Brachytherapy structural shielding calculations using

Monte Carlo generated, monoenergetic data

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Abstract

Purpose: To provide a method for calculating the transmission of any broad photon beam with a known energy spectrum in the range of 20 keV-1090 keV, through concrete and lead, based on the superposition of corresponding monoenergetic data obtained from Monte Carlo simulation.

Methods: MCNP5 was used to calculate broad photon beam transmission data through varying thickness of lead and concrete, for monoenergetic point sources of energy in the range pertinent to brachytherapy (20 to 1090 keV, in 10 keV intervals). The three parameter empirical model introduced by Archer *et al.*[1] was used to describe the transmission curve for each of the 216 energy-material combinations. These three parameters, and hence the transmission curve, for any polyenergetic spectrum can then be obtained by superposition along the lines of Kharrati *et al.*[2] A simple program, incorporating a graphical user interface, was developed to facilitate the superposition of monoenergetic data, the graphical and tabular display of broad photon beam transmission curves, and the calculation of material thickness required for a given transmission from these curves.

Results: Polyenergetic broad photon beam transmission curves of this work, calculated from the superposition of monoenergetic data, are compared to corresponding results in the literature. A good agreement is observed with results in the literature obtained from Monte Carlo simulations for the photon spectra emitted from bare point sources of various radionuclides. Differences are observed with corresponding results in the literature for x-ray spectra at various tube potentials, mainly due to the different broad beam conditions or x-ray spectra assumed.

Conclusions: The data of this work allow for the accurate calculation of structural shielding thickness, taking into account the oblique incidence of radiation to the shield, spectral variation with shield thickness, and broad beam conditions, in a

realistic geometry. The simplicity of calculations obviates the need for the use of crude transmission data estimates such as the HVL and TVL indices. Although this study was primarily designed for brachytherapy, results might also be useful for radiology and nuclear medicine facility design, provided broad beam conditions apply.

Key words: brachytherapy, radiation protection, shielding, Monte Carlo

I. INTRODUCTION

Broad beam radiation transmission data are essential for the structural shielding design of medical radiation facilities. Seeking to address the limited availability and disparity amongst such data for brachytherapy, a previous study presented Monte Carlo (MC) calculated transmission curves for the photon emissions of bare, point sources of radionuclides used in brachytherapy through various materials.[3] A three parameter analytical representation introduced by Archer *et al.*[1] was fit to the discrete values of transmission versus material thickness for each radionuclide-material combination. This fitting procedure was performed to obviate the need for interpolation or the use of transmission curve indices such as the half and tenth value layer (HVL and TVL, respectively). HVL and TVL do not remain constant due to spectral variation with increasing shielding barrier thickness[3-6] and their use was shown to introduce potentially significant errors. [6,7]

A method for calculating the transmission of any broad photon beam in the energy range of diagnostic x-ray applications and external beam radiation therapy, using superposition of corresponding monoenergetic data in the form of the model introduced by Archer *et al.*,[1] has been presented by Kharrati *et al.*[2,8] and Karoui and Kharrati[9] As intermediate energy radionuclides are proposed for use in brachytherapy to reduce shielding requirements[3,10] and the use of high energy radionuclides is revived based on economic aspects,[11] this work aims at extending the method of Kharrati *et al.*[2] to cover the energy range pertinent to brachytherapy (20 keV-1090 keV) for concrete and lead, and providing a simple program to facilitate calculations. While this study was primarily designed for brachytherapy, results might also be of use for radiology and nuclear medicine facility design, provided the assumed broad beam conditions apply.

II. MATERIALS AND METHODS

A. Monte Carlo Simulations

85   The MCNP5 v.1.40 general-purpose code[12] was used for simulations of this work, with the MCNPLIB04 cross section data library which comprises a collection of data from the ENDF/B-VI.8 data library,[13] based on EPDL97.[14]

The simulation geometry was identical to that of a previous study[7] to preclude comparison bias of transmission results for brachytherapy sources. In brief, it

90   comprised an air filled box ($x \times y \times z = 5 \times 5 \times 3$ m^3) with a point monoenergetic photon source centred on the yz plane at x=0 and a shield barrier of thickness Δx positioned with its distal surface to the source at x=1 m. Photons were emitted isotropically in a 2π solid angle towards the barrier to simulate realistic broad beam conditions. The energy of the source was varied from 20-1090 keV in 10 keV intervals. The shield

95   materials considered included concrete (2.3 gcm^{-3} density, elemental composition taken from Hubbell and Seltzer[15]) and lead (11.35 gcm^{-3} density).

Radiation transmission results were calculated by the ratio of air kerma per initial photon scored for a barrier thickness Δx, to that scored at the same point without any shielding barrier (Δx=0). Air kerma was scored in a spherical voxel of 20 cm diameter

100   centered at x=1.3 m along the vertical direction from the source to the shield, using an F6 photon energy deposition tally. The evaluation of radiation transmission at a distance of 30 cm behind a barrier is a conservative, yet common practice in radiation shielding calculations.[4,16]

The resolution of barrier thickness in the set of simulations for each point source

105   energy–shield material combination was adjusted so that three values of transmission were calculated per order of magnitude of transmission reduction, down to 10^{-4}. The number simulated initial photon histories varied so that type A uncertainty of air kerma results expressed as the fractional error was less than 10% (for low energy

photons at large attenuation). A rough estimate of type B uncertainty should combine

110   that of photon interaction cross section data for the shielding materials (2% at

maximum due to uncertainty in the photoionisation cross sections[14]) and air photon

mass energy-absorption coefficients (on the order of 2.3% standard uncertainty[17]).

B. Broad photon beam transmission calculations from monoenergetic data

115   The three-parameter model introduced by Archer *et al.*[1] to facilitate diagnostic x-

ray shielding calculations was used to describe MC calculated transmission results of

this study. The model has the form:

$$T(x,E) = \left[\left(1+\frac{\beta}{\alpha}\right)e^{\alpha\gamma x} - \frac{\beta}{\alpha}\right]^{-\frac{1}{\gamma}} \qquad (1)$$

where *T* stands for transmission of a broad, monoenergetic, photon beam though a

120   shielding barrier, *x* is the barrier thickness, E is the photon beam energy, and (α, β, γ)

are constant terms to be determined by the fit that depend on photon energy and

barrier material.

A weighted fit was performed using a trust region, non linear least squares

algorithm, with weights inversely proportional to the square of transmission standard

125   uncertainties calculated by propagation of MC type A uncertainties.

Given (α, β, γ) for a material and a specific beam quality, the thickness of material

required to achieve a given transmission can be calculated by solving Eq. (1) for *x*:

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

In order to obtain the transmission curve for any photon source emitting a

130   polyenergetic spectrum of energies E_n with relative intensities f_n, monoenergetic

transmission data results of this work $T(x,E)$ in the form of fitting results (α, β, γ), were combined according to the equation:

$$T[x,(E_n,f_n)] = \frac{\sum\limits_n E_n f_n (\mu_{en}/\rho)_{E_n} T(x,E_n)}{\sum\limits_n E_n f_n (\mu_{en}/\rho)_{E_n}} =$$

135   (3)

$$\frac{\sum\limits_n E_n f_n (\mu_{en}/\rho)_{E_n} \left[\left(1 + \beta_n/\alpha_n\right)\exp(\alpha_n\gamma_n x) - \beta_n/\alpha_n\right]^{-1/\gamma_n}}{\sum\limits_n E_n f_n (\mu_{en}/\rho)_{E_n}}$$

where $(\mu_{en}/\rho)_{E_n}$ is the mass energy absorption coefficient of air for energy E_n,

140   calculated by interpolation through μ_{en}/ρ data available as a function of energy.[15] The

constants (α_n, β_n, γ_n) are also determined by interpolation through (α, β, γ) results of

this work from fitting Eq. (1) to the MC calculated transmission of broad

monoenergetic photon beams through concrete and lead.

A simple program was prepared to facilitate the calculation of transmission curves

145   through concrete and lead for monoenergetic and polyenergetic photon sources using

Eq. (3).[18] The graphical user interface of the program is depicted in Fig. 1. Through

this interface the user can input a single photon energy or import a photon spectrum

from file, provided these lie in the energy range of 20 to 1090 keV. Following

selection of the shielding material (concrete or lead) from a pull-down menu, the user

150   is presented with the options to review the transmission curve graphically, export

numerical data to a file, calculate thickness required for a given transmission and

tabulate results. It should be noted that since Eq. (3) cannot be readily solved for

thickness, the program calculates the shielding thickness required to achieve a given

transmission by interpolation though transmission curve data of resolution sufficient

155   for accurate results.

III. RESULTS AND DISCUSSION

A. Broad monoenergetic photon beam transmission data and fit results

Figure 2 summarizes the results of fitting Eq. 1 to the MC generated data sets of

160   broad monoenergetic photon beam transmission, in the form of the three fitting

parameters (α, β, and γ) plotted versus photon energy for concrete and lead.

According to Eq. 1, transmission tends to $\exp(-\alpha x)$ at large thickness, x, and α is

the slope of a transmission curve beyond the depth where the relative directional and

energy photon distributions are almost independent of thickness. Hence α is the

165   equivalent of an effective attenuation coefficient for the equilibrium photon spectrum

at large attenuation. Its values can be seen to follow the trend of the linear attenuation

coefficients for concrete and lead[19] that are also plotted for comparison in Figs. 2a and

2c, respectively, and decrease with increasing photon energy for the same material, or

decreasing attenuating potential of the barrier material for the same energy. Values of

170   α are however lower than corresponding linear attenuation coefficients due to the

build up of scattered photons. This effect is more pronounced as the relative

importance of Compton interaction increases (i.e. energies greater than 40 keV for

concrete, Fig. 2a).

β is associated to the contribution of photon build up to the broad beam

175   transmission, and its absolute value is expected to decrease as the relative importance

of build up increases, as seen in Figs. 2b and 2d with the increase of energy for

concrete and lead, respectively. γ serves to describe the change of slope of a

transmission curve at small x where the equilibrium photon spectrum has not been

attained, and its values can be seen to decrease with increasing energy in Figs. 2b and

180   2d, exhibiting however considerable variation.

Corresponding results of fitting Eq. 1 to MC generated data sets of broad monoenergetic photon beam transmission have been presented in the literature in the energy range of diagnostic x-ray applications (15 keV-150 keV)[8] and external beam radiation therapy.[9] These data are also presented in Fig. 2 for comparison. Regarding

185   α values, in Fig. 2a for concrete it can be seen that results of Kharrati *et al.* [8] are lower than results of this work (20% at 40 keV and 12% at 100 keV). This is mainly due to differences in the broad beam conditions assumed since Kharrati *et al.* [8] simulated a beam of 30 x 30 cm^2 at the shielding barrier as opposed to emission in a 2π solid angle towards a 5 x 3 m^2 barrier simulated in this work. Hence the effect of photon

190   build up, or equivalently the departure from narrow beam conditions, represented by the linear attenuation coefficient in Fig. 2a, is greater for results of this work. On the contrary, results of Karoui and Kharrati[9] are in close agreement with results of this work since they correspond to comparable broad beam conditions.

For lead, broad beam conditions and photon build up is less important relative to

195   concrete. Hence, in Fig. 2c it can be seen that α values from the literature[8,9] are generally in excellent agreement with results of this work (within 3%). The only exception is results of Kharrati *et al.*[8] that exhibit an unexpected decrease in the energy range immediately after the K-edge for lead (90 keV-110 keV) and even attain negative values at 100 keV and 105 keV (not shown in the log scale of Fig. 2c).

200   Regarding β and γ values, differences between results of this work and Kharrati *et al.*,[8] that are systematic in Fig. 2b for concrete, are due to the broad beam conditions assumed in the two studies, as discussed above.

Besides graphic presentation, fitting results of this work are also provided as a table of the three fitting parameters (α, β, and γ) versus photon energy and shielding

205   material.[20] This table also includes maximum differences of shielding material thickness between fit results and MC data, for the same transmission. While goodness

of fit metrics were excellent for all energies, these maximum differences are considerable and while not systematic and generally under than 5%, they reach up to -14.9% for concrete and 770 keV and -19.6% for lead and 90 keV. They occur

210   however at large attenuation, owing to the relatively increased statistical uncertainty of results, and they are therefore considered acceptable within the scope of this work.

These findings are also presented in the comparison of MC data and fit results for indicative energies in Fig. 3. In this figure the greatest difference between fit results and MC data is observed for the energy of 100 keV in lead (Fig. 3c). This is probably

215   due to the energy degradation of the equilibrium spectrum at large attenuation below the K-edge for lead, which results to an increase of transmission that the fitting equation cannot account for.

Fit results of Kharrati *et al.*[8] are also plotted in Figs. 3a and 3c for comparison and noticeable differences from fit results of this work occur for concrete (Fig. 3a) as

220   expected form the difference in broad beam conditions assumed in the two studies discussed above.

B. Broad photon beam transmission calculations for polyenergetic brachytherapy sources

225   Broad photon beam transmission data for polyenergetic sources used in brachytherapy can be calculated according to Eq. (3), using the fit results for monoenergetic transmission data discussed in the previous section and the program developed in this work for this task.

Indicative results of this work for ^{169}Yb and ^{192}Ir are presented in Fig. 4.

230   Corresponding MC and fit results from a previous work,[7] calculated for the full spectra of photon emissions from bare, point sources of these radionuclides in the same geometry, are also presented in Fig. 4. Comparison shows excellent agreement

for both radionuclides and structural shielding materials for transmission down to 10^{-3}. At large attenuation, transmission differences between results of this work and MC

235   data for the full spectra are observed reaching up to 50%. These differences however translate to small differences in shielding material thickness required to achieve the same transmission (i.e. 1.22 cm at 42 cm and 0.73 cm at 60 cm for ^{169}Yb and ^{192}Ir in concrete, respectively, and -0.32 cm at 5.6 cm and -0.07 cm at 1.8 cm for ^{169}Yb and ^{192}Ir in lead, respectively) and can therefore be considered tolerable for shielding

240   design purposes.

C. Broad photon beam transmission calculations in the energy range of radiology and nuclear medicine applications

The fit results for monoenergetic transmission data and the accompanying

245   program developed in this work, were also used to calculate broad photon beam transmission data through concrete and lead for x-ray spectra produced by a Tungsten anode tube of 2.5 mm Al added filtration, operated at peak potentials of 70, 100 and 120 kV$_p$.[21] Results are presented in Fig. 5 and compared to corresponding results calculated for the same spectra using fit results of Kharrati *et al.*,[8] as well as

250   corresponding results calculated using the fit coefficients provided as a function of kV$_p$ for Tungsten anode tubes in NCRP 147[22] that are adapted from the work of Simpkin.[23]

In Fig. 5a for concrete it can be seen that transmission results of this work are systematically higher than corresponding results in the literature owing to the

255   difference in broad beam conditions from results of Kharrati at al,[8] and the combined effect of differences in broad beam conditions and the x-ray spectra assumed in the studies used to derive the data in Simpkin.[23]

For lead, since the effect of broad beam dimensions is less important than for concrete (see Sec. II.A), results of this work were expected to be in close agreement with

260   corresponding results of Kharrati at al[8] for the same x-ray spectra. Nevertheless, in Fig. 5b such agreement is only observed at small attenuation for the lower peak potentials of 70 kV_p. Significant differences are also observed between results of this work and NCRP 147.[22]

These findings imply that results of this work are not suitable in shielding calculations

265   for primary barriers in radiology due to the underlying broad beam assumptions. They could be used for secondary barrier calculations provided that the spectrum of scatter or leakage radiation is known.

In Fig. 6 results of this work are compared to corresponding MC data in the literature[6] for 511 keV photons that are of interest to the shielding design of positron emission

270   tomography facilities. A good agreement can be observed between the two data sets in concrete and lead with differences within 8%. In the absence of transmission curve results for radionuclides used in nuclear medicine, results of this work were compared to lead HVL data in the literature[24] and found in good agreement (i.e. 0.29 mm versus 0.23 mm for ^{201}Tl, 0.69 mm versus 0.66 mm for ^{67}Ga, and 2.70 mm versus 3.0 mm for

275   ^{131}I). A considerable difference was observed only for ^{111}In (0.34 mm versus 1.3 mm) which, considering the effective energy of the ^{111}In photon emissions, is attributed to an error in the NCRP report.[24]

The above results, combined with the fact that the broad beam conditions assumed in this work are comparable to those occurring in nuclear medicine applications, suggest

280   that results of this work can be used for nuclear medicine shielding calculations. Such calculations are expected to err on the safe side since patient absorption will not be taken into account.

Conclusions

285   Transmission data through concrete and lead were obtained for point, monoenergetic photon sources (20 keV – 1090 keV) and broad beam conditions using Monte Carlo simulation. After fitting to a three parameter empirical model, these results can be combined to obtain the transmission curve for any polyenergetic spectrum. A simple program was developed to facilitate calculations as well as

290   provide graphical and tabular display of broad photon beam transmission curves, and allow for the calculation of material thickness required for a given transmission. Results of this work can be used for structural shielding design calculations for brachytherapy and nuclear medicine applications. While the broad beam conditions assumption underlying results of this work renders their use inappropriate for

295   radiology primary barrier shielding calculations, they could be used for secondary barrier calculations provided that the spectrum of scatter or leakage radiation is known.

Acknowledgements

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program for the calculation of transmission curves through concrete and lead for

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Figure Captions

Figure 1. A depiction of the graphical user interface of the program prepared to facilitate the calculation of broad beam transmission curves through concrete and lead for any polyenergetic photon beam, based on corresponding monoenergetic results of this work.

Figure 2. Results of fitting the three parameter model of Eq. 1 to Monte Carlo calculated broad beam transmission data of this work for monoenergetic photon sources. (a) parameter α for concrete compared to corresponding results from literature[8, 9] and the linear attenuation coefficient, μ,[19] (b) parameters β and γ for concrete compared to corresponding results from the literature[8, 9], (c) parameter α for lead compared to corresponding results from the literature[8, 9] and the linear attenuation coefficient, μ,[19] (d) parameters β and γ for lead compared to corresponding results from the literature[8, 9].

Figure 3. Monte Carlo calculated broad beam transmission data plotted versus concrete (a, b) and lead (c,d) thickness, for selected photon energies. Results of fitting Eq. 1 to the data, as well as corresponding fit results from the literature,[8] are also plotted in Figs. (a) and (c) for comparison.

Figure 4. Broad beam transmission data through (a) concrete, and (b) lead, calculated using Eq. 3 with results of this work for the ^{169}Yb and ^{192}Ir photon spectra. Corresponding Monte Carlo and fit results from the literature[7] are also presented for comparison.

Figure 5. Broad beam transmission data through (a) concrete, and (b) lead, calculated using Eq. 3 with results of this work for x-ray spectra of a tube operated at three different peak potentials.[21] Corresponding results for the same x-ray spectra using the same method with results from the literature,[8] as well as corresponding results for the same peak potentials,[22] are also presented for comparison.

Figure 6. Broad beam transmission data through concrete and lead, calculated using

415   Eq. 3 with results of this work for 511 keV photons. Corresponding Monte Carlo and

fit results from the literature[6] are also presented for comparison.

Select data to create transmission curves

Poly-energetic photon source

Select i-energy spectrum
(i=1,2,3,4)

4

Import i-spectrum

OR

Mono-energetic photon source

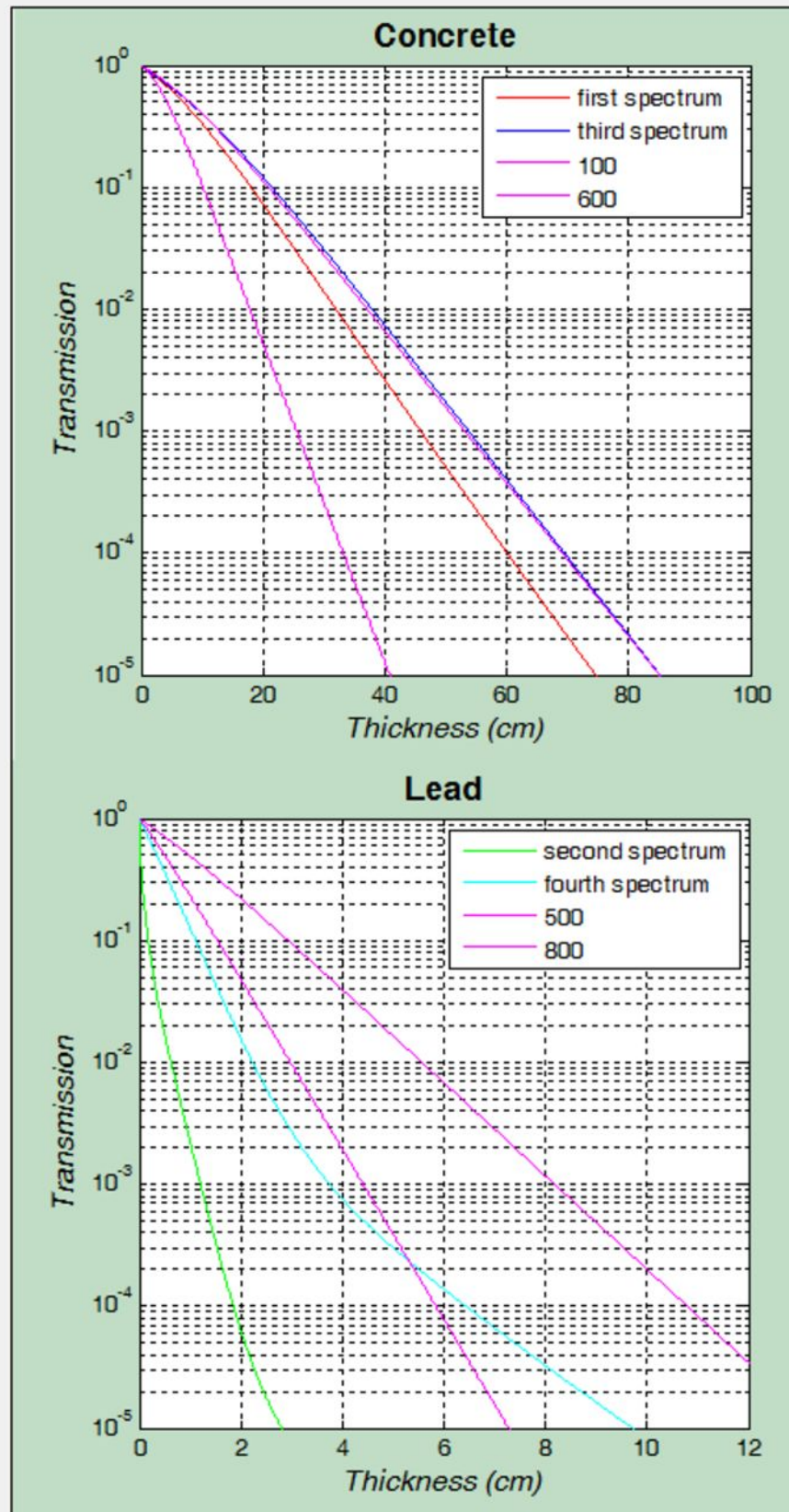Select energy Ei (keV)
(20keV <= Ei <= 1090keV)

800

Import Ei-energy

AND

Select material

Lead

Create Transmission Curves

Export Current Transmission Curve Data

Concrete

Lead

Restart

Exit

Calculate thickness for the last transmission curve

Transmission

0.05

Calculate thickness

Thickness (cm)

3.74209

Display results

Clear results

Concrete

Energy spectrum or Energy (keV)	Transmission	Thickness (cm)
1	0.1000	18.0456
3	0.2000	16.1424
100	0.5000	4.2326
600	0.7000	4.6631

Lead

Energy spectrum or Energy (keV)	Transmission	Thickness (cm)
2	1.0000e-04	1.8536
4	1.0000e-05	9.7244
500	0.0030	3.7258
800	0.0500	3.7421

——	511keV concrete this work
*	511keV concrete Ref. 6
- - -	511keV concrete Fit Ref. 6
——	511keV lead this work
*	511keV lead Ref. 6
- - -	511keV lead Fit Ref. 6

concrete thickness (cm), lead thickness (mm)