Interim report on NPL comparisons for BIPM.RI(I)-K2 and BIPM.RI(I)-K3

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1. Introduction

In 2007, two comparisons between the NPL and BIPM standards were carried out, a direct comparison in the series BIPM.RI(I)-K2 using the NPL free-air chamber transported to the BIPM and an indirect comparison in the series BIPM.RI(I)-K3 using two NE2611 transfer chambers belonging to the NPL, calibrated at both laboratories. Additional comparison measurements were made in the low-energy beams using two PTW23344 chambers belonging to the NPL. For a number of reasons, including personnel issues and the re-evaluation of correction factors for the NPL standard, the data analysis was greatly delayed and comparison reports were not prepared at the time. Consequently, the results for the NPL that currently appear in the BIPM KCDB are those for the comparisons in 1997, duly annotated as being more than 15 years old. The 1997 comparisons are reported in Boutillon *et al* (2002).

New comparisons are scheduled for October 2017 and it is the results of the 2017 comparisons that will be used to update the KCDB. The present interim report, approved by the CCRI(I), is not prepared with the rigour and detail of a full comparison report, but is intended to summarize the 2007 results in advance of the 2017 comparisons.

Details of the BIPM standards, correction factors, uncertainties and measurement procedures are given in the comparison reports for the two series', see for example Burns *et al* (2014) for the low-energy comparison and Burns *et al* (2015) for medium energies. Details of the NPL standards, which are the same as those used in 1997, are given in Table 1.

Table 1. Main dimensions of the NPL standards

Dimension	Low-energy free-air chamber	Medium-energy 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

2. Comparison BIPM.RI(I)-K2 for low-energy x-rays

The NPL free-air chamber was positioned on two separate occasions in the BIPM reference beam and the ionization current measured using the BIPM measurement system. The correction factors for the NPL standard at the BIPM qualities, which are essentially those used in 1997 with the addition of the fluorescence correction k_{fl}, are given in Table 2 and the NPL uncertainties in Table 3. Note that all BIPM measurements from 2007 are corrected for the changes made to the BIPM standards in 2009 (Burns *et al* 2009).

Table 2. NPL low-energy correction factors[1]

Radiation quality		10 kV	30 kV	25 kV	50 kVb	50 kVa
Al HVL / mm	NPL	0.036	-	0.25	-	-
	BIPM	0.037	0.169	0.242	1.017	2.262
k_a air attenuation[2]		1.1710	1.0398	1.0282	1.0081	1.0040
k_{sc} scattered radiation		0.9949	0.9968	0.9971	0.9979	0.9982
k_{fl} fluorescence		0.9951	0.9963	0.9966	0.9978	0.9983
k_e electron loss		1.0000	1.0000	1.0000	1.0000	1.0000
k_s ion recombination		1.0006	1.0006	1.0006	1.0006	1.0006
k_{pol} polarity effect		1.0004	1.0004	1.0004	1.0004	1.0004
k_d field distortion		1.0002	1.0002	1.0002	1.0002	1.0002
k_l aperture transmission k_p wall transmission		1.0000	1.0000	1.0000	1.0000	1.0000
k_h humidity		0.998	0.998	0.998	0.998	0.998
1-g bremsstrahlung		1.0000	1.0000	1.0000	1.0000	1.0000

[1] The 30 kV, 50 kVb and 50 kVa qualities are not in routine use at the NPL. The NPL factors for 30 kV and 50 kVa, interpolated as a function of HVL, are those used for the 1997 comparison (Boutillon *et al*, 2002). Those for 50 kVb have been interpolated for the present report.
[2] Air-attenuation correction at 101 325 Pa and 20 ºC.

Table 3. Relative standard uncertainties associated with the NPL low-energy standard when used at the BIPM

Component	Uncertainty[1]	
	u_{iA}	u_{iB}
k_a air attenuation[2]	0.0002	0.0001
k_{sc} scattered radiation	-	0.0010
k_{fl} fluorescence	-	0.0005
k_e electron loss	-	0.0001
k_s ion recombination	-	0.0003
k_{pol} polarity	-	0.0002
k_d field distortion	-	0.0001
k_l aperture transmission k_p wall transmission	-	0.0001
k_h humidity	-	0.0005
I ionization current	0.0002	0.0002
V volume	-	0.0015
Air density	-	0.0001
W_{air}/e	-	0.0015
Combined uncertainty	0.0003	0.0025

[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] Values corresponding to the use of the NPL standard at the BIPM.

The results of the direct comparison, expressed as the ratio $K_{\mathrm{NPL}}/K_{\mathrm{BIPM}}$, are given in Table 4. Also shown in the table are the results for the indirect comparison $N_{K,\mathrm{NPL}}/N_{K,\mathrm{BIPM}}$ using each of the two transfer chambers, corrected for the difference in HVL at the two laboratories (k_Q = 0.9996 and 10 kV and k_Q = 1.0008 at 25 kV). Calibration coefficients were supplied by the NPL for the 10 kV and 25 kV qualities only, as the other BIPM qualities are not in routine use at the NPL. The stated standard uncertainty for the NPL calibration coefficients is 0.6 %, and removing correlation the indirect results have a standard uncertainty also of around 0.4 %.

Table 4. Low-energy comparison results

Radiation quality		10 kV	30 kV	25 kV	50 kVb[3]	50 kVa
Direct result $K_{\mathrm{NPL}}/K_{\mathrm{BIPM}}$		0.9910	0.9922	0.9930	0.9936	0.9938
Indirect result $k_Q\, N_{K,\mathrm{NPL}}/N_{K,\mathrm{BIPM}}$	PTW23344-0791	0.9959	-	0.9965	-	-
	PTW23344-0792	0.9956	-	0.9966	-	-
1997 result (as given in KCDB)		*1.0011*	*0.9997*	*1.0014*	-	*0.9993*
1997 result (including k_{fl})		*0.9962*	*0.9960*	*0.9980*		*0.9976*

While the indirect results for the two transfer chambers are self-consistent, they differ from the results of the direct comparison by around 0.4 %. Moreover, the indirect results are closer to the results of the 1997 comparison when the latter are corrected for the fluorescence correction given in Table 2 (which was not applied in 1997), as shown in the final row of Table 4. The corrected results from 1997 and those of the 2007 indirect comparison indicate a stability of better than 0.2 %.

3. Comparison BIPM.RI(I)-K3 for medium-energy x-rays

Calibration coefficients were determined under reference conditions at each laboratory. The NPL radiation qualities and correction factors are given in Table 5 and the NPL uncertainties in Table 6. Note that the NPL has not implemented the 250 kV quality and the comparison result for this quality is derived by interpolation (in terms of HVL) from the $N_{K,\mathrm{NPL}}$ values for the NPL 220 kV and 280 kV qualities.

The results, expressed as the ratio $k_Q\, N_{K,\mathrm{NPL}}/N_{K,\mathrm{BIPM}}$, where k_Q is the correction for differences on HVL (at most 0.02 %), are given in Table 7 for the indirect comparison using each of the two transfer chambers. The final row of Table 7 shows the results of the 1997 comparison as they appear in the KCDB. The results for the two transfer chambers are consistent at the 0.1 % level. However, while the NPL and BIPM standards agree well at the 100 kV and 135 kV qualities, there is evidence of some deviation at higher energies that is not present in the results of the 1997 comparison.

Table 5. NPL and BIPM medium-energy radiation qualities and NPL correction factors

Radiation quality		100 kV	135 kV	180 kV	220 kV	250 kV	280 kV
Cu HVL / mm	NPL	0.15	0.50	1.0	2.0	-	4.0
	BIPM	0.149	0.489	0.977	-	2.484	-
k_a air attenuation[1]		1.0168	1.0116	1.0097	1.0089	-	1.0073
k_{sc} scattered radiation		0.9932	0.9945	0.9952	0.9960	-	0.9968
k_{fl} fluorescence		1.0000	1.0000	1.0000	1.0000	-	1.0000
k_e electron loss		1.0000	1.0000	1.0000	1.0008	-	1.0019
k_s ion recombination		1.0007	1.0007	1.0007	1.0007	-	1.0007
k_{pol} polarity effect		1.0000	1.0000	1.0000	1.0000	-	1.0000
k_d field distortion		1.0003	1.0003	1.0003	1.0003	-	1.0003
k_l aperture transmission k_p wall transmission		1.0000	1.0000	1.0000	1.0000	-	1.0000
k_h humidity		0.9980	0.9980	0.9980	0.9980	-	0.9980
1-g bremsstrahlung		0.9999	0.9999	0.9998	0.9997	-	0.9997

[1] Air-attenuation correction at 101 325 Pa and 20 ºC.

Table 6. Relative standard uncertainties associated with the NPL medium-energy standard and the calibration of transfer standards at the NPL

Component	Uncertainty	
Free-air chamber	u_{iA}	u_{iB}
k_{sc} scattered radiation	-	0.0010
k_e electron loss	-	0.0005
k_a air attenuation	-	0.0013
k_s recombination losses	-	0.0003
k_d field distortion	-	0.0001
k_l aperture transmission	-	0.0005
k_p wall transmission	-	0.0003
k_h humidity	-	0.0005
k_{pol} polarity	-	0.0002
k_{fl} fluorescence	-	0.0015
f_{elec} Electrometer current calibration	-	0.0010
R Repeatability	0.0010	-
V volume	-	0.0001
Calibration of transfer standard		
f_{elec} electrometer current calibration	-	0.0015
R repeatability	0.0010	-
T temperature	-	0.0007
p pressure	-	0.0002
I_l leakage current	0.0005	-
d distance	-	0.0002
Combined uncertainty	0.0015	0.0031

Table 7. Medium-energy comparison results

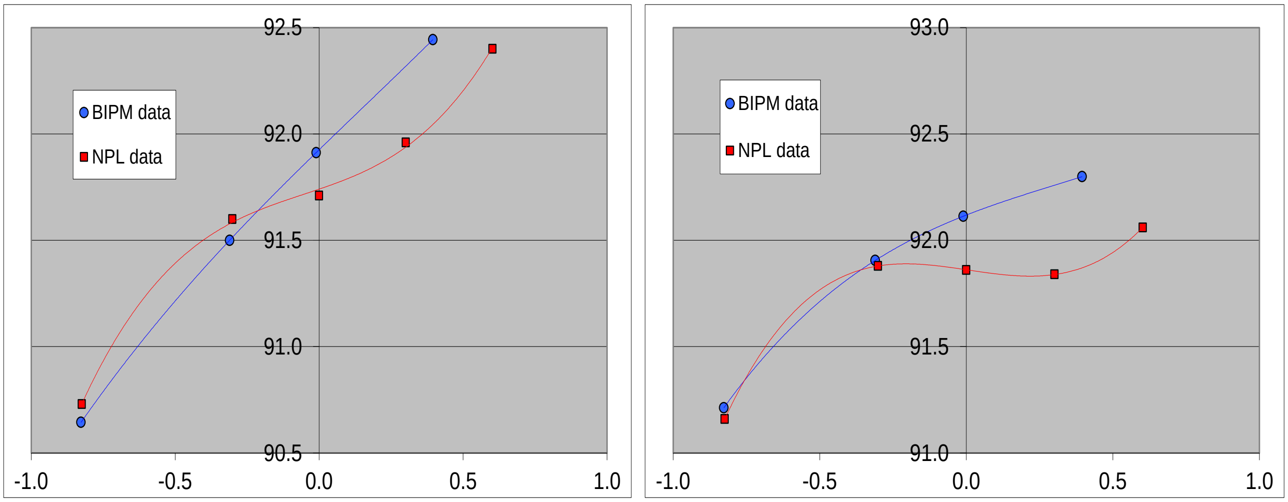
Radiation quality		100 kV	135 kV	180 kV	250 kV
Indirect result $k_Q\, N_{K,\mathrm{NPL}}/N_{K,\mathrm{BIPM}}$	NE2611-131	1.0009	1.0009	0.9977	0.9957
	NE2611-163	0.9994	0.9996	0.9972	0.9954
1997 result (as given in KCDB)		*0.9999*	*1.0005*	*1.0013*	*0.9993*

4. Summary

At low energies, the results of the indirect comparison show the NPL and BIPM standards to agree at the level of around 0.4 %, which is within the standard uncertainty of the comparison of around 0.6 %. The results are in agreement to better than 0.2 % with those of the 1997 comparison when account is taken of changes to correction factors at both laboratories. In contrast, the results of the direct comparison show the standards to differ by about 0.8 %, which is more than the expanded uncertainty (k = 2) of around 0.6 % for the direct comparison. No reason has been found for the difference between the direct and indirect comparisons. It might be postulated that there was a problem when using the NPL free-air chamber at the BIPM, although the chamber behaviour was stable and reproducible and gave no indication of a problem.

At medium energies there is good agreement between the NPL and BIPM standards at the 100 kV and 135 kV qualities, and good agreement with the 1997 comparison results. Agreement is less good for the 180 kV and 250 kV qualities, while still remaining well within the expanded uncertainty (k = 2) of around 0.6 %. Given that all NPL correction factors are the same as those used in 1997, there is no obvious reason why the 180 kV and 250 kV qualities show such behaviour.

It is interesting to present the medium-energy calibration coefficients graphically, as a function of log(HVL), as shown in Figure 1 for the two NE2611 chambers. While the BIPM results show the smooth behaviour typically seen for this chamber type, the NPL results have a curious form at the higher energies, particularly the right-hand plot for chamber NE2611-163. From these data alone it is not possible to determine if this unusual behaviour arises from the chamber calibrations or from the air-kerma determinations using the primary standard. One aspect that did arise during discussion is that thimble chamber orientation was not controlled at the NPL for these calibrations, whereas the BIPM procedure is to use a reference orientation for all calibrations. However, this is not likely to result in the observed behaviour.



NE2611-131 NE2611-163

Figure 1. Calibration coefficients (in Gy μC^{-1}) for the NE2611 chambers as a function of log(HVL). Blue circles are the BIPM data, red squares the NPL data and the solid lines cubic fits to each data set.

References

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