)$$

The value for k_{en} is taken to be 1.0020, with an estimated relative standard uncertainty of 1.5×10^{-3} (the statistical standard uncertainty of the calculated value is 6×10^{-4}).

The BIPM mean values for the thimble chamber made around the period of the comparison are compared to the long-term value to verify the stability of the chamber. The long-term reproducibility in the BIPM ^{60}Co beam is 0.7×10^{-4} in relative value (and 3.1×10^{-4} for the 250 kV x-ray beam). Considering the long-term stability for the ^{60}Co beam and the 250 kV x-ray beam a value of 2.0×10^{-4} is included in the BIPM uncertainty budget.

4.2 Reference values for the BIPM well chamber

Until now, the sealed source used to monitor the stability of the well-type HDR1000 ionization chamber is a low activity source (about 1.3 MBq) of ^{166m}Ho. The long-term reproducibility of the well chamber established using this source is about 2.5×10^{-3} in relative value. It is possible that some of this variation is due to the low activity and for this reason a higher activity source (about 1.7 GBq) of ^{137}Cs will be implemented for future comparisons.

To derive a reference value for the well chamber, the BIPM determines its calibration coefficient at each NMI using the NMI ^{192}Ir source as

$$N_{K,\mathrm{BIPM}}^{\mathrm{w}} = \frac{\dot{K}_{\mathrm{R,BIPM}}}{I} \qquad (2)$$

where $\dot{K}_{\mathrm{R,BIPM}}$ is the RAKR for the NMI source evaluated from the current determined by the NMI using the BIPM NE 2571 chamber (for the usual NMI reference conditions) and the BIPM $N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ determination. The well chamber current *I*, measured at the sweet-spot, is appropriately corrected to the reference conditions of measurements and normalized to the reference ambient conditions.

5. Comparison measurements at the VSL

5.1 Comparison measurements with the BIPM thimble chamber

The calibration coefficient $N_{K,\mathrm{VSL}}^{\mathrm{th}}$ for the BIPM thimble chamber at the VSL is given by

$$N_{K,\mathrm{VSL}}^{\mathrm{th}} = \dot{K}_{\mathrm{R,VSL}} \big/ I_{\mathrm{VSL}} \qquad (3)$$

where $\dot{K}_{R,\mathrm{VSL}}$ is the VSL reference air kerma rate and I_{VSL} is the ionization current of the BIPM thimble chamber measured by the VSL. The relative standard uncertainty of the mean ionization current was estimated to be 2×10^{-4} (two calibrations; for each calibration, three series of 8 measurements with source repositioning, as described below)

Determination of the BIPM calibration coefficient is described in Section 4.1. The chamber was calibrated before and after the measurements at the VSL; the relative standard uncertainty of the mean is taken to be 2 parts in 10^4.

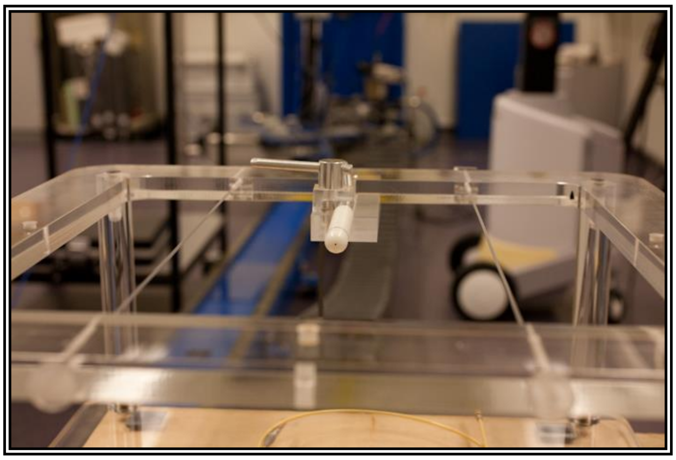
The ionization current in each case is corrected for the influence factors described below.

Positioning

At the BIPM, the BIPM thimble chamber is positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem (engraved line) facing the source; the build-up cap being used for both ^{60}Co and 250 kV x-rays.

At the VSL the BIPM thimble chamber is set up at the centre of the irradiation jig between two catheters that are each 10 cm from the chamber, as illustrated in Figure 1, and with the appropriate marking on the stem (engraved line) in the upward direction. The charges measured in these two arrangements are averaged, reducing the uncertainty related to positioning. A set of at least three runs with repositioning of the source in between was made for each catheter.

Figure 1. **Set-up for the NE 2571 thimble chamber**



The NE 2571 thimble chamber in the VSL irradiation jig, equidistant from each lateral source position**.**

Applied voltage and polarity

At the BIPM, a collecting voltage of 250 V (negative polarity) is applied to the outer electrode of the chamber at least 30 min before any measurements are made. At the VSL, a collecting voltage of 250 V (positive polarity) is applied to the central electrode of the chamber at least 30 min before any measurements were made. Consequently, no corrections were applied at either laboratory for polarity.

Volume recombination

Volume recombination is negligible at dose rates less than 15 mGy s^{-1} for the chamber at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied at either laboratory.

Charge and leakage measurements

At the BIPM, the charge *Q*, collected by the transfer instrument is measured using a Keithley electrometer, model 642. The radiation source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the VSL, the charge collected is measured similarly with a Keithley model 6517A electrometer.

At the BIPM, pre-irradiation was for at least 30 min (≈ 10 Gy) before any measurements were made and similarly at the VSL the chamber was pre-irradiated with at least 10 Gy. The measured ionization current was corrected for the leakage current at both laboratories. This correction was less than 1×10^{-4} in relative value at the BIPM and less than 1×10^{-2} at the VSL; the latter value being reproducible at the 1×10^{-4} level.

Ambient conditions

During the measurements, the air temperature was stable to better than 0.01 °C at both laboratories. The measurements are normalized to 293.15 K and 101.325 kPa. Relative humidity is controlled at (50 ± 5) % at the BIPM and (50 ± 5) % at the VSL. Consequently, no correction for humidity is applied to the measured ionization current.

Radial non-uniformity correction

At the BIPM, the correction applied to the ionization current for the radial non-uniformity would only be 1.0002 for the transfer instrument, with an uncertainty of 2×10^{-4}. However for this comparison no correction for radial non-uniformity is made at the BIPM. At the VSL, no non-uniformity correction is applied, since the thimble chamber is of the same type as the transfer standard used to calibrate the HDR ^{192}Ir source (the radial non-uniformity correction cancels in evaluating the calibration coefficient at the VSL). Consequently, the VSL calibration coefficient is valid for a uniform radiation field. However, an uncertainty of 2×10^{-4} is included in the VSL uncertainty budget.

Stem and room scatter

Since the thimble chamber transfer instrument is of the same type as the transfer standard used at the VSL to calibrate the HDR ^{192}Ir source, the stem and room scatter corrections cancel in evaluating the calibration coefficient at the VSL. Consequently, the VSL calibration coefficient is effectively scatter-free.

5.2 Comparison measurements with the BIPM well chamber

The HDR1000 well chamber, together with its electrometer and probes for temperature, pressure and humidity, is used as a transfer system to determine a comparison result for those NMIs that do not provide calibrations of thimble-type ionization chambers. The well chamber was calibrated at the VSL with respect to the BIPM determination of RAKR, as described in Section 4.2.

The essential details of the current measurements are reproduced here.

Sweet-spot

At the VSL, measurements at a series of dwell positions for the ^{192}Ir source showed the sweet-spot of the well chamber to be at 49.4 mm, measured from the inside base plate of the well chamber.

Charge and leakage measurements

For each dwell position, three series of 10 measurements of 60 s were made, the source being retracted and repositioned between each series. For each series, the first measurement was discarded to ensure that the chamber response had stabilized. Measurements were corrected by leakage, which was measured at each dwell position. This correction was, in relative value, less than 1×10^{-3}.

Ambient conditions

The measurements are normalized to 293.15 K and 101.325 kPa. No humidity correction is applied.

Decay correction

The measurements are corrected for the decay of the source to the reference date of 2009-06-12. The half-life used by the VSL for ^{192}Ir is 73.830 days with u_c = 0.018 days, taken from Woods *et al* (1992).

6. Results of the comparison

6.1 Thimble chamber comparison result

The individual calibration coefficients of the thimble chamber will not be disclosed as this transfer chamber will be calibrated by other NMIs participating in this ongoing comparison.

The comparison result is expressed as the ratio of the calibration coefficients of the thimble chamber determined at both laboratories,

$$R_{K,\mathrm{VSL}}^{\mathrm{th}} = \frac{N_{K,\mathrm{VSL}}^{\mathrm{th}}}{N_{K,\mathrm{BIPM}}^{\mathrm{th}}} \qquad (4)$$

in which the average value of measurements made at the BIPM before and after those made at the VSL is compared with the mean of the measurements made at the VSL. For the VSL, the comparison result R_K^{th} is 0.9873.

6.2 Additional results for the well chamber

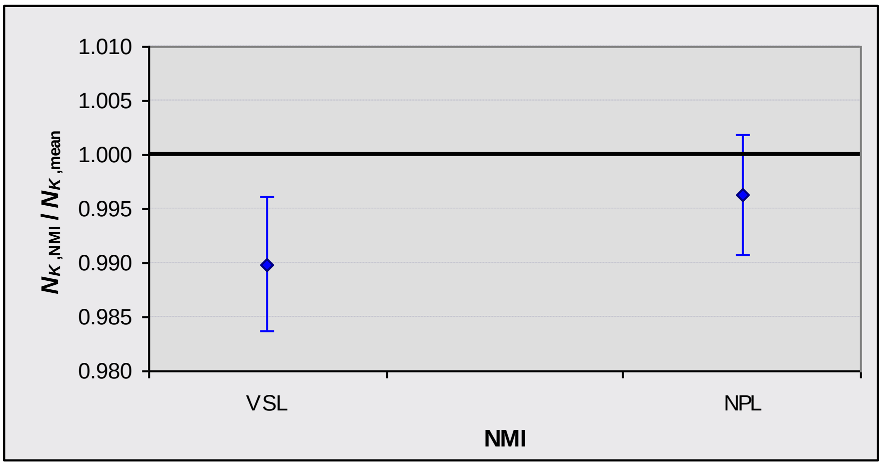
As explained in Section 4.2, the BIPM determines for each comparison the calibration coefficient of the well chamber $N_{K,\mathrm{BIPM}}^{\mathrm{w}}$ using equation (2). Although not used for the main comparison result, it is possible to derive a corresponding calibration coefficient $N_{K_{\mathrm{R}},\mathrm{VSL}}^{\mathrm{w}}$ for the VSL as

$$N_{K,\mathrm{VSL}}^{\mathrm{w}} = \frac{\dot{K}_{\mathrm{R,VSL}}}{I} \qquad (5)$$

where $\dot{K}_{R,\mathrm{VSL}}$ is the VSL reference air kerma rate. For the reasons stated above, the individual calibration coefficients are not disclosed.

At the time of producing this report, the National Physical Laboratory (NPL) had also participated in the BIPM.RI(I)-K8 comparison. Taking the mean of the two values determined by the BIPM (that is, at the VSL and at the NPL) as a normalization, is possible to see how the NMIs compare with each other in terms of well-chamber calibrations coefficients, as shown in Figure 2.

Figure 2. **NMI results for the well-chamber**



Relative calibration coefficients for the BIPM well chamber, as determined for each NMI ^{192}Ir source using the dedicated current measurement system of the well chamber. The uncertainty bars represent the combined standard uncertainties

Note that the well-chamber results in Figure 2 do not provide information that is independent of the main comparisons result using the thimble chamber, but rather provide a means of establishing a comparison result when no thimble chamber calibration is made by a particular NMI.

7. Uncertainties

7.1 Thimble chamber

The uncertainties associated with the BIPM thimble chamber calibration are listed in Tables 4 and 5 for the BIPM and the VSL, respectively (JCGM 2008).

Table 4. Uncertainties associated with the thimble chamber calibration at the BIPM

Relative standard uncertainty	u_{iA}	u_{iB}
^{60}Co air kerma determination K	0.0002	0.0015
Ionization current I_{th}	0.0001	0.0002
Positioning	0.0001	
Radial non-uniformity		0.0002
Long-term stability	0.0002	
Energy dependence k_{en}		0.0015
$N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ for ^{192}Ir	0.0003	0.0021

u_{iA} represents the relative standard uncertainty estimated by statistical methods, type A
u_{iB} represents the relative standard uncertainty estimated by other means, type B

Table 5. Uncertainties associated with the thimble chamber calibration at the VSL

Relative standard uncertainty		u_{iA}	u_{iB}
^{192}Ir air kerma determination			
Reference standard N_K			0.0050
Ionization current VSL reference standard		0.0002	
Calibraiton of the transfer chamber			
I	ionization current transfer chamber	0.0002	
k_{dec}	decay		0.0005
P	pressure		0.0010
T	temperature		0.0010
$k_{air\ abs}$	air absorption		<1x10^{-7}
k_{ion}	ion recombination		0.0003
k_{pol}	polarization		0.0003
k_{nu}	radial non-uniformity		0.0002
k_{stem}	stem scatter		0.0004
$k_{scatter}$	room scatter		0.0010
Lateral distance between source position			0.0020
Lateral and longitudinal positioning			0.0005
$N_{K,\mathrm{VSL}}^{\mathrm{th}}$		0.0003	0.0057

From the Tables 4 and 5, the combined standard uncertainty u_c for the comparison result $R_{K,\mathrm{VSL}}^{\mathrm{th}}$ is 6.1×10^{-3}.

7.2 Well chamber

The uncertainties associated with the well type chamber calibration are listed in Tables 6.

Table 6. Uncertainties associated with the well chamber calibration at the VSL

Relative standard uncertainty	BIPM		VSL	
	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
^{192}Ir air kerma determination				
Reference air kerma K_R	---	---	0.0002	0.0050
$N_{K,\mathrm{BIPM}}^{\mathrm{th}}$ for ^{192}Ir	0.0003	0.0021	---	---
Corrected ionization current NE2571 $I_{\mathrm{th}} \times k_i$ (1)	0.0001	0.0028	---	---
Calibration of the well type chamber				
Ionization current well chamber I_{w}	0.0002	0.0002	0.0002	0.0002
Temperature, pressure correction	---	0.0001	---	0.0001
Short-term stability	0.0010	---	0.0010	---
N_K^{w}	0.0011	0.0035	0.0010	0.0050

(1) k_i are the VSL correction factors listed in Table 5, as I_{th} was measured using the VSL measuring system

8. Discussion

The VSL method to determine the calibration coefficient for its reference standard for ^{192}Ir (and thus the RAKR) is briefly explained in Section 3 of this report and is fully described by van Dijk *et al* (2004), where the result obtained using the method adopted is compared with the result obtained using a linear interpolation between 250 kV and ^{137}Cs beams. The VSL method gives for a NE 2571 chamber a calibration coefficient that is 0.3 % higher that the linear interpolation.

To assess the effect of the different methods adopted at the VSL and the BIPM, the transfer chamber used for this comparison was also calibrated at the BIPM in the ^{137}Cs reference beam and a linear interpolation made with the 250 kV calibration coefficient. Following the VSL procedure, this interpolated BIPM value for ^{192}Ir was increased by 0.3 % and compared with the VSL reference value. Using this modified BIPM standard, the comparison result would be 0.9978, rather than the actual comparison result R_K^{th} = 0.9873. This result (0.9978) is closer to what would be expected given the VSL/BIPM comparison results for ^{60}Co (0.9985) and 250 kV (1.0012). We might deduce, therefore, that most of the difference between the two standards is due to the different methods used.

9. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

For each NMI i having a comparison result $R_{K,i}^{\mathrm{th}}$ (denoted x_i in the KCDB) with combined standard uncertainty, u_i, the degree of equivalence with respect to the reference value is given by a pair of terms:

the relative difference $$D_i = \left(N_{K_R,\mathrm{NMI}i}^{\mathrm{th}} - N_{K_R,\mathrm{BIPM}}^{\mathrm{th}}\right) \Big/ N_{K_R,\mathrm{BIPM}}^{\mathrm{th}} = R_{K,i}^{\mathrm{th}} - 1 \quad (6)$$

and its expanded uncertainty $U_i = 2\ u_i$. (7)

The results for D_i and U_i, are expressed in mGy/Gy.

Consequently, the degree of equivalence of the VSL with the reference value is expressed as

	D_i	U_i
	/(mGy/Gy)	
VSL	-12.7	12.2

The degree of equivalence of NMI *i* with respect to each NMI *j* is the difference,

$$D_{ij} = D_i - D_j = x_i - x_j \qquad (8)$$

and its expanded uncertainty $U_{ij} = 2\, u_{ij}$, where,

$$u_{ij}^2 = u_{\mathrm{NMI}i,corr}^2 + u_{\mathrm{NMI}j,\mathrm{corr}}^2 - \sum_n f_n^2 \left(u_{\mathrm{NMI}i,n}^2 + u_{\mathrm{NMI}j,n}^2\right) \qquad (9)$$

10. Conclusion

The VSL standard for the reference air kerma rate for ^{192}Ir gamma radiation compared with the BIPM reference value gives a comparison result of 0.9873 with a combined standard uncertainty u_c of 0.0061. This is the first result in this new ongoing comparison, registered as BIPM.RI(I)-K8. The degrees of equivalence with later participants will be published in due course.

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