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Comparison of the air-kerma standards of the NRC and the BIPM in the medium-energy x-ray range

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Abstract An indirect comparison has been made between the air-kerma standards of the NRC and the BIPM in the medium-energy x-ray range. The results show the standards to be in general agreement at the level of two to three standard uncertainties. There is evidence of a trend in the results for different radiation qualities.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the National Research Council of Canada (NRC) and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Three cylindrical cavity ionization chambers of type NE 2571 were used as transfer instruments. The measurements at the BIPM took place in November 1998 and those at the NRC in the period October to December 1998, 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 NRC medium-energy exposure standard (MEES), 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, 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 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 kPa.

Table 2. Main characteristics of the standards

Standard	BIPM	NRC MEES
Aperture diameter / mm	9.939	10.008
Air path length / mm	281.5	419
Collecting length / mm	60.004	101.73
Electrode separation / mm	180	260
Collector width / mm	200	350
Measuring volume / mm^3	4 655.4	8002.6
Polarizing voltage / V	4 000	5 000

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

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

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 kPa and h = 50 %).

In general, to derive a comparison result from the calibration coefficients $N_{K,\mathrm{BIPM}}$ and $N_{K,\mathrm{NMI}}$ measured, respectively, at the BIPM and at a national measurement institute (NMI), differences in the radiation qualities must be taken into account. Each quality used for the comparison has the same nominal 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 $N_{K,\mathrm{NMI}}$ determined at the NMI into one which applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

$$R_{K,\mathrm{NMI}} = \frac{k_{\mathrm{Q}} N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \tag{3}$$

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 instruments

Three cylindrical cavity ionization chambers belonging to the NRC were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The reference point for each chamber was taken to be on the cylindrical axis 13 mm from the chamber tip. Each chamber was oriented so that the line on the chamber stem was facing towards the source.

Table 3. Main characteristics of the transfer chambers

Chamber type	NE 2571
Serial numbers	2572, 2587 and 2595
Geometry	cylindrical
External diameter / mm	7.0
Wall material	graphite
Wall density / g cm^{-3}	1.8
Wall thickness / mm	0.36
Nominal volume / mm^3	690
Polarizing voltage / V	+300

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 at 25 °C). Air pressure is measured by means of a 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 reference plane for 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 produces a relative change in the measured current of no more than 3×10^{-4} at 100 kV.

During the calibration of the transfer chambers, measurements using the BIPM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 2×10^{-4} in relative value. The leakage current for the BIPM standard, relative to the ionization current, was measured to be around 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 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}† / 10^{-3} mm^{-1}	0.036 0	0.023 8	0.020 1	0.017 4
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.21	0.20	0.29	0.38

† Air attenuation coefficient at 293.15 K and 101.325 kPa, measured at the BIPM for an air path length of 270 mm.

Table 5. Correction factors for the BIPM standard

Generating potential / kV	100	135	180	250	Relative standard uncertainty	
					u_{iA}	u_{iB}
Air attenuation k_a†	1.010 2	1.006 7	1.005 7	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

† These are nominal values for 293.15 K and 101.325 kPa; each measurement is corrected using the air temperature and pressure measured at the time.

‡ The value is less for the 100 kV and 135 kV radiation qualities.

The factor k_a corrects for the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. It is 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 (1 200 mm from the radiation source), with a reproducibility of 0.03 mm. Each 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 was typically 8×10^{-4} for transfer chambers 2587 and 2595, and 3×10^{-4} for transfer chamber 2572.

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 all three transfer chambers, although the repeatability was poorer, typically 5×10^{-4}.

6. Calibration at the NRC

6.1 NRC irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the NRC comprises two constant-potential generators (Glassman, ±160 kV) and a tungsten-anode x-ray tube (Comet, bipolar, 320 kV) with a 3 mm beryllium window and a focal spot size of approximately 3 mm by 3 mm. The generating potential is measured at 3 s intervals using two voltage dividers [4], calibrated to 3 parts in 10^5, and is constant for a given radiation quality to better than 5 V. The x-ray tube current is stabilized over a wide dynamic range (µA to mA) using a feedback system developed at the NRC that controls the filament current. In relative terms, stability over the short term is around 5×10^{-5} and long-term stability (0.5 year) around 1×10^{-3}. The characteristics of the NRC realization of the CCRI comparison qualities [1] are given in Table 6.

The x-ray output is switched on and off using a mechanical shutter with a timing uncertainty of about 15 ms. The combination of tube current and shutter time serves as a beam monitor. A parallel-plate transmission ionization chamber provides a second, independent beam monitor. This is located 34 cm from the focal spot and consists of five layers of aluminized Mylar, totalling 5.6 mg cm^{-2} of Mylar and 0.21 mg cm^{-2} of aluminium. The air temperature for this monitor is measured by a sensor mounted inside the chamber. The two beam monitors typically agree at the level of 2 parts in 10^{-4}.

Ambient air pressure was recorded using a barometer positioned at the height of the beam axis. The relative humidity was measured using a thin polymer film sensor and during the measurements was around 30 %.

6.2 NRC standard and correction factors

The reference plane for the NRC standard was positioned at 1 000 mm from the radiation source, with a reproducibility of 0.1 mm. The standard was aligned on the beam axis to an uncertainty of 0.2 mm. The beam diameter in the reference plane is 90 mm for all radiation qualities.

The ionization current from the standard is measured using a Keithley 642 electrometer with a calibrated 2.2 nF feedback capacitor. The voltage generated across the capacitor is measured using a Keithley 2002 voltmeter with a relative accuracy of around 5×10^{-5}. The temperature of the air in the standard was measured using a sensor attached to the frame of the collector plate system. This temperature generally follows the ambient air temperature to within 0.05 °C.

During the calibration of the transfer chambers, measurements using the NRC standard were made at one polarity only. Previous measurements have shown the difference between positive and negative polarity to be less than 3×10^{-4} in relative value. The relative leakage current was measured to be less than 5×10^{-5}.

The correction factors applied to the ionization current measured at each radiation quality using the NRC standard, together with their associated uncertainties, are given in Table 7. Of note is the humidity correction factor of 0.9975, evaluated for a relative humidity around 30 %. This differs from the value 0.9980 applied at the BIPM where the relative humidity is close to 50 %.

Table 6. Characteristics of the NRC reference radiation qualities

Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.63	1.00	1.25	1.00
Additional Cu filtration / mm	-	0.25	0.50	1.70
Al HVL / mm	4.022	-	-	-
Cu HVL / mm	-	0.488	0.991	2.533
$\mu_{air}^{\dagger}$ / 10^{-3} mm^{-1}	0.0346	0.0240	0.0197	0.0164
$\dot{K}_{NRC}$ / mGy s^{-1}	0.95	0.96	1.33	1.01

† Air attenuation coefficient at 293.15 K and 101.325 kPa, measured at the NRC for an air path length of 419 mm.

Table 7. Correction factors for the NRC standard

Generating potential / kV	100	135	180	250	Relative standard uncertainty	
					u_{iA}	u_{iB}
Air attenuation $k_a^{\dagger}$	1.0146	1.0101	1.0083	1.0069	0.0002	0.0007
Scattered radiation k_{sc}	0.9931	0.9934	0.9937	0.9947	-	0.0010
Electron loss k_e	1.0000	1.0005	1.0011	1.0031	-	0.0007
Ion recombination k_s	1.0012	1.0012	1.0014	1.0012	0.0001	0.0002
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0015
Aperture edge transmission k_l	1.0000	1.0000	1.0000	1.0000	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	-	0.0002
Humidity k_h	0.9975	0.9975	0.9975	0.9975	-	0.0003
$1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	0.0001

† These are nominal values for 293.15 K and 101.325 kPa; each measurement is corrected using the air temperature and pressure measured at the time.

6.3 Transfer chamber positioning and calibration at the NRC

For each transfer chamber the reference point was positioned at the reference distance (1000 mm from the radiation source), reproducible to 0.1 mm. Each was aligned on the beam axis to an estimated uncertainty of 0.2 mm.

The air temperature for the transfer chambers was measured using a sensor mounted inside a dummy thimble chamber positioned around 15 cm from the chamber (outside the radiation field). This is known to follow the transfer chamber temperature within 0.05 °C. A correction factor 0.9995 has been applied to the current measured for each transfer chamber to account for the difference between the measured relative humidity of 30 % and the reference value of 50 %.

Each transfer chamber was pre-irradiated for about thirty minutes, during which time the relative response changed by typically 8×10^{-3}, most of the change taking place within the first ten minutes. The time required for a given chamber to stabilize depends on its irradiation history. The relative standard uncertainty arising from variations in radiation conditioning is estimated to be 3×10^{-4}. The leakage current for each transfer chamber was typically less than 10 fA, resulting in relative corrections of less than 5×10^{-4}.

The relative standard uncertainty of the mean of three series of five measurements at each radiation quality was typically 5×10^{-4} for each transfer chamber.

Table 8. Uncertainties associated with the standards

Laboratory	BIPM		NRC	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 3	0.000 2	0.000 3	0.000 3
Volume	0.000 1	0.000 5	0.000 1	0.000 4
Positioning	0.000 1	0.000 1	0.000 2	0.000 1
Correction factors (excl. k_h)	0.000 4	0.001 4	0.000 2	0.002 1
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}_{lab}$	0.000 5	0.002 1	0.000 4	0.002 6

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 NRC are two to five times higher than those at the BIPM. Thus volume recombination effects will be greater for the transfer chamber calibrations at the NRC, although no recombination corrections $k_{s,tr}$ have been applied at either laboratory. Based on previous measurements of recombination corrections for the NE 2571 chamber type, this effect is small and is accounted for by introducing a component of uncertainty of 2×10^{-4} in relative value.

Each transfer chamber was used with the same polarity at each laboratory and so no corrections $k_{pol,tr}$ are applied for polarity effects in the transfer chambers. The polarity correction for the NE 2571 chamber type in medium-energy x rays is typically within 2×10^{-3} of unity. The relative standard uncertainty associated with the neglect of polarity corrections is estimated to be 3×10^{-4}.

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 BIPM and NRC radiation qualities 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.

Table 9. Uncertainties associated with the calibration of the transfer chambers

Laboratory	BIPM		NRC	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}_{\mathrm{lab}}$	0.000 5	0.002 1	0.000 4	0.002 6
Positioning of transfer chamber	0.000 1	0.000 1	0.000 1	0.000 1
I_{tr}	0.000 5	0.000 2	0.000 4	0.000 5
Radial non-uniformity $k_{\mathrm{rn,tr}}$	-	0.000 1	-	0.000 1
$N_{K,\mathrm{lab}}$	0.000 7	0.002 1	0.000 6	0.002 7

Table 10. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{NRC}}/N_{K,\mathrm{BIPM}}$	0.000 9	0.002 7†
$k_{\mathrm{s,tr}}$	-	0.000 2
$k_{\mathrm{pol,tr}}$	-	0.000 3
$R_{K,\mathrm{NRC}}$	0.000 9	0.002 7
	$u_{\mathrm{c}} = 0.002\,8$	

† Takes account of correlations in Type B uncertainties.

The relative combined standard uncertainty u_{c} of the comparison result $R_{K,\mathrm{NRC}}$ takes into account correlations in the type B uncertainties associated with the physical constants and the humidity correction. Correlations between the BIPM and NRC 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 NRC are given in Table 11. The reference temperature for routine calibrations at the NRC is 22 °C; for the purpose of this comparison, the NRC calibration coefficients have been normalized to 20 °C. The calibration coefficients supplied by the NRC in December 1998 were corrected in March 1999 by the factor 1.0042. This correction results from the observation that two guard bars of the NRC standard had shorted. The uncertainty of this correction is negligible. No systematic changes were observed in the calibration results determined at the NRC before and after the calibrations at the BIPM.

Table 11. Calibration coefficients for the transfer chambers

Generating potential / kV	100	135	180	250
Transfer chamber 2572				
$N_{K,\mathrm{NRC}}$ / Gy µC^{-1}	42.16	41.56	41.12	40.73
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	42.39	41.82	41.49	41.12
Transfer chamber 2587				
$N_{K,\mathrm{NRC}}$ / Gy µC^{-1}	42.02	41.42	40.95	40.55
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	42.29	41.71	41.33	40.94
Transfer chamber 2595				
$N_{K,\mathrm{NRC}}$ / Gy µC^{-1}	42.23	41.51	40.98	40.51
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	42.43	41.80	41.36	40.91

The comparison results are summarized in Table 12. For all three transfer chambers, a significant trend in the ratio $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ is observed, the value lowering by 4×10^{-3} between 100 kV and 250 kV. The variation in the results obtained for the three transfer chambers at a given radiation quality is consistent with the statistical uncertainties, the relative standard uncertainty of the mean value being 5×10^{-4} in the worst case (100 kV). In view of the stated comparison uncertainty of 2.8×10^{-3} (Table 10), the agreement between the two standards is less satisfactory than one might expect, ranging from two standard uncertainties at 100 kV to over three at 250 kV.

Regarding the observed trend with radiation quality, since the attenuation coefficients determined at the BIPM and at the NRC are very similar, the existence of an energy-dependent effect is most likely to arise from the values used for the correction factors k_e and k_{sc}. Values for these factors for both standards have been calculated by Burns [5] using the Monte Carlo code EGS4 [6]. Although differences between the existing and new values are within the combined uncertainties (typical agreement 5×10^{-4}), their combined effect to some extent offsets the observed trend in the comparison results. Table 13 shows the results of this analysis. The revised comparison results at 100 kV, 135 kV and 180 kV are in reasonable agreement at the level of two standard uncertainties, although the result at 250 kV remains low. It should be emphasized that these Monte Carlo correction factors have not as yet been adopted by either laboratory and so the comparison result are those given in Table 12.

Table 12. Comparison results

Generating potential / kV	100	135	180	250
$N_{K,\mathrm{NRC}}/N_{K,\mathrm{BIPM}}$ using chamber 2572	0.9947	0.9936	0.9911	0.9905
$N_{K,\mathrm{NRC}}/N_{K,\mathrm{BIPM}}$ using chamber 2587	0.9936	0.9930	0.9908	0.9906
$N_{K,\mathrm{NRC}}/N_{K,\mathrm{BIPM}}$ using chamber 2595	0.9954	0.9931	0.9909	0.9904
$\boldsymbol{R_{K,\mathrm{NRC}}}$	**0.9946**	**0.9932**	**0.9910**	**0.9905**

Table 13. Analysis of comparison results using revised correction factors

Generating potential / kV	100	135	180	250
Monte Carlo k_e for NRC standard	1.000 0	1.000 1	1.000 9	1.002 5
Monte Carlo k_e for BIPM standard	1.000 1	1.001 5	1.004 4	1.007 8
Monte Carlo k_{sc} for NRC standard	0.992 4	0.993 7	0.994 4	0.995 9
Monte Carlo k_{sc} for BIPM standard	0.995 1	0.995 8	0.996 3	0.997 3
Revised $R_{K,\mathrm{NRC}}$†	0.9935	0.9943	0.9926	0.9907

† The Monte Carlo values for k_e and k_{sc} have not yet been adopted by either laboratory. Thus the comparison results are those given in Table 12.

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

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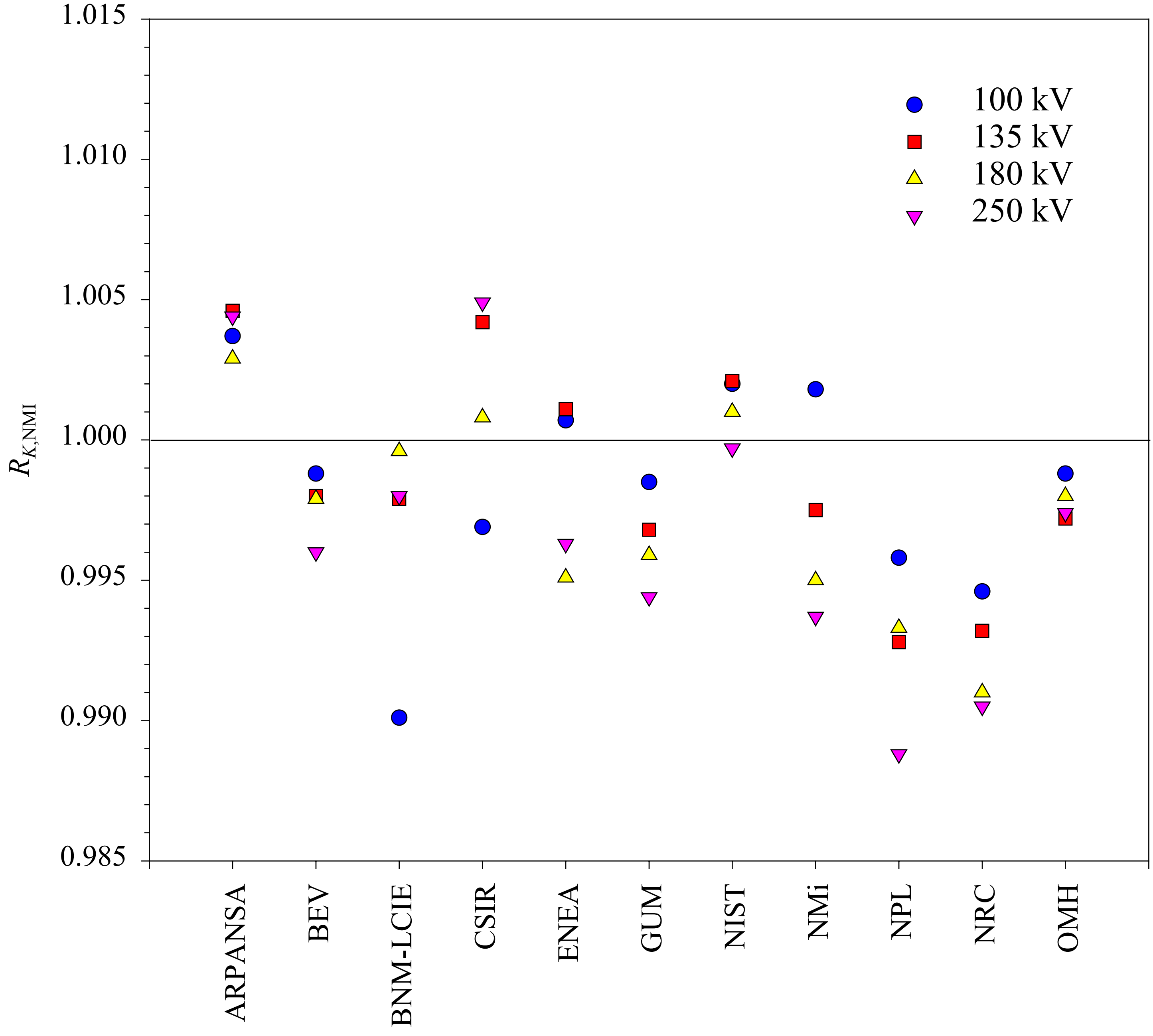

Figure 1. Results of BIPM medium-energy x-ray comparisons, expressed as the ratio $R_{K,\text{NMI}}$ of the air-kerma rate detemined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once with the BIPM, only the results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