# New correction factors for the BIPM free-air chamber standards

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## 1. Introduction

The correction factors for electron loss, $k_e$, and photon scatter, $k_{sc}$, were calculated by Burns [1] for many free-air chamber standards operating world-wide, using the Monte Carlo code EGS4 [2]. The same factors were re-calculated by Burns [3] using EGSnrc [4]. These calculations included the effect of fluorescence generated by the argon content of air, which had not been included in [1], leading to the proposal for a new correction factor, $k_{fl}$. A very recent set of calculations by Burns and Da Silva [5] calculated the same factors, for the BIPM standards only, using the code PENELOPE [6] and the same model for the free-air chambers. The present report draws together these various estimates and proposes new values for the correction factors for the BIPM standards.

## 2. BIPM standard for low-energy x rays

The electrode separation for the BIPM low-energy standard (10 kV to 50 kV) is sufficiently large that $k_e$ is unity, within 0.0001, for the highest reference radiation quality. Table 1 gives the calculated values for $k_{sc}$ and $k_{fl}$ for the five reference qualities, using the various codes. Each value has a statistical uncertainty below 0.0001.

**Table 1. Calculated values for correction factors for BIPM low-energy free-air chamber**

| Radiation Quality | 10 kV | 30 kV | 25 kV | 50 kV(b) | 50 kV(a) |
|---|---|---|---|---|---|
| Al HVL / mm | 0.037 | 0.17 | 0.24 | 1.02 | 2.26 |
| $k_{sc}$ | | | | | |
| EGS4 | 0.9959 | 0.9971 | 0.9971 | 0.9977 | 0.9979 |
| EGSnrc | 0.9963 | 0.9973 | 0.9974 | 0.9978 | 0.9980 |
| PENELOPE | 0.9964 | 0.9971 | 0.9974 | 0.9977 | 0.9979 |
| **Best estimate** | **0.9962** | **0.9972** | **0.9973** | **0.9977** | **0.9979** |
| $k_{fl}$ | | | | | |
| EGSnrc | 0.9947 | 0.9966 | 0.9967 | 0.9978 | 0.9983 |
| PENELOPE | 0.9957 | 0.9975 | 0.9972 | 0.9983 | 0.9987 |
| **Best estimate** | **0.9952** | **0.9971** | **0.9969** | **0.9980** | **0.9985** |

For $k_{sc}$, differences in the results for the three codes are very small. While certain correlations exist, there are many differences in the various implementations of photon interactions (cross sections and angular distributions), even between EGS4 and EGSnrc. Since no reliable weight can be attributed, the best estimate is taken as the arithmetic mean. Taking account only of the spread of the three results for each radiation quality, the standard uncertainty for each mean value is around 0.0001.

A more realistic estimate of the uncertainty must include the various components discussed in reference [1], particularly those that are common to the three calculations. Notably, the same x-ray spectrum is used; the use of alternative spectra was shown to introduce an uncertainty component of 0.0002 in $k_{sc}$. The same simplified model for the BIPM standard is also used; the neglect of guard bars and other scattering materials may introduce a further component of 0.0002. The combined standard uncertainty of the best estimates for $k_{sc}$ is taken to be 0.0003.

Regarding $k_{fl}$, the differences in the results for EGSnrc and PENELOPE are much larger (fluorescence was not simulated in the version of EGS4 used). The reason for this is not evident, since the implementations have much in common for K-shell emissions from argon (the dominant effect). The standard uncertainty derived from each pair of results rises from 0.0002 at 50 kV(a) to 0.0005 at 10 kV. Taking an overall value of 0.0004 and combining this with the component 0.0003 arising from correlations (as noted above for $k_{sc}$), a combined standard uncertainty of 0.0005 is taken for all qualities.

## 3. BIPM standard for medium-energy x rays

Table 2 gives the calculated values for $k_e$, $k_{sc}$ and $k_{fl}$ for the four reference qualities in the medium-energy x-ray range, using the various codes. Each value has a statistical uncertainty below 0.0001.

**Table 2. Calculated values for correction factors for BIPM medium-energy free-air chamber**

| Radiation Quality | 100 kV | 135 kV | 180 kV | 250 kV |
|---|---|---|---|---|
| Cu HVL / mm | 0.148 | 0.494 | 0.990 | 2.500 |
| $k_e$ | | | | |
| EGS4 | 1.0001 | 1.0015 | 1.0044 | 1.0078 |
| EGSnrc | 1.0000 | 1.0015 | 1.0048 | 1.0087 |
| PENELOPE | 1.0000 | 1.0010 | 1.0027 | 1.0048 |
| Present value | 1.0000 | 1.0023 | 1.0052 | 1.0078 |
| **Best estimate** | **1.0000** | **1.0016** | **1.0043** | **1.0073** |
| $k_{sc}$ | | | | |
| EGS4 | 0.9951 | 0.9958 | 0.9963 | 0.9973 |
| EGSnrc | 0.9952 | 0.9959 | 0.9964 | 0.9974 |
| PENELOPE | 0.9953 | 0.9959 | 0.9964 | 0.9973 |
| **Best estimate** | **0.9952** | **0.9959** | **0.9964** | **0.9974** |
| $k_{fl}$ | | | | |
| EGSnrc | 0.9984 | 0.9992 | 0.9994 | 0.9998 |
| PENELOPE | 0.9986 | 0.9993 | 0.9995 | 0.9999 |
| **Best estimate** | **0.9985** | **0.9992** | **0.9994** | **0.9999** |

For $k_{sc}$, the arguments relating to differences and correlations are similar to those presented for the low-energy standard, and the combined standard uncertainty of the best estimates is taken to be 0.0003. The differences for $k_{fl}$ are smaller than for the low-energy standard (the absolute values are closer to unity) and the uncertainty is dominated by the same arguments regarding correlations in the three calculations. The combined standard uncertainty is taken as 0.0003.

The results for $k_e$ show a larger spread. The results using PENELOPE are significantly lower than those using EGS4 and EGSnrc, as well as being lower than the values in use at present. In contrast to $k_{sc}$ and $k_{fl}$, $k_e$ is sensitive to the details of the electron transport, which is different in the three codes. In deriving a best estimate at each radiation quality, the values in use at present are included, since they are considered no less valid than the calculated values. The best estimate is taken to be the arithmetic mean. The standard uncertainty arising from the spread of these results is 0.0003 at 135 kV, 0.0006 at 180 kV and 0.0008 at 250 kV.

Although all three calculations use the same chamber model, $k_e$ is not sensitive to the simplifications made. The use of the same spectra in all three calculations introduces up to 0.0002. The results will also be sensitive to the electron stopping power in air, which is the same in the three codes (despite the fact that the version of PENELOPE used does not take its values from ICRU Report 37 [7]). A relative standard uncertainty of 2 % in the air stopping power (around 100 keV) gives rise to a standard uncertainty in $k_e$ of 0.0001 at 135 kV, 0.0002 at 180 kV and 0.0003 at 250 kV. Summing the various components, the combined standard uncertainty in $k_e$ is taken as: 0.0001 at 100 kV, 0.0003 at 135 kV, 0.0006 at 180 kV and 0.0009 at 250 kV.

## 4. Conclusions

The best estimates for the various correction factors at the reference radiation qualities, as given in Tables 1 and 2, are re-stated in Table 3 along with the values in use at present. The standard uncertainties are also given.

| Radiation Quality | 10 kV | 30 kV | 25 kV | 50 kV(b) | 50 kV(a) | 100 kV | 135 kV | 180 kV | 250 kV |
|---|---|---|---|---|---|---|---|---|---|
| $k_e$ new | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0016 (0.0003) | 1.0043 (00006) | 1.0073 (0.0009) |
| $k_e$ present | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0001) | 1.0000 (0.0010) | 1.0023 (0.0010) | 1.0052 (0.0010) | 1.0078 (0.0010) |
| $k_{sc}$ new | 0.9962 (0.0003) | 0.9972 (0.0003) | 0.9973 (0.0003) | 0.9977 (0.0003) | 0.9979 (0.0003) | 0.9952 (0.0003) | 0.9959 (0.0003) | 0.9964 (0.0003) | 0.9974 (0.0003) |
| $k_{sc}$ present | 0.9944 (0.0007) | 0.9956 (0.0007) | 0.9957 (0.0007) | 0.9966 (0.0007) | 0.9971 (0.0007) | 0.9948 (0.0007) | 0.9962 (0.0007) | 0.9967 (0.0007) | 0.9969 (0.0007) |
| $k_{fl}$ new | 0.9952 (0.0005) | 0.9971 (0.0005) | 0.9969 (0.0005) | 0.9980 (0.0005) | 0.9985 (0.0005) | 0.9985 (0.0003) | 0.9992 (0.0003) | 0.9994 (0.0003) | 0.9999 (0.0003) |
| $k_{fl}$ present | - | - | - | - | - | - | - | - | - |
| **Change to standard** | **0.9970** | **0.9987** | **0.9985** | **0.9991** | **0.9993** | **0.9989** | **0.9982** | **0.9982** | **0.9999** |

The overall change to the BIPM standard at each quality is given in the final row. Considering only the uncertainties of the values for $k_e$ and $k_{sc}$ in use at present, the overall change is within one standard uncertainty for three of the nine qualities (50 kV(a), 100 kV and 250 kV). For all other qualities it is within two standard uncertainties, with the exception of 10 kV. For all qualities the combined uncertainty is lower for the new values, although this improvement is only marginal for the low-energy qualities and for 250 kV.

## 5. References

[1] D T Burns, Consistent set of calculated values for electron-loss and photon-scatter corrections for parallel-plate free-air chambers, 1999, CCRI(I)/99-04.

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