Re-determination of the k_{sc}, k_e, k_{fl} correction factors for low and medium energy x-ray air-kerma measurement by the ENEA-INMRI free-air chambers.

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Introduction
The correction factors for electron loss, k_e, photon scatter k_{sc} and photon fluorescence, k_{fl}, were re-determined for the two standard free-air chambers at ENEA-INMRI. The correction factors k_{sc}, and k_e so far adopted were determined in the past years on the basis of literature data. No correction for photon fluorescence effects was applied so far. The new correction factors k_e, k_{sc} and k_{fl} were calculated by a two-step procedure: a) calculation for monoenergetic photons by the Monte Carlo Code PENELOPE, b) calculation of the factors by an averaging procedure in which the actual x-ray spectra are accounted for. The x-ray qualities are those adopted by CCRI(I) for low and medium energies air-kerma comparisons.

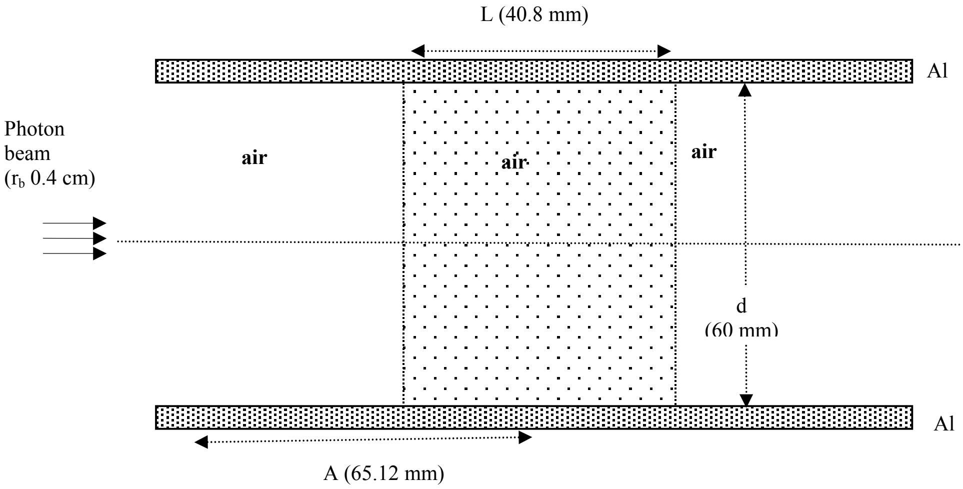
Methods
The factors k_e, k_{sc} and k_{fl} were calculated using the Monte Carlo Code PENELOPE [1]. The ENEA-INMRI air kerma standard in the x-ray low-energy range is a parallel-plate free-air chamber. For the Monte Carlo simulation the chamber was modelled as shown in Figure 1. The scoring regions are the air volume defined by the collector length, L, the collector width, w, and the electrode spacing, d and the central regions (length L and width w) of upper and lower electrode.
The ENEA-INMRI air kerma standard in the x-ray medium-energy range is a cylindrical Attix-type chamber with an off-center rod as collecting electrode [2,3]. The chamber geometry for the Monte Carlo simulation is shown in Figure 2. The scoring regions are the air central volume with length L and the central regions (length L) of the outer and internal electrode.
The photon and electron transport cut-off was set to 1 keV . The PENELOPE transport parameters were set as $C_1 = C_2 = 0.1$ and $Wcc = Wcr = 10^3$ eV for both chamber materials considered (i.e. aluminium and air). A user code was written using the ILB feature to score separately the energy deposition due to primary electrons (i.e. electrons generated in the first interaction of an incident photon), to electrons produced by scattered photons (Compton and Rayleigh photons) and to electrons produced by fluorescence photons.
According to [4] for a given incident photon energy E the factor $k_e(E)$ was calculated as:

$$\mathbf{k_e(E) = \frac{E_a + E_e}{E_a}} \qquad (1)$$

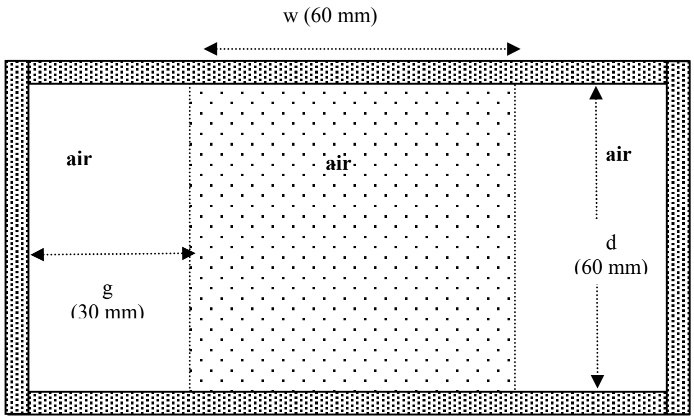
where E_a is the energy deposited in air by primary electrons and their progeny and E_e is the energy deposited in the electrodes by primary electrons and their progeny.
The factors $k_{sc}(E)$ and $k_{fl}(E)$ were calculated as:

$$\mathbf{k_{sc/fl}(E) = \frac{E_a}{E_a + E_{sc/fl}}} \qquad (2)$$

where $E_{sc/fl}$ is the energy deposited in air by electrons (and their progeny) produced by scattered photons (subscript *sc*) or by fluorescence photons (subscript *fl*). The quantities E_a, E_e and $E_{sc/fl}$ are normalized to the number of incident photons.
For the low-energy chamber, the calculation was made in the energy range from 4 keV to 50 keV in steps of 2 keV. For medium-energy chamber the calculation was made from 10 keV to 250 keV in steps of 10 keV. The statistical uncertainty on each correction factor, at a given energy, was estimated by sub-dividing the total number of histories in ten batches, calculating the correction factor for each batch and then evaluating the standard uncertainty of the average value, assuming a normal distribution. The resulting statistical uncertainty was always less than 0.01%.



(a)



(b)

Figure 1 – Geometry used to model the ENEA-INMRI parallel-plate free-air standard chamber: (a) side view, (b) front view. The scoring region is defined by L, d, w and the upper and lower electrode thickness.

The expressions for the k_e, k_{sc} and k_{fl} correction factors referring to a given energy distribution are similar to those used by Burns [4] . Then

$$\mathbf{k_e} = \frac{\sum_i \Phi_i \left[(\mathbf{E_a})_i + (\mathbf{E_e})_i\right]}{\sum_i \Phi_i (\mathbf{E_a})_i} \qquad (3)$$

and

$$\mathbf{k}_{\mathbf{sc/fl}} = \frac{\sum_{\mathbf{i}} \Phi_{\mathbf{i}} (\mathbf{E}_{\mathbf{a}})_{\mathbf{i}}}{\sum_{\mathbf{i}} \Phi_{\mathbf{i}} \left[(\mathbf{E}_{\mathbf{a}})_{\mathbf{i}} + (\mathbf{E}_{\mathbf{sc/fl}})_{\mathbf{i}} \right]} \qquad (4)$$

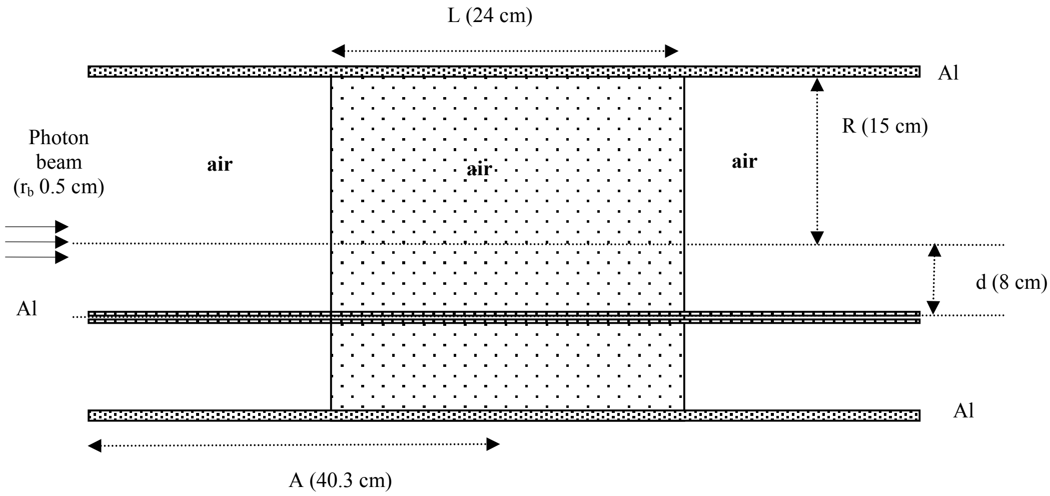


Figure 2- Geometry used to model the ENEA-INMRI cylindrical free-air standard chamber. The scoring region is the (dotted) central region including the volume of the electrodes of length L.

where, Φ_i is the photon fluence measured in the energy bin *i;* the other symbols have the same meaning as in the expression 1 and 2 with the subscript *i* indicating that the quantities (E_a , E_e and $E_{sc/fl}$) are referred to incident photons of energy equal to the mean energy of the i^{th} bin.
The x-ray energy distributions used in this calculation are those measured at ENEA-INMRI [5].

Results

a)free-air chamber for medium-energy x-ray
The energy dependence of the k_e, k_{sc} and k_{fl} factors is shown in figure 3 in the energy range from 10 to 250 keV. The k_e, k_{sc} and k_{fl} factors calculated for the CCRI(I) medium-energy x-ray qualities are given in Table 1. The relative standard uncertainty associated to each of these values is estimated as 0.06 %.
The old factors were estimated not individually but as the product $k_e k_{sc}$. For comparison the product of the new factors is reported in Table 1 together with the product of the old factors. The old values were derived by literature data [2, 6] with an estimated relative standard uncertainty of 0.15 %.
The new calculated values for the $k_e k_{sc}$ product are always larger than the old values. The differences range from 3 x 10^{-4} to 1.3 x 10^{-3} according to the x-ray quality. No correction was formerly applied for re-absorption of fluorescence photons. As shown in the last row of Table 1, after adopting the new correction factors, the change to the reference air kerma value is in the range from – 0.04% to 0.12%.

b)free-air chamber for low-energy x-ray range
The energy dependence of the k_e, k_{sc} and k_{fl} factors is shown in figure 4 in the energy range from 4 to 50 keV. The k_e, k_{sc} and k_{fl} factors calculated for the CCRI(I) low-energy x-ray qualities are given in Table 2. The relative standard uncertainty is estimated as 0.06 % for k_{fl}, and k_{sc} and 0.02% for k_e.
The old values of k_e and k_{sc} are also reported in Table 2 together with their product. The value for the individual factors was derived by literature data [7, 8] with an estimated relative standard uncertainty of 0.1 %.
The present calculation confirmed the old value 1.000 for the k_e correction. The new k_{sc} factors are higher than the old ones for all of the beams considered. The differences range from 1.5 x 10^{-3} to 3.3 x 10^{-3} according to the x-ray quality. No correction was applied in the past for photon fluorescence effect, assuming then implicitly $k_{fl} = 1$. The present calculated k_{fl} correction is significantly lower than unity for any of the x-ray qualities. The differences range from -1.2 x 10^{-3} to -3.9 x 10^{-3} according to the x-ray quality.

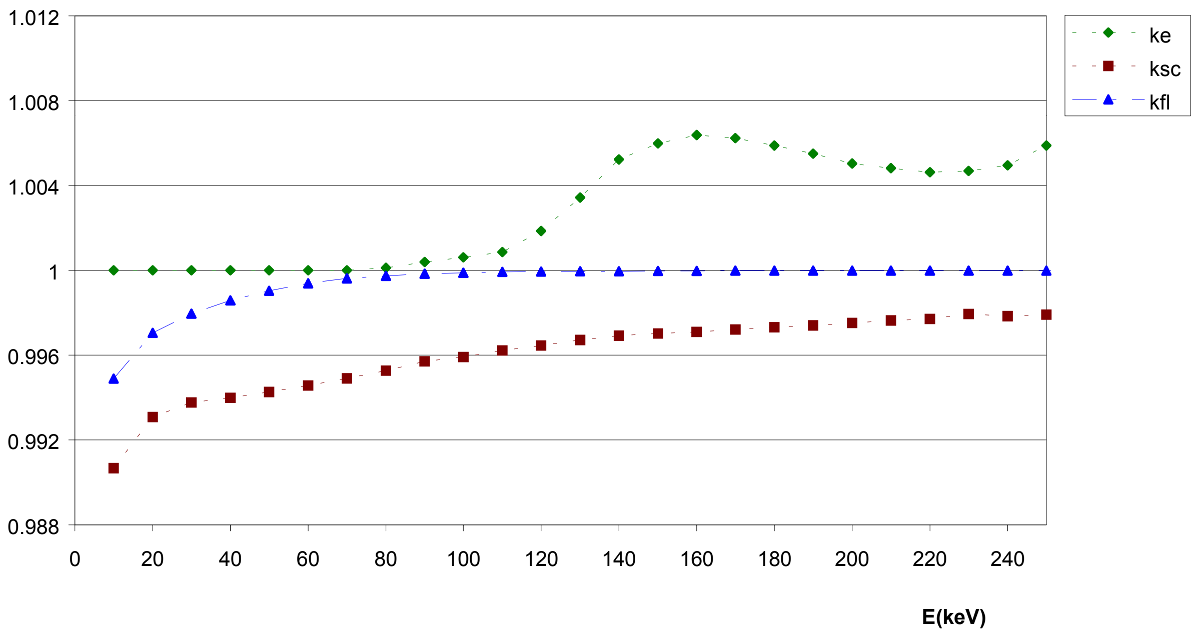


Figure 3 – Energy dependence of the correction factors, k_e, k_{sc} and k_{fl}, in the energy range from 10 to 250 keV, calculated for the ENEA-INMRI medium-energy free-air chamber. The relative statistical uncertainty is less than 0.01% .

Table 1- New values for k_e, k_{sc} and k_{fl} correction factors for the ENEA-INMRI medium-energy free-air chamber, determined by Monte Carlo calculation. The values used in the past years are also reported.

Generating potential 1stl HVL/ mm	*100 kV 4.00 Al*	*135 kV 0.499 Cu*	*180 kV 1.001 Cu*	*250 kV 2.497 Cu*
k_e	1.0000	1.0003	1.0015	1.0036
k_{sc}	0.9941	0.9950	0.9956	0.9967
k_{fl}	0.9985	0.9994	0.9997	0.9999
new correction k_e k_{sc}	0.9941	0.9953	0.9971	1.0003
old correction k_e k_{sc}	0.993	0.995	0.996	0.999
Change to air kerma reference value	0.9996	0.9997	1.0007	1.0012

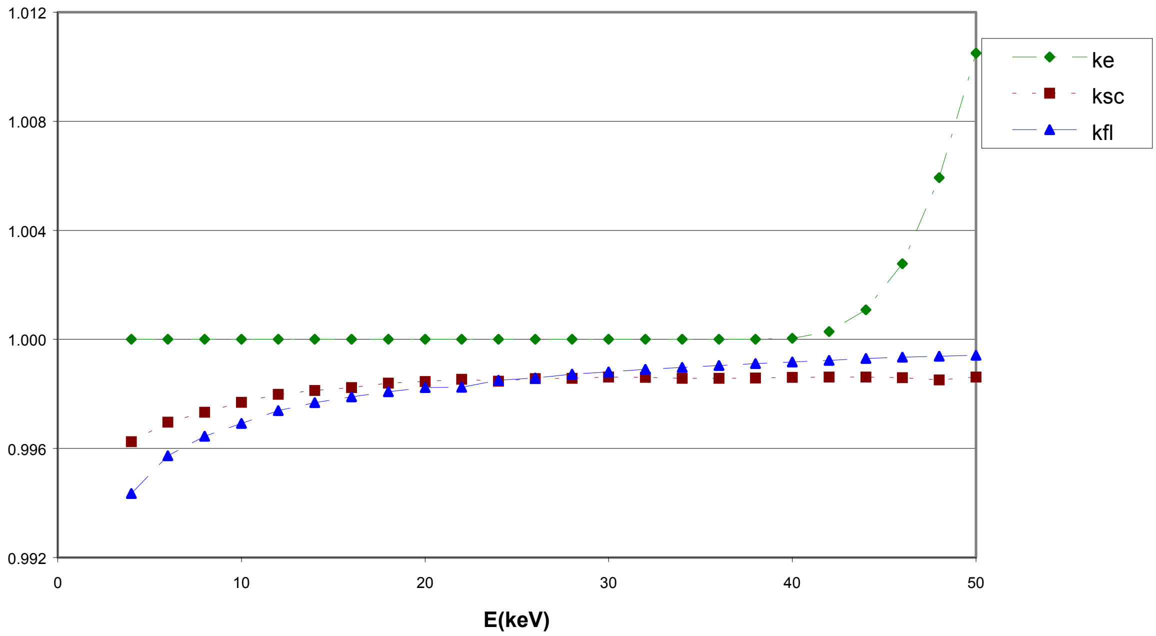


Figure 4 – Energy dependence of the correction factors, k_e, k_{sc} and k_{fl}, in the energy range from 4 to 50 keV, calculated for the ENEA-INMRI low-energy free-air chamber. The relative statistical uncertainty is less than 0.01% .

Table 2- New values for k_e, k_{sc} and k_{fl} correction factors for ENEA-INMRI low-energy free-air chamber, obtained by Monte Carlo calculation. The values used in the past are also reported.

Generating potential ***1st HVL /Al mm***	***10 kV*** ***0.03***	***30 kV*** ***0.18***	***25 kV*** ***0.25***	***50 kV(b)*** ***1.04***	***50 kV(a)*** ***2.27***
new correction factors					
k_e	1.0000	1.0000	1.0000	1.0000	1.0001
k_{sc}	0.9971	0.9978	0.9980	0.9984	0.9986
k_{fl}	0.9961	0.9972	0.9975	0.9983	0.9988
$k_e\, k_{sc}\, k_{fl}$	0.9932	0.9951	0.9955	0.9968	0.9975
old correction factors					
k_e	1.000	1.000	1.000	1.000	1.000
k_{sc}	0.9943	0.9950	0.9947	0.9967	0.9971
k_{fl}	1	1	1	1	1
$k_e\, k_{sc}\, k_{fl}$	0.9943	0.9950	0.9947	0.9967	0.9971
Change to air kerma reference value	0.9989	1.0001	1.0008	1.0001	1.0004

The differences between the old and new factors partially compensate with each other if the product ($k_e k_{sc} k_{fl}$) is considered. As shown in the last row of table 2, adopting the new correction factors the change to the reference air kerma value is within ±0.1%.

Conclusion

For the low-energy qualities the values of the k_e factor obtained by this Monte Carlo calculation agree with the old values, whereas the k_{sc} factors are larger, up to about 0.3%, than the old values. For the medium-energy qualities the present Monte Carlo values for the $k_{sc}k_e$ product differ up to 0.13% from the old value.

The new k_{fl} correction varies from 0.9961 to 0.9988 for the low-energy range and from 0.9985 to 0.9999 for the medium-energies. These values have to be compared with the unit value assumed for this factor in the past.

The new calculated correction factors are now adopted for the ENEA-INMRI standard chambers. The changes to primary ENEA-INMRI standards due to adopting the new values for k_e, k_{fl} and k_{sc} are within ±0.1% in low-energy range and from –0.04% to 0.12% in medium-energy range.

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