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Dose equivalent transmission data for shielding industrial x-ray facilities up to 800 kV

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Abstract

The transmission factors used to calculate radiation shielding around an industrial x-ray device are determined using the MCNP6 code. The transmission factors are given for high voltages ranging between 120 and 800 kV for lead and between 200 and 800 kV for concrete. In view of the high usage intensity of industrial devices, the transmission factors are evaluated up to 1.10^{-10}. The parameters used in the classic equation of Archer *et al* are derived from the transmission data calculated here. This type of data exists in the literature, but only for voltages lower than 150 kV to meet the design demands for facilities used in the medical field. In addition, this study markedly supplements the existing data, in particular for industrial and research installations.

Keywords: x-rays shielding, Monte Carlo calculations, industrial x-ray device

(Some figures may appear in colour only in the online journal)

1. Introduction

Transmission factors (T) are commonly used to assess the radiation protection around an installation comprising x-ray generators (see for example Antoni and Bourgois 2017a). This factor is calculated by dividing the dose equivalent with shielding by the dose equivalent without shielding. It permits to define a first design for an x-ray facility. Although this type of data exists in the literature, it is almost exclusively intended for installations in the medical field and thus for x-ray generators with accelerating high voltages (HVs) lower than or equal to 150 kV (see table 1). Since there are few data for x-ray industrial devices operating at voltages higher than 150 kV, it is useful to have transmission factors determined for higher voltage levels. This works presents the transmission factors calculated for lead between 120

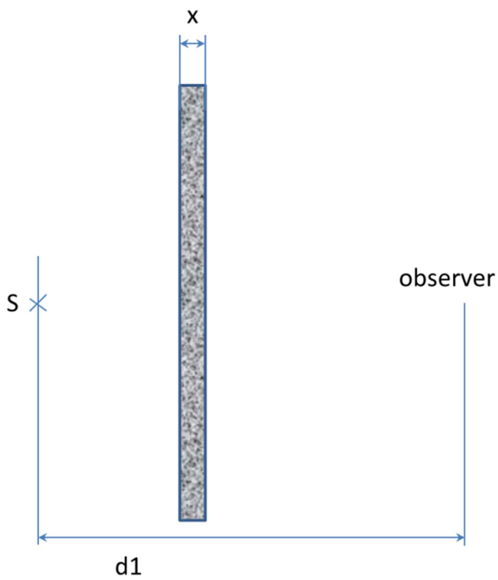

Figure 1. Geometry considered for calculation of dose equivalent behind an x-ray shielding material (thickness x).

Table 1. Transmission literature data.

Reference	HV	Shielding materials	Minimum value of T
Simpkin and Dixan 1998	25–150 kV	Lead, concrete, gypsum, steel, plate glass, wood	1.10^{-6}
Archer *et al* 1994	50–150 kV	Lead, steel, plate glass, gypsum, wood	1.10^{-3}
Costa *et al* 2015	100–150 kV	Different type of concrete	1.10^{-3}
Kharrati *et al* 2007	70–140 kV	Lead	1.10^{-4}
Platten 2014	120–140 kV	Lead	1.10^{-5}

and 800 kV and concrete between 200 and 800 kV using the Monte Carlo MCNP6 code. These values are then used to derive the parameters of the classic equation of Archer *et al* 1983. Moreover, in view of the high x-ray intensities of use of industrial devices, there is a need to determine transmission factors over a wide range (e.g. up to 1.10^{-10} in this study).

2. Methods

2.1. Expression for calculating dose equivalent rate delivered by primary radiation

To calculate the dose equivalent rate $\dot{H}_{\mathrm{obs}}$ at distance d_1 behind an x-ray shielding material (thickness x) with the geometry shown in figure 1, certain authors (NCRP 2005, Antoni and Bourgois 2017a) use the following equation:

$$\dot{H}_{\text{obs}} = \frac{\Gamma_{\text{R}} \cdot T(x)}{d_1^2} \tag{1}$$

where

- Γ_{R} is the dose equivalent rate due to a primary x-ray beam at 1 m from the source (the values of this parameter can be obtained from Antoni and Bourgois 2017b for voltages between 50 and 900 kV),
- d_1 is the distance between the source and the observer (in m),
- $T(x)$ is the transmission factor for a thickness x of material traversed.

2.2. Parametric equation for determining the transmission factor T and literature data

A parametric equation was developed by Archer *et al* 1983 (equation (2)) to determine the transmission factor T as a function of the thickness x of material traversed.

$$T = \left[\left(1 + \frac{\beta}{\alpha}\right)\exp(\alpha\gamma x) - \frac{\beta}{\alpha}\right]^{-\frac{1}{\gamma}}. \tag{2}$$

Thus, equation (3) can be used to obtain the thickness of the shielding, x, expressed in mm:

$$\text{x} = \frac{1}{\alpha\gamma} \times \ln\left[\frac{T^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right]. \tag{3}$$

A certain number of values are available in the literature for the transmission factors, T, and the parameters α, β and γ (see references in table 1). It should be noted that the T values are given to estimate the air kerma rate and not the ambient dose equivalent. Moreover, most of these studies are concerned with medical applications, so the HV settings are limited to 150 kV. In the same way, the transmission factors given in these studies range up to a maximum of 1.10^{-6}, which can be insufficient for industrial devices, which produce extremely high x-ray beam intensities (thus delivering high dose rates).

Therefore, it is useful to have some additional data, in terms of dose equivalent, for HV higher than 150 kV and transmission factors up to 1.10^{-10}, which would increase coverage to include the x-ray generators used in industrial installations and research.

2.3. Method for calculating the new data

Calculations are carried out with version 1.0 of the Monte Carlo MCNP6 code (Pelowitz 2013). The cross-sections used are from the MCPLIB04 library ENDF/B-VI Release 8 (White 2002). Calculations are performed in terms of the measure 'ambient dose equivalent under 10 mm': $H^*(10)$. For this purpose, this work determines the fluence at a point by means of a type-5 tally weighted by the coefficients used to convert the x-ray fluence to ambient dose equivalent at 10 mm as published by the ICRP 1996. Statistical tests on the whole set of calculated data show that the values obtained are in conformity with the results expected for a type-5 tally (calculation of the fluence at a point). All the statistical errors are less than 2%.

The geometry considered here is presented in figure 2. The x-rays are emitted from the source in a cone with a large apex angle. This 'broad-beam' geometry is thus more penalizing in terms of radiation protection.

To avoid problems of convergence, the calculation is divided into two steps. Initially, the spectrum in terms of the fluence of x-rays resulting from the interaction of a parallel beam of

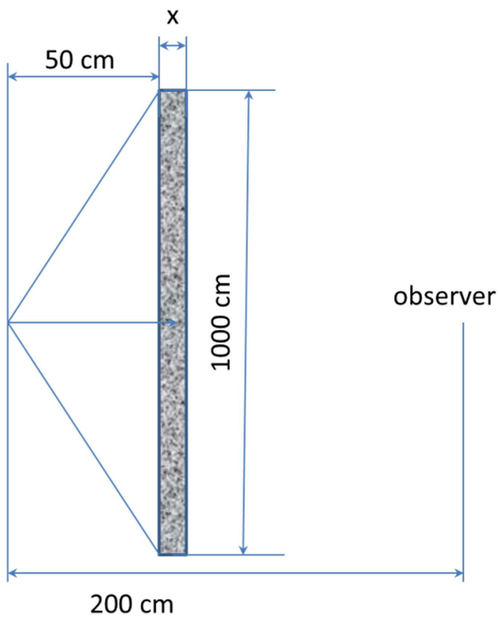

Figure 2. Geometry considered for MCNP6 calculation of the dose equivalent behind a shielding.

electrons of kinetic energy E (corresponding to an HV) interacting on a tungsten target (with an anode angle of 45°) is calculated. For this calculation, filtration through 6 mm of aluminum to simulate a spectrum of relatively high energy was taken into account. In this case, the MCNP6 code is used to carry out coupled transport of electrons and photons (mode P E).

In a second step, this work uses the x-ray spectrum thus obtained as a source of photons. In this calculation, only the photons are transported (mode P). Nevertheless, and to take account of the bremsstrahlung photons (due to the photoelectrons and Compton electrons), the mode 'thick-target bremsstrahlung approximation' is activated. To obtain convergence of the results, a biasing technique using the 'weight window generator' method is applied.

Two types of radiation shielding material are studied here: concrete and lead. Because of the HVs used in industrial applications, this work does not consider shielding composed of plastic, glass, wood or steel. The composition of the concrete is given in table 2.

2.4. Calculation of parameters in equations (equations (2) and (3))

The calculations carried out using the MCNP6 code make it possible to obtain a certain number of values for the couple (thickness x-transmission factor T).

From these discrete values, the values of the parameters α, β and γ in equations (2) and (3) can be calculated. For this purpose, the method described by Simpkin 1995 is applied.

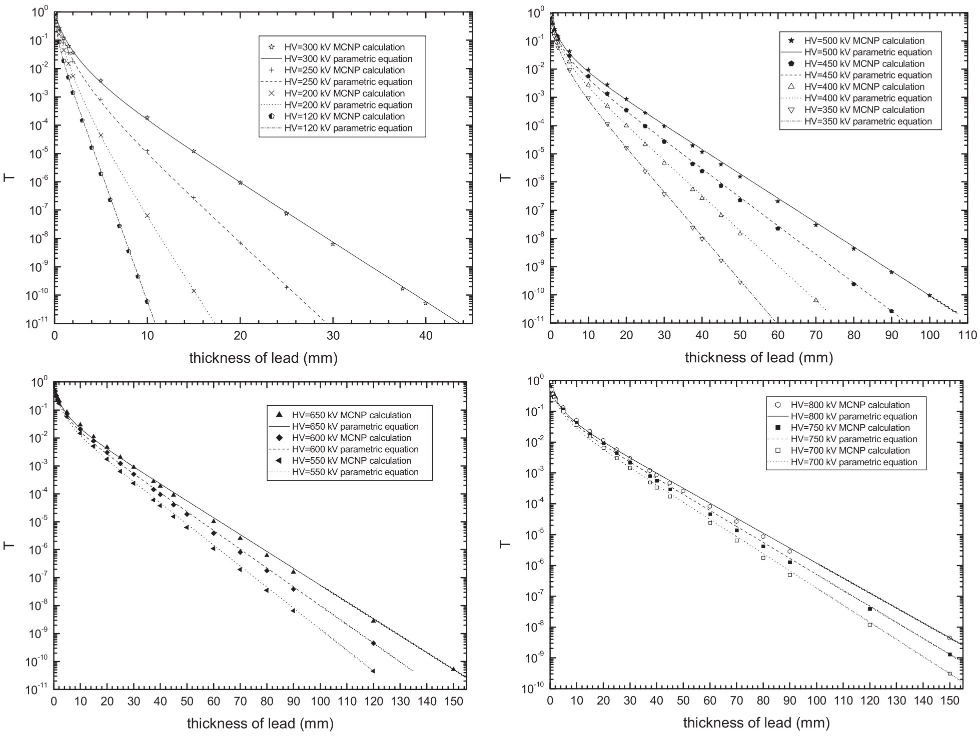

Figure 3. Variation of transmission factors T according to thickness of lead, calculated by the Monte Carlo method, with smoothing based on equation (2) and parameters of table 3.

Table 2. Composition of concrete (density 2.35) according to Bouniol (2001).

Composition	Element wt%
Si	20.68
Al	0.36
O	50.85
Ca	21.65
Mg	0.2
S	0.14
C	4.52
H	0.7
Fe	0.66

For lead, a density of 11.35 g cm^{-3} is assumed.

3. Results and discussion

3.1. Results for lead

Figure 3 shows the discrete values of transmission factors calculated by the MCNP6 code at various HV settings and plotted against thickness of lead, along with smoothed curves derived from equation (2) using the parameters of table 3.

Table 3. Parameters α, β and γ in equation (2) for HV ranging from 120–800 kV in the case of lead shielding.

HV (kV)	α (mm^{-1})	β (mm^{-1})	γ	Maximum deviation between smoothed curve and MCNP6 calculation (%)	Maximum value of x (mm) for validity of the parameters α, β, γ
120	2.12E+00	6.88E+00	6.24E-01	22	12
200	1.17E+00	2.51E+00	2.21E-01	19	30
250	6.99E-01	2.32E+00	3.05E-01	21	45
300	4.83E-01	2.21E+00	4.06E-01	20	50
350	3.60E-01	2.02E+00	4.92E-01	20	60
400	2.85E-01	1.84E+00	5.71E-01	23	70
450	2.32E-01	1.73E+00	6.17E-01	23	90
500	1.99E-01	1.58E+00	6.81E-01	23	100
550	1.73E-01	1.49E+00	7.45E-01	26	120
600	1.55E-01	1.33E+00	7.67E-01	23	120
650	1.39E-01	1.26E+00	8.08E-01	30	150
700	1.28E-01	1.18E+00	8.63E-01	29	150
750	1.19E-01	1.12E+00	9.23E-01	25	150
800	1.12E-01	1.05E+00	9.53E-01	25	150

For lead, this work notes that the difference between the transmission factor T calculated with MCNP6 and the approximation obtained from equation (2) attains a maximum of 30% at an HV value of 650 kV.

The values for α, β and γ are calculated using the method described in section 2.4. Table 3 also reports the maximum deviation between the values computed using the MCNP6 code and the values estimated according to equation (2). This table also gives the maximum value of x for which equation (2) remains valid.

3.2. Results for concrete

Figure 4 shows the discrete values of transmission factors calculated by the MCNP6 code at various HV settings and plotted against the thickness of concrete, along with smoothed curves derived from equation (2) using the parameters of table 4.

The values of α, β and γ are calculated with the method described in section 2.4. Table 4 also reports the maximum deviation between the values computed using the MCNP6 code and the values estimated according to equation (2). The maximum value of x for which equation (2) remains valid is also given.

3.3. Comparison with published data

Although abundant data are available for x-ray generators in the medical field (HV $<$ 150 kV), very little data exist in the industrial sector.

The NCRP (1976) gives some x-ray half-value layer thicknesses for high attenuations. With our data, we can recalculate the tenth-value layer thickness to derive the half-value layer ($x_{1/2} = x_{1/10}.\ \ln(2)/\ln(10)$) for high attenuations (1.10^{-10}). The x-ray half-value layer thicknesses evalulated here for high transmission factors are close to the literature values (see table 5).

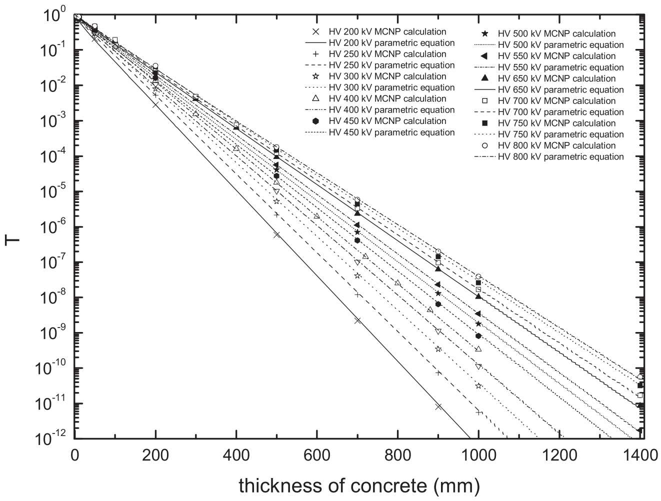

Figure 4. Variation of transmission factors T according to the thickness of concrete calculated by the Monte Carlo method, with smoothing based on equation (2) and parameters of table 4.

Table 4. Parameters α, β, γ of 22 for HT values ranging from 200–800 kV, in the case of concrete shielding.

HV (kV)	α (mm^{-1})	β (mm^{-1})	γ	Maximum deviation between smoothed curve and MCNP6 calculation (%)	Maximum value of x (mm) for the validity of the parameters α, β, γ
200	2.77E-02	1.99E-02	1.11E + 00	24.3	1400
250	2.57E-02	1.33E-02	3.65E + 00	15	1400
300	2.40E-02	2.38E-03	3.68E + 00	14.6	1400
350	2.27E-02	5.43E-03	1.69E + 00	14	1400
400	2.19E-02	7.79E-04	5.06E + 00	12	1000
450	2.07E-02	3.23E-03	8.17E-01	21	1400
500	1.99E-02	1.80E-03	5.86E-01	22	1400
550	1.94E-02	8.09E-04	6.20E-01	17.3	1400
650	1.83E-02	3.15E-03	1.65E + 00	24.6	1400
700	1.77E-02	8.71E-04	2.41E-01	21	1400
750	1.69E-02	8.14E-04	8.27E-02	14	1400
800	1.69E-02	1.72E-03	5.18E-01	22	1400

For concrete, the difference between the transmission factor T calculated with MCNP6 and the approximation obtained from equation (2) attains a maximum of 25% for an HV of 650 kV.

In the same way, the transmission factor for lead at an HV of 120 kV can be compared with the literature data. Figure 5 compares these transmission factors. It is noteworthy that the results of Kharrati *et al* 2007 fit perfectly with our calculations, including the transmission factors for thicknesses of lead up to 10 mm. On the other hand, for 3 mm of lead, we note that our transmission factor is twice as high as the value reported by Platten 2014 and the

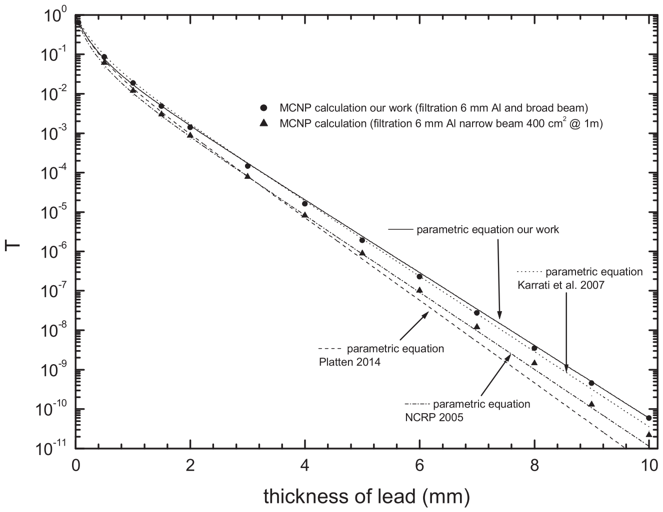

Figure 5. Comparison of transmission factors for an HV of 120 kV and with lead shielding.

Table 5. Comparison of half-value layer.

	Lead		Concrete	
HT (kV)	$x_{1/2}$ (NCRP 1976) mm	$x_{1/2}$ (this study) mm	$x_{1/2}$ (NCRP 1976) cm	$x_{1/2}$ (this study) cm
200	0.5	0.48	2.5	2.4
300	1.5	1.5	3.1	2.8
400	2.5	2.55	3.3	3.3
500	3.6	3.54	3.6	3.6

The half-value layer thicknesses evaluated here for high transmission factors are close to the literature values.

NCRP 2005. For a 10 mm thickness of lead, our factor is four times higher than that of Platten 2014 and three times higher than that of the NCRP 2005.

This discrepancy could be due to various factors. First of all, our transmission factors are calculated in terms of ambient dose equivalent under 10 mm: $H^*(10)$, while the results of Kharrati *et al* 2007 are given in terms of effective dose, and those of Platten 2014 and the NCRP 2005 in terms of kerma. Moreover, additional filtration also has an influence. For example, Hideki (2003) shows that, for a 3 mm thickness of lead and at an HV of 120 kV, the transmission factor with a filtration of 5 mm aluminum is approximately twice as high as without any filtration of aluminum. Finally, the geometry used has an influence on the result. Indeed, the value of the build-up is highly dependent on the dimension of the beam, and will have an impact on radiation protection. For example the same device as before (120 kV and 6 mm aluminum filtration) in the same geometry, but with a narrow beam (400 cm^2 at one meter) has been simulated. In this case (see figure 5), our calculations fit perfectly the results of the NCRP 2005.

4. Conclusions

The transmission factors reported here represent a considerable addition to the data published elsewhere. The present values are calculated for accelerating voltages varying from 120–800 kV for lead shielding and from 200–800 kV for concrete shielding. The x-ray half-value layer thicknesses given in the literature are comparable with the values estimated here. Nevertheless, we would need to be able to compare the values of transmission factors over the whole range of the values of *x*. Nevertheless, a 120 kV study shows that the influence parameters of the x-ray transmission are:

- Beam dimension (broad beam or narrow beam)
- Filtration
- Quantity study (kerma, effective dose, dose equivalent).

Equation (2) yields a good parametric approximation of the transmission function.

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