Degrees of equivalence for the key comparison BIPM.RI(I)-K3 between national primary standards for medium-energy x-rays

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Abstract Results are presented of comparisons of ten national primary standards for air kerma with the BIPM primary standard over the range of x-radiation qualities from 100 kV to 250 kV. For each radiation quality, the results are analysed in terms of the degree of equivalence, D_i, of each national standard i with respect to the key comparison reference value. The degrees of equivalence, D_{ij}, between each pairing of national standards i and j are also evaluated. These data form the basis of the matrices and graphs of results entered in the BIPM key comparison database for comparison BIPM.RI(I)-K3.

1. Introduction

The present report is based upon that presented to Section I of the CCRI in May 2003. In that report, the results of eleven BIPM comparisons for medium-energy x-rays were analysed and values proposed for the degrees of equivalence between the national primary standards that had taken part in these comparisons. The CCRI(I) showed support for the method of analysis and decided on a timescale for the validation of the data and their inclusion in the BIPM key comparison database.

Each data set was validated by the laboratory concerned with reference to the results published in the relevant comparison report. In addition, each laboratory confirmed that the standard presently being disseminated was correctly represented by the results presented to the CCRI(I), in particular that no changes had been made to correction factors, with the following two exceptions.

The NIST (USA) has recently changed several of their correction factors. Consequently, the NIST results presented to the CCRI(I) are no longer valid and have been updated for the present report. The changes to the NIST standard are documented in Appendix 1.

The x-ray facilities of the BNM-LNHB (France) are currently being relocated and for the present no calibrations in terms of medium-energy x-rays are available. This significant upheaval of the x-ray standards and equipment will require a new BIPM comparison to be made when the facilities are once again operational. For this reason, the BNM-LNHB results presented to the CCRI(I) have been removed from this report.

It should be noted that, following a decision of the CCRI(I) taken in 2001, the present report includes new values for the correction factors for photon scatter, k_{sc}, and electron loss, k_e, for the BIPM standard, as well as a new factor, k_{fl}, that corrects for the re-absorption of fluorescent photons in the free-air chamber. These changes are documented in [1].

2. BIPM key comparisons

Comparisons of national standards with the BIPM primary standard in medium-energy x rays are designated as key comparisons with reference BIPM.RI(I)-K3. Such comparisons have been conducted on an ongoing basis since 1975. As the standards are not generally transportable, these comparisons are carried out indirectly through the calibration at both the BIPM and at the national laboratory of one or more transfer ionization chambers at a series of reference radiation qualities.

The results of comparisons are expressed in the form of the mean ratio, x_i, of the calibration coefficients measured at laboratory i and at the BIPM, and the combined standard uncertainty u_i of this ratio, for each of the radiation qualities. The uncertainty u_i includes the uncertainties of the determinations of air-kerma rate by laboratory i and by the BIPM, taking into account correlations between the two standards, plus the uncertainty arising from the comparison procedure (the calibration of transfer instruments at each laboratory). The most notable correlations are in the values used for the physical constants ρ_{air} and W_{air} / e, for the humidity correction, k_h, and for the bremsstrahlung correction $(1 - g_{air})$, which therefore do not enter in the calculation of u_i.

Account must also be taken of correlations in the values used for k_e and k_{sc}. The new values for the BIPM standard are derived from Monte Carlo calculations, as are those for the NIST, the PTB (Germany) and the OMH (Hungary). As in the report presented to and approved by the CCRI(I), this correlation is treated by taking half the stated standard uncertainties for the BIPM and for the laboratory (NIST, PTB or OMH). Note also that correlations in k_e and k_{sc} exist when evaluating the degrees of equivalence between pairs of NMIs (see Section 4).

All other uncertainty components are assumed to be uncorrelated, namely those arising from the free-air chamber volume determinations V_{std}, the ionization current measurements for the standard I_{std} and for the transfer instruments I_{tr}, the positioning of the transfer instruments z_{tr}, and the correction factors for air attenuation k_a, ion recombination k_s, electric field distortion k_d, aperture edge transmission k_l, free-air chamber wall transmission k_p and the radiation quality factor k_Q.

The comparison results x_i for each laboratory are given in Table 1. For a given laboratory, the combined standard uncertainty of the comparison u_i applies to all of the radiation qualities. The uncertainty components giving rise to the u_i are presented in Table 2. These are taken from the appropriate reference cited in Table 1. For the GUM (Poland), the cited report [5] does not include an uncertainty budget and the values given in Table 2 are taken from the comparison file held at the BIPM. Two of the cited reports, [4] and [5], do not contain the detailed uncertainty budget for the BIPM standard. This is given in [12]. The final column of Table 2 is the combined relative standard uncertainty $u_{Lab\,i}$ for each standard, including the components ρ_{air}, W_{air} / e, k_h and $(1–g_{air})$ that are removed from the comparison uncertainty u_i due to correlations.

Table 1. Comparison results x_i at each of the radiation qualities. For each laboratory i, the standard uncertainty of the comparison u_i applies to all of the radiation qualities.

Lab i	Date of comparison	Report reference	x_i				u_i
			100 kV	135 kV	180 kV	250 kV	
ARPANSA	1988	[2]	1.0049	1.0056	1.0050	1.0051	0.0024
NIST	1991	[3][a]	0.9987	0.9963	0.9971	0.9951	0.0035
NMi	1991	[4]	1.0029	0.9993	0.9968	0.9938	0.0042
GUM	1994	[5]	0.9996	0.9986	0.9977	0.9945	0.0035
NPL	1997	[6]	0.9977	0.9960	0.9957	0.9919	0.0033
ENEA	1998	[7]	1.0018	1.0029	0.9969	0.9964	0.0037
OMH	1998	[8]	0.9999	0.9990	0.9998	0.9975	0.0026
NRC	1998	[9]	0.9957	0.9950	0.9928	0.9906	0.0027
VNIIM	1998	[10]	0.9990	0.9998	1.0014	0.9982	0.0025
PTB	1999	[11]	1.0002	0.9983	0.9983	0.9963	0.0026

a) See also Appendix 1.

3. Degrees of equivalence with respect to the reference value

The CCRI(I) took the decision at its meeting in 1999 to use the BIPM determination of air-kerma rate as the basis of the key comparison reference value, x_R. It follows that $x_R = 1$. For each laboratory i with a comparison result x_i determined with combined standard uncertainty u_i, the degree of equivalence D_i with respect to the reference value is therefore simply $x_i - 1$ with expanded uncertainty $U_i = 2\,u_i$. The results for the degrees of equivalence D_i and the expanded uncertainties U_i are presented in Figures 1 to 4 for the four radiation qualities.

Table 2. Components of the combined standard uncertainty $u_{\mathrm{Lab}\,i}$ for each laboratory *i*, expressed in parts in 10^3. These values apply to all radiation qualities.

Lab *i*	Uncertainty component V_{std}	I_{std}	I_{tr} [a]	z_{tr}	k_{a}	k_{sc}	k_{fl} [b]	k_{e}	k_{s}	k_{d} [c]	k_{l}	k_{p}	k_{Q} [d]	Combined uncertainty $u_{\mathrm{Lab}\,i}$ [e]
BIPM	**0.5**	**0.4**[f]	**0.5**[g]	**0.1**	**0.3**	**0.3**	**0.3**	**0.9**	**0.2**	**0.7**	**0.1**	**0.1**	**-**	**2.1**
ARPANSA	0.3	0.3	0.7	0.3	1.0	1.0	-	0.7	0.3	0.3	0.1	0.1	0.2	2.3
NIST	0.4	1.7	0.6	0.1	0.3	0.7	0.3	0.5	1.0	2.3	0.4	0.1	0.4	3.6
NMi	1.5	1.1	1.6	1.0	1.0	1.0	-	1.0	1.0	2.0	0.5	0.3	0.2	3.8
GUM	0.3	0.5	2.0	0.2	1.5	1.5	-	1.0[h]	0.3	0.5	0.1	0.1	0.2	2.9
NPL	0.1	1.0	1.0	1.5	1.4	1.2	-	0.6	0.3	0.3	0.6	0.3	0.2	2.8
ENEA	0.5	1.7	1.2	0.5	2.0	1.0	-	1.0	0.5	0.0	0.5	0.5	0.2	3.5
OMH	0.5	0.7	1.3	0.1	1.1	1.5	-	1.0	0.4	0.5	0.1	0.2	0.3	2.8
NRC	0.4	0.4	0.6	0.2	0.7	1.0	-	0.7	0.2	1.5	0.1	0.2	0.4	2.6
VNIIM	0.5	0.5	1.0	0.4	0.3	1.0	-	1.0	0.3	0.5	0.1	0.1	0.2	2.3
PTB	0.4	0.8	0.5	0.2	1.0	0.5		0.5	0.5	1.2	0.5	0.7[i]	0.8	2.7

a) This includes transfer chamber stability and differences in comparison results for different transfer chambers.
b) Only the BIPM and the NIST apply k_{fl} explicitly, although the effect of fluorescence is included in the PTB value for k_{sc}.
c) This includes the uncertainty of the polarity correction, where applicable.
d) This factor accounts for the effects of differences in the BIPM and laboratory radiation qualities and is included in the later comparison reports. For older comparisons, a value of 0.2 is assumed.
e) Includes 1.5 for W_{air}/e, 0.3 for k_{h}, 0.1 for ρ_{air} and 0.1 for $(1-g_{\mathrm{air}})$; these cancel in the comparison uncertainty u_i. Does not include the uncertainty components I_{tr} , z_{tr} and k_{Q}.
f) Only the statistical component of I_{std} for the BIPM standard, taken to be 0.2, is used in evaluating u_{ij}.
g) Only the statistical component of I_{tr} for the BIPM comparison, taken to be 0.3, is used in evaluating u_{ij}.
h) Increased from the unrealistic value 0.1 given in the relevant BIPM file, assuming a typographical error.
i) Includes 0.5 for shadow effect.

4. Degrees of equivalence between pairs of NMIs

For any pair of laboratories *i* and *j*, the degree of equivalence D_{ij} is the difference $D_i - D_j$, which is also the difference $x_i - x_j$ in the comparison results. The expanded uncertainty is $U_{ij} = 2\,u_{ij}$, where the combined standard uncertainty u_{ij} is principally the combined uncertainty of the air-kerma rate determinations for the laboratories *i* and *j*. In evaluating u_{ij} for each pairing, correlations between the standards are removed on the same basis as described above, notably regarding k_{e} and k_{sc}; if correction factors based on Monte Carlo calculations are used by both laboratories *i* and *j*, or by neither *i* nor *j*, then half the uncertainty value is taken for each. The uncertainty of the BIPM determination of air-kerma rate does not enter in u_{ij}, although the uncertainty arising from the comparison procedure is included. Thus the BIPM comparison with laboratory *i* contributes to u_{ij} the statistical component of the ionization current measurement for the BIPM standard (2×10^{-4} in relative value), a similar component for the transfer chamber measurements at the BIPM (3×10^{-4}) and the component z_{tr} for positioning relative to the BIPM standard (1×10^{-4}). The BIPM comparison with laboratory *j* contributes likewise to u_{ij}.

The results for the degrees of equivalence D_{ij} and expanded uncertainties U_{ij} are given in Tables 3 to 6 for the four radiation qualities.

5. Summary

The results of ten BIPM key comparisons for medium-energy x-ray standards are summarized in Table 1, the component uncertainties being listed in Table 2. These data give rise to the degrees of equivalence presented in Tables 3 to 6 and in Figures 1 to 4. The format of Tables 3 to 6 and Figures 1 to 4 and the wording of the introductory text to each table are those agreed by the CCRI(I) for the entry of these data in the BIPM key comparison database.

The degrees of equivalence arising from future BIPM comparisons will be added to the database as soon as each comparison report is approved. For repeat comparisons with a given laboratory, the new values will replace the old.

Table 3. Degrees of equivalence and introductory text for the 100 kV radiation quality

Key comparison BIPM.RI(I)-K3

MEASURAND : Air-kerma rate relative to the BIPM evaluation
Radiation quality 100 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇒

Lab i ⇓			ARPANSA		NIST		NMi		GUM		NPL		ENEA		OMH		NRC		VNIIM		PTB	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
	/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}		/ 10^{-3}	
ARPANSA	4.9	4.8	-	-	6.2	7.7	2.0	8.1	5.3	6.5	7.2	6.3	3.1	7.1	5.0	6.7	9.2	5.2	5.9	4.6	4.7	6.1
NIST	-1.3	6.9	-6.2	7.7	-	-	-4.2	10.3	-0.9	9.3	1.0	8.9	-3.1	9.6	-1.2	7.9	3.0	8.1	-0.3	7.8	-1.5	8.0
NMi	2.9	8.4	-2.0	8.1	4.2	10.3	-	-	3.3	9.4	5.2	9.3	1.1	9.9	3.0	9.6	7.2	8.5	3.9	8.2	2.7	9.2
GUM	-0.4	7.1	-5.3	6.5	0.9	9.3	-3.3	9.4	-	-	1.9	7.9	-2.2	8.5	-0.3	8.5	3.9	7.0	0.6	6.6	-0.6	8.1
NPL	-2.3	6.6	-7.2	6.3	-1.0	8.9	-5.2	9.3	-1.9	7.9	-	-	-4.1	8.4	-2.2	8.1	2.0	6.8	-1.3	6.4	-2.5	7.6
ENEA	1.8	7.4	-3.1	7.1	3.1	9.6	-1.1	9.9	2.2	8.5	4.1	8.4	-	-	1.9	8.8	6.1	7.6	2.8	7.2	1.6	8.4
OMH	-0.1	5.1	-5.0	6.7	1.2	7.9	-3.0	9.6	0.3	8.5	2.2	8.1	-1.9	8.8	-	-	4.2	7.2	0.9	6.9	-0.3	6.5
NRC	-4.3	5.4	-9.2	5.2	-3.0	8.1	-7.2	8.5	-3.9	7.0	-2.0	6.8	-6.1	7.6	-4.2	7.2	-	-	-3.3	5.3	-4.5	6.7
VNIIM	-1.0	5.0	-5.9	4.6	0.3	7.8	-3.9	8.2	-0.6	6.6	1.3	6.4	-2.8	7.2	-0.9	6.9	3.3	5.3	-	-	-1.2	6.4
PTB	0.2	5.2	-4.7	6.1	1.5	8.0	-2.7	9.2	0.6	8.1	2.5	7.6	-1.6	8.4	0.3	6.5	4.5	6.7	1.2	6.4	-	-

Table 4. Degrees of equivalence and introductory text for the 135 kV radiation quality

Key comparison BIPM.RI(I)-K3

MEASURAND : Air-kerma rate relative to the BIPM evaluation
Radiation quality 135 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⟹

Lab i ⇓

Lab i	D_i / 10^{-3}	U_i / 10^{-3}	ARPANSA D_{ij} / 10^{-3}	ARPANSA U_{ij} / 10^{-3}	NIST D_{ij} / 10^{-3}	NIST U_{ij} / 10^{-3}	NMi D_{ij} / 10^{-3}	NMi U_{ij} / 10^{-3}	GUM D_{ij} / 10^{-3}	GUM U_{ij} / 10^{-3}	NPL D_{ij} / 10^{-3}	NPL U_{ij} / 10^{-3}	ENEA D_{ij} / 10^{-3}	ENEA U_{ij} / 10^{-3}	OMH D_{ij} / 10^{-3}	OMH U_{ij} / 10^{-3}	NRC D_{ij} / 10^{-3}	NRC U_{ij} / 10^{-3}	VNIIM D_{ij} / 10^{-3}	VNIIM U_{ij} / 10^{-3}	PTB D_{ij} / 10^{-3}	PTB U_{ij} / 10^{-3}
ARPANSA	5.6	4.8	-	-	9.3	7.7	6.3	8.1	7.0	6.5	9.6	6.3	2.7	7.1	6.6	6.7	10.6	5.2	5.8	4.6	7.3	6.1
NIST	-3.7	6.9	-9.3	7.7	-	-	-3.0	10.3	-2.3	9.3	0.3	8.9	-6.6	9.6	-2.7	7.9	1.3	8.1	-3.5	7.8	-2.0	8.0
NMi	-0.7	8.4	-6.3	8.1	3.0	10.3	-	-	0.7	9.4	3.3	9.3	-3.6	9.9	0.3	9.6	4.3	8.5	-0.5	8.2	1.0	9.2
GUM	-1.4	7.1	-7.0	6.5	2.3	9.3	-0.7	9.4	-	-	2.6	7.9	-4.3	8.5	-0.4	8.5	3.6	7.0	-1.2	6.6	0.3	8.1
NPL	-4.0	6.6	-9.6	6.3	-0.3	8.9	-3.3	9.3	-2.6	7.9	-	-	-6.9	8.4	-3.0	8.1	1.0	6.8	-3.8	6.4	-2.3	7.6
ENEA	2.9	7.4	-2.7	7.1	6.6	9.6	3.6	9.9	4.3	8.5	6.9	8.4	-	-	3.9	8.8	7.9	7.6	3.1	7.2	4.6	8.4
OMH	-1.0	5.1	-6.6	6.7	2.7	7.9	-0.3	9.6	0.4	8.5	3.0	8.1	-3.9	8.8	-	-	4.0	7.2	-0.8	6.9	0.7	6.5
NRC	-5.0	5.4	-10.6	5.2	-1.3	8.1	-4.3	8.5	-3.6	7.0	-1.0	6.8	-7.9	7.6	-4.0	7.2	-	-	-4.8	5.3	-3.3	6.7
VNIIM	-0.2	5.0	-5.8	4.6	3.5	7.8	0.5	8.2	1.2	6.6	3.8	6.4	-3.1	7.2	0.8	6.9	4.8	5.3	-	-	1.5	6.4
PTB	-1.7	5.2	-7.3	6.1	2.0	8.0	-1.0	9.2	-0.3	8.1	2.3	7.6	-4.6	8.4	-0.7	6.5	3.3	6.7	-1.5	6.4	-	-

Table 5. Degrees of equivalence and introductory text for the 180 kV radiation quality

Key comparison BIPM.RI(I)-K3

MEASURAND : Air-kerma rate relative to the BIPM evaluation
Radiation quality 180 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇒

Lab i ⇓	D_i / 10^{-3}	U_i / 10^{-3}	ARPANSA D_{ij} / 10^{-3}	ARPANSA U_{ij} / 10^{-3}	NIST D_{ij} / 10^{-3}	NIST U_{ij} / 10^{-3}	NMi D_{ij} / 10^{-3}	NMi U_{ij} / 10^{-3}	GUM D_{ij} / 10^{-3}	GUM U_{ij} / 10^{-3}	NPL D_{ij} / 10^{-3}	NPL U_{ij} / 10^{-3}	ENEA D_{ij} / 10^{-3}	ENEA U_{ij} / 10^{-3}	OMH D_{ij} / 10^{-3}	OMH U_{ij} / 10^{-3}	NRC D_{ij} / 10^{-3}	NRC U_{ij} / 10^{-3}	VNIIM D_{ij} / 10^{-3}	VNIIM U_{ij} / 10^{-3}	PTB D_{ij} / 10^{-3}	PTB U_{ij} / 10^{-3}
ARPANSA	**5.0**	4.8	**-**	-	**7.9**	7.7	**8.2**	8.1	**7.3**	6.5	**9.3**	6.3	**8.1**	7.1	**5.2**	6.7	**12.2**	5.2	**3.6**	4.6	**6.7**	6.1
NIST	**-2.9**	6.9	**-7.9**	7.7	**-**	-	**0.3**	10.3	**-0.6**	9.3	**1.4**	8.9	**0.2**	9.6	**-2.7**	7.9	**4.3**	8.1	**-4.3**	7.8	**-1.2**	8.0
NMi	**-3.2**	8.4	**-8.2**	8.1	**-0.3**	10.3	**-**	-	**-0.9**	9.4	**1.1**	9.3	**-0.1**	9.9	**-3.0**	9.6	**4.0**	8.5	**-4.6**	8.2	**-1.5**	9.2
GUM	**-2.3**	7.1	**-7.3**	6.5	**0.6**	9.3	**0.9**	9.4	**-**	-	**2.0**	7.9	**0.8**	8.5	**-2.1**	8.5	**4.9**	7.0	**-3.7**	6.6	**-0.6**	8.1
NPL	**-4.3**	6.6	**-9.3**	6.3	**-1.4**	8.9	**-1.1**	9.3	**-2.0**	7.9	**-**	-	**-1.2**	8.4	**-4.1**	8.1	**2.9**	6.8	**-5.7**	6.4	**-2.6**	7.6
ENEA	**-3.1**	7.4	**-8.1**	7.1	**-0.2**	9.6	**0.1**	9.9	**-0.8**	8.5	**1.2**	8.4	**-**	-	**-2.9**	8.8	**4.1**	7.6	**-4.5**	7.2	**-1.4**	8.4
OMH	**-0.2**	5.1	**-5.2**	6.7	**2.7**	7.9	**3.0**	9.6	**2.1**	8.5	**4.1**	8.1	**2.9**	8.8	**-**	-	**7.0**	7.2	**-1.6**	6.9	**1.5**	6.5
NRC	**-7.2**	5.4	**-12.2**	5.2	**-4.3**	8.1	**-4.0**	8.5	**-4.9**	7.0	**-2.9**	6.8	**-4.1**	7.6	**-7.0**	7.2	**-**	-	**-8.6**	5.3	**-5.5**	6.7
VNIIM	**1.4**	5.0	**-3.6**	4.6	**4.3**	7.8	**4.6**	8.2	**3.7**	6.6	**5.7**	6.4	**4.5**	7.2	**1.6**	6.9	**8.6**	5.3	**-**	-	**3.1**	6.4
PTB	**-1.7**	5.2	**-6.7**	6.1	**1.2**	8.0	**1.5**	9.2	**0.6**	8.1	**2.6**	7.6	**1.4**	8.4	**-1.5**	6.5	**5.5**	6.7	**-3.1**	6.4	**-**	-

Table 6. Degrees of equivalence and introductory text for the 250 kV radiation quality

Key comparison BIPM.RI(I)-K3

MEASURAND : Air-kerma rate relative to the BIPM evaluation
Radiation quality 250 kV

Key comparison reference value: the measurand is a ratio with reference value $x_R = 1$

The degree of equivalence of each laboratory i with respect to x_R is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$), both dimensionless,
where $U_i = 2u_i$.

The degree of equivalence between two laboratories i and j is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), both dimensionless.
In evaluating $U_{ij} = 2\,u_{ij}$ for the table below, account is taken of correlations between u_i and u_j (see page 3 of the Summary Report).

Lab j ⇒

Lab i ⇓

Lab i	D_i	U_i	ARPANSA		NIST		NMi		GUM		NPL		ENEA		OMH		NRC		VNIIM		PTB	
	/ 10^{-3}		D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}
ARPANSA	5.1	4.8	-	-	10.0	7.7	11.3	8.1	10.6	6.5	13.2	6.3	8.7	7.1	7.6	6.7	14.5	5.2	6.9	4.6	8.8	6.1
NIST	-4.9	6.9	-10.0	7.7	-	-	1.3	10.3	0.6	9.3	3.2	8.9	-1.3	9.6	-2.4	7.9	4.5	8.1	-3.1	7.8	-1.2	8.0
NMi	-6.2	8.4	-11.3	8.1	-1.3	10.3	-	-	-0.7	9.4	1.9	9.3	-2.6	9.9	-3.7	9.6	3.2	8.5	-4.4	8.2	-2.5	9.2
GUM	-5.5	7.1	-10.6	6.5	-0.6	9.3	0.7	9.4	-	-	2.6	7.9	-1.9	8.5	-3.0	8.5	3.9	7.0	-3.7	6.6	-1.8	8.1
NPL	-8.1	6.6	-13.2	6.3	-3.2	8.9	-1.9	9.3	-2.6	7.9	-	-	-4.5	8.4	-5.6	8.1	1.3	6.8	-6.3	6.4	-4.4	7.6
ENEA	-3.6	7.4	-8.7	7.1	1.3	9.6	2.6	9.9	1.9	8.5	4.5	8.4	-	-	-1.1	8.8	5.8	7.6	-1.8	7.2	0.1	8.4
OMH	-2.5	5.1	-7.6	6.7	2.4	7.9	3.7	9.6	3.0	8.5	5.6	8.1	1.1	8.8	-	-	6.9	7.2	-0.7	6.9	1.2	6.5
NRC	-9.4	5.4	-14.5	5.2	-4.5	8.1	-3.2	8.5	-3.9	7.0	-1.3	6.8	-5.8	7.6	-6.9	7.2	-	-	-7.6	5.3	-5.7	6.7
VNIIM	-1.8	5.0	-6.9	4.6	3.1	7.8	4.4	8.2	3.7	6.6	6.3	6.4	1.8	7.2	0.7	6.9	7.6	5.3	-	-	1.9	6.4
PTB	-3.7	5.2	-8.8	6.1	1.2	8.0	2.5	9.2	1.8	8.1	4.4	7.6	-0.1	8.4	-1.2	6.5	5.7	6.7	-1.9	6.4	-	-

Appendix 1 – Note on change to published results of BIPM comparison with the NIST

The BIPM comparison with the NIST in medium-energy x-rays was carried out in 1991 and the results are published in report [3]. However, with effect from 1 January 2003, the NIST has revised its air-kerma standards. The changes to the standards are summarized in this appendix and the degrees of equivalence given in this report reflect the standards as they are currently disseminated.

In the medium-energy x-ray range (100 kV to 300 kV), new values for the correction factors for electron loss, k_e, and for photon scatter, $k_{sc,}$ have been introduced, as well as a new fluorescence correction factor, k_{fl}. The new values at the CCRI reference qualities are based on the calculations of Burns [13] using EGSnrc [14] and are given in Table A1 below. It should be noted that for the 1991 comparison the NIST did not use the CCRI reference qualities, but rather a series of NIST qualities spanning the CCRI qualities in terms of half-value layer. Consequently, the 1991 values for k_e and k_{sc} given in the table are interpolated from the actual values used at that time for the NIST qualities.

In addition, the opportunity was taken to introduce improved values for the air-attenuation correction factor, k_a, based on a combination of measurement and calculation. These are also given in the table, normalized to the NIST reference conditions of 22 °C and 101.325 kPa.

The revised comparison results, taking into account the changes to the NIST and BIPM standards at each of the CCRI reference qualities, are given in the final row of the table. The comparison uncertainty is unchanged at 0.0035, despite the lower uncertainty of many of the new values. It is the revised comparison results that are given in Table 2 and that have been used to evaluate the degrees of equivalence given in this report.

Table A1. Changes to results of BIPM comparison with the NIST as published in [3].

Radiation quality	100 kV	135 kV	180 kV	250 kV
Published 1991 comparison result NIST / BIPM	0.9952 (0.0035)	0.9953 (0.0035)	0.9942 (0.0035)	0.9930 (0.0035)
k_e 2003	1.0000 (0.0005)	1.0006 (0.0005)	1.0027 (0.0005)	1.0055 (0.0005)
k_e 1991 (interpolated)	1.0000 (0.0010)	1.0013 (0.0010)	1.0026 (0.0010)	1.0044 (0.0010)
k_{sc} 2003	0.9942 (0.0007)	0.9952 (0.0007)	0.9958 (0.0007)	0.9969 (0.0007)
k_{sc} 1991 (interpolated)	0.9939 (0.0007)	0.9953 (0.0007)	0.9959 (0.0007)	0.9965 (0.0007)
k_{fl} 2003	0.9981 (0.0003)	0.9991 (0.0003)	0.9995 (0.0003)	0.9999 (0.0003)
k_{fl} 1991	-	-	-	-
k_a 2003 [a]	1.0152 (0.0004)	1.0083 (0.0002)	1.0079 (0.0002)	1.0055 (0.0002)
k_a 1991 [a] (interpolated)	1.0111 (0.0007)	1.0074 (0.0007)	1.0063 (0.0007)	1.0049 (0.0007)
1991 result corrected for NIST changes	0.9976 (0.0035)	0.9945 (0.0035)	0.9953 (0.0035)	0.9950 (0.0035)
1991 result corrected for NIST and BIPM changes	**0.9987 (0.0035)**	**0.9963 (0.0035)**	**0.9971 (0.0035)**	**0.9951 (0.0035)**

a) For an air density of 1.1964 g cm^{-3}, corresponding to the NIST reference conditions of 22 °C and 101.325 kPa.

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Figure 1. Graph of degrees of equivalence with the KCRV for the 100 kV radiation quality (as it appears in Appendix B of the MRA)

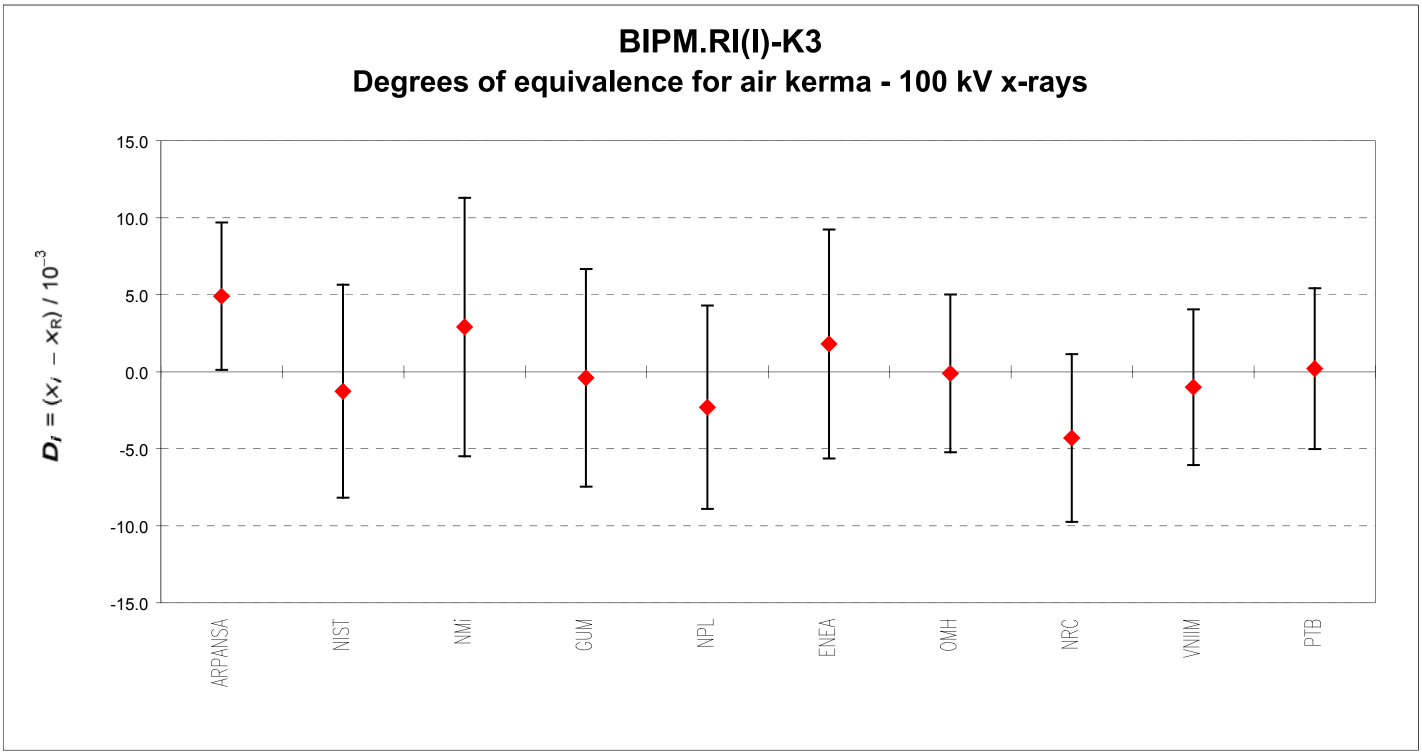

Figure 2. Graph of degrees of equivalence with the KCRV for the 135 kV radiation quality (as it appears in Appendix B of the MRA)

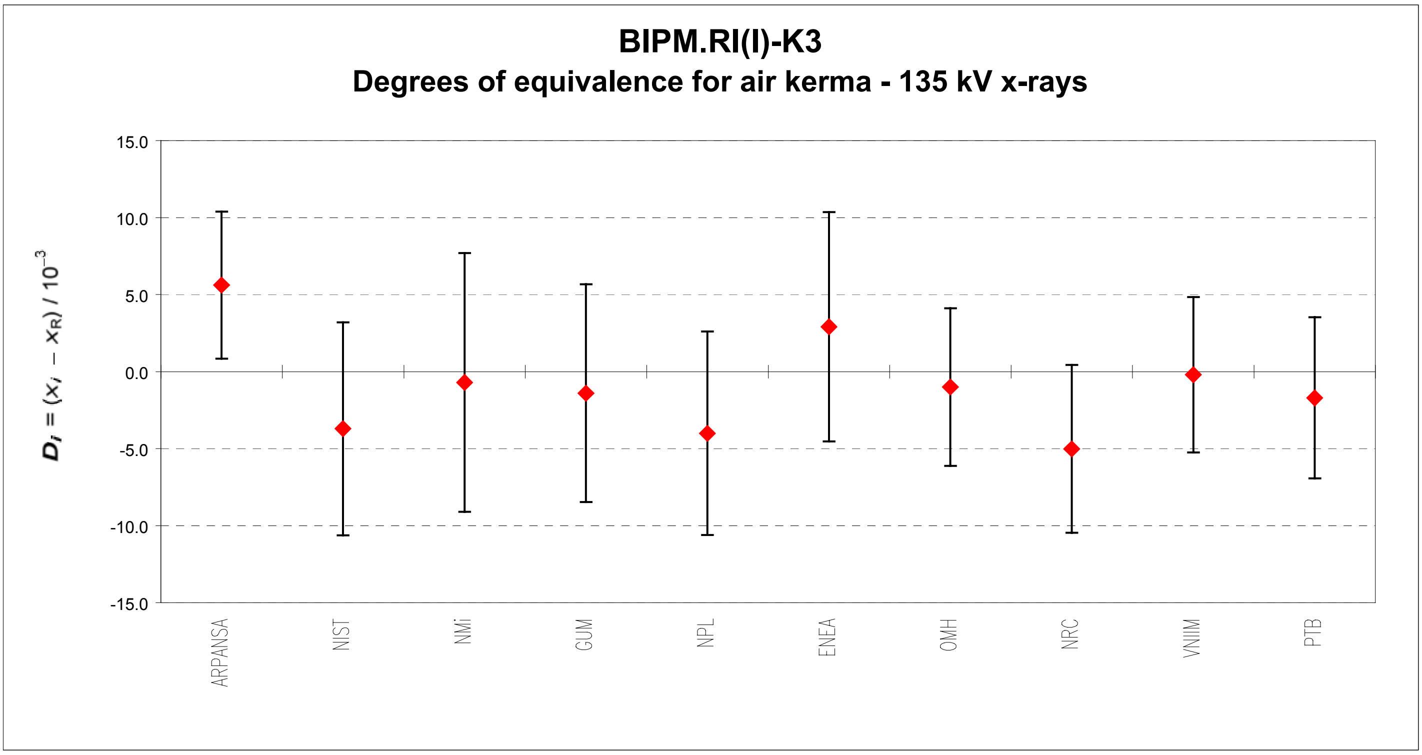

Figure 3. Graph of degrees of equivalence with the KCRV for the 180 kV radiation quality (as it appears in Appendix B of the MRA)

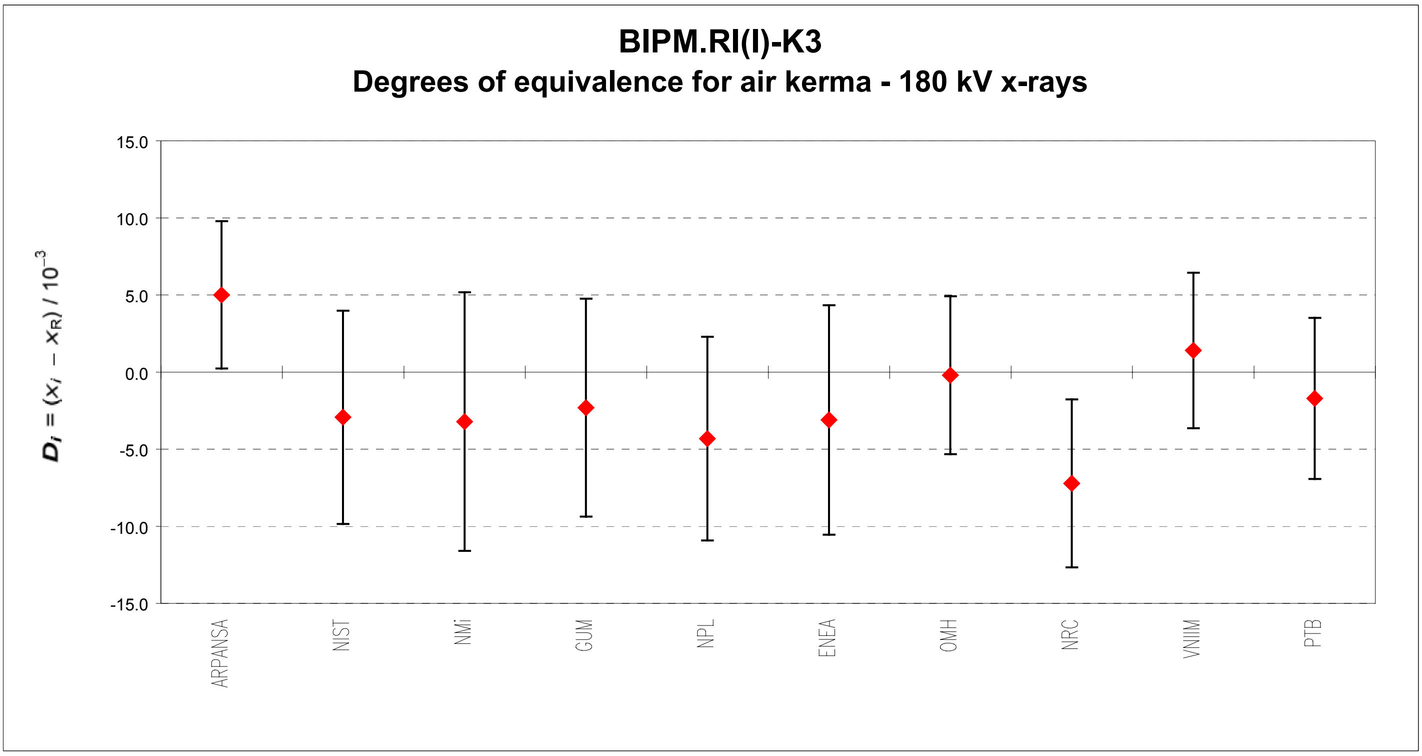

Figure 4. Graph of degrees of equivalence with the KCRV for the 250 kV radiation quality (as it appears in Appendix B of the MRA)