Calculation of k_{wall} for ^{60}Co air-kerma standards using PENELOPE

D T Burns
Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex

1. Introduction

The ^{60}Co air-kerma standard of the BIPM is of parallel-plate design [1], for which the extrapolation method for evaluating the wall correction factor k_{wall} should work best. A number of national laboratories employ as their primary standard the cylindrical chamber type CC01. Rogers and Treurniet [2] calculated k_{wall} for a number of chamber types, including the BIPM standard and the CC01, using the Monte Carlo code EGSnrc [3]. In the present work, k_{wall} is calculated independently using the code PENELOPE [4]. An important element of this work is the use of a realistic incident photon spectrum.

2. Source simulation

Using the PENELOPE geometry code PENGEOM, the BIPM 250 TBq ^{60}Co source, container, head and collimating jaws (set to give a 10 cm by 10 cm field in the reference plane) were simulated in detail, as shown in Fig. 1. More than fifty components were modelled. The collimator bars and central support (yellow) are of lead, except for the final trimmer bar in each jaw (green) which is of depleted uranium. A steel bar (violet) supports each jaw. The source shielding and primary collimator (red) are of tungsten. Not visible in the figure are the details of the cylindrical source container, which is of stainless steel 23.6 mm in diameter and 37 mm long with a 1 mm front wall and 3 mm rear wall. The source itself is 20 mm in diameter and 14 mm long, behind which (inside the source container) there is an 11 mm stack of steel discs and an 8 mm air space.

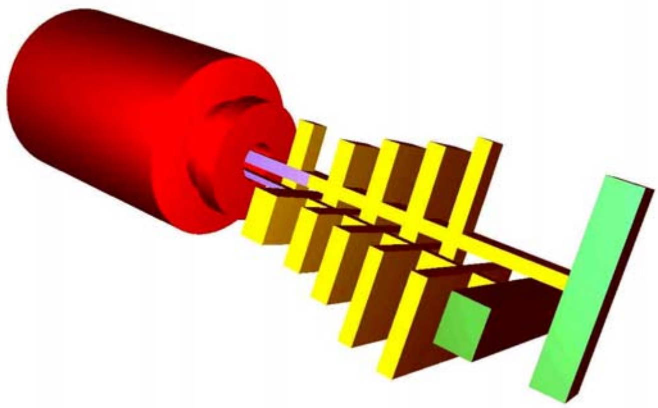

FIG. 1. Model used for the new ^{60}Co source. Only one of each pair of collimating jaws is shown.

This model was used to create a particle phase-space file in the plane 90 cm from the source, including information on the type, energy, angle and position of all particles crossing this plane. The photon transport cut-off energy was set to 25 keV. Raising the electron transport cut-off from 50 keV to 1.25 MeV (and therefore neglecting electron transport) resulted increased the speed of calculation by a factor of more than twenty. The consequent neglect of bremsstrahlung reduced the relative photon energy fluence by only 2×10^{-3}, which should have a negligible effect on the results.

Fig. 2 shows the normalized distribution of photon number with energy, at 90 cm and within a radius of 2.5 cm of the beam axis. A counter was used to label each particle with its body of origin. In this way, the scattered photon contribution from each component was identified, as indicated in the figure. The photon scatter component, expressed as relative energy fluence, is around 0.21 (compared with around 0.14 for the older source) and arises mainly from forward scattering in the source and its container. Only 0.03 of the relative photon energy fluence is from scatter in the collimator.

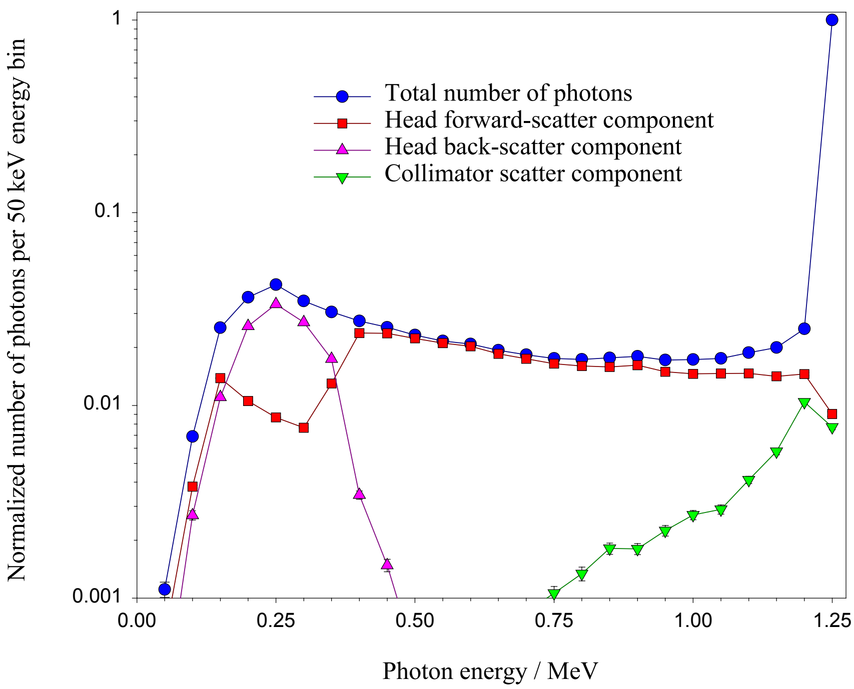

FIG. 2. The distribution of photon number with energy at 90 cm from the source and within 2.5 cm of the beam axis. Around 10^9 photon histories were required to generate this spectrum of 10^6 photons.

3. Chamber models

The phase-space file was used as input to the subsequent calculations of k_{wall} for the BIPM and CC01 standards. The BIPM ^{60}Co air-kerma standard serial number CH5-1 was modelled, for which the graphite density is 1.811 g cm^{-3}. The chamber dimensions are: external diameter 50.5 mm, front and rear wall thickness each 2.83 mm, air cavity diameter 45 mm, thickness 5.16 mm, graphite collector diameter 41 mm, thickness 1 mm. The collector divides the air cavity into two equal thicknesses (each 2.08 mm). The small support for the collector was not modelled, nor the electrical connections and chamber stem.

The model used for the CC01 was derived from a workshop drawing made at the ÖFS (Austria) in 1990. The cylindrical wall has inner diameter 11 mm, outer diameter 19 mm (i.e. radial wall thickness 4 mm), inner height 11 mm and outer height 19 mm. The collector has total length 9 mm. The upper 7 mm of the collector is of diameter 2 mm (the top 1 mm being the hemispherical tip). The lower 1 mm is of diameter 3 mm. Between these two is a section of length 1 mm where the collector diameter increases linearly from 2 mm to 3 mm. For the present calculations, the collector was simplified as an upper section of diameter 2 mm and length 7.5 mm (including the hemispherical tip) and a lower section of diameter 3 mm and length 1.5 mm (i.e. the same volume of material). Both wall and collector were modelled as graphite of density 1.75 g cm^{-3}. No insulator was modelled; it is evident from the results of [2] that the insulator has no effect at the level of 10^{-4}. The electrical connections and stem were not modelled.

4. Method of calculation

The attenuation component of k_{wall} was evaluated using the technique of photon regeneration [5]. At the point of interaction of each incident photon in the chamber wall and in the central electrode, a new photon is generated with the same energy and direction as the incident photon. These regenerated photons are labelled to allow the separate scoring of energy deposition in the air cavity due to incident and regenerated photons.

An important consideration in calculating energy deposition in the air cavity is the need to preserve electron equilibrium. This requires that the electron transport cut-off chosen for the cavity be used also for all bodies in contact with the cavity. For an electron cut-off energy of 1 keV in the cavity, this necessitates a similar cut-off in the walls and collector, which results in a very slow calculation. To optimize this situation, a skin of thickness 10 μm was modelled on all surfaces in contact with the cavity and the electron cut-off set to 1 keV in the cavity and skins. The cut-off in the remaining bodies was raised to 25 keV, this choice resulting from the fact that 10 μm of graphite is sufficient to stop 25 keV electrons. The result is a very low electron cut-off energy in the cavity without compromising either electron equilibrium or calculation speed.

A further advantage of this approach is that a detailed, event-by-event calculation can be made in the cavity and skins without great loss of speed. This is achieved by setting the PENELOPE parameters in the cavity and skin as $C_1 = C_2 = W_{CC} = 0$ and $W_{CR} = -1$. In the remaining graphite (walls and collector), the following were set: $C_1 = C_2 = 0.2$, $W_{CC} = W_{CR} = 10$ keV. The maximum electron step length in each body was set to around one tenth of the minimum dimension of that body. The photon transport cut-off was set to 1 keV in all bodies.

5. Results and discussion

The present results and those of Rogers and Treurniet [2] are given below. The statistical standard uncertainty for each calculation is given in brackets (the overall uncertainties remain to be evaluated). The results of [2] for the BIPM standard have been adjusted from the value 1.00139(3) calculated for a graphite density of 1.84 g cm^{-3} (and the same wall thickness).

Standard	BIPM (ρ_g = 1.811 g cm^{-3})	CC01 (ρ_g = 1.75 g cm^{-3})
k_{wall} – present work	1.00132(9)	1.02147(9)
k_{wall} – ref [2]	1.00137(3)	1.02190(5)

It is clear that the PENELOPE and EGSnrc codes are in close agreement, the results for the BIPM standard being within the statistical standard uncertainty (1×10^{-4}). The difference of 4×10^{-4} for the CC01 is statistically significant and may arise from small differences in the model used for the chamber, notably the form of the collector.

The value for k_{wall} in use at present for the BIPM standard is 1.0026 (standard uncertainty 0.0008), around 10^{-3} higher than the calculated value. In contrast, that for the CC01 is around 1.0127 with standard uncertainty 0.001 (slightly different values are used by different laboratories). The calculated value is higher by almost 10^{-2}, a difference very much greater than the stated uncertainty.

6. References

[1] M Boutillon, M T Niatel, A study of a graphite cavity chamber for absolute exposure measurements of ^{60}Co gamma rays, 1973, *Metrologia* **9,** 139 – 146.

[2] D W O Rogers, J Treurniet, Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, 1999, *NRCC Report* PIRS-663.

[3] I Kawrakow, D W O Rogers, The EGSnrc code system: Monte Carlo simulation of electron and photon transport, 2000, *NRCC Report* PIRS-701 (National Research Council of Canada).

[4] F Salvat, J M Fernandez-Varea, E Acosta, J Sempau, PENELOPE - A Code System for Monte Carlo Simulation of Electron and Photon Transport, 2001, Proceedings of a Workshop/Training Course, OECD/NEA, 5-7 November 2001, NEA/NSC/DOC(2001)19 (ISBN 92-64-18475-9).

[5] A F Bielajew, Correction factors for thick-walled ionization chambers in point-source photon beams, 1990, *Phys. Med. Biol.* **35**, 501 – 516.