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Comparison of the air-kerma standards of the NPL and the BIPM in the low- and medium-energy x-ray ranges

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Abstract

The air-kerma standards of the NPL and the BIPM have been compared in the low- and medium-energy x-ray ranges. The results for the low-energy comparison show the standards to be in agreement at the level of one standard uncertainty. At medium energies a slight trend with radiation quality is evident, with agreement at the level of one standard uncertainty for 100 kV rising to over two standard uncertainties for 250 kV. In relation to previous comparisons, the good stability of the standards over a period of twenty years is demonstrated.

1. Introduction

Comparisons have been made of the air-kerma standards of the UK National Physical Laboratory (NPL) and the Bureau International des Poids et Mesures (BIPM) in the low- and medium-energy x-ray ranges. For the latter comparison, two commercial ionization chambers, type NE 2561, were used as transfer instruments. The measurements at the BIPM were made in June 1997 using the reference conditions recommended by the CCRI [1].

2. Determination of the air-kerma rate

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

$$\dot{K} = \left(\frac{I}{\rho_{\text{air}} V}\right)\left(\frac{W}{e}\right)\frac{1}{1-\bar{g}}\prod k_i \qquad (1)$$

where

I	is the ionization current,
ρ_{air}	is the density of air under reference conditions,
W	is the mean energy expended by an electron of charge e to produce an ion pair in dry air,
$\bar{g}$	is the fraction of the initial electron energy lost through bremsstrahlung production, and
$\prod k_i$	is the product of the correction factors to be applied to the standard.

The values for the physical constants ρ_{air} and W are given in Table 1. For use with this value for ρ_{air}, the ionization current I is corrected for the difference between the air density at the time of measurement and that given in the table.

The BIPM standards have been described in [2], [3] and [4] and no further details are given in this report. The NPL standards are also parallel-plate free-air chambers, details of which can be found in [5], [6] and [7]. Their dimensions are given in Table 2. The polarizing voltage is applied with negative polarity.

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

Constant	Value	u_i (1)
ρ_{air} (2)	1.2930 kg m^{-3}	0.0001
W/e	33.97 J C^{-1}	0.0015

(1) u_i is the relative combined standard uncertainty.
(2) At 101 325 Pa and 273.15 K.

Table 2. Main dimensions of the NPL standards

Dimension	50 kV free-air chamber	300 kV free-air chamber
Plate separation / mm	62.5	264
Collecting plate width / mm	19.827	100.258
Air path length / mm	88.5	493
Aperture diameter / mm	8.0075	10.014
Measuring volume / mm^3	998.5	7896.3
Polarizing voltage / V	1500	3000

3. Comparison in the low-energy x-ray range

The NPL standard was positioned close to the BIPM standard with the reference plane at 500 mm from the exit window of the x-ray tube (beam diameter 95 mm). The air temperature was measured using a thermistor placed nearby, outside the beam. A polarizing voltage of 1500 V (negative polarity) was applied to the NPL standard. For the comparison, the x-ray tube was displaced so that the beam axis coincided with each standard in turn. Measurements with the BIPM standard were made immediately before and after the measurements with the NPL standard, to correct for any drift. At the BIPM both the generating potential and the anode current are stabilized and variations in the x-ray output are typically around 2×10^{-4} in relative value.

The standards were irradiated before each measurement and the leakage current measured. For the NPL standard the leakage current did not exceed 4×10^{-4} in relative value and an appropriate correction was made. The relative standard deviation of the mean of a series of measurements was in the range from 0.0001 to 0.0005, depending on the radiation quality.

The radiation qualities used for the comparison are those recommended by the CCRI [1] and are given in Table 3 in order of ascending half-value layer (HVL) from left to right. The table also gives the correction factors applied to the NPL standard. The relative standard uncertainty of the air-kerma rate determination in the BIPM radiation field is estimated to be 0.0020 using the BIPM standard and 0.0021 using the NPL standard. The uncertainties associated with the NPL standard are given in Table 4.

The results of the comparison are given in Table 5, together with those obtained in 1978. The relative standard uncertainty of the comparison result at each radiation quality is estimated to be 0.0023. This takes account correlations in the type B uncertainties associated with the determination of the ionization current, the measurement of the air-attenuation coefficient at the BIPM, the humidity correction and the physical constants. The two standards agree at the level of one standard uncertainty all all four radiation qualities.

The present results agree with those of 1978 to better than 10^{-3} in relative terms. This confirms the good stability of the two standards over a period of twenty years. For comparison, the present results are shown in Figure 1 together with the results of BIPM comparisons with other laboratories.

Table 3. Low-energy x-radiation qualities at the NPL and at the BIPM, and values for the NPL correction factors

Generating potential / kV		10	30	25	50
Al HVL / mm	NPL	0.036	- (1)	0.25	- (1)
	BIPM	0.036	0.176	0.250	2.257
μ_{air} (2) /m^{-1}	NPL	1.810	0.410	0.280	0.041
	BIPM	1.780	0.420	0.308	0.047
air-kerma rate / mGy s^{-1}	NPL	0.30	0.47	0.43	0.10
	BIPM	0.57	3.33	1.12	0.34
NPL correction factors					
k_{sc}	scattered radiation	0.9949	0.9968	0.9971	0.9982
k_e	electron loss	1.0000	1.0000	1.0000	1.0000
k_a (3)	air attenuation	1.1706	1.0379	1.0276	1.0042
k_s	ion recombination	1.0004	1.0015	1.0007	1.0000
k_d	field distortion	1.0002	1.0002	1.0002	1.0002
k_l	aperture transmission	1.0000	1.0000	1.0000	1.0000
k_p	wall transmission				
k_h	humidity	0.998	0.998	0.998	0.998
k_{pol}	polarity effect	1.0004	1.0004	1.0004	1.0004
$1-\bar{g}$	bremsstrahlung	1.0000	1.0000	1.0000	1.0000

(1) These qualities are not in routine use at the NPL. The NPL correction factors given have been interpolated as a function of HVL.

(2) Air-attenuation coefficient at 101 325 Pa and 20 °C.

(3) Correction at 101 325 Pa and 20 °C using the BIPM value for the air-attenuation coefficient.

Table 4. Estimated relative standard uncertainties associated with the NPL 50 kV standard when used at the BIPM

Component	Uncertainty (1) u_{iA}	u_{iB}
k_{sc} scattered radiation	-	0.0012
k_e electron loss	-	0.0001
k_a air attenuation (2)	0.0003	0.0001
k_s ion recombination	-	0.0003
k_d field distortion	-	0.0001
k_l aperture transmission	-	0.0001
k_p wall transmission		
k_h humidity	-	0.0006
k_{pol} polarity	-	0.0002
I ionization current	0.0003	0.0002
V volume	-	0.0015
quadratic summation	0.0021	

(1) u_{iA} represents the relative standard uncertainty estimated by statistical means (Type A).
u_{iB} represents the relative standard uncertainty estimated by other means (Type B).

(2) Determined for the present comparison qualites by the BIPM.

Table 5. Comparison results in the low-energy x-ray range

Generating potential / kV		10	30	25	50
$\dot{K}_{NPL}/\dot{K}_{BIPM}$	1978	0.9985	0.9986	0.9988	0.9989
	1997	**0.9983**	**0.9980**	**0.9995**	**0.9977**

4. Comparison of air-attenuation measurements

For this comparison, the air-attenuation correction for each standard was determined using the BIPM measurement of the air-attenuation coefficient, which employs a variable air-pressure tube located between the x-ray tube and the standard. This differs from the NPL method, which uses a special ionization chamber with two collecting plates separated by a known distance. Thus a comparison of the two methods was made for the 10 kV quality. For practical reasons, the distance between the x-ray tube and the reference plane during these measurements was 564 mm instead of 500 mm, and the air attenuation was measured over a distance of around 89 mm corresponding to the air path length of the NPL standard. The air-attenuation coefficients measured under these conditions by the NPL and BIPM methods are 1.700 m^{-1} and 1.714 m^{-1}, respectively, each with a standard uncertainty of 0.005 m^{-1}. This result demonstrates the reasonable agreement between the two methods.

5. Comparison in the medium-energy x-ray range

The NPL standard in the medium-energy x-ray range is a free-air chamber, the dimensions of which are given in Table 2 and the correction factors in Table 6. Two commercial ionization chambers, type NE 2561, were used for an indirect comparison of the NPL and BIPM standards at the radiation qualities given in Table 6. The polarizing voltage applied to the transfer chambers at each laboratory was 200 V (negative polarity).

Table 6. Medium-energy x-radiation qualities at the NPL and the BIPM, and the correction factors for the NPL standard

Generating potential / kV		100	135	180	220	250	280
Cu HVL /mm	NPL	0.15	0.50	1.0	2.0	-	4.0
	BIPM	0.148	0.494	0.99	-	2.50	-
μ_{air} (1) / 10^{-4} cm^{-1}	NPL	3.38	2.34	1.96	1.80	-	1.48
	BIPM	3.55	2.35	1.98	-	1.72	-
air-kerma rate / mGy s^{-1}	NPL	1.4	1.6	1.4	1.5	-	1.5
	BIPM	0.21	0.21	0.30	-	0.39	-
NPL correction factors							
k_{sc}	scattered radiation	0.9932	0.9945	0.9952	0.9960	-	0.9968
k_e	electron loss	1.0000	1.0000	1.0000	1.0008	-	1.0019
k_a (1)	air attenuation	1.0168	1.0116	1.0097	1.0089	-	1.0073
k_s	ion recombination	1.0007	1.0007	1.0007	1.0007	-	1.0007
k_d	field distortion	1.0003	1.0003	1.0003	1.0003	-	1.0003
k_l / k_p	aperture transmission / wall transmission	1.0000	1.0000	1.0000	1.0000	-	0.9978
k_h	humidity	0.9980	0.9980	0.9980	0.9980	-	0.9980
k_{pol}	polarity effect	1.0000	1.0000	1.0000	1.0000	-	1.0000
$1-\bar{g}$	bremsstrahlung	0.9999	0.9999	0.9998	0.9997	-	0.9997

(1) At 101 325 Pa and 20 °C.

The air-kerma calibration coefficient N_K for each transfer chamber is given by

$$N_K = \dot{K} / I_{trans} \qquad (2)$$

where $\dot{K}$ is the air-kerma rate determined by the standard and I_{trans} is the ionization current measured by the transfer chamber, normalized to the reference conditions (20 °C, 101 325 Pa and 50 % relative humidity). The current I_{trans} is not corrected for the non-uniformity of the beam. This effect should be small because the chamber size is similar to the aperture diameter. The air-kerma rate at the NPL, up to eight times larger than that at the BIPM, is still sufficiently low that volume recombination be neglibigle. Initial recombination is neglected since it will be the same at each laboratory.

The transfer chambers were calibrated on a number of occasions at the NPL both before and after the calibrations at the BIPM, at the reference qualities 100 kV, 135 kV and 180 kV. The comparison result for the 250 kV quality was derived by interpolation from NPL calibration coefficients for their 220 kV and 280 kV beam qualities. The leakage current, although less than 10^{-3} in relative value, was not constant in time and a leakage correction was applied. The relative standard uncertainty for a series of measurements at the BIPM was typically 3×10^{-4}.

The estimated relative standard uncertainty of the BIPM calibration coefficients is 2.2×10^{-3} [3]. The uncertainties for the NPL standard and calibration process are given in Table 7, which when combined with the uncertainty of the physical constants gives a total relative standard uncertainty of 3.4×10^{-3}. The relative standard uncertainty of the comparison result at each quality is also estimated to be 3.4×10^{-3}. This takes account correlations in the type B uncertainties associated with the humidity correction and the physical constants.

Table 7. Relative standard uncertainties associated with the NPL 300 kV primary standard and the calibration of transfer standards at the NPL

Component	Uncertainty	
Free-air chamber	u_{iA}	u_{iB}
k_{sc} scattered radiation	-	0.0012
k_e electron loss	-	0.0006
k_a air attenuation	-	0.0014
k_s recombination losses	-	0.0003
k_d field distortion	-	0.0001
k_l aperture transmission	-	0.0006
k_p wall transmission	-	0.0003
k_h humidity	-	0.0006
k_{pol} polarity	-	0.0002
I ionization current	0.0005	0.0009
V volume	-	0.0001
Calibration of transfer standard		
I ionization current	0.0005	0.0009
calibration procedure	-	0.0015
quadratic summation	0.0030	

The comparison results, expressed as the mean value $R_{K,\mathrm{NPL}}$ of the ratio of calibration coefficients $N_{K,\mathrm{NPL}} / N_{K,\mathrm{BIPM}}$, are given in Table 8, together with the results obtained in 1975 and 1982. For the present comparison, the standards agree at the level of one standard uncertainty for the 100 kV quality, rising to over two standard uncertainties for the 250 kV quality. This trend with radiation quality has been observed in certain comparisons with other laboratories, as can be seen in Figure 2 which summarizes the results of medium-energy comparisons with the BIPM. It can also be seen, to a lesser extent, in the NPL comparison results of 1975 and 1982. The three comparisons agree at the level of around 1×10^{-3}, except for the 250 kV quality which is closer to 2×10^{-3}. This demonstrates the good stability of the standards over a period of twenty years.

The NPL measurements for each chamber at each radiation quality before and after the BIPM measurements agree typically at the level of 1×10^{-3} in relative terms, which is consistent with the type A uncertainties, except for chamber 225 at 280 kV which changed by 5×10^{-3}. The comparison results for chamber 225 are higher than those for chamber 319 at all radiation qualities, by up to 4×10^{-3}. This is unusual given that they are of the same type and are stable at the level of 1×10^{-3}

(for the 100 kV, 135 kV and 180 kV qualities). Neglecting the suspect result for chamber 225 at 280 kV serves only to increase the observed progression with radiation quality.

Table 8. Calibration coefficients and comparison results in the medium-energy x-ray range

Transfer chamber	Laboratory	Radiation quality 100 kV	135 kV	180 kV	220 kV	250 kV	280 kV
NE 2561 serial number 319	NPL(1)	0.908	0.914	0.917	0.918	0.919(3)	0.920
	BIPM	0.9126	0.9200	0.9250	-	0.9278	-
	NPL(2)	0.909	0.913	0.918	0.917	0.918(3)	0.920
	NPL/BIPM	0.9955	0.9929	0.9919		0.9900	
NE 2561 serial number 225	NPL(1)	0.924	0.932	0.937	0.938	0.939(3)	0.942
	BIPM	0.9261	0.9363	0.9404	-	0.9461	-
	NPL(2)	0.924	0.932	0.936	0.939	0.941(3)	0.947
	NPL/BIPM	0.9977	0.9954	0.9959		0.9936	
Comparison results							
$R_{K,\text{NPL}}$	**1997**	**0.9966**	**0.9942**	**0.9939**	**-**	**0.9918**	**-**
	1975	0.9984	0.9950	0.9943	-	0.9956	-
	1982	0.9978	0.9941	0.9935	-	0.9935	-

(1) Mean of values measured before the BIPM calibrations.
(2) Mean of values measured after the BIPM calibrations.
(3) Value interpolated in terms of copper HVL.

6. Conclusions

The results for the low-energy comparison show the standards to be in agreement at the level of one standard uncertainty, a result which is consistent with the previous comparison of 1978. At medium energies a slight trend with radiation quality is evident, with agreement at the level of one standard uncertainty for 100 kV rising to over two standard uncertainties for 250 kV. The larger spread of the results at medium energies may be due, at least in part, to the indirect nature of the comparison and to the use of interpolation for the 250 kV quality.

References

[1] BIPM, Qualites de rayonnements, CCEMRI (Section I), 1972, 2, R15.

[2] BOUTILLON M., HENRY W. H., LAMPERTI P. J., Comparison of exposure standards in the 10 - 50 kV x-ray region, *Metrologia* 5, 1969, pp. 1-11.

[3] BOUTILLON M., Measurement conditions used for the calibration of ionization chambers at the BIPM, 1996, *Rapport BIPM*-96/1.

[4] BOUTILLON M., Mesure de l'exposition au BIPM dans le domaine des rayons x de 100 kV à 250 kV, 1978, *Rapport BIPM*-78/3.

[5] MARSH A. R. S., WILLIAMS T., 50 kV primary standard of exposure 1978 design of free-air chamber, 1982, *NPL Report* RS(EXT) 54.

[6] ANGLISS, R. F., PALMER, J. A., MORETTI, C. J., The 1996 primary standard of air kerma for 300 kV X-rays, *NPL report*, in preparation.

[7] MARSH, A. R. S., WILLIAMS, T. T., Comparison of exposure standards for x-rays generated between 10 and 50 kV, BIPM/NPL, CCEMRI(I)/79-6.

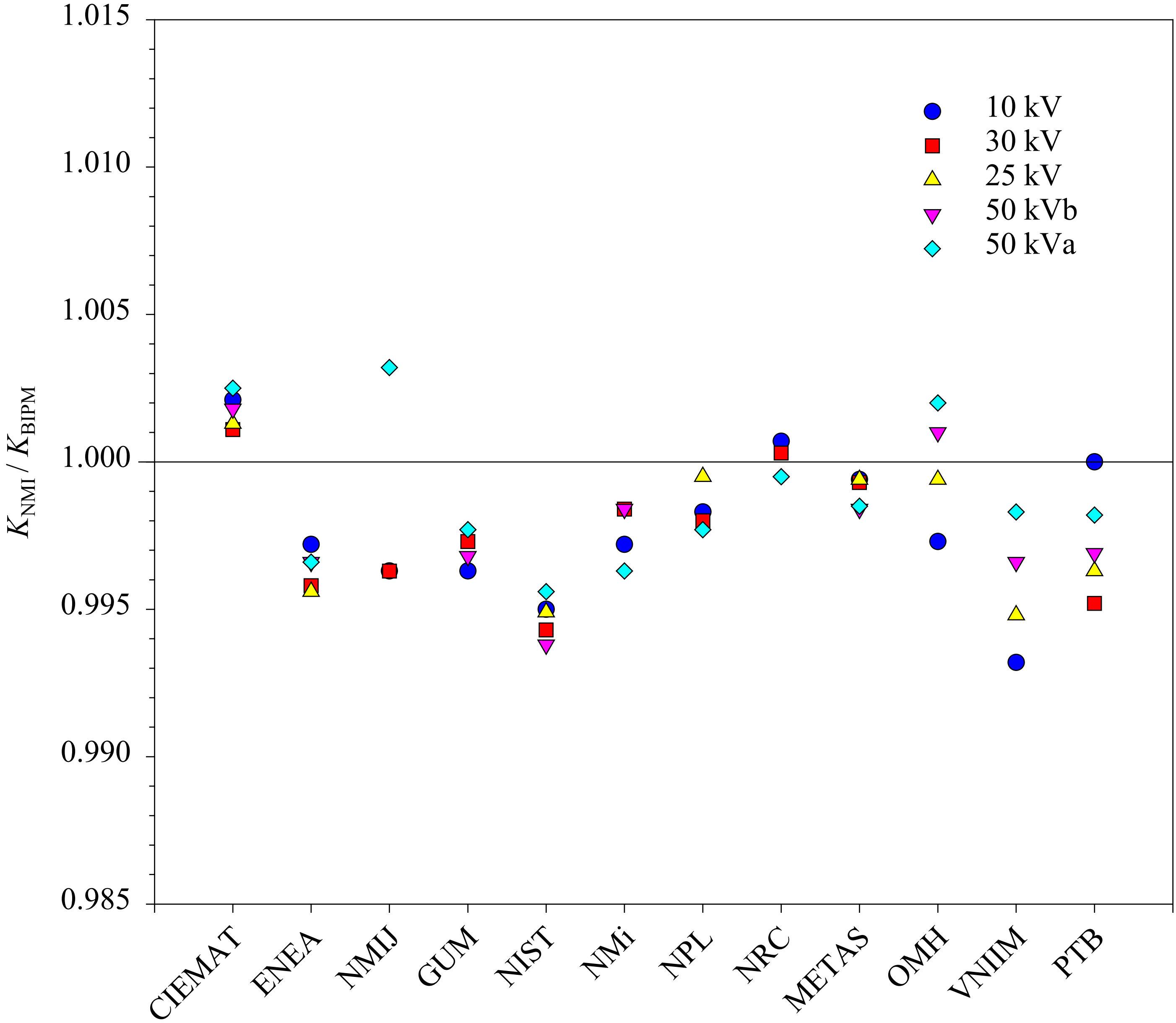

Figure 1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once at the BIPM, only the results of the most recent comparison are included.

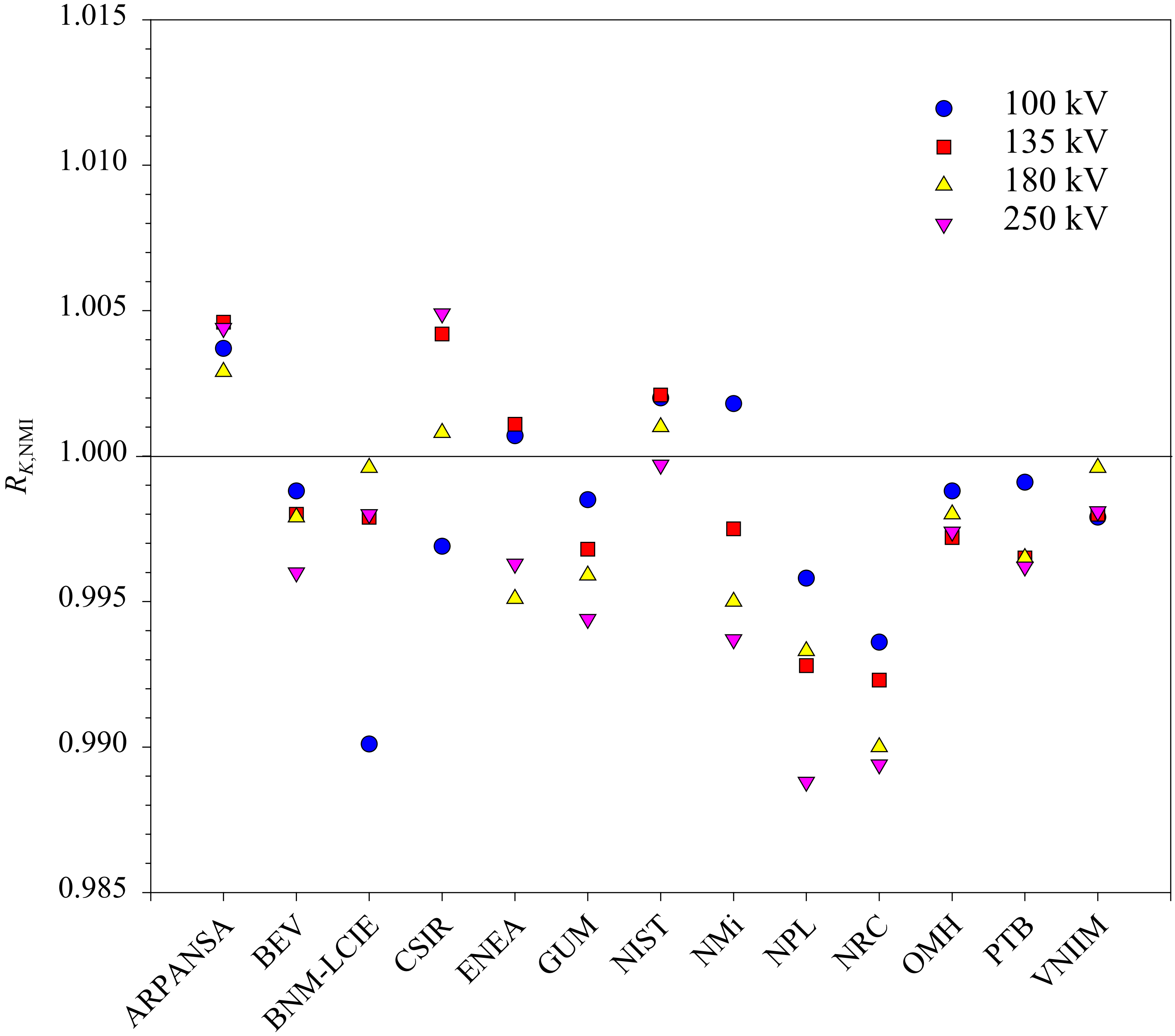

Figure 2. Results of BIPM medium-energy x-ray comparisons, expressed as the ratio $R_{K,\mathrm{NMI}}$ of the air-kerma rate detemined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once with the BIPM, only the results of the most recent comparison are included.