Determination of Attenuation Properties for some Building Materials by MCNP Simulation

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ABSTRACT

The present study was conducted to investigate the attenuation properties of building materials commonly used. The mass attenuation coefficients, linear attenuation coefficients, mean free path and half thickness of building materials with densities ranged from 1.52 to 2.58 g. cm⁻³, have been simulated by Monte Carlo simulation techniques at 59.5, 356, 662, 1173, 1274 and 1333 KeV. For validation purpose, the numerical simulation results have been compared with experimental results. Comparisons are also made with predictions from the XCOM program in the energy region from 1 KeV to 20 MeV. A good agreement between the experimental data and MCNP simulated results as well as XCOM calculated results. Linear attenuation coefficient and half thickness of the samples are found density and photon energy dependent. The half thickness values of the samples increase with increasing in photon energy. Also, this study proved that the MCNP simulation can be employed for the determination of different attenuation properties when no experimental values are available.

Key words: Monte Carlo simulation, shielding, building materials, linear attenuation.

INTRODUCTION

In recent years, in the context of growing energy demands and rising oil prices, many countries have expressed an interest in including nuclear power into their energy plans. Radioactive releases are possible from a major event within a reactor or other activities, such as spent fuel transportation and accident involving large medical radioactive sources. Emergency response planning should therefore include a range of accident response scenarios to assure that adequate protective measures can be taken to protect the public. Depending on the exposure route, radionuclides involved and projected dose, different counter measures will need to be considered. At the first moment, decisions concerning where to seek shelter and when to evacuate, must be taken. In emergency situations, however, a properly designed database that can provide an access to information regarding main protective measures, sheltering and/or evacuation, for example, is invaluable tool to help first responders to make the correct decisions. If the public is evacuated during the passage of the contaminated plume, they may receive a much higher dose than if they sought shelter. Shelter in place may be recommended and this means going indoors and remaining indoors until the emergency is over.(1)

Such action will reduce an individual’s exposure to radiation resulting from a release of short duration. However, to make such a decision, complete information about the effective shielding of the dwellings’ walls and roofs should be available to estimate the protection one could receive by seeking shelter in a home(1).

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Compton scattering of gamma photon in the interacting medium is one of the most important interaction for the shielding analysis compared with total absorption or removal of the photon by photoelectric absorption and pair-production process\(^{(2)}\).

The aim of this study to validate the experimental data of photon interaction with Limestone, cement plaster, concrete and bricks using Monte Carlo N-Particle Transport (MCNP) simulation as well as XCOM\(^{(3)}\) calculation. Firstly, the linear attenuation coefficient of building materials samples for photon energy 59.5, 356, 662, 1173, 1274 and 1333 keV were calculated by MCNP, and the results were compared with the experimental data provided in the literature\(^{(1)}\).

**MATERIALS AND METHODS**

In the present study, building material samples have been chosen. The elemental compositions (percentage by weight) of the building material samples are given in Table (1). These elemental compositions of the building material samples are taken from literature\(^{(1)}\). The densities of the building materials are of densities ranging from 1.52 to 2.58 g cm\(^{-3}\).

**Table (1): Elemental composition of building materials.**

<table>
<thead>
<tr>
<th></th>
<th>Limestone (2.58 g cm(^{-3}))</th>
<th>cement plaster (1.52 g cm(^{-3}))</th>
<th>Concrete (2.26 g cm(^{-3}))</th>
<th>Bricks (1.92 g cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.0009</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0.1134</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>O</td>
<td>0.4961</td>
<td>0.468</td>
<td>0.492</td>
<td>0.504</td>
</tr>
<tr>
<td>Na</td>
<td>0.0004</td>
<td>0</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg</td>
<td>0.0476</td>
<td>0.006</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Al</td>
<td>0.0043</td>
<td>0.062</td>
<td>0.037</td>
<td>0.041</td>
</tr>
<tr>
<td>Si</td>
<td>0.0243</td>
<td>0.301</td>
<td>0.37</td>
<td>0.387</td>
</tr>
<tr>
<td>P</td>
<td>0.0002</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>0.0011</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>0.0027</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ca</td>
<td>0.3042</td>
<td>0.114</td>
<td>0.082</td>
<td>0.065</td>
</tr>
<tr>
<td>Ti</td>
<td>0.0004</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mn</td>
<td>0.0004</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fe</td>
<td>0.004</td>
<td>0.049</td>
<td>0.011</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The photon interaction is defined by Lambert law \((I=I_0e^{-\mu x})\) for transmitted intensity of the photon through a medium. The transmission of gamma photon is dependent upon the thickness, \(x\) of the medium and linear attenuation coefficient, \(\mu\). The \(\mu\) value is a parameter which is dependent upon material density of the absorber and energy of incident photon. The mass attenuation coefficient, \(\mu/\rho\) is another parameter defined for the photon interaction. The \(\mu/\rho\) values of the building material samples are calculated by mixture rule\(^{(4)}\).

The linear attenuation coefficient of the building material samples are calculated by multiplication of \(\mu/\rho\) with the density of the building material samples. Half thickness \((X_{1/2})\) is another parameter to determine gamma photon reaction rate. The \(X_{1/2}\) is the thickness of the building materials which reduces the photon density to one half of its incident value. The \(X_{1/2}\) is expressed\(^{(4)}\) in units of length as:

\[
X_{1/2} = \frac{\ln(2)}{\mu} \tag{1}
\]
Mean free path (MFP) is another parameter used to determine gamma photon reaction rate. The MFP is the average distance travelled per second by a photon before undergoing an interaction. The MFP is the reciprocal of the linear attenuation coefficient and expressed in unit of length as:

\[ MFP = \frac{1}{\mu} \quad (2) \]

The Monte Carlo N-Particle Transport MCNP 4B code was used for simulating gamma attenuation by the building materials. MCNP 4B is a general purpose Monte Carlo transport code that can track thousands of particles over a large energy range (up to 100 MeV) and has been benchmarked for various uses. MCNP 4B was used to estimate mass attenuation coefficients, \( \mu/\rho \), linear attenuation coefficients, \( \mu \), mean free path, MFP and half thickness \( X_{1/2} \) of some building materials. The simulation used the same basic set-up for narrow beam as shown in Fig 1, however the source was approximated as a point source. The transmitted beam of photons is estimated for different thicknesses of each sample (1 cm to 7 cm) then the average value is calculated over these thicknesses. The samples were considered as cylindrical shape of radius 4 cm. The samples were estimated to be homogeneously mixed. The calculations were performed for gamma photons of energies 59.5, 356, 662, 1173, 1274 and 1333 KeV. MCNP 4B uses mcplib22 cross section data file for performing these calculations. The simulated results pass all statistical checks and have relative error less than 0.1.

1. Mass Attenuation Coefficient:

The dependency of mass attenuation coefficient of building materials under investigation on photon energy is shown in Fig. (2). The experimental data of mass attenuation coefficient at energies 59.5, 356, 662, 1173, 1274 and 1333 KeV are compared with the MCNP simulated results at the same energies. Fig. (2) also displays the calculated XCOM results at an energy range from 8 KeV to 2 MeV. Fig. (2) shows a good agreement between the experimental data and simulated MCNP results as well as calculated XCOM results. The values of mass attenuation coefficient are very high at low energies (below 100 KeV) and decreases rapidly with increasing photon energy. The values of mass attenuation coefficient slowly decrease with increasing photon energy in the range 100 – 1200 KeV.
Above 1200 KeV, the values of mass attenuation coefficient are approximately constant. Moreover, the values of mass attenuation coefficient of limestone are slightly higher than those of the other samples. This is because limestone is of higher density than the other samples.

This behavior could be attributed to the fact that, the dominant interaction at energy values from 10 to 100 KeV is photoelectric absorption and from 100 to 1200 KeV is Compton scattering\(^{(5)}\). In the low energy (below 100 KeV), due to the dominance of the photoelectric effect, the values of mass attenuation coefficient depend strongly on chemical composition \((Z)\) of the sample while in the intermediate energy region where the Compton effect predominates, it shows little dependence on chemical composition \((Z)\) and a slight decrease. In the higher energy region (above 1 MeV), the mass attenuation coefficient is almost independent on \(Z\) due to the dominance of pair production process.

Fig. (2): Relation between the mass attenuation coefficients and the photon energy for the building materials.

2. Mean Free Path (MFP):

The relation between the mean free path (MFP) of the building material samples and the photon energy is shown in fig. (3). The experimental data and simulated MCNP results at energies 59.5, 365, 662, 1173, 1274 and 1333 KeV are displayed in the graph along with XCOM calculated results at energy range from 10 KeV to 20 MeV. Fig. (3) shows a very good agreement between the simulated and measured data for all samples. The values of MFP rapidly increase with increasing the photon energy at energy below 100 KeV and slowly increase in the range from 100 KeV to 1 MeV, moreover,
the MFP values are approximately constant at energy greater than 1 MeV. This behavior could be attributed to that MFP is the reciprocal of the linear attenuation coefficient (MFP=1/\(\mu\)). So, the profile of MFP is the inverse of the profile of \(\mu/\rho\).

![Graphs showing MFP vs Energy for different building materials](image)

**Fig. (3):** The relation between MFP and the photon energy for building material samples.

3. **Dependency of the Half Thickness on the Density:**

The dependence of half thickness on material density for different energies is shown in Fig. (4). The dependence of half thickness on density are simulated by MCNP data for photon energies 59.5, 365, 662, 1173, 1274 and 1333 KeV. It is clear that the relation between half thickness and sample density is not linear for energy below 1333 KeV. The values of half thickness decrease with increasing the material density. Half thickness increases with increasing the photon energy.
Fig. (4): The Relation between the half thickness and material density for different energies.

CONCLUSIONS

The photon mass attenuation coefficients ($\mu/\rho$), mean free path (MFP), and half thickness ($X_{1/2}$) of building materials samples are compared by experimental data and simulation by MCNP for energies 59.5, 356, 662, 1173, 1274 and 1333 keV as well as calculated XCOM results. It was found that the simulated MCNP and calculated XCOM results of $\mu/\rho$, MFP and $X_{1/2}$ are in very good agreement with the experimental data. The $X_{1/2}$ values of building materials increase with the increase in photon energy. The $X_{1/2}$ values of building materials decrease with increasing the material density and increase with increasing the photon energy. Limestone is better as gamma ray shielding material than the other samples. One can conclude that simulated results, which have relative error less than 0.1, shows a good agreement with experimental data. MCNP may be employed for additional calculations on the photon attenuation where no analogous experimental data exist.

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