Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NPL, UK, and the BIPM in low-energy x-rays

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Abstract A key comparison has been made between the air-kerma standards of the NPL, UK and the BIPM in the low-energy x-ray range. The results indicate a progressive drift of the NPL standard, now lower than the BIPM standard by around 1 part in 10^2. The expanded uncertainty (k = 2) of the comparison is 4.2 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.

1. Introduction

A direct comparison has been made between the air-kerma standards of the National Physical Laboratory (NPL), UK, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. The comparison took place at the BIPM in November 2017 using the reference conditions recommended by the CCRI (CCEMRI 1972). An indirect comparison was also made using two parallel-plate ionization chambers as transfer instruments. Final results were supplied by the NPL in May 2018 and final uncertainties in November 2018.

2. Determination of the air-kerma rate

For a free-air ionization chamber standard with measuring volume V, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1-g_{\mathrm{air}}} \prod_i k_i \qquad (1)$$

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost through radiative processes in air, and $\Pi\, k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table[1].

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard L-01 is described in Boutillon *et al* (1969) and the changes made to certain correction factors given in Burns (2004), Burns *et al* (2009) and the references

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[1] For an air temperature T ~ 293 K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction k_{h} = 0.9980. At the BIPM, the factor 1.0002 is included to account for the compressibility of dry air between T ~ 293 K and T_0 = 273.15 K.

therein. The NPL standard is described in Marsh and Williams (1982) and details are given in the reports of previous comparisons with the BIPM in 2007 (Burns *et al* 2017) and in 1997 (Boutillon *et al* 2002). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i[a]
ρ_{air}[b] (BIPM)	1.2930 kg m^{-3}	0.0001
ρ_{air}[c] (NPL)	1.2045 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0015

[a] u_i is the relative standard uncertainty.
[b] Density of dry air at T_0 = 273.15 K and P_0 = 101 325 Pa adopted at the BIPM.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101 325 Pa adopted at the NPL.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	NPL B2
Aperture diameter / mm	9.941	8.0075
Air path length / mm	100.0	88.5
Collecting length / mm	15.466	19.827
Electrode separation / mm	70	62.5
Collector width / mm	71	75
Measuring volume / mm^3	1200.4	998.48
Polarizing voltage / V	1500	1500

4. Comparison procedure

4.1 The BIPM irradiation facility and reference beam qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. A beryllium filter of thickness 2.16 mm is added (for all radiation qualities) so that the half-value layer (HVL) of the present 10 kV radiation quality matches that of the original BIPM x-ray tube. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of the BIPM. Rather than use a transmission monitor, which might introduce its own variability, the anode current is measured and the ionization chamber current normalized for any deviation from the reference anode current. The resulting variation in the BIPM free-air chamber current over the duration of a comparison is normally not more than 2 parts in 10^4 and the standard deviation of repeat air-kerma determinations over the past few years is below 3 parts in 10^4. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI (CCEMRI 1972) and are given in Table 3 in ascending HVL from left to right.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range from 40 % to 50 %.

Table 3. Characteristics of the BIPM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.2082	0.3723	1.0082	3.989
Al HVL / mm	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}$[a] / $cm^2\ g^{-1}$	14.84	3.661	2.604	0.753	0.378
$\dot{K}_{BIPM}$ / mGy s^{-1}	1.00	1.00	1.00	1.00	1.00

[a] Measured at the BIPM for an equivalent air-path length of 100 mm using a variable-pressure tube.

4.2 Correction factors

The correction factors applied to the ionization current measured at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in Table 5 for the NPL standard.

Table 4. Correction factors for the BIPM standard L-01

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a[a]	1.1957	1.0451	1.0319	1.0091	1.0046	0.0002	0.0001
Scattered radiation k_{sc}	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence k_{fl}	0.9952	0.9971	0.9969	0.9980	0.9985	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Ion recombination k_s	1.0006	1.0007	1.0007	1.0007	1.0007	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	1.0005	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia}	0.9999	0.9995	0.9996	0.9989	0.9984	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

The largest correction at low energies is that due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The correction factor k_a is evaluated (for both standards) using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 3. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane. At 10 kV, an additional correction factor of 1.0005 has been applied because the mean attenuation per unit length for the NPL standard with attenuation length 88.5 mm is not exactly the same as that for the BIPM standard (with attenuation length 100 mm).

Measurements using the BIPM standard were made using positive polarity only and a correction factor applied to correct for the known polarity effect in the standard (see Table 4). Similarly, measurements using the NPL standard were made using negative polarity only and a polarity correction applied (see Table 5). During the comparison, a measurement was made of the polarity correction for the NPL standard; the result was 1.0006(2), consistent with the NPL value of 1.0004(4).

All measured ionization currents are corrected for ion recombination. The measured values for the ion recombination correction k_s for the BIPM standard are given in Table 4. For the NPL standard, the fixed value of 1.0006(5) determined at the NPL was applied (see Table 5), consistent with the values generally applied for free-air chambers at the BIPM air-kerma rates.

Table 5. Correction factors for the NPL standard B2 used at the BIPM

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.1708	1.0398	1.0281	1.0081	1.0040	0.0002[b]	0.0001[b]
Scattered radiation k_{sc}	0.9949	0.9968	0.9971	0.9979	0.9982	-	0.0010
Fluorescence k_{fl} [c]	0.9951	0.9963	0.9966	0.9978	0.9983	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	-
Ion recombination k_s	1.0006	1.0006	1.0006	1.0006	1.0006	-	0.0005
Polarity k_{pol}	1.0004	1.0004	1.0004	1.0004	1.0004	-	0.0004
Field distortion k_d	1.0002	1.0002	1.0002	1.0002	1.0002	-	0.0002
Aperture transmission k_l	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000		
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0005
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	-

[a] Values for 293.15 K and 101.325 kPa, determined using the BIPM values for the air-attenuation coefficient; each measurement is corrected using the air density measured at the time.
[b] For measurements at the NPL, the uncertainty is u_{iB} = 0.0015 (no type A uncertainty).
[c] These values are based on the calculations of Burns (2001) and additional calculations made at the NPL.

4.3 Positioning and measurement procedure for NPL standard

The NPL standard was positioned close to the BIPM standard and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Lateral alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm. No correction is applied for the radial non-uniformity of the beam as the aperture diameter is similar; the corresponding uncertainty is less than 1 part in 10^4. The reference plane for each chamber was positioned at 500 mm from the radiation source for all qualities. This distance was measured to 0.03 mm and was reproducible to 0.01 mm. The beam diameter in the reference plane is 98 mm for all qualities.

The NPL standard does not incorporate a temperature sensor, although a hole exists for insertion of an external probe. A platinum resistance thermometer of the BIPM was used and a corresponding uncertainty of 3 parts in 10^4 is included in the type B uncertainty for the NPL ionization current in Table 7.

The ionization current for the NPL standard was measured using the BIPM current measurement system. The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For both standards the relative leakage current was below 1 part in 10^4.

For the NPL chamber, the standard uncertainty of the mean of a series of seven measurements, each with integration time 60 s, was less than 1 part in 10^4. Two series were made for each comparison. For the BIPM standard, a similar series was made for each comparison with a standard uncertainty below 1 part in 10^4. The 10 kV and 30 kV qualities were repeated at a later date, the chambers remaining fixed in position. The observed reproducibility of around 3 parts in 10^4 is included as the type A uncertainty for the NPL ionization current given in Table 7.

5. Supporting measurements using a transfer chamber

Two thin-window parallel-plate transfer ionization chambers belonging to the NPL, type PTW 23344, serial numbers 0791 and 0792, were calibrated in both laboratories to obtain an indirect comparison result. The chambers were used in each laboratory with a polarizing voltage of –200 V applied to the chamber window, with this circular entrance window centred on the beam axis and with the front plane of the chamber casing positioned in the reference plane.

While the BIPM calibrated the chambers at the reference qualities recommended by the CCRI (CCEMRI 1972), the NPL used a set of 11 qualities from 8.5 kV (Al HVL = 0.024 mm) to 50 kV (Al HVL = 1.00 mm, as for the 50 kVb quality). For comparison with the BIPM results, a 4^{th} order polynomial fit to the NPL data in terms of log(Al HVL) was made and fitted calibration coefficients obtained at the Al HVLs corresponding to the BIPM qualities. The r.m.s. deviation of the measured calibration coefficients from the polynomial fit was around 1.2 parts in 10^3 for each of the two transfer chambers.

Further, while the NPL reference distance of 500 mm matches that of the BIPM, the field diameter was only 53 mm compared to the BIPM value of 98 mm. The NPL field diameter covers the collecting electrode of diameter 13 mm, but it does not cover the entire casing of the PTW 23344 chamber type, which results in a lower current reading and thus a calibration coefficient that is too high (as the free-air chamber response does not change appreciably with field diameter). The approximate magnitude of this effect is known from previous (unpublished) measurements with different field sizes at the BIPM and was verified by new measurements using the NPL transfer chambers at different field sizes during the present comparison. As a result, the calibration coefficients derived by interpolation as described above are modified by the following factors; 0.9979, 0.9974, 0.9975 and 0.9942 for the 10 kV, 30 kV, 25 kV and

50 kVb qualities, respectively. The uncertainty of these correction factors is estimated to be 1 part in 10^3. No corrections are applied for radial non-uniformity, based on the assumption that the effect is relatively small for the PTW 23344 chamber type and the beam profiles should be similar at the two laboratories.

The air-kerma rates at the NPL are in the range from 1.3 mGy s^{-1} to 7.2 mGy s^{-1}, significantly higher than the BIPM value of 1 mGy s^{-1} (for all qualities). From previous measurements using the PTW 23344 chamber type, volume recombination is estimated to be higher at the NPL by up to 1.5 parts in 10^3. An approximate volume recombination correction was applied to the $N_{K,\mathrm{NPL}}$ values before the fit as a function of AL HVL noted above. The uncertainty of this correction is estimated to be 5 parts in 10^4. No correction is made for initial recombination, which will cancel at the two laboratories.

The results for $N_{K,\mathrm{BIPM}}$ and the interpolated results for $N_{K,\mathrm{NPL}}$, corrected for field size and for ion recombination as described above, are shown in Table 6 and are discussed later. The r.m.s. change in the pre- and post-BIPM values for $N_{K,\mathrm{NPL}}$ *before* interpolation is around 1.5 parts in 10^3 for each of the transfer chambers. Taking into account the stated calibration uncertainties of 6 parts in 10^3 for the NPL and 2 parts in 10^3 for the BIPM, the uncertainties for field size, ion recombination and polynomial fitting noted above, plus a component of 1.5 parts in 10^3 for the difference in the results for the two transfer chambers, the combined standard uncertainty for the indirect comparison (removing correlation in the standards) is 6.3 parts in 10^3.

Table 6. Results for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
PTW 23344-0791					
$N_{K,\mathrm{NPL}}$ (pre-BIPM) / Gy µC^{-1}	75.57	73.32	72.68	69.89	- [a]
$N_{K,\mathrm{NPL}}$ (post-BIPM) / Gy µC^{-1}	75.43	73.27	72.63	69.89	-
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	76.34	73.85	73.31	70.22	
$N_{K,\mathrm{NPL,mean}} / N_{K,\mathrm{BIPM}}$	0.9890	0.9925	0.9911	0.9953	-
PTW 23344-0792					
$N_{K,\mathrm{NPL}}$ (pre-BIPM) / Gy µC^{-1}	74.06	71.75	71.02	67.80	-
$N_{K,\mathrm{NPL}}$ (post-BIPM) / Gy µC^{-1}	74.25	71.80	71.06	67.96	-
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	75.13	72.39	71.78	68.25	
$N_{K,\mathrm{NPL,mean}} / N_{K,\mathrm{BIPM}}$	0.9870	0.9915	0.9897	0.9946	-

[a] The highest calibration quality at the NPL has Al HVL = 1.0 mm, making extrapolation to the 50 kVa quality (Al HVL = 2.3 mm) unreliable.

6. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 7. The uncertainties associated with the measurement of the ionization current and with chamber positioning are those that apply to measurements at the BIPM.

The combined standard uncertainty u_c of the ratio $\dot{K}_{NPL}/\dot{K}_{BIPM}$ takes into account correlation in the type B uncertainties associated with the humidity correction and the physical constants. Correlation in the values for k_{fl} is taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory, consistent with the analysis presented in Burns (2003). The NPL values for k_{sc} are derived from measurement (later verified by Monte Carlo calculation) and so are assumed to be uncorrelated with the BIPM values.

Table 7. Uncertainties associated with the comparison results

Standard	BIPM		NPL	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0003[a]	0.0004[a]
Positioning	0.0001	0.0001	0.0001[b]	0.0001[b]
Volume	0.0003	0.0005	-	0.0010
Correction factors (excl. k_h)	0.0003	0.0010	0.0002	0.0013
Humidity k_h	-	0.0003	-	0.0005
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{Standard}$	0.0005	0.0019	0.0004	0.0023
	0.0020		0.0023 [c]	
$\dot{K}_{NPL}/\dot{K}_{BIPM}$	u_c = 0.0021[d]			

[a] For measurements at the NPL, the uncertainty components for ionization current are u_{iA} = 0.0005 and u_{iB} = 0.0011.
[b] At the NPL, the uncertainty for positioning is also u_{iA} = 0.0001 and u_{iB} = 0.0001.
[c] The uncertainty of the air-kerma determination at the NPL is 0.0030, rather than the value 0.0023 tabulated here. It includes the uncertainty u_{iB} = 0.0015 for air attenuation noted in footnote b of Table 5. It is the NPL value 0.0030 that appears as $u_{Lab\,i}$ in the KCDB.
[d] Takes account of correlation in the type B uncertainties as described in Section 6.

7. Results and discussion

The comparison results are given in Table 8. The results of the direct comparison of the free-air chambers at the BIPM show the NPL standard to be lower than the BIPM standard by around 1 part in 10^2, with only a small dependence on radiation quality. The expanded uncertainty (k = 2) of the comparison is 4.2 parts in 10^3. These results are largely confirmed, except for the 50 kVb quality, by those of the indirect comparison using the two transfer chambers. For the 50 kVb quality the indirect result is less clear, given the stated uncertainty of 6.3 parts in 10^3. It is notable that the field-size correction is particularly large for this quality (6 parts in 10^3) and it might be that this effect has been underestimated (for example if the small-field measurements at the BIPM did not well simulate the actual field at the NPL).

Also given in Table 8 are the results of the previous comparison of the NPL and BIPM standards in 2007 (Burns *et al* 2017) and in 1997 (Boutillon *et al* 2002), revised for the published changes made to the BIPM standard in 2003 (Burns 2004) and in 2009 (Burns *et al* 2009). The result from 1997 is also corrected here for the introduction of k_{fl} at the NPL. Because of the difficulties experienced in 2007, as described in Burns *et al* (2017), it is the results for the 1997 comparison (not corrected for k_{fl}) that currently appear in the BIPM key comparison database (KCDB 2018).

Table 8. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\dot{K}_{NPL}/\dot{K}_{BIPM}$ **(direct)**	**0.9878**	**0.9886**	**0.9889**	**0.9899**	**0.9904**
$N_{K,NPL}/N_{K,BIPM}$ (indirect)	0.9880	0.9920	0.9904	0.9950	-
Results of 2007 comparison	*0.9910*	*0.9922*	*0.9930*	*0.9936*	*0.9938*
Results of 1997comparison [a]	*0.9962*	*0.9960*	*0.9980*	-	*0.9976*

[a] The results from 1997 are modified by the correction factor k_{fl} for the NPL standard (as given in Table 5) to allow the results from 1997, 2007 and 2017 to be assessed on the basis of a consistent set of correction factors for both standards.

It appears from these results that there has been as systematic decrease in the NPL standard over the past 20 years, as shown graphically in Figure 1. This was not evident at the time of the 2007 comparison because of the difficulties experienced in the analysis, as noted in Burns *et al* (2017), and perhaps also because the effect of field size on the transfer chambers was not appreciated at that time.

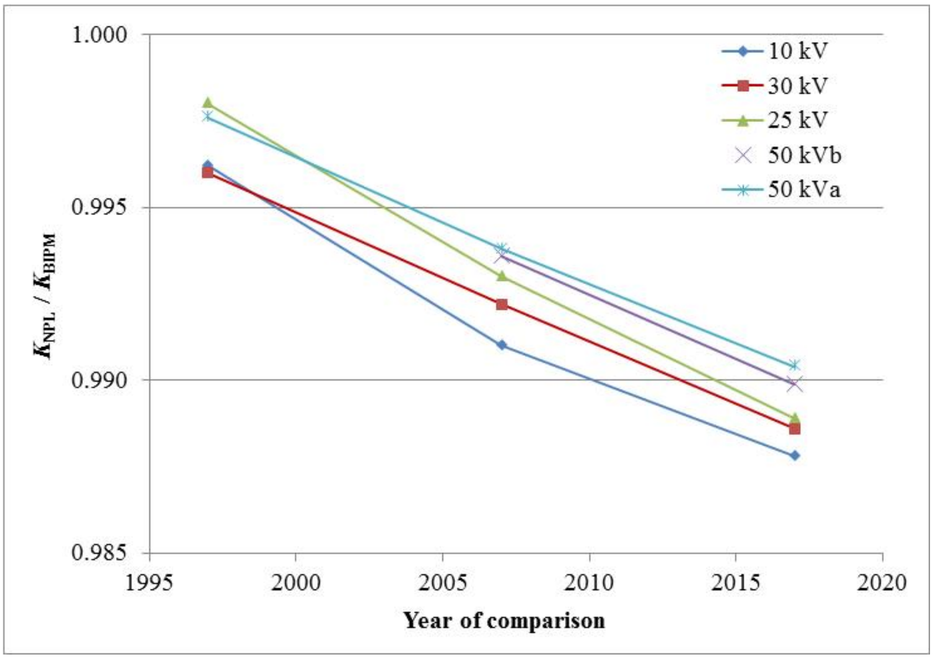

Figure 1. Summary of the results for direct comparisons with the NPL in 1997, 2007 and 2017.

Following the present comparison and the indication of a problem, an NPL investigation of their free-air chamber serial number B, as used for all three comparisons, found that the collector-guard insulation resistance has reduced from the expected value of 10^{15} ohms to around 10^{9} ohms. This is thought to be due to the PMMA rods supporting the electrodes, and in particular ageing of the glue holding them in place. Drift of the standard has been confirmed by comparison against the serial number A chamber, which has sapphire rods and shows an insulation resistance of 10^{15} ohms. Quality assurance measurements on reference chambers at the

NPL have been operated on a 3-year cycle and it appears that the drift over each 3-year cycle, estimated in retrospect to be around 1 part in 10^3, was too small to be observed.

8. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described in Burns (2003). Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows that for each laboratory *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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$. The results for D_i and U_i, expressed in mGy/Gy and including those of the present comparison, are shown in Table 9 and in Figure 2, which include the linked results of the corresponding regional key comparisons APMP.RI(I)-K2 (Tanaka *et al* 2014). Note that these data, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database (KCDB 2018).

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. The results in red are for comparison BIPM.RI(I)-K2 and those in blue for APMP.RI(I)-K2.

	10 kV		30 kV		25 kV		50 kVb		50 kVa	
Lab *i*	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
METAS	2.2	3.4	1.0	3.4	1.3	3.4	0.2	3.4	0.1	3.4
ARPANSA	-1.5	14.0	-2.5	7.5	-2.6	7.5	-1.0	7.5	0.2	7.5
LNE-LNHB	-0.8	3.2	0.2	3.2	0.7	3.2	0.1	3.2	0.7	3.2
NIST			-3.1	8.4	0.0	8.4	1.5	8.4	-2.6	8.4
GUM	-5.1	6.0	-3.7	6.0	-0.1	6.0	-2.8	6.0	0.5	6.0
ENEA	-2.2	3.8	-3.2	3.8	-2.4	3.8	-2.0	3.8	-2.1	3.8
MKEH	-2.7	4.1	-2.5	4.1	-1.2	4.1	-2.6	4.1	-3.4	4.1
VNIIM	-3.2	4.7	-2.1	4.7	-2.2	4.7	-1.3	4.7	-0.7	4.7
VSL	7.8	6.6	6.9	6.6	7.5	6.6	11.5	6.6	13.0	6.6
PTB	0.3	4.3	-1.8	4.3	-2.1	4.3	-1.1	4.3	-0.6	4.3
BEV	-2.0	13.6	-0.8	9.5	-1.3	9.5	-0.8	9.5	-1.6	9.5
NMIJ	3.2	6.0	1.0	6.0	-2.3	6.0	-0.9	6.0	-2.6	6.0
CMI	5.5	7.0	3.9	7.0	4.5	7.0	4.2	7.0	4.4	7.0
NPL	-12.2	4.2	-11.4	4.2	-11.1	4.2	-10.1	4.2	-9.6	4.2
NRC	0.3	6.7	-2.4	6.7	-1.4	6.7	0.6	6.7	0.4	6.7
Nuc. Malaysia	42.0	14.0	25.7	14.0	25.9	14.0	34.9	14.0	37.0	14.0
BARC			13.5	100.0	42.8	100.0	30.9	100.0	19.0	100.0
INER	2.8	13.4	8.6	13.4	8.3	13.4	6.4	13.4	10.2	13.4
IAEA	4.5	10.8	2.8	10.8	4.3	10.8	4.9	10.8	4.8	10.8
NIM	14.7	12.4	11.7	12.4	10.7	12.4	7.8	12.4	6.1	12.4

9. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the NPL and the BIPM to differ by around 1 part in 10^2. The expanded uncertainty (k = 2) of the comparison is 4.2 parts in 10^3. Subsequent investigation has shown that the response of the NPL standard has progressively decreased over the past 20 years, thought to result from an observed decrease in the collector-guard insulation resistance.

The NPL plans to replace the insulating rods and to repeat the direct comparison at the BIPM at the soonest opportunity. The present report has been prepared in the interest of transparency and serves to demonstrate the importance of international comparisons.

Tables and graphs of degrees of equivalence, including those for the NPL, are presented for entry in the BIPM key comparison database.

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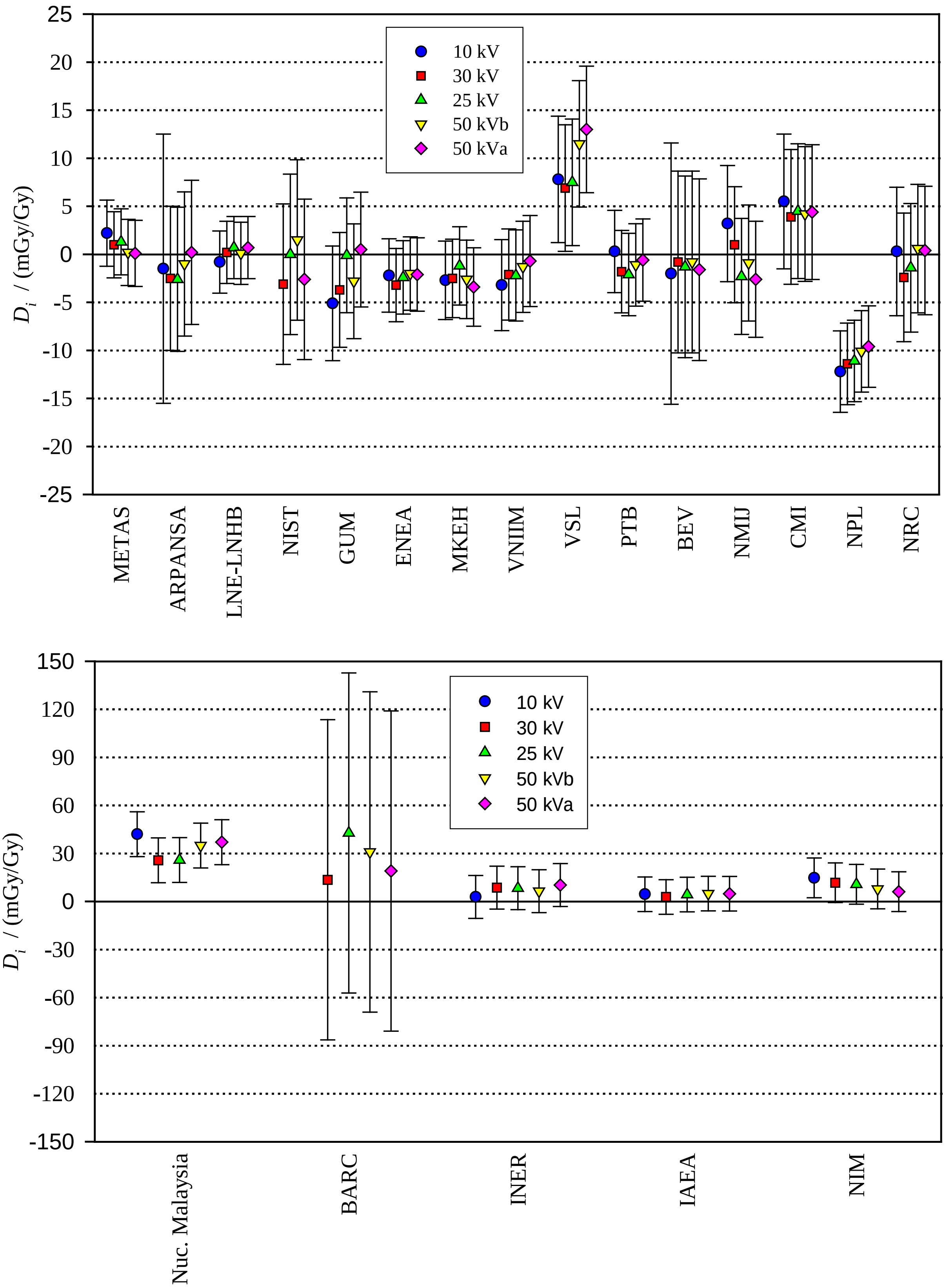

Figure 2. Degrees of equivalence for each NMI i with respect to the key comparison reference value. The top graph shows the results for the comparison BIPM.RI(I)-K2 and the bottom graph those for the regional comparison APMP.RI(I)-K2 (note the expanded ordinate axis for the latter).