Free-air chamber correction factors for electron loss, photon scatter, fluorescence and bremsstrahlung

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1. Introduction

Values for the correction factors for electron loss k_e and photon scatter k_{sc} were calculated by Burns [1] using the Monte Carlo code EGS4 [2], for all of the free-air chamber standards in use worldwide at that time. Spectral values were derived for the CCRI reference radiation qualities for low- and medium-energy x radiation [3]. In general, the calculated values were in close agreement with the values used at present by each NMI. The most notable discrepancy was in the values for k_{sc} at the lower-energy qualities, where the calculated values were closer to unity by typically 0.2 %. This was attributed to the lack of inclusion of x-ray fluorescence transport in the standard EGS4 code.

These calculations have now been repeated using the new code EGSnrc [4] which, amongst other improvements, includes the transport of fluorescence x-rays and Auger and Coster-Kronig electrons. By separating the effects of scattered photons, resulting from coherent (Rayleigh) and incoherent (Compton) scattering processes, from those of fluorescence photons, the new values k_{sc} can be compared directly with the EGS4 values (and indeed with the existing values based on measurement). An additional correction factor k_{fl} is introduced to account seperately for the re-absorption of fluorescence photons.

The new calculations also score separately the total energy given to bremsstrahlung photons and the component of this energy which is re-absorbed in the collecting volume, giving rise to the correction factors $(1 - g)^{-1}$ and k_{br}, respectively.

2. Calculations

Details of the simplified model used for the free-air chambers are given in [1], which also includes details of the spectra and the EGS4 parameters used. The same values for the cut-off parameters (PCUT = 1 keV and ECUT = 512 keV) are used here, although no choice need be made for ESTEPE since this is controlled by the new electron transport algorithm PRESTA II. As well as the inclusion of atomic relaxation (and the bound Compton formalism rather than Klein-Nishina), several other changes have been made, notably the removal of range rejection so that bremsstrahlung is generated and its re-absorption scored.

Some changes have also been made to the PEGS4 input data, notably the use of a better air mixture (with argon content 1.28 % by weight instead of 0.94 %). Density effect corrections of ICRU 37 [5] are introduced (which should have neglibible effect at the energies of interest) and bremsstrahlung is now sampled from the NIST database. The statistical standard uncertainty of all results is less than 0.0001.

3. Results for electron-loss correction k_e

The values for k_e for the medium- and low-energy x-ray qualities are given in Tables 1 and 2, respectively.

For the medium energy qualities, the new values are on average within 0.02 % of the values in use at present, with a spread on this result of 0.04 % which probably arises from differences in the method used by each NMI to derive, from the same input data, the correction factor for their own chamber dimensions and radiation spectrum. The new values are a little higher than those obtained using EGS4; for the largest corrections, namely the BIPM and BNM-LCIE standards at 250 kV, the new values are 0.08 % higher than those using EGS4. Almost all of this difference arises from the new PEGS4 data.

For the 50 kVa quality and for the smallest chambers (NIST Lamperti and NMi), the new values are lower than the best estimates using EGS4 by 0.1 %. This is not surprising, since when using EGS4 the results at low energies showed an unexplained dependence on the value chosen for ESTEPE. The improved electron transport in EGSnrc using PRESTA II should be more reliable. The values used at present for the 50 kVa quality are 1.0076 for the NMi standard (calculated using EGS4) and 1.005 for the NIST Lamperti chamber (not used as the standard for this quality).

Table 1. Calculated values for k_e for medium-energy x-ray standards at the CCRI reference qualities

NMI	Country	k_e 135 kV	180 kV	250 kV
BIPM	**-**	**1.0015**	**1.0048**	**1.0087**
ARPANSA	Australia	1.0006	1.0025	1.0051
BEV	Austria	1.0000	1.0005	1.0019
BNM-LCIE	France	1.0016	1.0049	1.0087
CSIR	S. Africa	1.0000	1.0008	1.0025
GUM	Poland	1.0002	1.0016	1.0039
ISS	Italy	1.0003	1.0020	1.0045
NIST	USA	1.0006	1.0027	1.0056
NMi	Netherlands	1.0000	1.0006	1.0021
NPL	UK	1.0000	1.0008	1.0025
NRC	Canada	1.0001	1.0009	1.0027
NRL	New Zealand	1.0000	1.0003	1.0016
OMH	Hungary	1.0000	1.0005	1.0020
VNIIM	Russian Fed.	1.0000	1.0008	1.0025

Table 2. Calculated values for k_e for low-energy x-ray standards at the CCRI reference qualities

NMI	Country	k_e 50 kVb	50 kVa
BIPM	**-**	**1.0000**	**1.0000**
ARPANSA	Australia	1.0000	1.0001
CIEMAT	Spain	1.0000	1.0000
ENEA	Italy	1.0001	1.0004
GUM	Poland	1.0000	1.0000
ISS	Italy	1.0000	1.0001
METAS	Switzerland	1.0000	1.0001
NIST (Lamperti)	USA	1.0022	1.0065
NIST (Ritz)	USA	1.0000	1.0000
NMi	Netherlands	1.0021	1.0062
NMIJ	Japan	1.0013	1.0039
NPL	UK	1.0000	1.0001
NRC	Canada	1.0000	1.0001
NRL	New Zealand	1.0001	1.0003
OMH	Hungary	1.0001	1.0003
PTB	Germany	1.0000	1.0000
VNIIM	Russia	1.0018	1.0051

4. Results for the photon-scatter correction k_{sc}

The values for k_{sc} for the medium- and low-energy x-ray qualities are given in Tables 3 and 4, respectively.

For the medium-energy qualities, the new values are typically within 0.01 % of those obtained using EGS4. The calculated values for the 100 kV, 135 kV and 180 kV qualities are on average within 0.01 % of the values in use at present, but the spread on this result is 0.1 % which again probably arises from differences in the method used by each NMI to derive the correction factor for their own conditions. At 250 kV, the calculated values are on average 0.05 % higher than those in use at present.

At low energies, the EGSnrc values for k_{sc} are typically 0.02 % higher than those obtained using EGS4. The calculated values are significantly higher than those in use at present, by 0.08 % at 50 kVa rising progressively to 0.23 % at 10 kV. It is these discrepancies which motivated the inclusion of fluorescence in the calculations, although the measured values for k_{sc} are probably not very sensitive to the fluorescence component.

Table 3. Calculated values for k_{sc} for medium-energy x-ray standards at the CCRI reference qualities

NMI	k_{sc} 100 kV	135 kV	180 kV	250 kV
BIPM	**0.9952**	**0.9959**	**0.9964**	**0.9974**
ARPANSA	0.9943	0.9951	0.9956	0.9968
BEV	0.9922	0.9933	0.9942	0.9956
BNM-LCIE	0.9952	0.9960	0.9965	0.9974
CSIR	0.9918	0.9931	0.9939	0.9955
GUM	0.9935	0.9944	0.9951	0.9964
ISS	0.9941	0.9949	0.9955	0.9967
NIST	0.9943	0.9952	0.9958	0.9969
NMi	0.9920	0.9931	0.9940	0.9955
NPL	0.9923	0.9934	0.9942	0.9957
NRC	0.9927	0.9938	0.9945	0.9959
NRL	0.9931	0.9943	0.9950	0.9963
OMH	0.9922	0.9934	0.9942	0.9957
VNIIM	0.9927	0.9938	0.9945	0.9958

Table 4. Calculated values for k_{sc} for low-energy x-ray standards at the CCRI reference qualities

NMI	k_{sc} 10 kV	30 kV	25 kV	50 kVb	50 kVa
BIPM	**0.9963**	**0.9973**	**0.9974**	**0.9978**	**0.9980**
ARPANSA	0.9964	0.9974	0.9975	0.9979	0.9981
CIEMAT	0.9962	0.9973	0.9974	0.9978	0.9980
ENEA	0.9970	0.9979	0.9980	0.9983	0.9985
GUM	0.9962	0.9973	0.9974	0.9978	0.9979
ISS	0.9963	0.9974	0.9975	0.9979	0.9981
METAS	0.9963	0.9974	0.9975	0.9979	0.9981
NIST (Lamperti)	0.9979	0.9984	0.9985	0.9987	0.9989
NIST (Ritz)	0.9953	0.9966	0.9967	0.9973	0.9975
NMi	0.9979	0.9984	0.9985	0.9987	0.9988
NMIJ	0.9970	0.9978	0.9979	0.9982	0.9983
NPL	0.9963	0.9974	0.9975	0.9979	0.9981
NRC	0.9964	0.9975	0.9975	0.9979	0.9981
NRL	0.9963	0.9973	0.9975	0.9978	0.9979
OMH	0.9970	0.9979	0.9980	0.9983	0.9985
PTB	0.9926	0.9945	0.9946	0.9953	0.9955
VNIIM	0.9973	0.9980	0.9980	0.9983	0.9984

5. Results for the fluorescence correction k_{fl}

The values for k_{fl} for the medium-energy qualities are the same for all of the standards (at the level of 3×10^{-5}). The values are: 0.9983 at 100 kV, 0.9991 at 135 kV, 0.9994 at 180 kV and 0.9998 at 250 kV. Thus, although the 100 kV and 135 kV correction factors are significant in terms of the overall uncertainty of the air kerma determination, the introduction of fluorescence correction factors will have no impact on the results of comparisons at medium energies.

The results for k_{fl} for the low-energy qualities are given in Table 5. In the most significant case, the very large PTB standard at 10 kV, the correction is 0.8 %. This is a particularly interesting result because the PTB is the only NMI to date to include a correction for this effect. The values for k_{sc} used by the PTB are derived from Monte Carlo calculations using EGS4 with low-energy extensions and include the transport of fluorescence photons. The PTB values for the product $k_{sc}\,k_{fl}$ (in the present notation), using the same spectra as used for the present calculations, are 0.9854 (10 kV), 0.9897 (30 kV), 0.9897 (25 kV), 0.9924 (50 kVb) and 0.9936 (50 kVa), compared with the present results (0.9850, 0.9896, 0.9897, 0.9920 and 0.9931) which are around 0.03 % lower.

For all other NMIs, the variations in k_{fl} from chamber to chamber, at a given radiation quality, are up to 0.2 %, which will have some impact on the results of comparisons at low energies.

Table 5. Calculated values for k_{fl} for low-energy x-ray standards at the CCRI reference qualities

NMI	k_{fl}				
	10 kV	30 kV	25 kV	50 kVb	50 kVa
BIPM	**0.9947**	**0.9966**	**0.9967**	**0.9978**	**0.9983**
ARPANSA	0.9946	0.9966	0.9967	0.9978	0.9984
CIEMAT	0.9947	0.9966	0.9966	0.9977	0.9983
ENEA	0.9951	0.9969	0.9970	0.9980	0.9985
GUM	0.9947	0.9966	0.9967	0.9978	0.9983
ISS	0.9948	0.9967	0.9967	0.9978	0.9984
METAS	0.9948	0.9966	0.9967	0.9978	0.9983
NIST (Lamperti)	0.9959	0.9973	0.9975	0.9983	0.9988
NIST (Ritz)	0.9941	0.9962	0.9962	0.9975	0.9981
NMi	0.9959	0.9973	0.9974	0.9983	0.9988
NMIJ	0.9958	0.9974	0.9974	0.9982	0.9986
NPL	0.9948	0.9967	0.9967	0.9978	0.9984
NRC	0.9949	0.9967	0.9968	0.9978	0.9984
NRL	0.9944	0.9964	0.9965	0.9977	0.9983
OMH	0.9951	0.9968	0.9970	0.9980	0.9985
PTB	0.9923	0.9950	0.9951	0.9967	0.9975
VNIIM	0.9955	0.9972	0.9973	0.9981	0.9986

6. Results for the bremsstrahlung correction k_{br}

The results of the bremsstrahlung calculations for a given radiation quality are the same for all of the standards (at the level of 10^{-5}). These are expressed as the product of the correction factor $(1-g)^{-1}$, which accounts for the energy loss due to bremsstrahlung production, and the factor k_{br}, which accounts for the component of bremsstrahlung re-absorbed. The results are summarized in Table 6. The difference between the product $k_{br}(1-g)^{-1}$ and the values for $(1-g)^{-1}$ in use at present is at most 0.015 %.

Table 6. The effect of bremsstrahlung for medium-energy x-ray standards at the CCRI reference qualities

Bremsstrahlung component	10 kV	30 kV	25 kV	50 kVb	50 kVa	100 kV	135 kV	180 kV	250 kV
existing $(1-g)^{-1}$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0001	1.0001	1.0002	1.0003
new $(1-g)^{-1}$	1.00001	1.00007	1.00007	1.00014	1.00019	1.00020	1.00020	1.00020	1.00027
k_{br}	1.00000	0.99997	0.99997	0.99996	0.99996	0.99994	0.99994	0.99994	0.99994
combined $k_{br}(1-g)^{-1}$	1.00001	1.00004	1.00004	1.00010	1.00015	1.00014	1.00014	1.00014	1.00021

7. Further remarks

There are two significant outcomes from the present calculations. Firstly, the results k_{sc} using EGSnrc are extremely close to those obtained using EGS4 which gives greater confidence in the calculated values. For most chambers, the results for k_e are also very close, although significant differences are observed for large values of k_e.

Secondly, the extent to which fluorescence radiation is produced and re-absorbed is larger than anticipated and results in correction factors which are very significant in terms of the stated combined standard uncertainty of air kerma standards. In hindsight, one could have estimated this effect at the lowest energies, where the photoelectric effect is dominant, from the known argon content of the air and the average fluorescence yields given, for example, in [6]. For photon energies below 10 keV, this gives values within around 0.05 % of those obtained using EGSnrc.

8. References

[1] D T Burns, 1999, Consistent set of calculated values for electron-loss and photon-scatter corrections for parallel-plate free-air chambers, CCRI(I)/99-4 (BIPM).

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