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PRELIMINARY CHARACTERIZATION OF THE NIS FREE-AIR CHAMBER STANDARD AT THE BIPM

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Preliminary characterization of the NIS free-air chamber standard at the BIPM

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1 Introduction

In the context of a joint project to set up a primary standard for medium-energy x-rays at the National Institute of Standards (NIS), Egypt, the free-air chamber standard of the NIS (a Victoreen Model 480 cylindrical chamber, serial number 111) was transported to the BIPM for measurements during the period 15 to 26 January 2009. All measurements were made using calibrated devices belonging to the BIPM, notably the ionization current measurement system, micrometers and callipers. This report presents the results of the measurements made at the BIPM and makes recommendations for the next stage of the project which will be the installation of the chamber at the NIS.

2 Chamber positioning

The size and mass (around 150 kg) of the chamber prevented it from being positioned on the BIPM measurement rails and it was therefore positioned downstream of the measurement table. A hydraulic lifting device was used to support the chamber throughout the measurement period. A small hydraulic leak resulted in a drop in the chamber position of around 2 mm over the course of each working day. The height was therefore reset to be 1 mm too high each morning. This variation in height during the day, although not normally acceptable for primary measurements, was considered acceptable for the present characterization.

The BIPM beam axis is horizontal and so the chamber was set horizontal using a spirit level referenced to the rails on either side of the chamber body. These rails were also used to set the chamber angle in the horizontal plane, using a spirit level incorporating a laser pointer. In setting up the chamber in its definitive position at the NIS, the aim should be to have the chamber axis parallel to the beam axis with a tolerance of around 1 mm over the chamber length.

After these angular adjustments, the chamber position in the horizontal plane was set to within about 0.2 mm. The chamber distance was then measured. With the diaphragm thickness measured as 13.7 mm and the length of the conical section as 1.3 mm, the distance from the source to the reference plane was measured to be 2027.3 mm (although, because of the inherent instability of the hydraulic support, the distance for the NIS chamber was not stable at the level of 0.1 mm).

3 Polarizing potential and polarity correction

Using data provided by the NIS for the chamber response as a function of polarizing potential, a value of 1000 V was chosen for the polarizing potential. In retrospect, this value is lower than ideal, resulting in non-linear behaviour and a significant correction for ion recombination (see Section 3). An identical chamber at the ENEA, Italy [1], uses a potential of 5000 V. If the potential is not limited by the choice of power supply at the NIS, it is strongly recommended to operate at the higher potential of 5000 V.

Measurements at +1000 V and –1000 V in the BIPM 100 kV reference beam, with a delay of approximately fifteen minutes after changing polarity, showed the polarity effect to be negligible within the standard uncertainty of the measurement of around 0.01 %. It is recommended that routine measurements at the NIS are made with a positive polarizing potential and a component of 0.01 % be considered as a standard uncertainty for inclusion in the uncertainty budget. This avoids regular changes in the sign of the polarizing potential and should result in better stability through the day.

4 Ion recombination and the saturation correction k_s

The method preferred at the BIPM to determine the saturation correction is described by Boutillon [2] and the same method is recommended for use by the NIS. This involves ionization current measurements at two potentials, V and V/n, where V is the normal polarizing potential (here, 1000 V) and n is typically between 2 and 4. The current ratio $R = I_V / I_{V/n}$ is evaluated, where I_V and $I_{V/n}$ are each corrected for air temperature and pressure. This procedure is then repeated for different values of the air-kerma rate, which are achieved preferably by changing the anode current, but can also be achieved using different filtrations.

The result is a series of values R, which can be plotted as a function of $I_{V,\mathrm{uncorr}}$. It is important to note here that $I_{V,\mathrm{uncorr}}$ is the ionization current *measured* at the potential V, that is, the raw ionization current before correction for temperature, pressure, attenuation, etc. Measurements should be made for four or five air-kerma rates, ideally as low as half of the reference air-kerma rate and as high as twice the reference air-kerma rate. A plot of R against $I_{V,\mathrm{uncorr}}$ should be linear. The intercept of a linear fit to this data is denoted a_0 and the gradient is a_1. Then the recombination coefficients k_init and k_vol (representing initial and volume recombination, respectively) are derived using

$$k_\mathrm{init} = (a_0 - 1) / (n - 1) \qquad (1)$$

and $$k_\mathrm{vol} = a_1 / (n^2 - 1). \qquad (2)$$

When used subsequently at the polarizing potential V in a beam that results in an ionization current that day denoted $I_{V,\mathrm{day}}$, the correction for ion recombination is derived using

$$k_\mathrm{s} = 1 + k_\mathrm{init} + k_\mathrm{vol}\, I_{V,\mathrm{day}} \qquad (3)$$

(Note that the units used for $I_{V,\mathrm{day}}$ must be consistent with those used to evaluate k_vol.)

Measurements were made at the BIPM at an x-ray generating potential of 100 kV using $V = +1000$ V and $V/n = +400$ V, (i.e. $n = 2.5$), and for four air-kerma rates (obtained using two values of anode current, each with and without the usual 100 kV filtration). Strictly, measurements should be made with both polarizing potentials, but as noted in Section 3 the polarity effect was measured to be negligible (this was also verified at 400 V). The results are shown in Figure 1 for the collapsed [2,2] and expanded [15,15] chamber configurations. (In this notation, the first number refers to the position setting of the front cylinder and the second number to the rear cylinder.)

A non-linearity is seen in both data sets, which is unusual and results in negative, non-physical values for k_init (although not when the uncertainties arising from the linear fits are taken into account). This non-linear behaviour might be a further indication that the polarizing potential of 1000 V is too low (it is commonplace to employ a value of around 200 V cm^{-1}) and it is strongly recommended that a higher value (up to 5000 V) is used at the NIS. The method described here should be used to determine k_s for the higher polarizing potential. The NIS should also verify whether the polarity effect remains negligible at higher polarizing potentials.

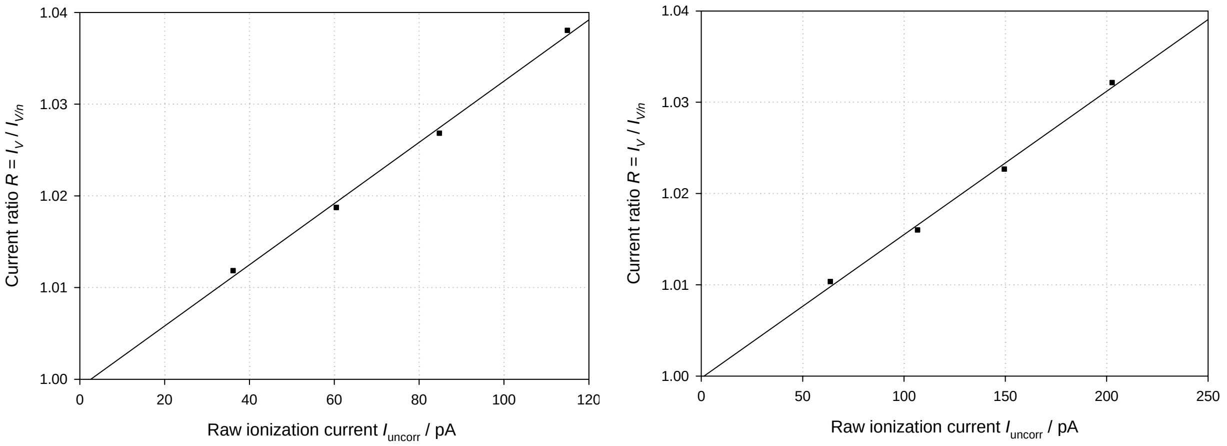

Figure 1 Measurement of ion recombination using the method described by Boutillon [2], for the NIS standard in the collapsed (left) and expanded (right) configurations, using the pair of polarizing potentials 1000 V and 400 V. The parameters of each linear fit $y = a_1x + a_0$ are used to determined the recombination coefficients k_{init} and k_{vol}. Note that there is evidence of curvature in the data and the use of higher polarizing potentials is strongly recommended.

When repeated at the NIS these measurements should include the other relevant chamber configurations (only those that keep the chamber centre at 40.46 cm from the aperture are important). The uncertainty should be evaluated and is likely to be dominated by the statistical uncertainty of the linear fit parameters a_0 and a_1. Note that ion recombination depends only on the ionization current, not on the beam quality, and therefore the results of a single, careful set of measurements for the relevant chamber configurations can be used for all the reference beams at the NIS.

5 Air attenuation correction k_a

The maximum movement possible is between the pair of settings [15,0] and [0,15], which moves the air cylinder by 15 cm, that is, around one third of the attenuation length under reference conditions (40.46 cm). Initial measurements of k_a for the BIPM 100 kV quality differed by 0.3 % from the value determined using the BIPM air-attenuation coefficient ($k_a = 1.0141$). Repeat measurement showed this determination to be unstable and further investigation highlighted two problems. Firstly, the true cylinder length at [15,0] is 0.1 % greater (that is, 0.5 mm) from that at [0,15], which results in a systematic error. Secondly, there is some variability in repeat settings of a given position which is typically 0.2 mm to 0.3 mm and can be up to 1 mm in the worst case. In effect, the position locking mechanism is no longer reliable. This arises mainly because the mechanism acts only on one of the two rails on which the cylinders move. This results in some mechanical ‘play’ in the cylinder positions and can even cause a slight skewing of the cylinders (so that they are no longer perfectly concentric). Pushing the two cylinders together by hand eliminates this play, although this is not normally possible because of the presence of the top cover and the applied potential.

One solution to these problems is to *measure* the cylinder length L using a suitable calliper. Since positioning is not sufficiently repeatable, the ionization current and calliper measurements for a given position must be made without disturbing the position. This is complicated by the fact that the calliper measurement cannot be made with the polarizing potential on the chamber. The following sequence is recommended:

a) Pre-irradiate the chamber, with polarizing potential applied, for at least 30 minutes.

b) Close the beam shutter, remove the polarizing potential and the chamber top cover.

c) Set position [15,0] and measure L_0 several times with a calliper (approximately 670 mm).

d) Replace cover, apply polarizing potential, pre-irradiate for 15 minutes and measure I_0.

e) Close the shutter and set position [0,15] (keeping the polarizing potential applied).

f) Pre-irradiate for 5 minutes then measure the reduced current I_1.

g) Close the shutter, remove the polarizing potential and top cover and measure L_1.

The corrected current ratio is then

$$R = (I_0/I_1) \,/\, (L_0/L_1) \tag{4}$$

and the linear air-attenuation coefficient is evaluated as

$$\mu = \ln(R) \,/ L_{\mathrm{eff}}, \tag{5}$$

where L_{eff} is the 15 cm air path corrected for air density, that is,

$$L_{\mathrm{eff}} = 15 \times (P/P_0) \times (T_0/T) \text{ cm} \tag{6}$$

(T_0 and P_0 being the reference values 293.15 K and 101.325 kPa).

The attenuation correction to be applied to any particular series of measurements is

$$k_{\mathrm{a}} = \exp(\mu L_{\mathrm{cor}}), \tag{7}$$

where L_{cor} is the reference attenuation length L_{ref} = 40.46 cm corrected for the temperature and pressure at the time of the measurements using an equation similar to (6).

This measurement sequence was followed using the NIS chamber in the BIPM 100 kV beam and resulted in the value μ = 0.000 343 cm^{-1}, compared to the reference value μ = 0.000 345 cm^{-1}. Over the length 40.46 cm, the NIS measurement gives k_{a} = 1.001 40, compared to the BIPM determination k_{a} = 1.001 41. These agree within the statistical standard uncertainty of the NIS determination, which is estimated to be 0.05 %.

It is thereby demonstrated that the NIS chamber has the capability to measure the air-attenuation correction at the level of around 0.05 %, but it is critical that the actual chamber length is known for each current measurement, for example using the measurement sequence described above. These measurements should be straightforward to achieve at the NIS, provided the radiation output and current measurement system are sufficiently stable.

6 Photon scatter, electron loss and fluorescence

The chamber design contains an internal ‘equilibrium’ wall, and this together with the differential nature of the measurement makes the correction for photon scatter, k_{sc}, far from straightforward. The ENEA (Italy) has a Victoreen 480 standard and in their report [1] give values for k_{sc} and the electron loss correction, k_{e}, based on early experimental work and incorporating a correction for the shadow effect of the collecting electrode. The values are given in the third and fourth columns of Table 1 for each of the three x-ray generating potentials and their combined standard uncertainty is given as 0.15 %. A subsequent work [3] gives values for the same ENEA standard that differ by up to 0.2 %, as shown in the fifth column, but with the same standard uncertainty. However, the detail of both evaluations is lacking. Strictly, the NIS needs to evaluate each correction factor for the collapsed chamber [2,2] and for the expanded chamber [15,15] to determine the net effect on the differential air-kerma determination.

The results for k_{sc} given by Burns [4] are calculated for parallel-plate chambers with no internal wall and consequently cannot easily be used to provide estimates for the NIS cylindrical chamber. Nevertheless, this reference can provide information on the systematic behaviour with changes in chamber dimensions. For example, k_{sc} is observed to vary with the axial length L over which scattered photons can be generated and with the lateral dimensions d and w of the collecting volume (d is the electrode spacing and w is the collecting electrode width). This data for k_{sc} has been conveniently parameterized in Figure 4 of reference [5] by introducing an empirical parameter P which is a function of L, d and w. For a cylindrical chamber of diameter 30 cm, it might be appropriate to take $d = w = 26.6$ cm, which represents a square with the same area.

Table 1 Estimates of the photon gain and electron loss corrections.

Generating Potential / kV	Cu HVL / mm	k_{sc} ref [1]	k_e ref [1]	$k_{sc}\, k_e$ ref [3]
100	0.15	0.9949	1.0000	0.993
135	0.50	0.9956	1.0008	0.995
180	1.00	0.9958	1.0016	0.996

For k_e, the lateral dimensions d and w (each taken as 26.6 cm) are the dominant parameters and in this respect the NIS standard falls between the standards of the NRC (Canada) and the GUM (Poland). One can therefore deduce from [4] the values 1.0000, 1.0002 and 1.0012 for 100 kV, 135 kV and 180 kV, respectively. However, these values do not take account of the fact that in the cylindrical chamber design electrons can stop in the collecting rod.

Reference [4] also gives calculated values for the fluorescence correction factor k_{fl} that are largely independent of chamber dimensions, the values being 0.9983, 0.9991 and 0.9994 for these same three radiation qualities (standard uncertainty 0.03 %). These values have been used for the pilot study described in the present report.

The NIS should consider all of the available information in arriving at the best estimates for these three sets of correction factors for their radiation beams, and their uncertainties, and might also consider making Monte Carlo calculations for their chamber design (a collaboration with the ENEA might prove fruitful). For the purpose of the present pilot study, the combined values given in reference [1] and noted in columns three and four of Table 1 have been used.

7 Other correction factors

A number of other correction factors need to be considered for the determination of air kerma. These are described below and the values used for the present study are summarized in Table 2.

Field distortion

The operating principle of the parallel-plate design renders it sensitive to the uniformity of the electric field in the collecting region. In contrast, the variable-volume cylindrical chamber is a differential technique that does not depend on field uniformity. Consequently, there is no need to correct for field uniformity.

Diaphragm corrections

Traditionally, only a correction for transmission through the aperture edge, k_l, has been applied. Recent Monte Carlo calculations for the BIPM standard [6] have included corrections for photon scattering from the inner wall of the diaphragm and fluorescence produced in the diaphragm. The largest effect observed is 0.09 % at 180 kV, but it is not straightforward to estimate the magnitude of the effect for the NIS standard and experimental arrangement, particularly as the chamber has an internal wall. In the absence of more specific information, an acceptable solution might be to apply a correction factor of 0.9995 for all three radiation qualities, with an estimated standard uncertainty of the order of 0.05 %.

Wall transmission

Transmission of radiation through the chamber walls, in particular the front wall, is normally very small for radiation qualities up to 180 kV. The value for the ENEA standard at 180 kV is 0.02 %. The effect of any wall transmission can be measured by blocking the aperture with an appropriate thickness of lead or other suitable material. When making these measurements at the NIS, it is important to distinguish the effect of transmitted radiation from the usual leakage current, which is not negligible for this chamber. For example, when using the NIS chamber at the BIPM, a leakage current of typically 0.12 pA was measured. Compared with the maximum measurement current of 120 pA, this is a relative effect of around 0.1 %, which is significantly larger than the expected wall transmission. An alternative solution for the NIS is to set the wall transmission correction factor, k_p, to unity and to include a standard uncertainty component of at least 0.02 %.

Table 2 Correction factors and uncertainties employed for the pilot study of the NIS standard at the BIPM.

	Generating potential / kV			Standard uncertainty	
Correction factor	100	135	180	u_A / %	u_B / %
Air attenuation k_a[a]	1.0140	-	-	0.05	-
Ion recombination k_s[b]	1.0037	-	-	0.08	-
Polarity k_{pol}	1.0000	1.0000	1.0000	0.01	-
Scattered radiation k_{sc}	0.9949	0.9956	0.9958	-	0.15
Electron loss k_e	1.0000	1.0008	1.0016	-	
Fluorescence k_{fl}	0.9983	0.9991	0.9994	-	0.03
Diaphragm corrections k_{dia}	0.9995	0.9995	0.9995	-	0.05
Wall transmission k_p	1.0000	1.0000	1.0000	-	0.02
Equilibrium wall k_{wall}	1.0073	1.0050	1.0040	-	0.10
Bremsstrahlung $(1–g)$	0.9999	0.9999	0.9999	-	0.01
Humidity correction k_h	0.9980	0.9980	0.9980	-	0.03
Combined uncertainty				**0.09**	**0.19**

a The attenuation coefficient will be different at the NIS and, depending on the method used and the stability of the measurement system and radiation beam, the uncertainty is also likely to be different.

b This is the value for the collapsed cylinder and a polarizing potential of 1000 V. A higher potential is strongly recommended, which should have the effect of reducing both the correction and the uncertainty.

Effect of equilibrium wall

The Victoreen chamber design includes an entrance window on the front cylinder, described in the chamber documentation as an ‘equilibrium wall cover’. The stated purpose of this wall is to provide sufficient build-up material to establish electronic equilibrium. For radiation qualities up to 180 kV, this window is probably not required, but it cannot be removed and has the advantage of helping to keep the inside of the chamber free from dust and other contamination.

Correction factors for the attenuation that takes place in this wall are provided in the chamber documentation as a function of HVL. From these data, the following values for the correction factor, k_{wall}, are interpolated: 1.0073 at 100 kV, 1.0050 at 135 kV and 1.0040 at 180 kV. As the wall material and thickness are not given, these estimates cannot be verified at present and a standard uncertainty of 0.1 % is adopted here. More specific information on the window obtained by the NIS from the instrument supplier would enable this uncertainty to be reduced.

Bremsstrahlung production

The bremsstrahlung correction $(1–g)$ was included in the calculations of Burns [4], modified for the fact that some of the bremsstrahlung produced is reabsorbed. These results indicate that the value 0.9999 can be used up to 180 kV, with a standard uncertainty of 0.01 %.

Humidity correction

The correction for humidity is linked to the value used for the air density in the air-kerma determination. It is common practice to adopt the value 1.2045 mg cm^{-3} for the density of dry air at 20 °C and 101.325 kPa. The use of this dry-air value requires a correction for the presence of water vapour in the air of the standard. Information on the required correction factor, k_{h}, is given in Section 5.6 of ICRU Report 31 [7]. For a relative humidity in the range from 40 % to 60 %, the correction factor 0.9980 is appropriate for medium-energy x-rays, with a standard uncertainty of 0.03 %. Relative humidity beyond this range is avoided in many standards laboratories by active control of the humidity. If this is not possible at the NIS and measurements must proceed when the relative humidity is outside of this range, the data in [7] should be used to derive the appropriate humidity correction, different from the value 0.9980, with an appropriate uncertainty.

8 Measurement of air-kerma rate

While a differential measurement of air-kerma rate can be made by using only the collapsed and expanded configurations, a more accurate estimate, and a better understanding of the uncertainties, can be achieved by making measurements at all seven of the available configurations and applying a linear fit to these data. For these measurements, it is impractical to combine the length and ionization measurements as this requires repeatedly removing and applying the polarizing potential. The measurement therefore takes place in two stages. Firstly, a mean value of the chamber length is determined for each configuration based on a series of length measurements, each length being measured several times (and perhaps with more than one calliper). Subsequently, the ionization current is measured for each configuration.

As noted in Section 5, variations in the chamber length for a given configuration arise from the fact that the position locking mechanism acts only on the nearside supporting rail. The NIS should examine whether the mechanical play in the farside rail can be reduced and might consider implementing a system that directly measures the cylinder displacements (mechanical and optical systems of this type are available commercially). Variations of typically 0.2 mm or 0.3 mm were observed at the BIPM, and in the worst case a 1 mm variation was measured. These variations give rise to a statistical uncertainty in the air-kerma determination that might be unacceptably large if one or more of the configurations adopts a 'skewed' position.

In view of this, it is advisable during the ionization current measurements to plot the data and observe the goodness of the linear fit while the measurements are in progress. In this way, any point which is observed to have a significant deviation can be repeated. More robust data, with a lower uncertainty, could be achieved by measuring each configuration more than once, although such a measurement series would be limited by the stability of the x-ray source (or beam monitoring) over the duration of the measurements. For both the length measurements and the ionization current measurements, the order in which the configurations are measured should be randomized. For the length measurements, this randomizes the sense of the mechanical play, while for the current measurement this also randomizes the effect of drift in the x-ray output or beam monitoring.

A single set of seven measurements was made for the 100 kV beam at the BIPM, at a distance of 2.027 m from the x-ray source (no BIPM determination of the air-kerma rate exists at this location). The results are shown in Figure 2.

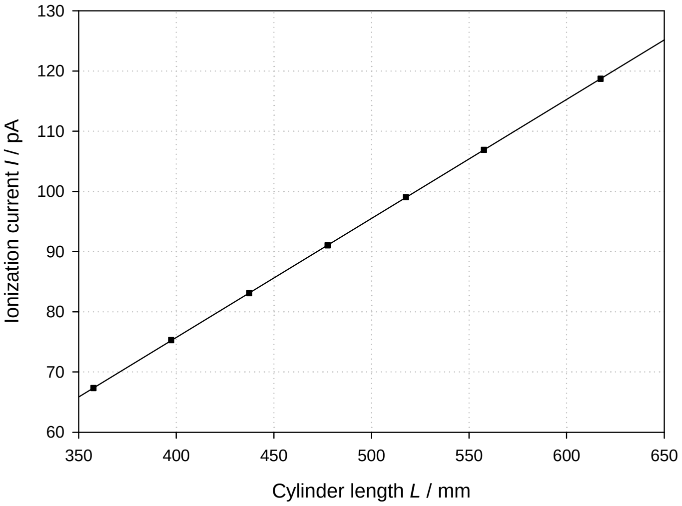

Figure 2 Variation of the ionization current as a function of external cylinder length for the NIS standard, measured for the BIPM 100 kV beam at a distance of 2.027 m. The standard deviation about the linear fit is 0.22 mm and the standard uncertainty of the gradient is 0.12 %.

Note that, for each chamber configuration, the ionization current is corrected to the reference conditions of air temperature and pressure (20 °C and 101.325 kPa) and for ion recombination. The gradient of this data is the ionization current per length, d*I*/d*L*, from which the reference air-kerma rate is determined using

$$\dot{K}_{\text{ref}} = \frac{\mathrm{d}I}{\mathrm{d}L}\frac{(W/e)}{\rho A}\frac{\prod k_i}{(1-g)}, \tag{8}$$

where W/e is the mean energy per charge in dry air (33.97 J C^{-1}, with standard uncertainty 0.15 %), ρ is the reference air density (1.2045 mg cm^{-3} at 20 °C and 101.325 kPa, with standard uncertainty 0.01 %), A is the aperture area (diameter 6.254 mm) and the product k_i is of the correction factors listed in Table 2 (excluding 1–g, which is explicitly included in the denominator). The standard deviation of the points about the linear fit, expressed in terms of length measurements, is 0.22 mm and the statistical standard uncertainty of the gradient d*I*/d*L* is 0.12 %.

For routine air-kerma measurements, the use of multiple chamber configurations is prohibitive and the following procedure might be adopted into the local quality system. The linear fit establishes a relation between I, L and the reference air-kerma rate. On any subsequent day when the air-kerma rate is to be determined, the chamber length L_{day} should be measured (before the polarizing potential is applied or after it is removed). Using the linear fit parameters, the expected current $I_{\mathrm{fit}}(L_{\mathrm{day}})$ can be calculated. If the actual current (corrected to standard air density) is determined as I_{day}, then the daily air-kerma rate can be evaluated as

$$\dot{K}_{\mathrm{day}} = \dot{K}_{\mathrm{ref}} \frac{I_{\mathrm{day}}}{I_{\mathrm{fit}}(L_{\mathrm{day}})} . \tag{9}$$

In effect, the daily air-kerma rate can be derived from the reference air-kerma rate using a single measurement of length and current. This more efficient procedure should not be used indefinitely, however, and the quality system should specify the frequency of full air-kerma rate determinations using all seven configurations (perhaps once per year).

9 Uncertainty budget

The uncertainty budget for K_{ref} must include estimates for all of the parameters entering in the measurement equation (8), as listed in Table 3. As well as the statistical (Type A) uncertainty of dI/dL noted above (which includes the statistical uncertainties of I and L), Type B components exist for I, for example the uncertainty of temperature and pressure corrections and the electrometer calibration, and for L, namely the calibration uncertainty of the length measuring device. The aperture area A will have also have Type A and Type B components. The uncertainty of the physical constants is dominated by the 0.15 % uncertainty of W/e. A positioning uncertainty is also normally required because, for the purpose of chamber calibrations, the standard is necessarily moved out of the beam and there is an uncertainty in repositioning. Values are given in Table 3 only for those components estimated in the present pilot study. These will need to be re-evaluated at the NIS in addition to the missing values denoted by a question mark.

For chamber calibrations, the daily air-kerma rate must be determined using equation (9), which gives rise to additional statistical uncertainty components for I_{day} and L_{day}. Chamber calibrations will also include uncertainties for the chamber positioning, the current measuring system, temperature and pressure corrections and the stability of the air-kerma rate or beam monitoring over the duration of the calibration.

Table 3 Example of an uncertainty budget for the determination of reference air-kerma rate.

Component	u_{A} /%	u_{B} /%
Sensitivity dI/dL	0.12	-
Ionization current I	-	?
Cylinder length L	-	?
Aperture area A	?	?
Correction factors (Table 1)	0.09	0.19
Physical constants	-	0.15
Positioning	?	?

10 Calibration of the BIPM reference Shonka chamber

The NIS standard was removed and the BIPM Shonka 1 chamber, used as a local reference at the BIPM, was positioned with its centre at the same point, 2027.3 mm from the x-ray source. This in effect enabled a calibration of the chamber against the NIS standard. However, the results of this measurement are not given in the present report, for three reasons:

(i) The values for the correction factors for the NIS standard used for this pilot study and given in Table 2 are not definitive and some are likely to change when a full study is made at the NIS.

(ii) The calibration coefficient for the Shonka chamber cannot be compared directly with the value obtained by calibration against the BIPM standard because the calibration conditions are different, notably the chamber distance and the field size.

(iii) Publication of such results is not in the spirit of the CIPM MRA as they might prejudice a subsequent comparison of the BIPM and NIS standards.

It is sufficient for the present purpose to state that the results demonstrate that the NIS standard appears to be in reasonable working order and that an air-kerma determination using this standard should not be in serious conflict with determinations using the other national primary standards for medium-energy x-rays that appear in the BIPM key comparison database. However, this conclusion must not preclude a re-examination of the standard and consequent changes to correction factors.

11 Summary

The present evaluation of the NIS cylindrical free-air chamber has produced preliminary values for certain correction factors, gives advice on the evaluation of the remaining correction factors and offers recommendations on the practical implementation and routine use of the standard at the NIS. Specific recommendations are given for the measurement of ion recombination, air attenuation and air-kerma rate, as well as the recommendation to use a higher polarizing potential. Regarding the mechanical play in the cylinder movements, the possibility of implementing a new system to measure the cylinder displacements is raised. Further work on correction factors is proposed, the most difficult to estimate being the photon scatter correction. Despite certain reservations regarding the cylinder movements and non-linearity in the ion recombination data, the chamber is shown to have the potential to be an effective national primary standard when operated in the recommended manner and when coupled with the appropriate measuring equipment and x-ray source.

Acknowledgments

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