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Abstract An indirect comparison has been made between the air-kerma standards of the VNIIM and the BIPM in the medium-energy x-ray range. The results show the standards to be in agreement within the stated uncertainty.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the D.I. Mendeleyev Institute for Metrology (VNIIM), Russia, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. A cavity ionization chamber of type PTW M300001 was used as the transfer instrument. The measurements at the BIPM took place in December 1998 and those at the VNIIM in November 1998 and February 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

Both free-air chamber standards are 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]. Details of the VNIIM standard, which has not previously been compared with the BIPM standard, are given in [3]. The main dimensions, the measuring volume and the polarizing voltage for each chamber are shown in Table 2.

[1] For an air temperature $T \sim 293$ K, air 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.

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 standards

Standard	BIPM	VNIIM
Aperture diameter / mm	9.939	16.007
Air path length / mm	281.5	448.7
Collecting length / mm	60.004	100.233
Electrode separation / mm	180	300
Collector width / mm	200	300
Measuring volume / mm^3	4 655.4	20 171
Polarizing voltage / V	4 000	4 000

4. The transfer instruments

4.1 Determination of the calibration coefficient for a transfer instrument

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

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

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 $N_{K,BIPM}$ and $N_{K,NMI}$ 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 $N_{K,NMI}$ determined at the NMI into one which applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,NMI}$ values in terms of log(HVL). The comparison result at each quality is then taken as

$$R_{K,NMI} = \frac{k_Q N_{K,NMI}}{N_{K,BIPM}} \tag{3}$$

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

4.2 Details of the transfer instrument

A thimble-type cavity ionization chamber belonging to the VNIIM was used as the transfer instrument for the comparison. Its main characteristics are given in Table 3. The reference point for the chamber was taken to be on the cylindrical axis 13 mm from the chamber tip. The chamber was oriented so that the line marked on the chamber stem faced the source.

Table 3. Main characteristics of the transfer chamber

Chamber type	PTW M300001
Serial number	0109
Geometry	thimble
External diameter / mm	7.00
Wall material	Graphite-coated PMMA
Wall thickness / mm	0.425
Nominal volume / cm^3	0.6
Polarizing voltage / V	–300
Typical polarity correction $k_{pol,tr}$	1.0004

5. Calibration at the BIPM

5.1 BIPM irradiation facility and reference radiation qualities

The BIPM medium-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.3 mm aluminium. 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 100 kV to 250 kV are those recommended by the CCRI [1] and are given in Table 4.

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 (which is controlled around 25 °C). 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 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

5.2 BIPM standard and correction factors

The defining plane of the aperture of the BIPM standard was positioned at 1 200 mm from the radiation source, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 105 mm for all radiation qualities; an off-axis displacement of 0.1 mm changes the measured current by no more than 3×10^{-4} in relative value at 100 kV.

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 8×10^{-4} at 100 kV and around 3×10^{-4} at the other radiation qualities. The leakage current for the BIPM standard, relative to the ionization current, was measured to be around 2×10^{-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 5.

Table 4. Characteristics of the BIPM reference radiation qualities

Generating potential / kV	100	135	180	250
Additional Al filtration / mm	1.203 2	-	-	-
Additional Cu filtration / mm	-	0.232 1	0.484 7	1.570 1
Al HVL / mm	4.027	-	-	-
Cu HVL / mm	0.148	0.494	0.990	2.500
μ_{air}† / m^{-1}	0.035 5	0.023 5	0.019 8	0.017 2
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.21	0.20	0.29	0.38

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

Table 5. Correction factors for the BIPM standard

Generating potential / kV	100	135	180	250	u_{iA}	u_{iB}
Air attenuation k_a†	1.010 0	1.006 6	1.005 6	1.004 9	0.000 3	0.000 1
Scattered radiation k_{sc}	0.994 8	0.996 2	0.996 7	0.996 9	-	0.000 7
Electron loss k_e	1.000 0	1.002 3	1.005 2	1.007 8	-	0.001 0
Ion recombination k_s	1.000 5	1.000 5	1.000 5	1.000 5	0.000 2	0.000 1
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 7
Aperture edge transmission k_l	0.999 9	0.999 8	0.999 7	0.999 6	-	0.000 1
Wall transmission k_p	1.000 0	1.000 0	0.999 9	0.998 8	0.000 1	-
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	-	0.000 3
$1 - g_{air}$	0.999 9	0.999 9	0.999 8	0.999 7	-	0.000 1

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

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 4. 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 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.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane, with a reproducibility of 0.03 mm. The transfer chamber was aligned on the beam axis to an estimated uncertainty of 0.1 mm.

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 typically 1×10^{-4}.

The relative standard uncertainty of the mean of each of two series of ten measurements at each radiation quality was typically 2×10^{-4} for the transfer chamber, although the repeatability was poorer, typically 4×10^{-4}.

6. Calibration at the VNIIM

6.1 VNIIM irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the VNIIM is an ISOVOLT-400 industrial unit, with a tungsten-anode x-ray tube having an inherent filtration of around 4 mm aluminium. The stability of the generating potential is typically 3×10^{-3} in relative value. The x-ray output is monitored by means of a transmission ionization chamber whose aluminium mylar windows introduce a filtration of 2.136 mg cm^{-2}. The typical relative standard uncertainty of short-term current measurents using the VNIIM standard, relative to the transmission monitor current, is typically 5×10^{-4}; the longer-term reproducibility of the monitor is around 8×10^{-4}. The characteristics of the VNIIM realization of the CCRI comparison qualities [1] are given in Table 6.

Table 6. Characteristics of the VNIIM reference radiation qualities

Generating potential / kV	100	135	180	250
Additional Al filtration / mm	-	1.670	0.761	0.761
Additional Cu filtration / mm	-	0.101	0.265	1.291
Al HVL / mm	4.120	-	-	-
Cu HVL / mm	-	0.490	0.982	2.496
μ_{air}† / m^{-1}	0.0310	0.0222	0.0198	0.0171
$\dot{K}_{VNIIM}$ / mGy s^{-1}	0.44	0.49	0.83	1.13

† Air attenuation coefficient at 293.15 K and 100 kPa, measured at the VNIIM for an air path length of 150 mm.

Two calibrated platinum resistance thermometers are used to measure the ambient air temperature, one positioned close to the transfer chamber and the second close to the transmission monitor. Air pressure is recorded using a calibrated barometer positioned at the height of the beam axis. The relative humidity in the VNIIM measurement area is controlled within the range 42 % to 50 %. No humidity correction is applied to the transfer chamber current measurements.

6.2 VNIIM standard and correction factors

The reference plane for the VNIIM standard was positioned at 1 000 mm from the radiation source, with a reproducibility of 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 95 mm for all radiation qualities; an off-axis displacement of 0.2 mm changes the measured current in relative terms by no more than 5×10^{-4} at 100 kV.

During the calibration of the transfer chambers, measurements using the VNIIM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 4×10^{-4} in relative value. The relative leakage current was measured to be less than 2×10^{-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 7.

Table 7. Correction factors for the VNIIM standard

Generating potential / kV	100	135	180	250	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a†	1.0140	1.0100	1.0089	1.0077	0.0003	0.0001
Scattered radiation k_{sc}	0.9949	0.9956	0.9963	0.9964	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0016	1.0030	-	0.0010
Ion recombination k_s	1.0009	1.0010	1.0035	1.0044	0.0002	0.0002
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0005
Aperture edge transmission k_l	0.9999	0.9997	0.9997	0.9996	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	0.0001

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

The correction factor k_a is evaluated using the measured air-attenuation coefficients μ_{air} given in Table 6. 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 (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

6.3 Transfer chamber positioning and calibration at the VNIIM

The reference point for the transfer chamber was positioned at the reference distance, with a reproducibility of 0.05 mm. Alignment on the beam axis was to an estimated uncertainty of 0.1 mm.

The leakage current of the transfer chamber was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current was typically 2×10^{-4}.

The relative standard uncertainty of the mean of three series of thirteen measurements at each radiation quality was typically 3×10^{-4}.

7. Additional corrections to transfer chamber measurements

7.1 Ion recombination, polarity and beam non-uniformity

As can be seen from Tables 4 and 6, the air-kerma rates at the VNIIM are two to three times higher than those at the BIPM. Thus volume recombination effects will be greater for the transfer chamber calibrations at the VNIIM; recombination corrections $k_{\mathrm{s,tr}}$ were determined experimentally at the VNIIM to be 1.000 0, 1.000 0, 1.000 4 and 1.000 8 for the four comparison qualities 100 kV, 135 kV, 180 kV and 250 kV, respectively. From these, the corresponding correction factors 1.000 0, 1.000 0, 1.000 1 and 1.000 3, respectively, were derived for the BIPM qualities by scaling according to the air-kerma rates given in Tables 4 and 6. Initial recombination effects were assumed to be negligible. The uncertainty arising from this treatment of ion recombination effects is estimated to be 1×10^{-4} in relative value.

The transfer chamber was used with the same polarity at each laboratory and so no corrections $k_{\mathrm{pol,tr}}$ are applied for polarity effects in the transfer chamber. From the typical value for the polarity effect in PTW M300001 chamber types given in Table 3, a relative uncertainty of 1×10^{-4} is estimated.

No correction $k_{\mathrm{rn,tr}}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For small cylindrical transfer chambers the effect will be very small, less than 1×10^{-4} in relative value.

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities may require a correction factor k_{Q}. However, from Tables 4 and 6 it is evident that the radiation qualities at the BIPM and at the VNIIM are very closely matched in terms of HVL and so the correction factor k_{Q} is taken to be unity for all qualities, with a negligible uncertainty.

8. Uncertainties

The uncertainties associated with the primary standards are listed in Table 8, those for the transfer chamber calibrations in Table 9 and those for the comparison results in Table 10.

The relative combined standard uncertainty u_{c} of the comparison result $R_{K,\mathrm{VNIIM}}$ 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.

9. Results and discussion

The calibration coefficients determined at the BIPM and at the VNIIM are given in Table 11. For the 100 kV, 135 kV and 180 kV qualities, the pre- and post-comparison calibrations at the VNIIM agree at a level which is consistent with the uncertainties associated with chamber positioning, ionization current measurements and transmission monitor stability. However, the calibrations at 250 kV show a relative change of 2.5×10^{-3}.

Table 8. 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 2	0.000 5
Positioning	0.000 1	0.000 1	0.000 2	0.000 2
Correction factors (excl. k_h)	0.000 4	0.001 4	0.000 4	0.001 5
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	0.000 7	0.002 2

Table 9. 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	0.000 7	0.002 2
Positioning of transfer chamber	0.000 1	0.000 1	0.000 2	0.000 2
I_{tr}	0.000 4	0.000 2	0.000 3	0.000 2
Stability of transmission monitor	-	-	0.000 8	-
Radial non-uniformity $k_{rn,tr}$	-	0.000 3	-	0.000 5
$N_{K,std}$	0.000 7	0.002 1	0.001 1	0.002 3

Table 10. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,VNIIM}/N_{K,BIPM}$	0.001 3	0.002 2†
$k_{s,tr}$	-	0.000 1
$k_{pol,tr}$	-	0.000 1
$R_{K,VNIIM}$	0.001 3	0.002 2
	$u_c = 0.002\,6$	

† Takes account of correlations in type B uncertainties.

The comparison results $R_{K,\mathrm{VNIIM}}$ are also given in Table 11. General agreement between the standards is observed, the mean result for the four qualities being 0.9982 (standard uncertainty of the distribution 8×10^{-4}). The deviation from unity of this mean value is consistent with the stated comparison uncertainty of 2.6×10^{-3} (Table 10). No significant trend with radiation quality is observed, except perhaps for the result at 180 kV which is notably higher.

Table 11. Calibration coefficients for the transfer chamber

Generating potential / kV	100	135	180	250
$N_{K,\mathrm{VNIIM}}$ (pre-comp) / Gy μC^{-1}	48.19	48.09	48.28	48.32
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	48.27	48.19	48.30	48.47
$N_{K,\mathrm{VNIIM}}$ (post-comp) / Gy μC^{-1}	48.15	48.10	48.28	48.44
$\boldsymbol{R_{K,\mathrm{VNIIM}}}$	**0.9979**	**0.9980**	**0.9996**	**0.9981**

In an attempt to explain the higher comparison result for the 180 kV quality, several possibilities were considered. Values for the correction factors k_e and k_{sc} for both standards have recently been calculated by Burns [4] using the Monte Calro Code EGSnrc [5]. Table 12 shows the values obtained and the effect of including these in the present comparison. No improvement is observed; the results are farther from unity and consistency with radiation quality is no better.

Table 12. Analysis of comparison results using revised correction factors

Generating potential / kV	100	135	180	250
Monte Carlo k_e for VNIIM standard	1.0000	1.0000	1.0008	1.0025
Monte Carlo k_e for BIPM standard	1.0000	1.0015	1.0048	1.0087
Monte Carlo k_{sc} for VNIIM standard	0.9927	0.9938	0.9945	0.9958
Monte Carlo k_{sc} for BIPM standard	0.9952	0.9959	0.9964	0.9974
Revised $R_{K,\mathrm{VNIIM}}$ if these values adotped	0.9953	0.9973	0.9977	0.9956

A second quality-dependent effect was considered. The corrections for ion recombination determined at the VNIIM (using the $1 / I$ *vs* $1 / V$ method) are significantly different from those which one would calculate for the VNIIM standard following the work of Boutillon [6]. A re-evaluation using [6] gives values for k_s of 1.0020, 1.0022, 1.0030, 1.0038, respectively, the use of which leads to the revised comparison results 0.9990, 0.9992, 0.9991 and 0.9975, respectively. Bearing in mind the large change in the pre- and post-comparison calibrations for the 250 kV quality, this set of results may be considered to be more satisfactory. However, when combined with the new Monte Carlo values for correction factors, this improvement is lost and no strong conclusions can be drawn. It should be emphasized that Monte Carlo correction factors have not as yet been adopted by either institute and so the comparison results stand as those given in bold in Table 11.

A summary of the results of BIPM comparisons of air-kerma standards for medium-energy x-rays, including the present comparison, is presented in Figure 1.

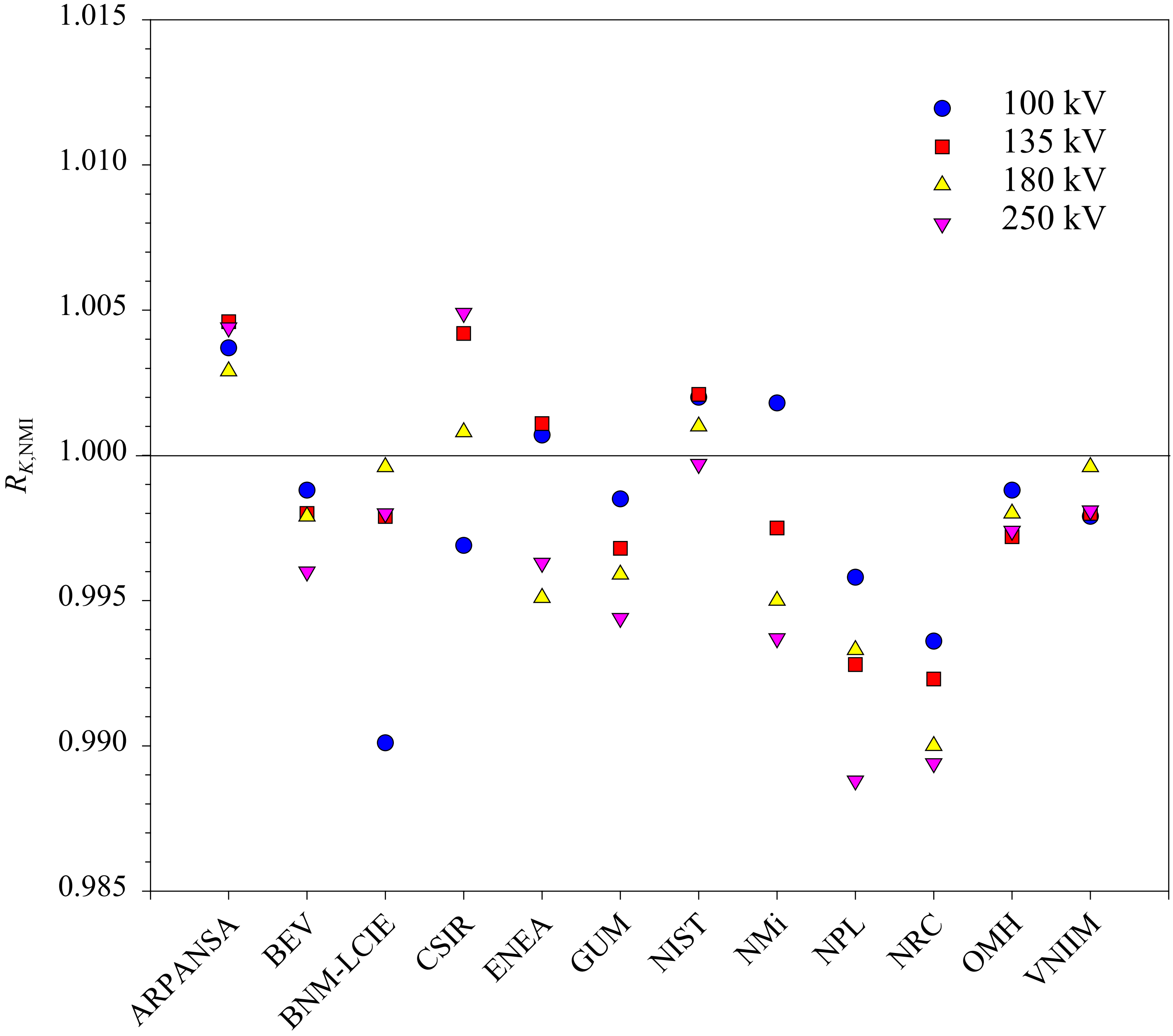

Figure 1. Results of BIPM medium-energy x-ray comparisons, expressed as the ratio $R_{K,\mathrm{NMI}}$ of the air-kerma rate detemined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once with the BIPM, only the results of the most recent comparison are included.

References

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