Nederlands Meetinstituut

NMi report nr: VSL-ESL-IO-2006/1

Wall correction factors for cavity chambers and ^{60}Co radiation using Monte-Carlo methods

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March 2006

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Summary

At present the primary standard for air kerma for ^{60}Co photon beams in the Netherlands is a spherical Bragg-Gray cavity, having an air volume of 5 cm^3. To determine the correction factor for the influence of the graphite chamber wall, measurements were performed using wall thicknesses from 3 mm up to 6 mm. Using a linear extrapolation to zero wall thickness, the correction to eliminate the influence of the graphite walls, k_{att}, was determined. The slight overestimation of the effect by k_{att} was compensated by an additional correction for the upstream mean centre of production of electrons, k_{cep}. At the end of 2005 Monte-Carlo calculations were performed to estimate the influence of the graphite walls for the 5 cm^3 Bragg-Gray cavity. Similar Monte-Carlo calculations were performed for a cylindrical Bragg-Gray cavity having a 2.5 cm^3 air volume. Using the Monte-Carlo calculations, this 2.5 cm^3 Bragg-Gray cavity was upgraded to a primary standard for ^{60}Co photon beams. As a result of these changes, the kerma rate of the ^{60}Co photon beam at the Nederlands Meetinstituut increases by a factor of 1.00024, due to the average change in both primary standards. The related uncertainty has decreased from 0.86 % to 0.45 % (coverage factor $k = 2$).

1. Introduction

In the Netherlands, the Nederlands Meetinstituut (NMi) is in charge of the primary standard for air kerma in ^{60}Co and ^{137}Cs photon beams. This standard is a thick walled graphite cavity ionization chamber. The sensitive air volume of the cavity is known and the measured charge in the sensitive air volume can be converted to kerma-in-air by applying the Spencer-Attix Bragg-Gray theory [1]. This theory includes a correction for the absorption and scatter of photons in the wall of the ionization chamber. The correction factors for these phenomena have been determined by measuring the charge in the sensitive air volume at different wall thicknesses surrounding the air volume. In this approach the correction factor is the ratio of a linear extrapolation of the measured charges to a wall thickness of zero and the charge measured with the wall thickness used in practice. This correction factor itself needs a small correction due to the mean centre of production of those electrons that contribute to the measured charge. This centre of production is somewhat upstream from the air volume.

The validity of the approach of a linear extrapolation has been discussed already for several years and an alternative method using Monte-Carlo calculations is considered to give a more accurate result. In this work the alternative is used to determine the correction factor for the wall of the ionization chamber for ^{60}Co radiation using the Monte-Carlo calculation method [2, 3].

A change in the correction factor for attenuation and scatter in the wall of the NMi standard will also give a change in the results of the key comparison made using this standard with BIPM in 1996 (BIPM Rapport 97/04) [4] for ^{60}Co radiation. ^{137}Cs correction factors will be calculated in 2006.

2. Theory

At the Nederlands Meetinstituut, the primary standard for air kerma in ^{60}Co beams is a spherical ionization chamber. This ionization chamber is made out of graphite with an air volume of 5 cm^3, with sufficient build-up material to provide charged particle equilibrium. As such, the chamber can be considered as a Bragg-Gray cavity for photons in the energy range of ^{60}Co.

The ionization current measured with this standard in a ^{60}Co beam can be transformed into an air kerma rate ($\dot{K}_{\text{air}}$) according to:

$$\dot{K}_{\text{air}} = \frac{I}{V \cdot \rho} \cdot \frac{W}{e} \cdot \frac{1}{1-\overline{g}} \left(\frac{\overline{S}}{\rho}\right)_{air}^{wall} \cdot \left(\frac{\overline{\mu}_{\text{en}}}{\rho}\right)_{wall}^{air} \cdot k_{\text{h}}\, k_{\text{s}}\, k_{st}\, k_{\text{an}}\, k_{\text{rn}}\, k_{\text{att}}\, k_{\text{sc}}\, k_{\text{cep}} \qquad \textbf{(1)}$$

where I is the measured ionization current, V is the air volume of the ionization chamber, ρ is the mass density of dry air, W is the mean energy required to produce a pair of ions in dry air by an electron with charge e, $\overline{g}$ is the fraction of energy lost by bremsstrahlung, $\left(\frac{\overline{S}}{\rho}\right)_{air}^{wall}$ is the restricted stopping power ratio of the effective wall material and air, $\left(\frac{\overline{\mu}_{\text{en}}}{\rho}\right)_{wall}^{air}$ is the ratio of the mass energy absorption coefficients of air and the effective wall material and k_i are correction factors to be applied to the standard; k_{h} corrects for the influence of air humidity, k_{s} for ion recombination losses, k_{st} for the stem scattering, k_{an} and k_{rn} for the axial and radial non-uniformity of the beam; k_{att} and k_{sc} correct for the attenuation and the scattering of photons in the chamber wall and k_{cep} corrects for the mean origin of the electrons produced by the photons in the chamber wall.

The correction factor for the product $k_{\text{att}}.k_{\text{sc}}$ was determined by a linear extrapolation to zero wall thickness of the ionization chamber, using ionization measurements with wall thicknesses of 3mm, 4mm, 5mm and 6mm graphite and applied to the standard wall thickness of 4 mm. The correction factor k_{cep} is a correction for the overestimation of the product of $k_{\text{att}}.k_{\text{sc}}$. The mean centre of production of electrons that contribute to the ionization current is somewhat upstream from the air volume where the photon fluence has not been attenuated by the full wall thickness. Thus extrapolation to zero wall thickness overestimates the effects of $k_{\text{att}}.k_{\text{sc}}$.

The concept of a linear extrapolation to zero wall thickness is an assumption and does not include all the physical aspects for wall thicknesses below full build-up conditions.

Another method is to calculate k_{wall} directly by the use of Monte-Carlo methods. At the NMi the approach described by Rogers and Bielajew [5] is used. The principle of this approach is shown in figure 1.

This figure illustrates the relation between the processes of absorption (k_{att}) and scatter (k_{sc}) in the wall of the ionization chamber and the energy deposition in the gas of the cavity.

$$k_{\text{att}} = \frac{\sum_i E_{i,0} \cdot e^{\mu_i s_i}}{\sum_i E_{i,0}} \qquad (2)$$

$$k_{SC} = \frac{\sum_i E_{i,0}}{\sum_i \left(E_{i,0} + E_{i,1}\right)} \tag{3}$$

The correction for the influence of the graphite wall (k_{wall}) is k_{att} . k_{sc}

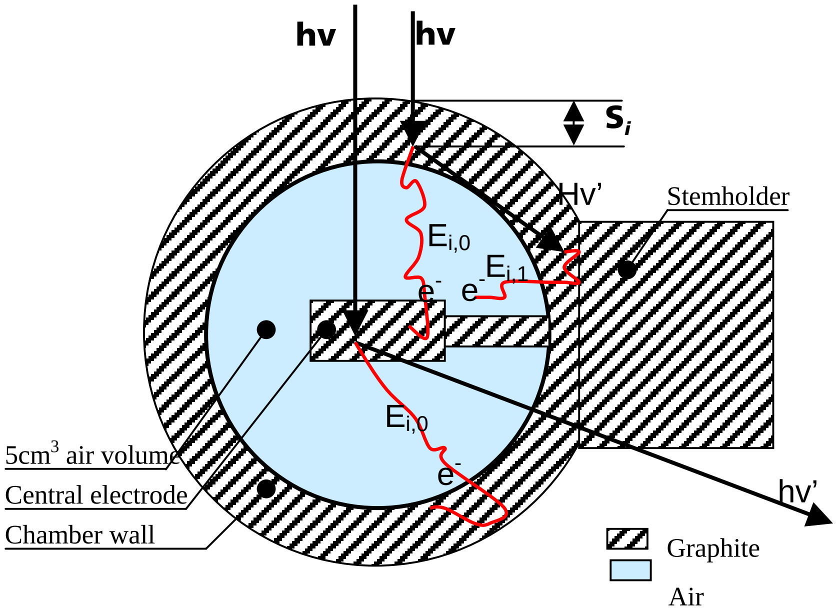

Figure 1. A schematic overview of the spherical 5 cm^3 ionization chamber

3. Experiments

The 5 cm^3 spherical ionization chamber was only measured with the standard 4 mm graphite wall thickness and only in the radial orientation shown in figure 1. The actual air volume of this ionization chamber is 4.845 cm^3. Due to the spherical shape, the orientation with respect to the ^{60}Co beam axis is not critical. At the NMi, a 2.5 cm^3 cylindrical graphite ionization chamber, machined with the same accuracy as the 5 cm^3 standard, is also available. The diameter of the air volume of this ionization chamber is 1.2 cm and the length of the air volume is 2.2 cm. The actual air volume is 2.4284 cm^3. The minimum wall thickness is 2 mm and four graphite caps are available to realize wall thicknesses of 3 mm, 4 mm, 5 mm and 6 mm. The orientation of this 2.5 cm^3 cylindrical ionization chamber with respect to the ^{60}Co beam axis is critical.

To validate experimentally the Monte-Carlo calculations for the 5 cm^3 standard with a 4 mm wall thickness, additional calculations and experiments were performed with the 2.5 cm^3 ionization chamber. The calculations of k_{wall} have been performed with different wall thicknesses and with different orientations of the 2.5 cm^3 ionization chamber to the ^{60}Co beam axis. Measurements have been performed with the same wall thicknesses and orientations in the ^{60}Co beam of the NMi. The orientations were radial, axial and oblique (45°). Applying the calculated correction factors k_{wall} to equation (1), together with the corresponding measured ionization currents, the air kerma rate determined should be the same for each wall thickness, assuming that the other correction factors do not change with orientation.

N.B. In this study, a compressibility factor of 1.0002 for the determination of the mass of air in the ionization chambers is used. In former air kerma rates determined by NMi, the compressibility factor was set to 1.000

4. Results

The estimated uncertainty in the determination of the air kerma rate is 0.3 % (k = 2) when the type B uncertainties, common to all the measurements, are omitted.

Table 1 gives the calculated values and measured values for the 2.5 cm^3 ionization chamber radially oriented to the ^{60}Co beam axis.

	Calculated			Measured	Air Kerma rate
Wall (mm)	k_{wall}	k_{att}	k_{sc}	I (pA)	Gy/h
3	1.0111	1.0431	0.9693	802.06	34.058
4	1.0151	1.0554	0.9618	798.04	34.024
5	1.0193	1.0674	0.9549	794.38	34.006
6	1.0232	1.0795	0.9478	790.72	33.979

Table 1. 2.5 cm^3 ionization chamber radially oriented to the beam axis

Radially oriented, the mean air kerma rate over 4 different wall thickness was 34.017 Gy/h, with a standard deviation of 0.1 %.

Table 2 gives the calculated values and measured values for the 2.5 cm^3 ionization chamber axially oriented to the ^{60}Co beam axis.

	Calculated			Measured	Air Kerma rate
Wall (mm)	k_{wall}	k_{att}	k_{sc}	I (pA)	Gy/h
3	1.0491	1.0871	0.9650	774.11	34.109
4	1.0510	1.0984	0.9568	772.64	34.104
5	1.0545	1.1103	0.9498	769.66	34.088
6	1.0563	1.1216	0.9418	767.07	34.030

Table 2. 2.5 cm^3 ionization chamber axially oriented to the beam axis

Axially oriented, the mean air kerma rate over 4 different wall thicknesses was 34.083 Gy/h, with a standard deviation of 0.1 %.

Table 3 gives the calculated values and measured values for the 2.5 cm^3 ionization chamber obliquely oriented to the ^{60}Co beam axis.

	Calculated			Measured	Air Kerma rate
Wall (mm)	k_{wall}	k_{att}	k_{sc}	I (pA)	Gy/h
4	1.0255	1.0683	0.9600	790.3	34.037
5	1.0345	1.0851	0.9534	784.1	34.065
6	1.0409	1.1021	0.9445	778.5	34.033

Table 3. 2.5 cm^3 ionization chamber obliquely oriented to the beam axis

Obliquely oriented, the mean air kerma rate over three different wall thicknesses was 34.045 Gy/h, with a standard deviation of 0.1 %.

The air kerma rate averaged over all orientations and wall thicknesses is 34.048 Gy/h, with an expanded uncertainty of 0.2 % (coverage factor k = 2).

Table 4 gives the calculated values and measured value for the 5 cm^3 standard ionization chamber, radially oriented to the ^{60}Co beam axis as shown in figure 1.

	Calculated			Measured	Air Kerma rate
Wall (mm)	k_{wall}	k_{att}	k_{sc}	I (pA)	Gy/h
4	1.0214	1.0621	0.9617	1581.115	34.019

Table 4. 5 cm^3 ionization chamber, standard laboratory position.

The ratio of the air kerma rates determined with the 5 cm^3 standard and the 2.5 cm^3 ionization chamber, both having a 4 mm wall thickness, is 1.0002, with an expanded uncertainty of 0.36 % (coverage factor k = 2).

The measured correction $k_{att}.k_{sc}.k_{cep}$ using the linear extrapolation method for the 5 cm^3 and used in all the comparisons made and published with BIPM is 1.0209.

5. Conclusion

1. Independent of the orientation and the wall thickness of the ionization chambers, a consistent and, by inference, accurate set of values has been calculated for the correction factor k_{wall}.

2. Applying the calculated 4 mm wall thickness correction factor (1.0214 ± 0.15 %, k = 2) for the 5 cm^3 standard, the measured air kerma rate using this standard will increase by a factor of 1.0002.

3. The 2.5 cm^3 cylindrical ionization chamber was machined at the same time as the 5 cm^3 primary standard, with the same mechanical precision. The same batch of graphite was used and the air volume measurements of both ionization chambers were performed simultaneously.

4. Applying the calculated values for the correction factor k_{wall}, the 2.5 cm^3 ionization chamber is upgraded to a primary standard, radially oriented with 4mm graphite wall.

5. Using both primary standards, the kerma rate of the ^{60}Co photon beam at the Nederlands Meetinstituut increases by a factor of 1.00024. The related uncertainty has decreased from 0.86 % to 0.45 % (coverage factor k = 2).

6. Due to the change in the correction factor k_{wall} and the adoption of the newly combined NMi standard, the 1996 comparison result with the BIPM will change from 1.0031 to 1.0033 [4] with a relative combined uncertainty of 0.0020. However, the recalculated air kerma rate for the BIPM is also likely to change as a result of new calculations, perhaps by 0.46 % [6], which would reduce the comparison ratio to 0.9987 [4]. In either case, the agreement is within the expanded uncertainty.

7. The uncertainty budgets for the 5 cm^3 and 2.5 cm^3 ionization chambers are given in annexes I and II, respectively.

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Annex 1 Uncertainty for the NMi 5 cm^3 primary air-kerma standard for ^{60}Co gamma radiation

Symbol	**quantity** **X_i**	**estimate** **x_i**	**standard uncertainty** **$u(x_i)$**	**probability distribution**	**sensitivity coefficient** **c_i**	**uncertainty contribution** **$u_i(y)$**
V	volume	4.845 cm^3	0.1	normal	1	0.1
ρ_{air}	density of air (22 °C, 101.325 kPa)	1.1966 kg m^{-3}	0.01	normal	1	0.01
(S/ρ)	stopping power ratio	1.00062	0.11*	normal	1	0.11
(μ_{en}/ρ)	absorption coefficient ratio	0.999	0.05	normal	1	0.05
W/e	Energy per ion pair	33.97 J C^{-1}				
$\frac{1}{1-g}$	correction for bremsstrahlung losses	1.0032	0.03	normal	1	0.03
k_s	correction for recombination	**	0.03	normal	1	0.03
k_{st}	stem correction	0.999	0.05	normal	1	0.05
k_{att}	correction for wall absorption and scatter	1.0214	0.08	normal	1	0.08
k_h	correction for air humidity	0.997	0.05	rectangular	1	0.03
k_{rn}	correction for radial non uniformity	1	0.03	rectangular	1	0.02
k_{an}	correction for axial non uniformity	1	0.15	rectangular	1	0.09
	Combined uncertainty					0.21
	Expanded uncertainty (k = 2)					**0.42**

* Combined uncertainty for the product $(\overline{s}_{w,a} \cdot W/e)$

** Depends on air kerma rate and polarizing voltage applied to the ionization chamber and is determined during the ionization measurements.

As a result of the newly calculated correction factors, the corrections for k_{att} and k_{cep}, each having an uncertainty of 0.2 % (k = 1), are combined in the correction factor k_{att} for wall absorption and scatter, with an uncertainty of 0.08 % (k = 1) . This results in an expanded uncertainty reduced from 0.86 % to 0.42 % (k = 2).

Annex 2 Uncertainty for the NMi 2.5 cm^3 primary air-kerma standard for ^{60}Co gamma radiation.

Symbol	**quantity** **X_i**	**estimate** **x_i**	**standard uncertainty** **$u(x_i)$**	**probability distribution**	**sensitivity coefficient** **c_i**	**uncertainty contribution** **$u_i(y)$**
V	volume	2.4284 cm^3	0.15	normal	1	0.15
ρ_{air}	density of air (22 °C, 101.325 kPa)	1.1966 kg m^{-3}	0.01	normal	1	0.01
(S/ρ)	stopping power ratio	1.00092	0.11*	normal	1	0.11
(μ_{en}/ρ)	absorption coefficient ratio	0.999	0.05	normal	1	0.05
W/e	energy per ion pair	33.97 J C^{-1}				
$\frac{1}{1-g}$	correction for bremsstrahlung losses	1.0032	0.03	normal	1	0.03
k_s	correction for recombination	**	0.03	normal	1	0.03
k_{st}	stem correction	0.998	0.05	normal	1	0.05
k_{att}	correction for wall absorption and scatter	1.0151	0.08	normal	1	0.08
k_h	correction for air humidity	0.997	0.05	rectangular	1	0.03
k_{rn}	correction for radial non uniformity	1	0.03	rectangular	1	0.02
k_{an}	correction for axial non uniformity	1	0.15	rectangular	1	0.09
	Combined uncertainty					0.24
	Expanded uncertainty (k = 2)					**0.48**

* Combined uncertainty for the product ($\overline{s}_{w,a} \cdot {}^{W}\!/_{e}$)

** Depends on air kerma rate and polarizing voltage applied to the ionization chamber. Is determined during the ionization measurements.

As a result of the newly calculated correction factors, the corrections for k_{att} and k_{cep}, each having an uncertainty of 0.2 % (k = 1), are combined in the correction factor k_{att} for wall absorption and scatter, with an uncertainty of 0.08 % (k = 1) . This results in an expanded uncertainty reduced from 0.88 % to 0.48 % (k = 2).