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Pavillon de Breteuil, F-92312 Sèvres Cedex

Comparison of the air-kerma standards of the VNIIM and the BIPM in the low-energy x-ray range

D.T. Burns and N.D. Villevalde*, A.V.Oborin* and E.N.Yurjatin*

Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
* D.I. Mendeleyev Institute for Metrology, Moskowsky Prospekt 19
198005 St. Petersburg, Russian Federation

Abstract An indirect comparison has been made between the air-kerma standards of the VNIIM and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of one to two standard uncertainties. The trend in the results at different radiation qualities is explained in terms of the photon-scatter correction applied to the VNIIM standard.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the D.I. Mendeleyev Institute for Metrology (VNIIM), Russian Federation, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. A parallel-plate free-air chamber was used as the transfer instrument. The measurements at the BIPM took place in December 1998 and those at the VNIIM in October 1998 and March 1999, using the reference conditions recommended by the CCRI [1].

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

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

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 mean fraction of the initial electron energy lost by bremsstrahlung production 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 and transfer instrument

The BIPM and VNIIM free-air chamber standards and the VNIIM IK10-60 transfer chamber (serial number 2) are all of the conventional parallel-plate design. The measuring volume V is defined by the diameter of the defining aperture and the length of the collecting region. The BIPM air-kerma standard is described in [2] and [3]. Details of the VNIIM standard, which has

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

not previously been compared with the BIPM standard, are given in [4]. The main dimensions, the measuring volume and the polarizing voltage for each free-air chamber are shown in Table 2.

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

Constant	Value	u_i †
ρ_{air} ‡	1.293 0 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

† u_i is the relative standard uncertainty.

‡ Density of dry air at T_0 = 273.15 K and P_0 = 101 325 Pa.

Table 2. Main characteristics of the free-air chambers

Free-air chamber	BIPM standard	VNIIM standard	IK10-60/2 transfer
Aperture diameter / mm	9.941	9.991	10
Air path length / mm	100.0	78.2	78
Collecting length / mm	15.466	30.99	29
Electrode separation / mm	70	42	42
Collector width / mm	71	60	60
Measuring volume / mm^3	1 200.4	2 429.6	2 280
Polarizing voltage / V	1 500	3 000	–3 000

The air-kerma calibration coefficient N_K for a transfer instrument is given by the relation

$$N_K = \frac{\dot{K}}{I_{\text{tr}}} \tag{2}$$

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) and I_{tr} is the ionization current measured by the transfer instrument and the associated current-measuring system. The current I_{tr} is corrected to the standard conditions of air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101 325 Pa and h = 50 %).

To derive a comparison result from the calibration coefficients $N_{K,\text{BIPM}}$ and $N_{K,\text{NMI}}$ measured, respectively, at the BIPM and at a national measurement institute (NMI), differences in the radiation qualities must be taken into account. Normally, each quality used for the comparison has the same generating potential at each institute, but the half-value layers (HVLs) may differ. A radiation quality correction factor k_{Q} is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,\text{NMI}}$ determined at the NMI into one which applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\text{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

$$\frac{\dot{K}_{\text{NMI}}}{\dot{K}_{\text{BIPM}}} = \frac{k_{\text{Q}} N_{K,\text{NMI}}}{N_{K,\text{BIPM}}}. \tag{3}$$

In practice, the half-value layers normally differ by only a small amount and k_{Q} is close to unity.

4. Calibration at the BIPM

4.1 BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.9 mm beryllium. Both the generating potential and the tube current are stabilized using feedback systems constructed at the BIPM; this results in a very high stability and obviates the need for a transmission current monitor. The radiation qualities used in the range from 10 kV to 50 kVa are those recommended by the CCRI [1] and are given in Table 3 in ascending half-value layer (HVL) from left to right.

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	0.036	0.176	0.250	1.020	2.257
μ_{air}† / m^{-1}	1.757	0.415	0.304	0.091	0.046
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.56	3.31	1.13	1.57	0.34

† Air attenuation coefficient at 293.15 K and 100 kPa, measured at the BIPM for an air path length of 100 mm.

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 thermistors, calibrated to a few mK, 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. All ionization current measurements are corrected for air temperature and pressure. The relative humidity is controlled within the range from 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

4.2 BIPM standard and correction factors

The defining plane of the aperture of the BIPM standard was positioned at 500 mm from the beam exit window. This distance was measured to 0.03 mm and reproducible to better than 0.01 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm, reproducible to better than 0.01 mm; an off-axis displacement of 0.1 mm changes the measured current by no more than 3×10^{-4} in relative value at 10 kV and at 50 kV. The beam diameter in the reference plane is 45 mm for all qualities.

During the calibration of the transfer chamber, measurements using the BIPM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 1.4×10^{-3} in relative value. The leakage current for the BIPM standard, relative to the ionization current, was measured to be less than 1×10^{-4}.

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

The factors k_a correct for the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. They are evaluated using the measured air-attenuation coefficients μ_{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. Ionization current measurements (both for the standard and for transfer chambers) 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.

Table 4. Correction factors for the BIPM standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a †	1.192 1	1.042 4	1.030 9	1.009 1	1.004 6	0.000 3	0.000 1
Scattered radiation k_{sc}	0.994 4	0.995 6	0.995 7	0.996 6	0.997 1	-	0.000 7
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1
Ion recombination k_s	1.000 7	1.001 9	1.001 0	1.001 1	1.000 6	0.000 2	0.000 1
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 7
Aperture edge transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.000 1	-
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	-	0.000 3
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1

† Nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air density measured at the time.

4.3 Transfer chamber positioning and calibration at the BIPM

The VNIIM transfer chamber was positioned close to the BIPM chamber and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Distance and alignment on the beam axis were as described above for the BIPM standard.

All transfer chamber measurements were made on negative polarity. The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current for the transfer chamber was always less than 1×10^{-4}. The relative standard uncertainty of the mean of each of two series of five measurements at each radiation quality was around 1×10^{-4} for the transfer chamber, and reproducibility better than 2×10^{-4}.

5. Calibration at the VNIIM

5.1 VNIIM irradiation facility and reference radiation qualities

The low-energy x-ray facility at the VNIIM comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of around 1 mm of beryllium. The stability of the generating potential is typically 1×10^{-3} in relative value. The characteristics of the VNIIM realization of the CCRI comparison qualities [1] are given in Table 5. It is evident from a comparison of these qualities with those of the BIPM in Table 3 that the 30 kV quality at the VNIIM is closer in HVL to the 25 kV quality at the BIPM. For this reason, no calibration was made at the 30 kV quality at the BIPM.

Table 5. Characteristics of the VNIIM reference radiation qualities

Radiation quality	10 kV	30 kV	50 kVb	50 kVa
Generating potential / kV	10	30	50	50
Additional Al filtration / mm	-	0.291	1.004	4.002
Al HVL / mm	0.028	0.231	1.030	2.060
$\mu_{air}^{\dagger}$ / m^{-1}	2.390	0.391	0.080	0.046
$\dot{K}_{VNIIM}$ / mGy s^{-1}	2.10	4.42	2.95	0.64

† Air attenuation coefficient at 293.15 K and 100 kPa, measured at the VNIIM for an air path length of 78 mm.

5.2 VNIIM standard and correction factors

The defining plane of the VNIIM standard was positioned at 500 mm from the focal spot, measured to 0.05 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.2 mm. The beam diameter in the reference plane is 100 mm for all radiation qualities.

During the calibration of the transfer chamber, measurements using the VNIIM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 3×10^{-4} in relative value . The relative leakage current was measured to be less than 1×10^{-4}.

The correction factors applied to the ionization current measured at each radiation quality using the VNIIM standard, together with their associated uncertainties, are given in Table 6.

Table 6. Correction factors for the VNIIM standard

Radiation quality	10 kV	30 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation $k_a^{\dagger}$	1.2053	1.0310	1.0063	1.0036	0.0010	0.0004
Scattered radiation k_{sc}	0.9919	0.9947	0.9960	0.9970	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0024	1.0061	-	0.0005
Ion recombination k_s	1.0003	1.0004	1.0003	1.0000	0.0001	0.0001
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0007
Aperture edge transmission k_l	1.0000	1.0000	1.0000	0.9999	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.998	0.998	0.998	0.998	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	-	0.0001

† Nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air density measured at the time.

5.3 Transfer chamber positioning and calibration at the VNIIM

The transfer chamber was positioned in distance and aligned on the beam axis as described above for the VNIIM standard. The relative humidity in the VNIIM measurement area is controlled within the range from 42 % to 50 % and consequently no humidity correction is applied to the transfer chamber current measurements.

All transfer chamber measurements were made on negative polarity. The leakage current was measured before and after each series of ionization current measurements and a correction applied using the mean value. The relative leakage current for the transfer chamber was typically 1×10^{-4}. The relative standard uncertainty of the mean of two series of ten measurements at each radiation quality was typically 2×10^{-4}.

6. Additional corrections to transfer chamber measurements

6.1 Ion recombination, polarity and beam non-uniformity

As can be seen from Tables 3 and 5, the air-kerma rates at the BIPM and at the VNIIM are not matched. For free-air chambers, the correction for ion recombination can be estimated using [5] and for the present transfer chamber and BIPM air-kerma rates should be approximately 1.000 2 (mainly due to initial recombination). This value for $k_{\mathrm{s,tr}}$ has been applied to the calibration coefficients for all qualities at the BIPM. The VNIIM air-kerma rates are higher and the value 1.000 3 has been applied for all qualities. The uncertainty introduced by this simplified approach is taken as 1×10^{-4} in relative value.

The transfer chamber was used with the same polarity at each institute and so no correction factors $k_{\mathrm{pol,tr}}$ are applied for polarity effects in the transfer chamber. The uncertainty introduced by the assumption that the polarity effect for a given radiation quality is the same at both institutes is taken to be 1×10^{-4} in relative value.

Because the transfer chamber has an aperture diameter matched to both standards, no corrections have been applied for radial non-uniformity.

6.2 Air attenuation in the transfer free-air chamber

Measurements using the transfer free-air chamber must also be corrected for air attenuation, using correction factors $k_{\mathrm{a,tr}}$ evaluated for the air path length given in Table 2 and the air attenuation coefficients μ_{air} given in Tables 3 and 5 for the BIPM and the VNIIM, respectively. The value so derived for $k_{\mathrm{a,tr}}$ for the 10 kV quality at the BIPM has been increased by the factor 1.000 7 to account for the larger mean air attenuation coefficient for an air path length of 78 mm (the values given in Table 3 were measured at the BIPM for an air path length of 100 mm). This effect is negligible at the other radiation qualities. No such correction is required at the VNIIM because the attenuation length is the same for both the VNIIM standard and the transfer chamber.

6.3 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities may require a correction factor k_{Q}. From Tables 3 and 5 it is evident that the radiation qualities at the BIPM and at the VNIIM are not closely matched in terms of HVL, except for the 50 kVb quality. The results for the calibration coefficients N_K as a function of log(HVL) are shown in Figure 1. The solid line is a quadratic fit to the values for $N_{K,\mathrm{VNIIM}}$. From this fit, the following values for the correction factor k_{Q}, as described in Section 3, are applied to the VNIIM results: 1.000 2 at 10 kV, 1.0001 at 30 kV, 1.000 0 at 50 kVb and 1.000 2 at 50 kVa. The uncertainty of these values is neglected.

7. Uncertainties

The uncertainties associated with the primary standards are listed in Table 7, those for the transfer chamber calibrations in Table 8 and those for the comparison results in Table 9. The uncertainty u_c of the comparison result takes into account correlations in the type B uncertainties associated with the physical constants and the humidity correction. Correlations between the BIPM and VNIIM values for k_e and k_{sc} are not taken into account, although these are derived from the same basic data.

Table 7. Uncertainties associated with the standards

Standard	BIPM		VNIIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 3	0.000 2	0.000 5	0.000 2
Volume	0.000 1	0.000 5	0.000 3	0.000 7
Positioning	0.000 1	0.000 1	0.000 2	0.000 2
Correction factors (excl. k_h)	0.000 4	0.001 4	0.001 0	0.001 3
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}_{std}$	0.000 5	0.002 1	0.001 2	0.002 1

Table 8. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		VNIIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}_{std}$	0.000 5	0.002 1	0.001 2	0.002 1
Positioning of transfer chamber	0.000 1	0.000 1	0.000 2	0.000 2
I_{tr}	0.0002	0.000 2	0.000 5	0.000 2
Stability of x-ray generator	0.0003	-	0.001 0	-
$N_{K,std}$	0.000 6	0.002 1	0.001 6	0.002 2

8. Results and discussion

The calibration coefficients determined at the BIPM and at the VNIIM are given in Table 10. The post-comparison calibrations at the VNIIM show an increase relative to the pre-comparison values of, in the worst case, 0.001 3 in relative value, which is consistent with the stated type A uncertainties associated with ionization current measurements and x-ray generator stability at the VNIIM.

Table 9. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{VNIIM}}/N_{K,\mathrm{BIPM}}$	0.001 7	0.002 2†
$k_{\mathrm{s,tr}}$	-	0.000 1
$k_{\mathrm{pol,tr}}$	-	0.000 1
$\dot{K}_{\mathrm{VNIIM}}/\dot{K}_{\mathrm{BIPM}}$	u_c = 0.002 8	

† Takes account of correlations in type B uncertainties.

Table 10. Calibration coefficients for the transfer chamber

Radiation quality	10 kV	25 kV†	30 kV†	50 kVb	50 kVa
$N_{K,\mathrm{VNIIM}}$ (pre-comp) / Gy μC^{-1}	12.331	-	12.378	12.398	12.433
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	12.426	12.445	-	12.443	12.459
$N_{K,\mathrm{VNIIM}}$ (post-comp) / Gy μC^{-1}	12.347	-	12.380	12.404	12.437

† The 25 kV radiation quality at the BIPM is most closely matched by the 30 kV quality at the VNIIM. A radiation quality correction factor k_Q is applied to account for differences in the HVL (see Section 6.3).

The comparison results are summarized in bold in Table 11, where the radiation qualities are those at the BIPM. General agreement is observed, the mean ratio $\dot{K}_{\mathrm{VNIIM}}/\dot{K}_{\mathrm{BIPM}}$ for all four qualities being 0.995 7, which is around one-and-a-half times the standard uncertainty. However, a significant trend is observed, the comparison result increasing by 0.005 between 10 kV and 50 kVa. This arises mainly from the large quality dependence of the photon-scatter correction applied to the VNIIM standard.

Table 11. Comparison results

Radiation quality†	10 kV	25 kV	50 kVb	50 kVa
$N_{K,\mathrm{VNIIM}}/N_{K,\mathrm{BIPM}}$	0.993 0	0.994 7	0.996 6	0.998 1
k_Q	1.000 2	1.000 1	1.000 0	1.000 2
$\dot{K}_{\mathrm{VNIIM}}/\dot{K}_{\mathrm{BIPM}}$	**0.993 2**	**0.994 8**	**0.996 6**	**0.998 3**
With k_e and k_{sc} from Burns [6] (both stds)	0.996 8	0.996 4	0.997 1	0.997 8
With k_e, k_{sc} and k_{fl} from Burns [6] (both stds)	0.997 6	0.997 0	0.997 4	0.998 1

† The radiation qualites refered to in this table are those at the BIPM. The calibration coefficients determined at the VNIIM have been corrected for differences in the HVL using the correction factors k_Q given in the table.

Burns [6] has recently calculated electron-loss and photon-scatter correction factors for the BIPM and VNIIM standards using the Monte Carlo code EGSnrc [7]. The values for k_e and k_{sc}

obtained in this way are given in Table 12, and the effect of including these new values in the present comparison shown in Table 11. The trend in the comparison results has largely disappeared.

Also given in Table 12 are values for fluorescence correction factors k_{fl}, which correct for the re-absorption of fluorescence photons generated by argon in the air of the free-air chambers. Neither standard is corrected for this effect at present. The results of including these correction factors for both standards are shown in the final row of Table 11. No significant trend with radiation quality remains. It should be noted, however, that these new correction factors have not as yet been adopted by either standard.

Table 12. Values for correction factors calculated by Burns [6]†.

Radiation quality	10 kV	25 kV	50 kVb	50 kVa
BIPM standard				
k_e	1.000 0	1.000 0	1.000 0	1.000 0
k_{sc}	0.996 2	0.997 4	0.997 8	0.998 0
k_{fl}	0.994 7	0.996 7	0.997 8	0.998 3
VNIIM standard				
k_e	1.000 0	1.000 0	1.001 8	1.005 1
k_{sc}	0.997 3	0.998 0	0.998 3	0.998 4
k_{fl}	0.995 5	0.997 3	0.998 1	0.998 6

† The type A uncertainties associated with the stated values are less than 0.000 1. The type B uncertainties have yet to be evaluated rigorously, but approximate values are: 0.000 5 for k_{sc}, 0.000 7 for k_{fl} and 0.000 7 for the two k_e values which are greater than 1.000 0 (and less than 0.000 2 where k_e = 1.000 0).

A summary of the results of BIPM comparisons of air-kerma standards for low-energy x-rays, including the present comparison, is presented in Figure 2.

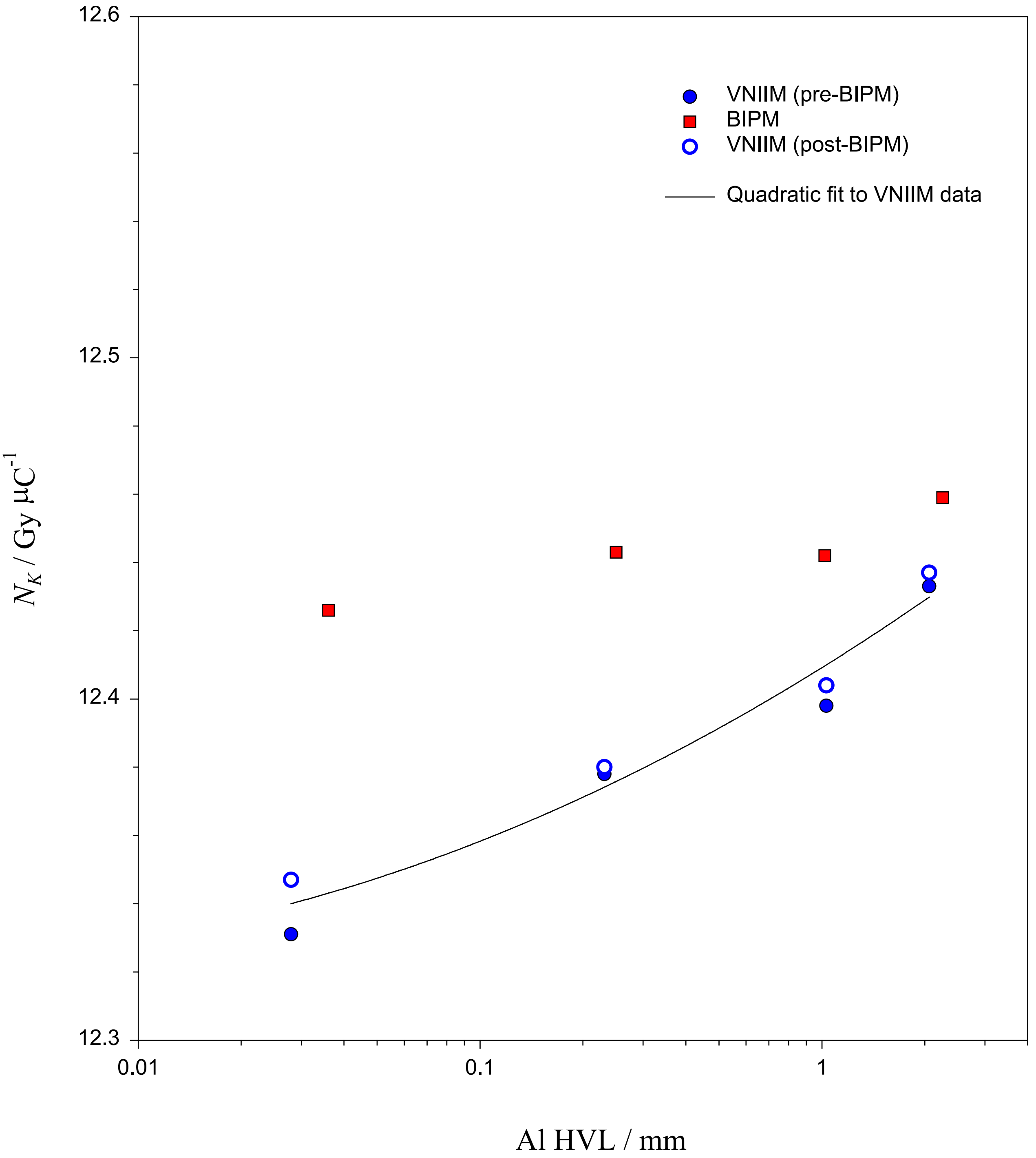

Figure 1. Results for the calibration coefficient N_K for transfer chamber IK10-60/2 at the BIPM and at the VNIIM, as a function of HVL. The line is a quadratic fit to the VNIIM data (open and closed circles) and is used to derive radiation quality correction factors k_Q (see text).

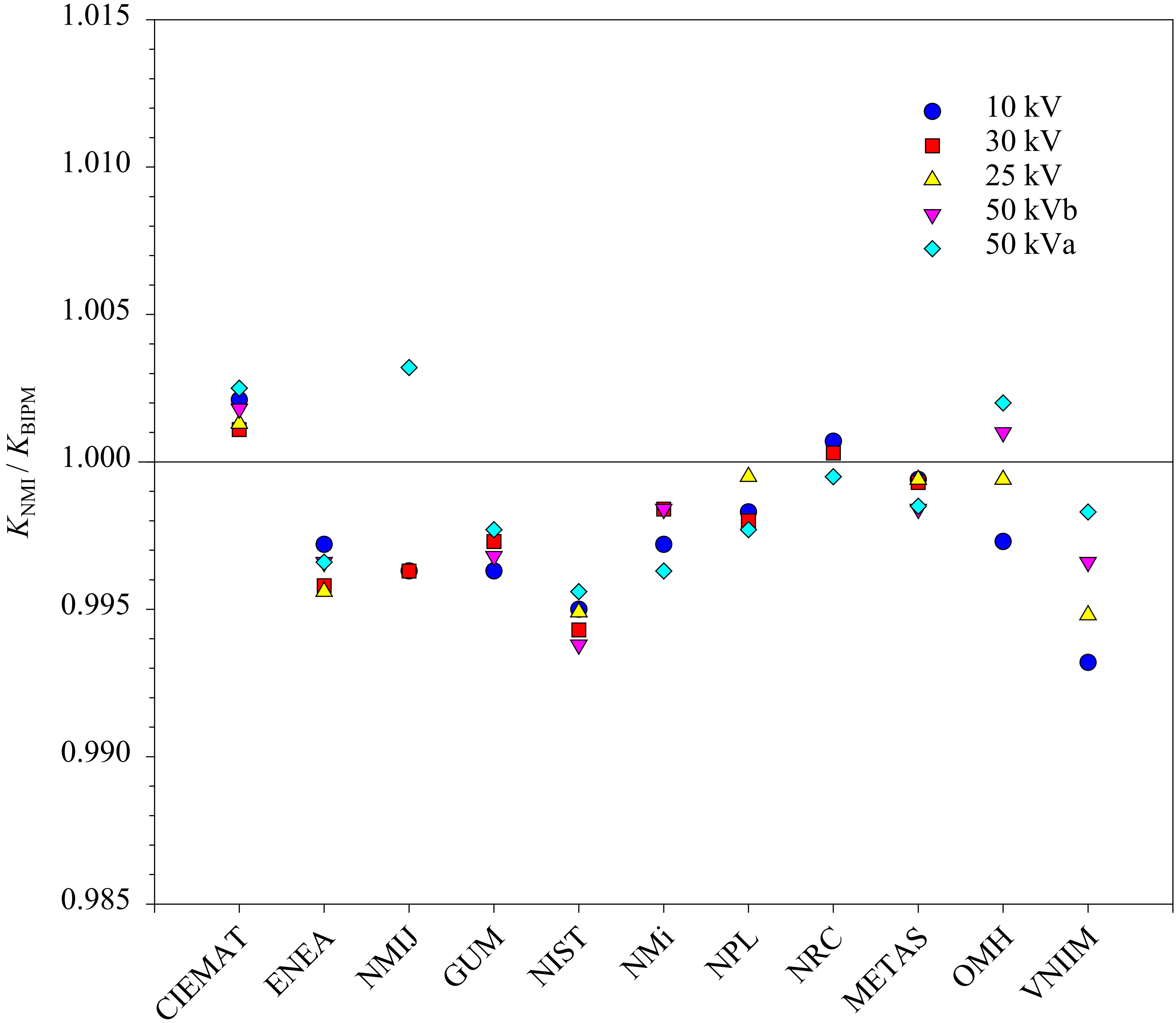

Figure 2. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once at the BIPM, only the results of the most recent comparison are included.

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