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Research Article

Study of Radiation Shielding Properties of selected Tropical Wood Species for X-rays in the 50-150 keV Range

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Abstract. This paper compares the attenuation coefficients of 20 tropical hard wood species based on their linear and mass attenuation and half value layer (HVL) properties for X-rays of energy 50–150 keV using a narrow collimated beam from a Cs-137 source. The narrow collimated beam method made corrections from multiple and small-angle scatterings of photons unnecessary. The attenuation depended on the chemical composition and densities of the wood species. The linear attenuation coefficients of wood species at 50–150 keV were highest for *Pterygota macrocarpa* (4.53 m^{-1}) and lowest for *Antiaris africana* (1.24 m^{-1}); the mass attenuation coefficient was highest for *Triplochiton scleroxylon* (17.62 m^2/kg) and lowest for *Nesogordonia papaverifera* (2.27 m^2/kg).The HVL was highest for *Antiaris africana* (0.27 m) and lowest for *Pterygota macrocarpa* (0.149 m). *Pterygota macrocarpa* of about 0.36 m thickness could serve as a more affordable radiation shielding material against secondary scatter and leakage radiations in place of lead, copper or concrete for low X-ray radiations up to 150 keV.

Keywords: Attenuation; radiation shielding; half-value layer; x-rays; photons

1. Introduction

Radiation shielding is essential for the protection of human and environment because the harmful effects of ionising radiation can cause significant health hazards. With the development of technology, human health has started to be exposed to extra radiation which can damage the human cell [1]. Various materials, placed between a source and a receptor, can affect the amount of radiation transmitted from the source to the receptor. Such effects are due to attenuation and absorption of the emitted radiation in the source itself, in material used for encapsulation of the source, or in a shielding barrier [2].

Radiations which are hazardous to human health may come in the form of neutron particles, gamma rays or X-rays. The negative effects of such hazardous radiations can be annulled if proper shielding materials are used [3].Theoretically, all materials could be used to attenuate radiation to safe limits, however, due to certain characteristics, lead, copper and concrete are among the most commonly used materials. There are various factors that are considered for the choice of the shield material: final desired attenuated radiation levels, ease of heat dissipation, resistance to radiation damage, required thickness and weight, permanence of shielding and availability [4].

A shield material is expected to have high photon attenuation coefficient in order that a small thickness will produce significant reduction in intensity. Linear attenuation coefficients depend on the densities of woods; there exists a linear proportionality. High attenuation coefficient corresponds to a high density of woods. Attenuation coefficients and density are characteristics that can best be used in sorting radiation attenuation abilities of wood species.

Care should be taken in the selection of shielding materials especially for the case of lead. This is because the purity of the material has a relation to the nature of the radiation. For example, the use of an impure lead may trigger secondary radiation from the impurities thereby increasing the level of hazards by the radiation recipient. Some tropical wood species have been found to provide shielding against ionising radiations (e.g., X-rays, gamma rays); these could be employed to replace imported lead shields due to their availability.

Gamma radiation shielding characteristics for some tropical wood species from Western Nigeria have been studied by [5]. The researchers used gamma scintillation detection method to show that there is an appreciable evidence of radiation attenuation due to the changes in the chemical composition of the wood species. The attenuation coefficient also depended on the energy and densities of the wood species.

[6] investigated the X-ray attenuation properties of four tropical hardwoods (*Klainedoxa gabonesis, Piptadenia africana, Erythrophleum suaveolens and Chlorophora excels) from Ghana* for some ISO 4037 X-ray reference qualities. Their results compared favourably with that of gypsum wallboard and brick already in use as shielding materials for low energy X-ray application in dental and mammography rooms. They established the feasibility of using *Klainedoxa gabonesis* and *Erythrophleum suaveolens* to replace lead lined doors if the X-ray room is designed to have scatter radiation levels at door location of $5\mu\text{Svh}^{-1}$ dose equivalent.

[7] investigated gamma radiation shielding characteristics of eight types of wood species with gamma energy within the range (0.511–1.332) MeV using gamma spectrometer NaI (TI) scintillation detector. Their results showed that attenuation coefficient related inversely to the gamma energy and directly with the density of the wood species.

Since the turn of the 20^{th} century human lifestyle and environment have changed due to the drastic increase in the number of radiation sources such as communication devices and high-energy medical equipment [8] In order to protect human from the hazardous effects of these radiations, metal shields and non-metallic shields such as polymers are most often employed.

The quest for reducing the cost of importing expensive metallic and non-metallic shields by replacing them with more affordable and ubiquitous hard woods especially in a tropical African country like Ghana is becoming more important. Wood is a good foreign earner of the country and the development of wood composites for low cost radiation shielding material will certainly add more economic value to the woods. Certain hardwoods like *Klainedoxa gabonesis* and *Erythrophleum suaveolens* and their composites have the potential of being used as shielding materials for low-energy X-rays.

This paper seeks to measure radiation attenuation properties of twenty tropical hardwoods for three ISO4037 X-ray reference qualities,50 kV, 100 kV, and 150 kV respectively. The attenuation properties discussed are: Linear Attenuation (μ), Mass Attenuation (μ/P) and Half Value Layer (HVL). The paper shall further seek to explore the suitability of replacing shielding materials like lead, concrete and copper shields with these tropical wood species especially for use as shielding for low energy X-ray diagnostic applications.

2. Materials and Methods

2.1. Description of Study site. The study site (located between longitudes 1° 1' and 1° 1'W and latitude 6° 14' and 6° 20'N) is about 200 km^2 in extent and lies between Asante Ofoase in the Ashanti Region and Akyem Ofoase in the Eastern Region of Ghana. The site area has an equatorial type of climate with mainly woodland vegetation while thicket is intermingled with tall hardwood species. The average temperature is 22C and with annual rainfall value of 15.5 mm.

The Pra-Anum forest reserve is underlain by three geological formations which are Lower Birimian Rocks, Tarkwaian System and Cape Coast Granite rocks [9]. The prevalent soil series is the Bekwai Series or the ferric acrisol. This soil is reddish, well drained, and sedentary in nature and found on summit and upper slopes where slope gradient lies between 3% and 12%. The soil profile consists of 15 cm to 45 cm of dark brown or dusky red, humus, porous, silty clay loam top soil which grades below into 60 cm to 150 cm of reddish brown or red, silty clay loam subsoil containing frequent quartz gravels and stones and ironstone concretions [10].

2.2. Preparation of samples. The twenty (20) hardwoods (*Morinda lucida, Terminalia ivorensis, Blighia sopida, Aningeria altissima, Khaya ivorensis, Sterculia rhinopetalia, Pycnanthus angolensis, Triplochiton scleroxylon, Bridelia micranthia, Celtis mildraedii, Terminalia superba, Daniellia ogeafaro, Chrysophylum perpalchrum, Entandrophragma angolense, Holorrhena floribunda, Stromboria glaucescens,*

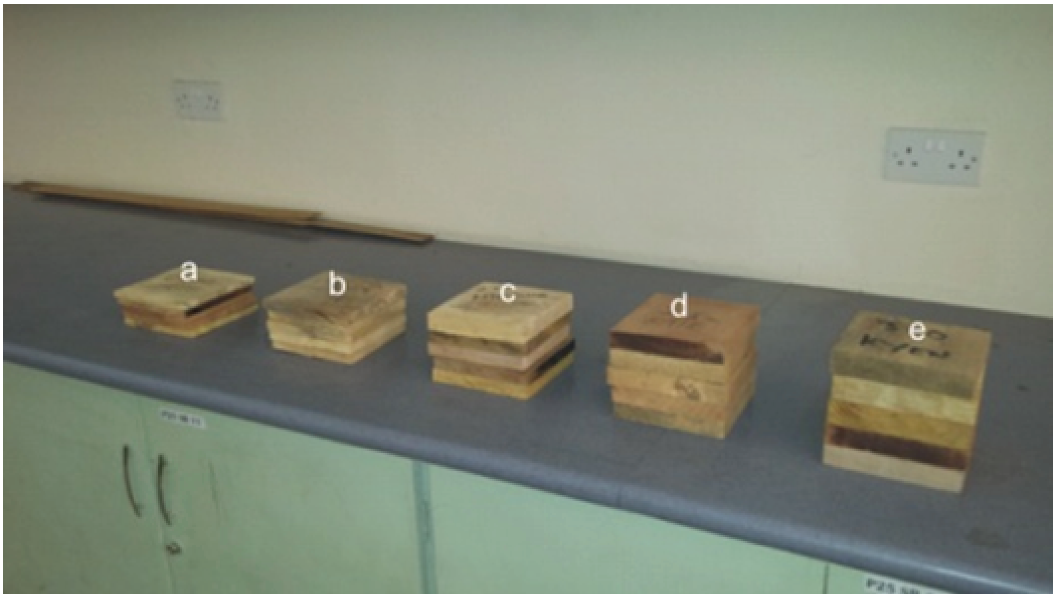

Figure 1: Wood samples of varying thickness: **a:**1.0 cm **b:** 1.5 cm **c:** 2.0 cm **d:** 2.5 cm **e:** 3.0 cm.

Nesogordonia papaverifera, Albizia zygia, Pterygota macrocarpa and Antiaris africana) were obtained from the forest reserves of Forestry Research of Ghana (FORIG) and the Pra Anum forest concession of Logs and Lumber Limited (LLL) Company of Kumasi in the Ashanti region of Ghana.

The trees directly from the forest were transversely cut at the mid stem into square slabs of dimensions 15.0 cm by 15.0 cm. Five different thicknesses of 1.0 cm, 1.5 cm, 2.0 cm, 2.5 cm, and 3.0 cm were used for irradiation. The samples were dried up at a room temperature of 28°C for a period of 180 days. During this time they were weighed continuously and their weights monitored until the rate of change in weight became less than 0.1% per day. They were then considered stable to changes in moisture content with time.

2.3. Measurement Procedure. Irradiation of the wood samples required ambient conditions (as close as possible to standard temperature and pressure (STP)). An air-conditioner was used to achieve these conditions. Prior to taking of measurements a test run was performed on the X-ray machine to condition it ("warm- it-up").

Subsequently, the ionization chamber was affixed to the calibration bench in the secondary standards dosimetry laboratory (SSDL) and connected to the electrometer in the control room via a cable. The central vertical axis of the ionization chamber was placed at a distance of 1.0 m from the focus of the radiation source with the aid of laser pointers. The horizontal centres of the radiation source and the detector were aligned [11]. The wood sample whose shielding properties was to be determined was then placed mid-way between the radiation source and detector and aligned horizontally for the transmission tests [12].The experimental set up is shown in Figure 2.

With this set-up, the ionization chamber was then pre-irradiated for 300 s (5 minutes). For a chosen X-ray tube kV potential, the X-rays which were collimated to ensure a narrow beam and limit build-up were collected by the ionization chamber and integrated (read) on the electrometer for 120 seconds (2 minutes). The irradiation was repeated ten times for each wood sample of a given thickness and kV potential and the average attenuations were calculated.

Again, for a chosen kV potential, the irradiations were done without an absorber (wood sample) between the detector and the source and then subsequently, the sample was placed mid-way between them with increasing thickness to obtain the attenuation properties of the wood samples for the X-ray energy range 50–150 keV. The whole experimental set-up in the irradiation room could be viewed on the CCTV set-up. The X-ray machine was conditioned to ensure stability of X-ray equipment. The chamber was irradiated to a high dose rate and a low dose rate by nulling or zeroing the X-ray machine as a quality control measure. The chamber was calibrated to International Atomic Energy Agency (IAEA) laboratory standards at Seibezsdorf, Austria, the national metrology institute of Germany which measures with the highest accuracy and reliability [13]. Test results were reviewed daily and if a test result fell outside the established tolerance, it was repeated to validate the results as corrective action. System constancy tests were performed to ensure the radiographic system was performing consistently. Radiographic visual checklist was performed to ensure that all components of the radiographic X-ray system indicator lights, displays and mechanical locks and detents were working properly and that the mechanical rigidity and stability of the equipment was optimum [14]. The densities of the wood samples were determined by measuring their masses and

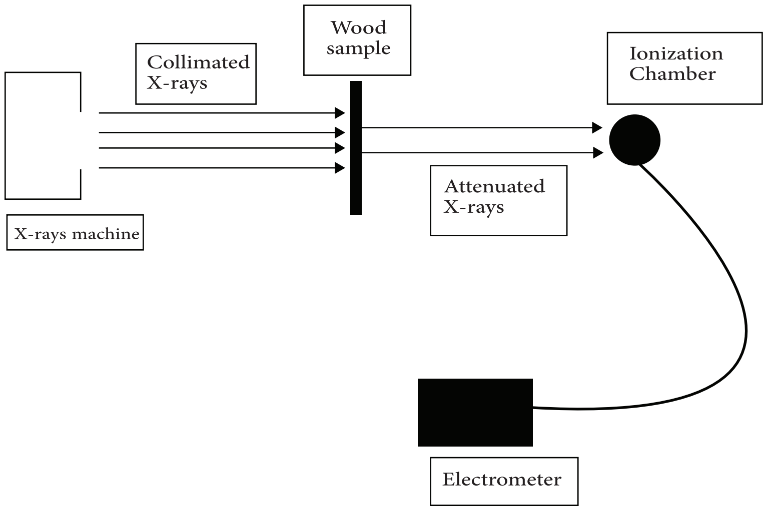

Figure 2: Schematic diagram of experimental procedure.

dimensions (Table 1). For this table and subsequent tables the mean values and their corresponding standard deviations are put in brackets.

2.4. Background on Attenuation. For a non- radiation scattering attenuation medium, Beer-Lambert's law gives,

$$I = I_0 e^{-\mu x}, \tag{1}$$

where μ is the attenuation coefficient, I is the initial radiation intensity and I_0 is the final radiation intensity, and x is wood thickness. Equation (??) thus gives the attenuation coefficient as

$$\mu = \frac{1}{x} \text{In} \frac{I_0}{I}. \tag{2}$$

The range R, which is the average distance travelled by the photons before interaction is given by

$$R = \frac{1}{\mu}. \tag{3}$$

The penetrating depth X of the photons in a wood species is given by

$$X = \frac{R}{\rho}, \tag{4}$$

where ρ is the density of the wood species.

The average distance or range that photons penetrate the material is determined by the same factors that affect the rate of attenuation [15].

The mass attenuation coefficient *I*, is given by

$$I = I_0 e^{-(\mu/\rho)\rho x}, \tag{5}$$

where μ/ρ is the mass attenuation coefficient, ρx is the mass thickness (or area density).

Thus,

$$\mu/\rho = \frac{1}{\rho x} \text{In} \frac{I_0}{I} \tag{6}$$

The half value layer (HVL) is the thickness of the material at which the initial radiation intensity is reduced by one half and it is related to μ by

$$HVL = \frac{0.693}{\mu} \tag{7}$$

HVL is related to, but not the same as the photon range. There is a difference between the two because of the exponential characteristic of X-ray attenuation and penetration. The HVL is the amount of filtration or thickness of the object needed to reduce the intensity of the X-ray by one half. Attenuation coefficients, density and half value layers are characteristics that can best be used in sorting radiation attenuation abilities of wood species.

3. Results and Discussion

3.1. Linear attenuation. *Pterygota macrocarpa* recorded the highest attenuation coefficient for the various wood samples considered for X-rays of energy 50–150 keV. This was followed by *Terminalia ivorensis* and *Blighia sopida* (Table 2). *Albizia zygia, Morinda lucida* and *Antiaris africana* had the lowest linear attenuation coefficients.

Besides *Pterygota macrocarpa* which consistently had the highest linear attenuation coefficient the other wood species had fluctuating linear attenuations. This might be due to variations in wood structure and constituents. The attenuation coefficient of wood is directly proportional to its density [16], however, this paper exhibits some inconsistencies in the attenuation coefficient-density relationship for wood. For example, *Pterygota macrocarpa* with density of 0.72

Table 1: Densities of wood species.

Woods Samples	Density [g/cm^3] (0.54±0.15)	Woods Samples	Density [g/cm^3] (0.54±0.15)
Albizia zygia	0.40	*Khaya ivorensis*	0.47
Aningeria altissima	0.62	*Morinda lucida*	0.59
Antiaris africana	0.39	*Nesogordonia papaverifera*	0.90
Blighiasopida	0.49	*Pterygota macrocarpa*	0.72
Brideliamicranthia	0.43	*Pycnanthus angolensis*	0.51
Celtis mildraedii	0.56	*Sterculia rhinopetalia*	0.49
Chrysophylum perpalchrum	0.43	*Stromboria glaucescens*	0.60
Daniellia ogeafaro	0.69	*Terminalia ivorensis*	0.52
Entandrophragma angolense	0.52	*Terminalia superba*	0.58
Holorrhena floribunda	0.74	*Triplochiton scleroxylon*	0.22

Table 2: Linear Attenuation of wood species.

Wood Samples	Linear attenuation μ[m^{-1}] (3.56±0.62)	Wood Samples	Linear attenuation μ[m^{-1}] (3.56±0.62)
Triplochiton scleroxylon	3.86	*Celtis mildraedii*	3.72
Antiaris africana	2.51	*Terminalia superba*	3.46
Albizia zygia	2.73	*Morinda lucida*	2.69
Chrysophylum perpalchrum	3.29	*Stromboria glaucescens*	2.97
Bridelia micranthia	3.72	*Aningeria altissima*	4.28
Khaya ivorensis	3.98	*Daniellia ogeafaro*	3.36
Blighia sopida	4.41	*Pterygota macrocarpa*	4.53
Sterculia rhinopetalia	3.95	*Holorrhena floribunda*	3.15
Pycnanthus angolensis	3.94	*Nesogordonia papaverifera*	2.88
Entandrophragma angolense	3.29	*Terminalia ivorensis*	4.47

Table 3: Mass attenuation of wood species.

Woods Samples	Mass attenuation [m^2/kg] (6.79±3.22)	Woods Samples	Mass attenuation [m^2/kg] (6.79±3.22)
Triplochiton scleroxylon	17.62	*Celtis mildraedii*	5.70
Antiaris africana	3.92	*Terminalia superba*	5.89
Albiziazygia	6.81	*Morinda lucida*	4.49
Chrysophylum perpalchrum	5.04	*Stromboria glaucescens*	4.93
Bridelia micranthia	6.58	*Aningeria altissima*	6.85
Khaya ivorensis	8.49	*Daniellia ogeafaro*	4.83
Blighiasopida	11.32	*Pterygota macrocarpa*	6.28
Sterculia rhinopetalia	8.03	*Holorrhena floribunda*	4.23
Pycnanthus angolensis	7.72	*Nesogordonia papaverifera*	3.04
Entandrophragma angolense	5.10	*Terminalia ivorensis*	8.88

Table 4: Half-value layers of wood species.

Wood Samples	HVL[cm] (20±4)	Wood Samples	HVL[cm] (20±4)
Triplochiton scleroxylon	18	*Celtis mildraedii*	20
Antiaris africana	28	*Terminalia superba*	20
Albizia zygia	25	*Morinda lucida*	26
Chrysophylum perpalchrum	21	*Stromboria glaucescens*	23
Bridelia micranthia	19	*Aningeria altissima*	16
Khaya ivorensis	17	*Daniellia ogeafaro*	21
Blighiasopida	16	*Pterygota macrocarpa*	15
Sterculia rhinopetalia	18	*Holorrhena floribunda*	22
Pycnanthus angolensis	18	*Nesogordonia papaverifera*	24
Entandrophragma angolense	20	*Terminalia ivorensis*	15

Table 5: Penetrating depths of wood.

		Energy [keV]	
	50	100	150
Wood Samples	Depth [cm]	Depth [cm]	Depth [cm]
	(57.88±22.38)	(68.83±28.79)	(88.05±49.80)
Albiziazygia	91.54	93.63	144.34
Aningeria altissima	37.68	40.91	47.05
Antiaris africana	102.24	135.81	206.28
Blighia sopida	46.31	57.63	68.19
Bridelia micranthia	62.57	74.85	91.02
Celtis mildraedii	48.04	64.10	73.70
Chrysophylum perpalchrum	70.69	76.35	84.47
Daniellia ogeafaro	43.12	52.68	64.27
Entandrophragma angolense	58.50	63.13	69.81
Holorrhena floribunda	42.93	48.79	56.00
Khaya ivorensis	53.45	76.15	107.24
Morinda lucida	63.13	82.60	92.06
Nesogordonia papaverifera	38.63	47.91	51.68
Pterygota macrocarpa	30.65	34.46	36.12
Pycnanthus angolensis	49.79	52.02	66.99
Sterculia rhinopetalia	51.64	55.17	68.19
Stromboria glaucescens	56.10	64.23	71.50
Terminalia ivorensis	43.05	50.16	62.91
Terminalia superba	49.82	58.97	71.90
Triplochiton scleroxylon	117.90	147.15	427.20

g/cm^3 had linear attenuation coefficient of 4.532 m^{-1} while *Holorrhena floribunda* with density 0.74 g/cm^3 had linear attenuation coefficient of 3.148 m^{-1} for energy of 50 keV. Thus, it is seen that even though *Pterygota macrocarpa* had a lower density than *Holorrhena floribunda* the former had a higher linear attenuation. This might due to the fact that linear attenuation does not depend on density alone but also on other factors such as the chemical, physical and mechanical properties of the wood. In addition the densities of the wood determined in this paper were the apparent densities which are highly water content dependent. The nature of the wood has a substantial influence on the linear attenuation. The structure and the inherent constituents of the wood influence its strength and shielding capacity. This also explains why a less dense wood might have higher linear attenuation than a denser wood.

3.2. Mass attenuation. *Triplochiton scleroxylon* had the highest mass attenuation for the energy range 50–150 keV. This was followed by *Blighia sopida* and *Terminalia ivorensis* (Table 3). For the same energy range 50–150 keV, the three wood species, *Nesogordonia papaverifera, Antiaris africana* and *Morinda lucida* displayed the lowest mass attenuation coefficients (Table 3). Comparing the densities of the wood species (Table 1) carefully with their respective mass attenuation coefficients it is seen that unlike the linear attenuation the mass attenuation is independent of density.

3.3. Half-Value Layer. The best attenuating material is the one with the highest density and lowest HVL. From Table 4, *Pterygota macrocarpa* and *Terminalia ivorensis* had the least HVL of 15 cm, and densities of 0.72 g/cm^3 and 0.52 g/cm^3 respectively (Table 1). They are followed by *Aningeria altissima* at HVL 16 cm and density of 0.62 g/cm^3 and *Khaya ivorensis* at HVL 17 cm and density of 0.47 g/cm^3. The worst attenuating material is *Antiaris africana* with HVL of 28 cm and density of 0.39 g/cm^3.

3.4. Penetrating Depth. The penetrating depth of the twenty wood species are shown in Table 5. The various levels of penetration at various energies are shown indicating that higher energies produce higher penetration depths and vice versa. From Table 5, *Pterygota macrocarpa* recorded the lowest penetrating depth of 30.65 cm at 50 keV. *Antiaris africana* recorded highest penetration depth of 206.28 cm at 150 keV.

4. Conclusions

The linear attenuation coefficient of the wood species was found to depend on the energy of incident photons, the thickness and nature of the wood species. *Pterygota macrocarpa* of about 31 cm thickness was found capable of offering a more affordable radiation shielding material to replace lead, copper or concrete shields for low X-ray radiations up to 150 keV (Table 6).The mass attenuation coefficient was highest for *Triplochiton scleroxylon* (17.62 m^2/kg) and lowest for *Nesogordonia Papa Verifera* (2.27 m^2/kg) . The HVL was highest for *Antiaris africana* (0.27 m) and lowest for *Pterygota macrocarpa* (0.149 m).

Attenuation coefficients, density and half value layers are characteristics that can best be used in sorting radiation attenuation properties of wood species. The best attenuation is the wood with highest attenuation coefficient, highest density and lowest half value layer. Fundamental to radiation protection is the reduction of expected dose and the measurement of human dose uptake. The tropical rainforest which contains the greatest tree species diversity is found in Africa and this constitutes the world's oldest living ecosystem. The tropical rainforest has more trees and their diversity is high especially in the tropics. Hence, replacing *Macrocarpa* shields with conventional shields like lead, copper and concrete would be more affordable and would not destabilize the ecosystem. However, further investigations are ongoing to replace the best attenuating woods with their more affordable and environmentally friendlier composites.

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The various levels of penetration at various energies are shown indicating that higher energies produce higher penetration depths and vice versa. From Table 6, lead recorded the lowest penetration depth 0.0009 cm at 50 keV making it most useful for shielding among copper and concrete materials. However, concrete recorded highest penetration depth of 1.3163 cm at 150 keV Table 6. This makes it the least useful material among copper and lead for radiation shielding purposes.

Table 6: Penetrating depth of copper, lead, and concrete [cm].

E/keV	Copper	Lead	Concrete
50	0.0047	0.0009	0.5540
60	0.0078	0.0015	0.7107
70	0.0121	0.0025	0.8474
80	0.0163	0.0032	0.9386
100	0.0271	0.0013	1.0878
150	0.0562	0.0038	1.3163

Table 7: Linear attenuation of copper, lead, and concrete [cm].

E/keV	Copper	Lead	Concrete
50	23.4125	91.2654	0.7848
60	14.2733	56.9884	0.6118
70	9.2401	35.0670	0.5131
80	6.8365	27.4557	0.4632
100	4.1073	62.9812	0.3997
150	1.9864	22.8589	0.3303

Table 8: Mass attenuation of copper, lead, and concrete [cm].

E/keV	Copper	Lead	Concrete
50	2.6130	8.0410	0.3412
60	1.5930	5.0210	0.2660
70	1.0313	3.0896	0.2231
80	0.7630	2.4190	0.2014
100	0.4584	5.5490	0.1738
150	0.2217	2.0140	0.1436

Table 9: Mass attenuation of copper, lead, and concrete [cm].

E/keV	Copper	Lead	Concrete
50	0.0296	0.0076	0.8832
60	0.0486	0.0122	1.1329
70	0.0750	0.0198	1.3508
80	0.1014	0.0252	1.4963
100	0.1688	0.0110	1.7341
150	0.3489	0.0303	2.0984

Appendix

Table 6 by [2], 2006 illustrates penetration depths of Copper, Lead and Concrete for energies between 50-150 keV. These show an overall increase with increasing photon energy.

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