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# Assessment of Radiation Shielding Properties of Polyester Steel Composite using MCNP5

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## ABSTRACT

Human safety and structural material that may be compromised from radiation exposure are vital concerns in nuclear technology. This research discusses the shielding properties of a polyester composite as nuclear shielding material. The linear attenuation coefficient (μ) of composite mixtures comprising of different mass percentages of locally available steel wool particles and polyester resin were investigated using 0.662 MeV gamma ray photon from Cesium-137 source under condition of narrow beam geometry.
Calculated values using Monte Carlo code (MCNP5) were used to validate the values of the transmission experiment. The MCNP5 was used to calculate the linear attenuation coefficient of some known radiation shielding materials in literature to validate the code. Attenuation curves of the experimental results are presented along with Monte Carlo simulation results. The Ghana Research Reactor-1 (GHARR-1) was used to determine the elemental constituents of the steel wool, needed for the MCNP5 input file, using neutron activation technique.
A mass attenuation coefficient ($\mu/\rho$) of 8.2 x $10^{-3}$ $m^2.kg^{-1}$ was determined in ten percent polyester composite (i.e. steel wool mass %). It was concluded that the steel wool polyester composites may be used for both neutrons and gamma rays shielding.

**Keywords**: *Mass attenuation coefficient; Linear attenuation coefficient; Monte carlo code; Narrow beam geometry; Neutron activation*.

## 1. INTRODUCTION

Radiation shielding of personnel and the public at the work place means placing a suitable material between the radioactive source and the personnel or public. The radiation is attenuated and the effect may be completely eliminated or reduced to an acceptable level. Some materials are more effective than others in shielding particular type of radiation, the type and amount of shielding material needed for shielding will vary with the type and quantity of radioactive material being shielded.

When x-rays or gamma rays traverse matter, some are absorbed (attenuated photon) some pass through without interaction (transmitted photon), and some are scattered as lower energy photons in directions that are quite different from those in the incident beam. In narrow beam geometry attenuation, every photon that interacts is either absorbed or scattered out of the incident beam and the detector is assumed to detect only the transmitted photons. With broad-beam geometry, a fraction of the scattered photons is detected in addition to the transmitted beam. The experimental set-up to this work was under the condition of narrow beam geometry.

The attenuation of photons by a medium follows the exponential-attenuation relationship under narrow beam geometry. The coefficient of the exponential relationship is the linear attenuation coefficient μ ($cm^{-1}$) which is dependent on the shielding material and photon energy.

The use of lead in many products and devices poses certain health risks and environmental concerns [15]. A new line of nontoxic, high density, polymer-metal composites, can replace lead and many other traditional metallic materials in a variety of application areas including weighting, balancing, vibration dampening, and radiation shielding (Robert R. Durkee) [15].

Whereas photon attenuation and absorption coefficients vary smoothly with atomic number and energy, neutron removal coefficients can change irregularly from element to element because neutron cross-sections have complicated resonance structures as their energies change [9]. As the neutron undergoes various interactions with the attenuating medium their energy is reduced to intermediate and thermal energies. Materials such as water, polyethylene, polyester with higher hydrogen content have greater chance of shielding neutrons.

Monte Carlo N-Particle code (MCNP5) was used to verify the experimental data. MCNP5 is an internationally recognized code which can be used for analyzing the transport of neutrons and photons through various materials. It was developed and maintained by Los Alamos National Laboratory [4; 10; 17].

The MCNP5 requires the input of elemental mass percentages of all materials in the experimental set up. The elemental constituents of the steel wool filler was determine using neutron activation analysis (NAA). NAA is a sensitive analytical technique useful for performing both qualitative and quantitative multielement analysis of major, minor, and trace elements in samples. For many elements and applications, NAA offers sensitivities that are superior to those attainable by other methods, in the order of parts per billion [12]. The NAA results were applied by the MCNP5 code for verification of the experimental results.

The NAA analysis bombards samples with neutrons and converts elements in the sample into radioactive isotopes. The characteristic energy intensities of the elements forming the radioisotopes are used to quantify elements in the sample by equation (1):

$$Mass\ of\ element\ in\ sample = Mass\ of\ element\ in\ standard \times \left[\frac{Radiation\ Intensity\ of\ radioactive\ isotope\ from\ Sample}{Radiation\ Intensity\ of\ radioactive\ isotope\ from\ Standard}\right] \quad (1)$$

## 2. MATERIALS AND METHODS

### 2.1 Materials

Materials used are diamond brand steel wool and duwa brand steel wool mostly used in cleaning cooking utensils shown in figure 2.1,


**Figure 2.1: 'Diamond' and Duwa Steel Wool.** methyl ethyl ketone peroxide (MEKP), composite mold figure2.2A and mold release agent figure 2.2B,

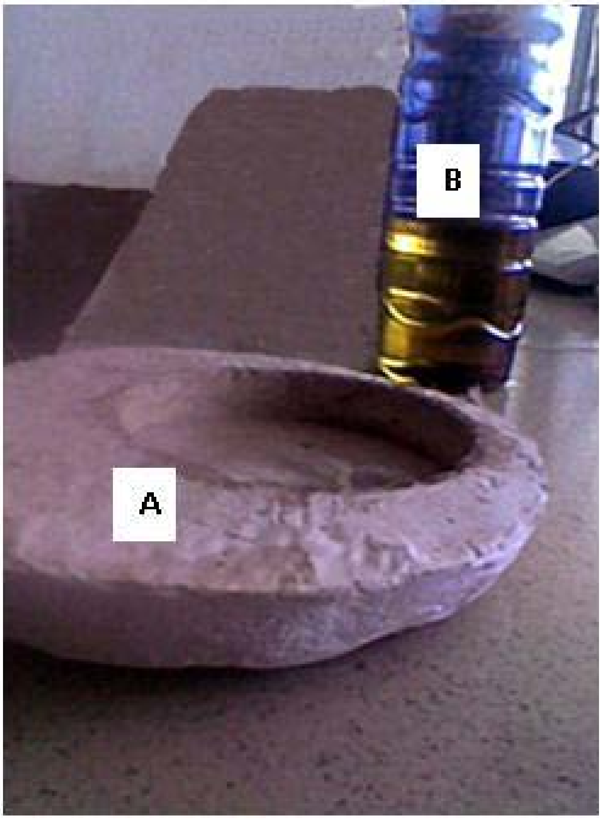


**Figure 2.2 Composite mold (A) and mold release agent (B)**.


**Figure 2.3: Steel Wool Filler (A) and Polyester Resin (B)**

Polyester Resin figure 2.3B and steel wool filler figure 2.3A

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## 2.2 Methods

## 2.3 Composite Development

The steel wool is blended (figure 2.3A) and uniformly mixed in the polyester resin. The methyl ethyl ketone peroxide, in a ratio of 1:40 by volume to the polyester resin, was added to the resin-steel wool mix, the mixture is finally poured into the pop-fibre glass mold (figure 2.2A) which has already been smeared with a mold release agent.

Steel wool fillers in increments of 1g are added to a fixed weight of 89g polyester resin to obtain a polyester composite of different filler loadings. Each composite was cured at room temperature (25-27°C) for 3-4 hours after the mixture is poured into the pop-fibre glass mold. Composites of different filler loadings are developed as shown in figure 2.4.

**Figure 2.4: Polyester Composites of Different Filler Loadings**

## 2.4 Determination of Composite Material Density

Density of the polyester composite material was determined by the buoyancy method using equation (2).

$$\rho_m = \frac{W_a}{W_a + W_W - W_b} \times (0.9975)\,, \qquad (2)$$

where:

$\rho_m$ = the density of the material, in g/cm$^3$
$W_a$ = the weight of the specimen when hung in the air
$W_w$ = the weight of the partly immersed wire holding the specimen.
$W_b$ = the weight of the specimen when immersed fully in distilled water, along with the partly immersed wire holding the specimen.
0.9975 = the density in g/cm$^3$ of the distilled water at 23°C.

## 2.5 Transmission Experiment

The transmitted gamma-rays intensities for each composite material were determined for a fixed preset time in each experiment by recording the corresponding counts, using the 2″×2″ NaI(Tl) detector with a 0.2% statistical uncertainty at the fixed counting time of 5minutes. The incident gamma intensity was determined when no composite material is in place; the experimental set-up is shown in figure 2.5.

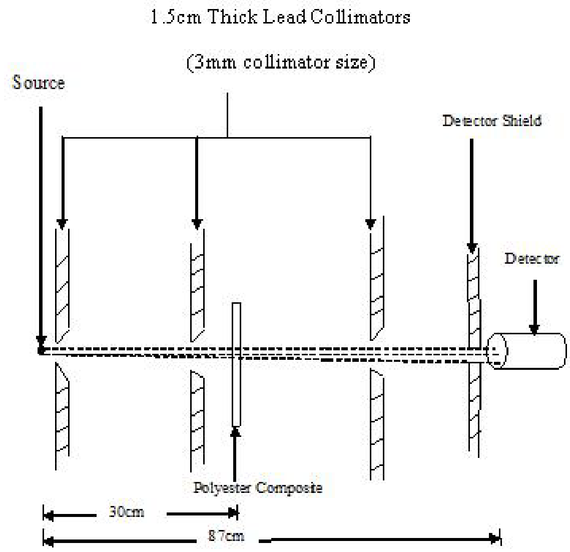


**Figure 2.5: Narrow Beam Gamma Photon Transmission Experimental Set-Up.**

Five composite materials of the same filler loading and thickness x, are used to determined the linear attenuation coefficient for each composite using equation (3).

$$\mu = \frac{\left(\ln\left(\frac{I_o}{I}\right)\right)}{x} \qquad (3)$$

$\mu$ = linear attenuation coefficient (cm$^{-1}$)

$I_o$= Gamma photon counts without composite material (counts/sec)

I = Gamma photon count with composite material (counts/sec)
x = Thickness of composite (cm).

Table 3.1 represents the average linear attenuation values for duwa brand steel wool composites.

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**Table 3.1: Linear Attenuation Coefficient of 'duwa' Composites at 0.662MeV**

| MATERIAL | LINEAR ATTENUATION COEFFICIENT ($cm^{-1}$) EXPERIMENT | LINEAR ATTENUATION COEFFICIENT ($cm^{-1}$) MCNP5 |
|---|---|---|
| Du1 | 0.101 | 0.100 |
| Du2 | 0.102 | 0.103 |
| Du3 | 0.105 | 0.105 |
| Du4 | 0.106 | 0.107 |
| Du5 | 0.107 | 0.106 |
| Du6 | 0.109 | 0.108 |
| Du7 | 0.111 | 0.111 |
| Du10 | 0.115 | 0.115 |
| Du15 | 0.117 | 0.115 |

## 2.6 Irradiation and Counting

The prepared steel wool samples were irradiated using the Ghana Research Reactor-1 (GHARR-1) at Ghana Atomic Energy Commission Kwabenya, Accra-Ghana. Samples were irradiated at a flux of $5x10^{11}$ neutrons $cm^{-2}s^{-1}$ Short lived radioactive elements in the sample (i.e. aluminium, manganese and vanadium) were activated after 10 seconds of irradiation and photon intensities were counted. Long lived radioactive elements (i.e. Iron and Chromium) were irradiated for 2 hours. The counting of the induced activity in the samples was determined by the gamma ray spectrometer. The gamma spectral analysis was done using a PC with an N-type High purity Germanium (HPGe) detector.

Three samples of each brand are irradiated for 10 seconds and counted for 600 seconds, thus Du(1), Du(2), Du(3) represents the three duwa brand steel wool samples. The long lived elements were left to decay for fourteen days after irradiation and counted for two hours. Elemental standards were used to quantify the elements in the steel wool samples. Elemental standards were prepared by pipetting known concentration of elemental solutions into a vial containing sucrose media and are irradiated alongside the samples.

Different volumes of 1000 ppm solutions of aluminium, manganese and vanadium pipetted into a sucrose media were irradiated for 10 seconds. Graphs of gamma photon count versus quantity of standard irradiated (average sensitivity graph) were plotted for aluminium, manganese and vanadium. The plots were used to quantify the short lived radioactive elements Al, Mn and V in the steel wool samples and the average of the three values are shown in table 3.2.

**Table 3.2: Elemental Constituents in 0.05g Steel Wool Sample Irradiated**

| ELEMENT | SAMPLE | AVERAGE MASS OF ELEMENT (µg) | WEIGHT PERCENTAGE |
|---|---|---|---|
| IRON | Du(1) Du(2) Du(3) | 46473.33 ± 56.86 | 92.95 |
| MANGANESE | Du(1) Du(2) Du(3) | 2909.50±205.91 | 5.82 |
| ALUMINIUM | Du(1) Du(2) Du(3) | 93.20 ± 6.80 | 0.19 |
| CHROMIUM | Du(1) Du(2) Du(3) | 8.58 ± 0.63 | $1.72 \times 10^{-2}$ |
| VANADIUM | Du(1) Du(2) Du(3) | $0.07 \pm 6 \times 10^{-3}$ | $1.4 \times 10^{-4}$ |

For the long lived elements, the standard solutions of long lived elements also pippetted into sucrose media were irradiated for two hours and counted for two hours, after left to decay for the fourteen (14) days. Equation (1) was used to quantify the long lived elements, i.e. iron and chromium, in the steel wool samples and is shown in table 3.2.

## 2.7 MCNP Input File

The MCNP5 input file was coded to fit the experimental set-up using cell and surface cards in the input file, the MCNP5 output of the experimental setup is shown in figure 2.6.

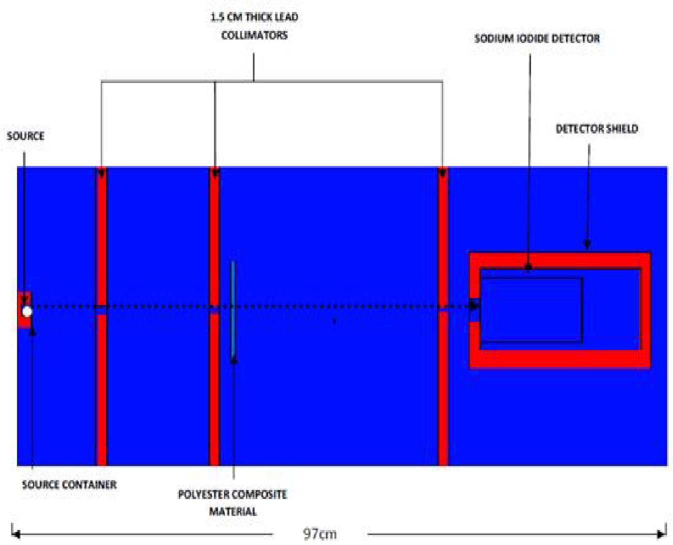


**Figure 2.6: MCNP5 Visual Editor Plot of Experimental Set-Up**

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The elemental composition of the materials in the experimental set-up and polyester composite were defined in the input file under the data cards. The linear attenuation for a particular composite material at specified photon energy was determined using the output file value of the composite material and an output file value without a composite material (i.e. air as the attenuating medium) to represent transmitted and incident gamma photon intensities respectively. The values were substituted into equation (3) to evaluate the linear attenuation coefficient of the material. The code was repeated for composites of different filler loadings and the results compared with the experimentally determined linear attenuation coefficient values.

The MCNP5 code, was verified by running the code using ordinary concrete and lead as the attenuating material. The composition for the ordinary concrete used were: 0.56%H, 49.56% O, 31.35%Si, 4.56%Al, 8.26%Ca, 1.22%Fe, 0.24%Mg, 1.71%Na, 1.92%K, and 0.12%S [7] and results indicated in Table 4.4, figure 2.7 and 2.8.

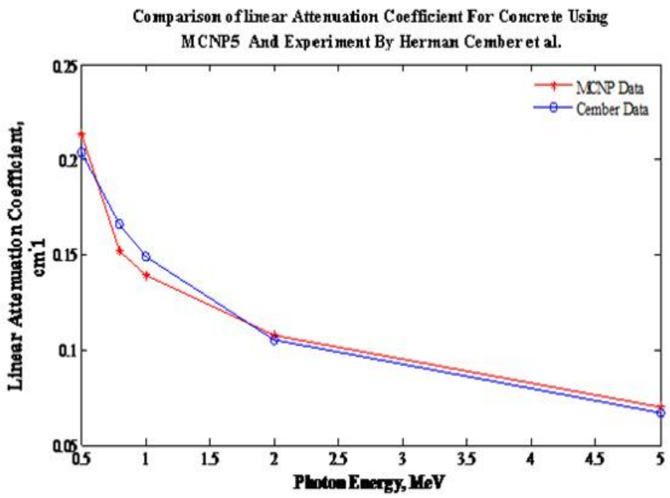


**Figure 2.7: Comparison of Linear Attenuation Coefficient for Concrete**

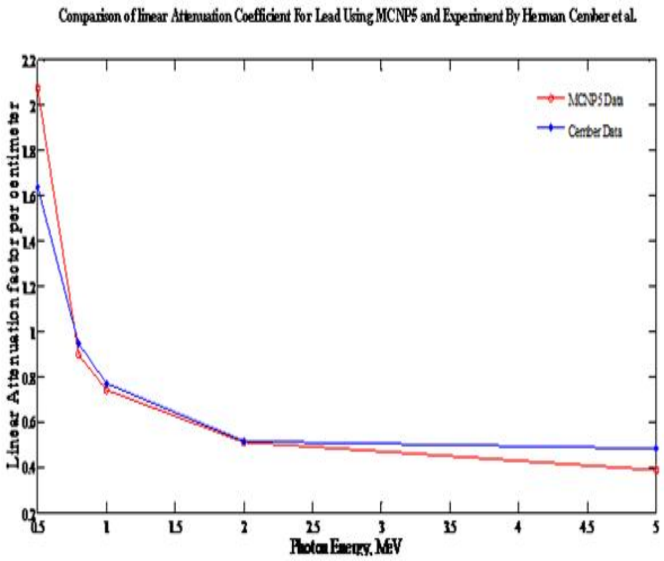


**Figure 2.8: Comparison of Linear Attenuation Coefficient for Lead**

## 3. RESULTS AND DISCUSSION

### 3.1 Density of Composite Materials

The densities of composites were evaluated using equation (2) and the results are listed in table 3.1.

**Table 3.1: Density of Polyester Composites of Different Steel Wool Filler Loading**

| Composite material | Density ($gcm^{-3}$) |
|---|---|
| Du1 | 1.2082 |
| Du2 | 1.2369 |
| Du3 | 1.2627 |
| Du4 | 1.2881 |
| Du5 | 1.2841 |
| Du6 | 1.3082 |
| Du7 | 1.3484 |
| Du10 | 1.4039 |
| Du15 | 1.4100 |

In the composite material nomenclature, 'Du' stands for 'duwa' steel wool filler, the preceding number represent weight of the steel wool filler in composite. Thus Du1 means a duwa brand polyester composite containing 1 g of duwa steel wool filler mixed with 89 g of polyester resin.

### 3.2 Linear Attenuation Coefficient of Composite Materials

The linear attenuation coefficients of both brands gave almost the same values. Table 3.2 shows the linear attenuation coefficient of duwa polyester composite materials.

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**Table 3.2: Linear Attenuation Coefficient of 'Duwa' Composites at 0.662mev**

| COMPOSITE MATERIAL | LINEAR ATTENUATION COEFFICIENT ($cm^{-1}$) EXPERIMENT | LINEAR ATTENUATION COEFFICIENT ($cm^{-1}$) MCNP5 |
|---|---|---|
| Du1 | 0.101 | 0.100 |
| Du2 | 0.102 | 0.103 |
| Du3 | 0.105 | 0.105 |
| Du4 | 0.106 | 0.107 |
| Du5 | 0.107 | 0.106 |
| Du6 | 0.109 | 0.108 |
| Du7 | 0.111 | 0.111 |
| Du10 | 0.115 | 0.115 |
| Du15 | 0.117 | 0.115 |

The experimental values shows an increase in linear attenuation coefficient as the steel wool filler loading increases, likewise was values calculated using MCNP5.

## 3.3 Discussion

Polymer composites have numerous desirable properties as an engineering material such as chemical resistance, strength and fracture toughness. Polymer composite fillers are usually harder and stiffer than the matrix material. These properties are making polymer composite the desirable choice over metals and wood in many industries today [13].

From the results, polyester composites showed good agreement with values evaluated by the MCNP5 code (Table 3.2).

Calculated values using MCNP5 depend on factors such as the elemental compositions of materials in the input file. Hence the choice of NAA technique which uses lesser sample preparation methods prior to sample analysis and yields a higher level of accuracy as compared to other analytical methods.

Both steel wool fillers have almost the same elemental compositions, with diamond brand steel wool having slightly higher iron content. Although a Du15 composite (i.e.14.5% filler loading) yielded a slightly higher linear attenuation coefficient value compared to Du10 composite (10% filler loading). Du10 composite material yielded a good linear attenuation result, since the difference in linear attenuation values for Du10 and Du15 composites (Table 3.2) did not improved much as compared to the much higher increased in filler loading from 10g to 15g for Du10 and Du15 respectively. Using the values of density ($\rho$) and linear attenuation coefficient ($\mu$) of Du10 composite, the mass attenuation coefficient ($\mu/\rho$) for Du10 composite was calculated as 8.2 x $10^{-3}$ $m^2.kg^{-1}$ at photon energy of 0.662MeV. Which compares very well with aluminium and concrete at 7.5 x $10^{-3}$ $m^2.kg^{-1}$ and 7.9 x $10^{-3}$ $m^2.kg^{-1}$ respectively. Considering cost and weight Du10 meet the demands of as low as is reasonably practicable (ALARP) principle compared with Du15, making it the polyester material of choice against Du15.

The experimentally evaluated linear attenuation values are substituted into the exponential equation to generate transmission curves for duwa composites at different filler composition and shown in figure 3.1.

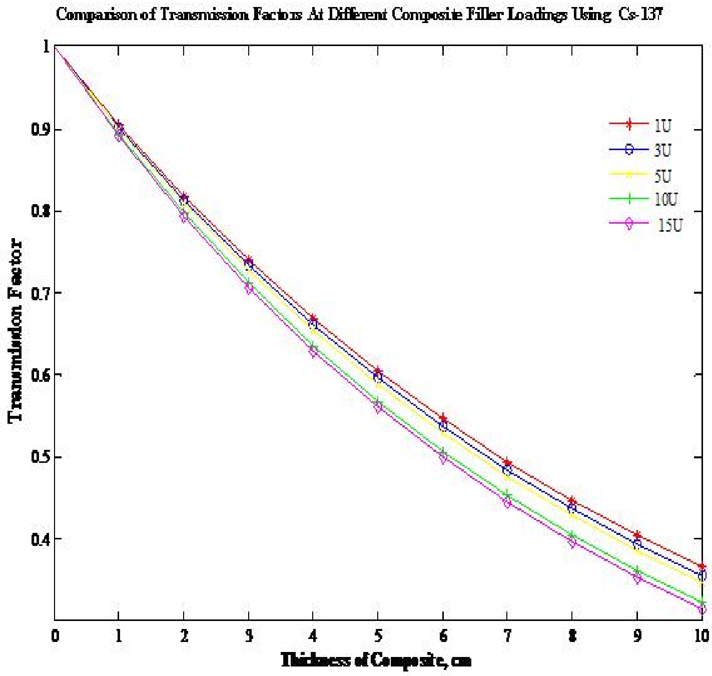


**Figure 3.1: Comparison of Transmission Factors at Different Composite Filler Loadings.**

Figure 3.1 can be used to determine the half value layer (HVL) of the different composite materials (i.e. thickness of the different composite materials at transmission factor of 0.5).

The results illustrate the potential of using steel wool polyester composite in radiation shielding as it can be used to shield against gamma rays and neutrons and their readily availability from the market.

This work experimentally verified the linear attenuation coefficients of a polyester-steel wool composite material that will be suitable for use as a radiation shielding material at gamma photon energy of 0.662MeV. The investigation was carried out on the effectiveness of using the composite material to provide shielding against gamma radiation at 0.662MeV energy only. But since more than one type of radiations are generated by a radiation source, further research has to be carried out on the attenuation effect of the composite material against other forms of radiations especially gamma photons at different energies and neutrons radiation.

Also further work to verify the durability of the composite material has to be carried out to ascertain the mechanical strength of the polyester-steel wool composite over an extended period of time. The durability studies will have to include the radiation-tolerance of the material; this is because at higher radiation dosage certain defects occur in radiation shielding materials which can alter the mechanical properties of the material.

Since in practice the interaction of radiation and a material occurs under broad beam arrangement there is also the need to evaluate the build-up factor values for the composite material. This will help to determine the total dosage received due to contribution from scattered photons when the composite is used as a shielding material.

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