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Original Article

Feasibility of clay-shielding material for low-energy photons (Gamma/X)

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ABSTRACT

While considering the photon attenuation coefficient (μ) and its related parameters for photons shielding, it is necessary to account for its transmitted and reflected photons energy spectra and dose contribution. Monte Carlo simulation was used to study the efficiency of clay (1.99 g cm^{-3}) as a shielding material below 150 keV photon. Am-241 gamma source and an X-ray of 150 kVp were calculated. The calculated value of μ for Am-241 is higher within 5.61% compared to theoretical value for a single-energy photon. The calculated half-value layer (HVL) is 0.9335 cm, which is lower than that of ordinary concrete for X-ray of 150 kVp. A thickness of 2 cm clay was adequate to attenuate 90% and 85% of the incident photons from Am-241 and X-ray of 150 kVp, respectively. The same thickness of 2 cm could shield the gamma source dose rate of Am-241 (1 MBq) down to 0.0528 μSv/hr. For X-ray of 150 kVp, photons below 60 keV were significantly decreased with 2 cm clay and a dose rate reduction by ~80%. The contribution of reflected photons and dose from the clay is negligible for both sources.

1. Introduction

In work places with radioactive sources and radiation-generating devices such as accelerators and X-ray tubes, radiation dose must be controlled properly to prevent hazards caused by exposure to radiation. Radiation shielding is indispensable for this situation to reduce the number of transmitted photons. For example, lead (Pb-82) material in the order of millimeter (mm) thickness had been widely used to attenuate the photons, either to shield the emission of photons from a gamma source in a source pig or used as a shielding material for the wall thickness of an irradiation facility room [1,2], such as our X-ray laboratory (150 kVp).

Recently, the development and properties of non-lead material as a radiation-shielding material has been studied by many scientists [3-7]. Lead material is known for its toxicity and expense [8-10]. For example, Olukotun et al. proposed the use of clay and kaolin as an effective shielding material for photons [11], while Akkurt and Canakci doped the clay with boron as a shielding material for higher-energy gamma sources [12]. However, there is no information for neutron shielding as expected, even when boron was used as a doping material. In a recent study, metallic alloy was reviewed as a potential gamma-shielding material by doping with a high atomic number (Z) element [13,14].

In many cases of photon shielding studied, the main concern was for the transmitted photons, either un-scattered or scattered photons that penetrate the shielding materials, depending on the point at which the quantity of interest will be measured or calculated from the attenuating material. As example, M. Kurudirek et al. had studied the attenuation properties for glass based shielding compound through experimental work [15,16]. Another study of radiation attenuation had been performed by theoretical calculations for various concretes [17] and germanates glass [18]. In addition to attenuation coefficient (μ) and its related parameters, it is necessary to evaluate photon energy (keV) and intensity transmitted or reflected due to the shielding material, particularly for a newly developed shielding material. Such evaluation is important when designing a radiation-shielding facility or for source storage, as we need to ensure the radiation dose rate is as low as possible as per background radiation. Thus, we propagate the study of our

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relatively new developed clay [11] as a shielding material for low-energy gamma source and X-ray below 150 keV photons. The material data of the clay is shown in Table 1.

In this study, the transmitted and reflected photon's spectra and its ambient dose equivalent (Sv/photon) of the clay material were evaluated by Monte Carlo simulation (EGS5 code [19]). The clay compound as a shielding material will be optimized by calculating for photon (gamma/X) energy below 150 keV as based on our irradiation facility to have an Am-241 gamma source and an X-ray machine at UniSZA, which has a maximum setting of 150 kVp. In the first case, photon dosimetry using clay material was calculated for gamma ray of low-energy source such as Am-241 (16.1 keV, 26.3 keV, and 59.5 keV photons). In the latter case, we include the calculation for X-ray of 150 kVp. This outcome proved and enabled us to shield properly and efficiently the photons transmitted and reflected by the clay compound in our X-ray laboratory facility.

2. Calculated transmitted photons of the clay for multi-energy gamma source

In our previous study, clay had been successfully demonstrated to decrease transmitted photon compared to ordinary concrete for low-incident photon energy due to dominant photoelectric absorption [11]. As a benchmark of our current study, the transmitted photon after the clay was calculated for single-photon energy (609.31 keV photons) for comparison with theory and literature data. A pencil beam of photons was incident to the center of cylinder clay. The photon's interaction, such as photoelectric absorption, Compton scattering (including Rayleigh scattering), and pair productions were considered in our calculation. Compton scattered photons that penetrate the clay-shielding material were ignored for comparison with the attenuation coefficients generated by XCOM [20]. Fig. 1 shows the calculation of transmitted photons as a function of ball clay thickness for a pencil beam of 609.31 keV incident photon. The full square points were fitted with an exponential function to obtain linear attenuation coefficient (μ) values of 0.1569 cm^{-1}. The calculated μ value has a good agreement, within 0.2% with the theory, and 3.8% with the measured values [11], to justify the subsequent calculations.

For the latter point, μ value was calculated for multi-energies gamma source of Am-241. The branching ratio of the gamma source was sampled as the JRIA data book [21]. Table 2 shows the energies and corresponding branching ratio adopted in the calculation.

Table 1
Elemental Composition of the clay.

Element	Clay Density (g cm^{-3}) = 1.99 Ele. Conc. By Wt.
Mg	1.44E-02
Al	3.54E-01
Si	5.59E-01
P	0.00E+00
Cl	6.40E-04
K	1.74E-02
Ca	2.70E-03
Ti	8.58E-03
V	1.56E-04
Cr	9.88E-05
Mn	4.58E-04
Fe	4.18E-02
Cu	1.51E-05
Zn	5.73E-05
Rb	1.05E-04
Zr	4.56E-04
Total	**1.0000**

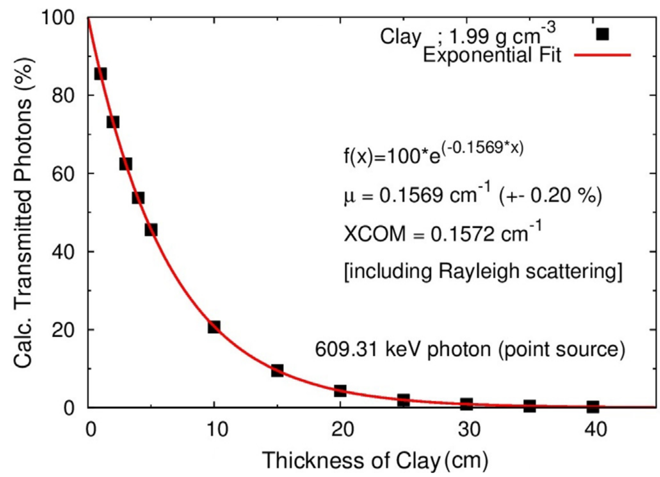

Fig. 1. Calculated μ of clay for single-photon energy compared to theoretical value. Calculated μ value is 0.1596 cm^{-1} for 609.31 keV incident photon.

Table 2
Am-241 gamma energies and branching ratio.

Source	Energy (MeV)	Branching ratio (%)
Am-241	0.0263	2.4
	0.0595	35.9
	0.0161	37.9

Fig. 2 shows the calculated transmitted photons of Am-241 source. A thickness of 2 cm clay is adequate to attenuate up to 90% of the photons from Am-241 source. The calculated μ value is 0.7527 cm^{-1}, which is higher, within 5.61%, than the theoretical values of 59.5 keV (0.7126 cm^{-1}). The amount of difference was as expected, as the Am-241 source has lower gamma energies of 16.1 and 26.3 keV photons, which are not considered in the theoretical value. The error of 1.021% shown in the Figure for the calculated μ value comes from exponential fitting error.

3. Calculated ambient dose equivalent and photon spectra for multi-energy gamma source

Calculation of ambient photon dose (Sv/photon) becomes

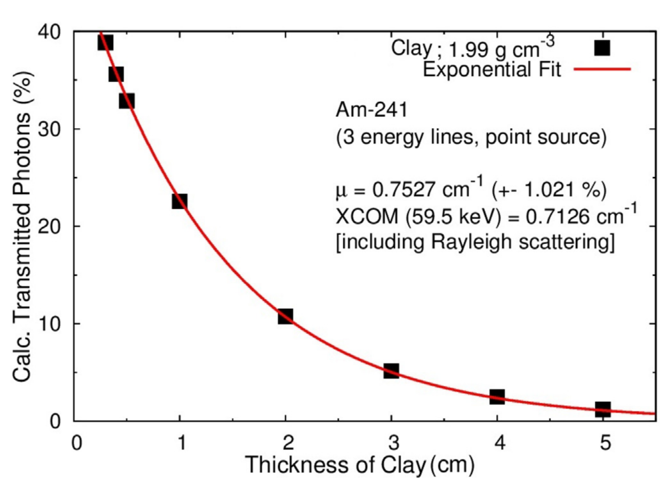

Fig. 2. The calculated μ of clay for multi-energies gamma source compared to theoretical values. Calculated μ value is 0.7527 cm^{-1} for Am-241 source.

important for the public and radiation workers, as the radiation must be estimated for the radiation safety area. It is necessary to ensure that the dose rate from the gamma source attenuated down to background radiation level for radiation safety, particularly if the storage location of the gamma source is easily assessable. As an example, the measured background dose rate at our X-ray laboratory is 0.055 ± 0.008 μSv/hr. Ambient dose equivalent is one of the dose unit as an operational quantity by ICRU [22] body for radiation protection. For example, an environmental dosimeter or ionization chamber survey meter was calibrated to measure ambient dose in the unit of Sievert (Sv) to read the photon dose equivalent at 1 cm depth (H*(10)). In such a case, the calculated and measured values of photon dose rate are comparable in absolute values [23].

Surface crossing was used to calculate the ambient dose on the surface of 2 cm × 2 cm scoring region at a distance of 20 cm from the gamma source in air. In this part of the calculation, the solid angle of the source photons was 4π that was isotropically incident to the clay. To obtain ambient dose equivalent, air absorbed dose (Gy) was calculated as a first step by using kerma approximation, which calculates collision kerma by multiplying mass energy absorption coefficient to the energy fluence. The following conversions were used to convert the unit of MeV g^{-1} to Gy:

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J} \tag{1}$$

$$1 \text{ MeV g}^{-1} = 1.602 \times 10^{-13} \text{ (J/MeV)} \times 1000 \text{ (g/kg)} = 1.602 \times 10^{-10} \text{ Gy} \tag{2}$$

A function was adopted in the calculation to evaluate the ratio of ambient dose equivalent (Sv) to air absorbed dose. Then the ambient dose equivalent was calculated by multiplying the ratio of ambient dose to air absorbed dose.

As a first step, the calculated ambient dose rate without the clay was compared to the theory 1 cm depth dose rate at a distance of 20 cm for Am-241. For the theoretical dose rate, the dose rate conversion factor ($\mu Sv.m^2.MBq^{-1}.hr^{-1}$) for above 10 keV was obtained from radioisotope data book [21]. The constant value for Am-241 at 1-meter distance is 0.0151 $\mu Sv\ m^2.MBq^{-1}.hr^{-1}$. Table 3 shows the result of calculated dose rate compared to the theoretical dose rate (μSv/hr) at a distance of 20 cm. The statistical error for the calculated values is less than 0.12%. A good agreement with less than 1% different was achieved to confirm the subsequent dose calculations with the clay material.

Fig. 3 shows the calculated dose rate at a distance of 20 cm for 1 MBq Am-241 source as a function of clay thickness. The average calculated dose errors are within 0.66%. A thickness of 2 cm is adequate to shield 1 MBq Am-241 source from 0.3796 μSv/hr down to 0.0528 μSv/hr (~86% decrease), which could be considered a safe value as per our background radiation value. Fig. 4 shows the corresponding calculated photon spectra at a distance of 20 cm for Am-241 source with 2 cm thickness of the clay. The detector response was not considered in the calculated photon spectra. The peaks of 16.1 keV and 26.3 keV were significantly reduced, while the main peak of 59.5 keV decreased almost ~74%.

While considering the transmitted photon energies and dose rate after the clay to ensure radiation safety area, it is necessary to investigate the photons that might be reflected from the clay-shielding material, as the clay compound contain many elements as listed in Table 1, including high Z elements. The calculations were done in two cases; by turn-on (full line) and off (dotted line) the option of K and L fluorescence to understand whether the reflected photons from the clay material towards the source position were contributed by the K characteristic X-rays by any elements of the clay or not. In Fig. 5, a very small reflected peak at 49 keV photons appeared as a result of backscattered photons for Am-241 source (59.5 keV photon) to have a scattering angle of ~160°. Consequently, a reflected peak of 16 keV photons will be easily attenuated in air as a function of distance. The calculated reflected dose rate is 0.0582 μSv/hr (error is 0.18%) at a distance of 20 cm from the clay surface, which thus could be ignored. Nevertheless, there is no contribution of the characteristic X-ray for reflected photons due to Am-241 source. The number of reflected photons will have no change if thicker clay used. However, the contribution of reflected photon and dose might be considered if higher energy sources, such as Cs-137 and Co-60, are used. In this case, the inner layer (source-facing side) of the clay-shielding material is necessary to attenuate such effect. As an example, when a thin layer of iron (Fe-26, thickness of 0.5 cm) was added to the source surface side of the

Table 3
The calculated and theoretical dose rates for 1MBq gamma sources.

Source	1 MBq Dose Rate (μSv/hr) at 20 cm		% of difference
	Calculated	Theoretical	
Am-241	0.3796	0.3775	0.56

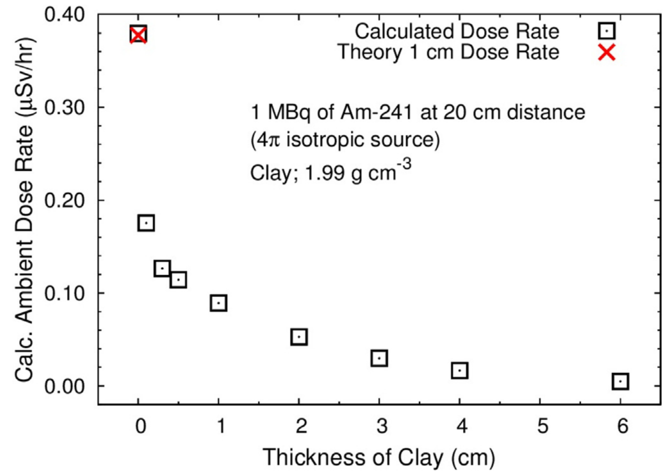

Fig. 3. The calculated dose rate (μSv/hr) at a distance of 20 cm for 1 MBq Am-241 source. The open square points are the calculated values, while the cross point at 0 cm (without clay) is the theoretical dose rate.

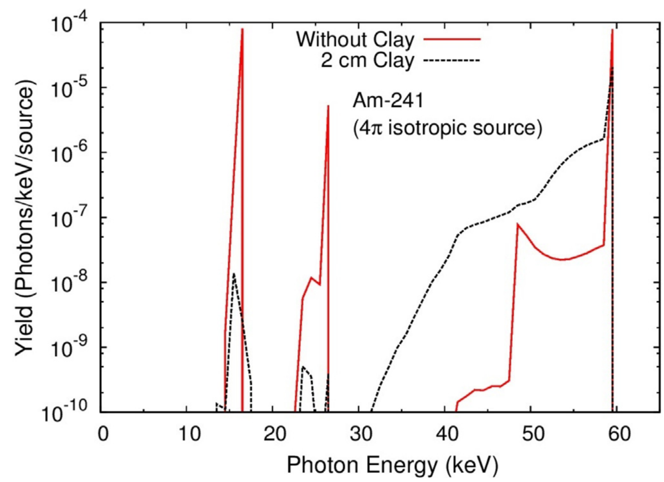

Fig. 4. Calculation of transmitted photon spectra for Am-241 source at a distance of 20 cm. The peaks of 16.1 and 26.3 keV photons significantly decreased, while the main peak of 59.5 keV photon decreased by 74%.

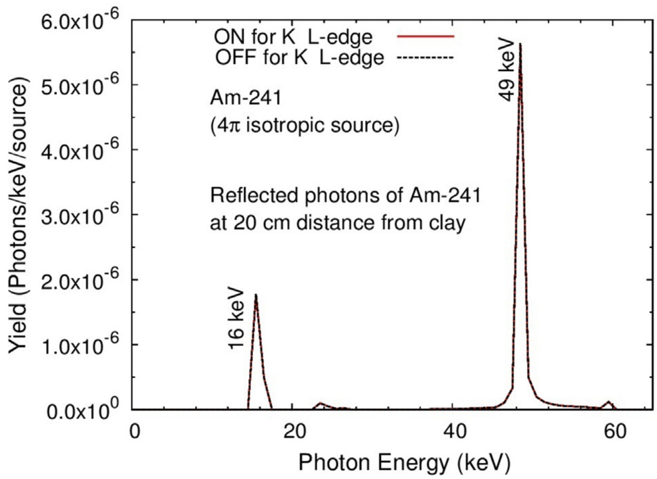

Fig. 5. Calculation of reflected photon spectra from the clay material for Am-241 source. A very small Compton scattered peak was observed at 49 keV as a result of reflected photon at scattering angle ~160° for 59.5 keV incident photons.

clay material, a peak of 49 keV will be significantly attenuated, as shown in Fig. 6 for Am-241 source. The calculated dose rate is 0.0056 μSv/hr (error is 0.56%), which reduce 90% compared to the calculated reflected dose rate without the inner layer.

4. Calculated half-value layer (HVL) and photon spectra of X-ray 150 kVp

Report 78, Spectrum Processor, of IPEM 1997 software [24] was used to obtain the unfiltered X-ray spectra of 150 kVp as a source input for EGS5 code as shown in Fig. 7. The parallel photons go toward the clay and cover only the front face of the clay area, as shown in Fig. 8. All the photons interaction and consideration in the calculation are same as mentioned in the Section 2.

The calculated μ value for X-ray of 150 kVp is 0.7424 cm^{-1} (±2.68%) as shown in Fig. 9. The calculated HVL value is 0.9335 cm which is lower in comparison to the ordinary concrete value, 2.23 cm [25]. Fig. 10 shows the calculation of transmitted (full line) and reflected (dotted line) photon spectra of X-ray 150 kVp for 2 cm

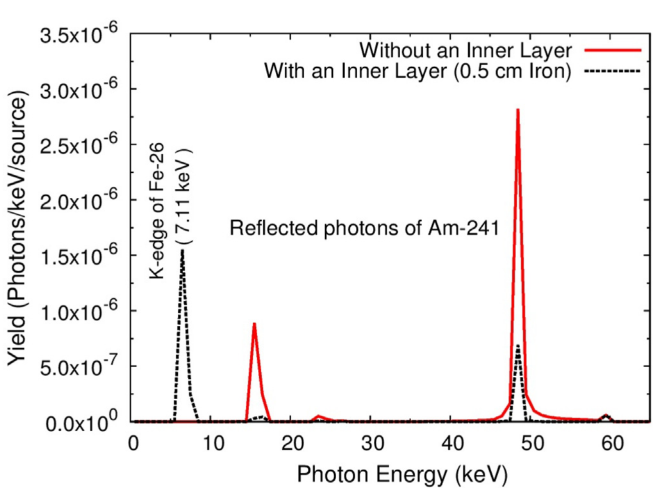

Fig. 6. The Figure shows reflected photon spectra with (dotted line) and without (full line) the inner layer (source-facing side) added to the clay shielding compound. Both reflected photons at 16 and 49 keV were successfully attenuated with 0.5 cm iron (Fe-26). The calculated dose rate decreased by 90% with an inner shield layer of clay.

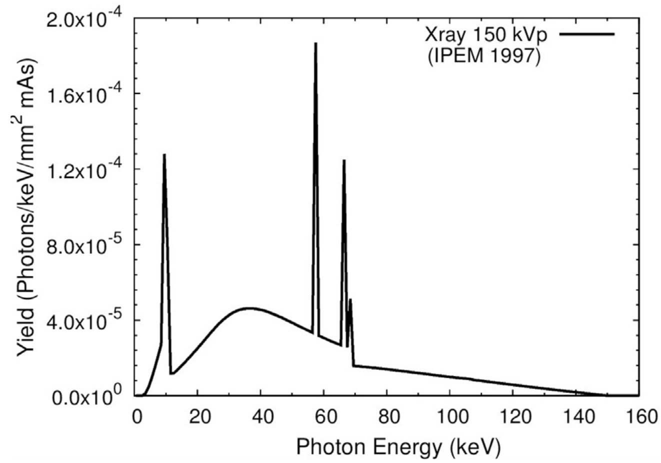

Fig. 7. X-ray photon spectra of 150 kVp as a source input in the calculation. The average energy is 49.8 keV. The X-ray spectra was adopted from Report 78 [15].

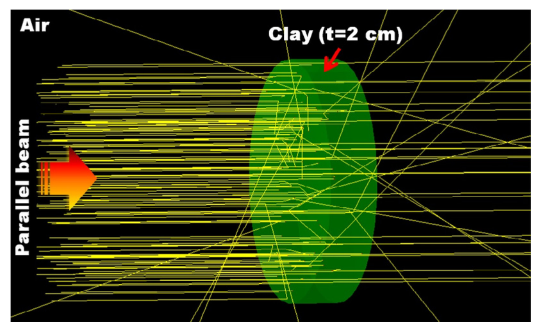

Fig. 8. Simulation geometry modeled in simulation for estimating the effect of clay on the X-ray photon spectra and dose. The parallel photon beams were incident on the 2 cm clay thickness.

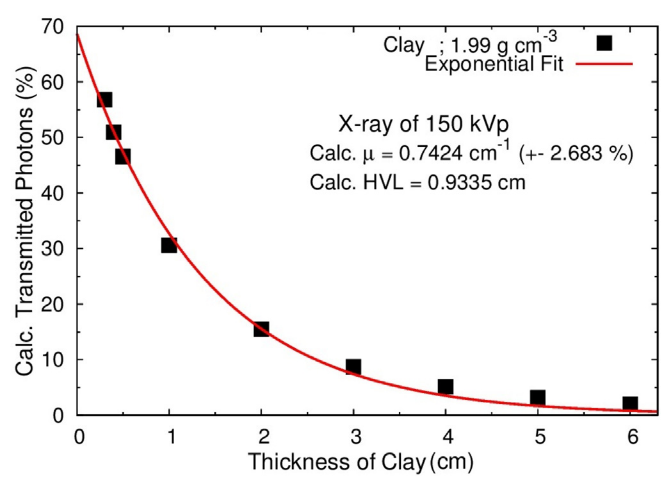

Fig. 9. The calculated transmitted photons of clay for X-ray of 150 kVp. Calculated μ value is 0.7424 cm^{-1} and HVL is 0.9335 cm.

clay at a distance of 20 cm. The reflected photon spectra due to the clay is negligible, while the transmitted photon spectra significantly reduced, particularly for photons below 60 keV, indicating the effectiveness of the clay as a shielding compound for the X-ray laboratory. The calculated dose rate without the clay is 1.85×10^{-15}Sv/photon while the transmitted dose rate of 2 cm clay is 3.78×10^{-16} Sv/photon, to reduce by about 80%. The calculated

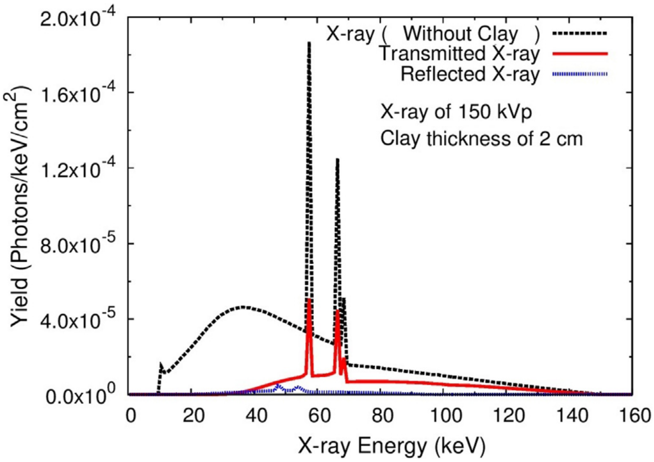

Fig. 10. The Figure shows the transmitted (full line) and reflected (dotted line) photon spectra for the X-ray source of 150 kVp. The contribution of both reflected photons and dose for the X-ray source is negligible.

dose error is less than 0.5%. When the photon intensity or electron beam current of the X-ray machine is known, the absolute dose rate value could be obtained.

5. Conclusion

An approach of calculations for photon energy spectra and dose rate either it is transmitted or reflected one must be considered, particularly in exploring the new element or compound materials when designing a radiation shielding. In the case of multi-energy gamma source such as Am-241, the linear attenuation coefficient is higher, within 5.6% compared to theoretical value for its single-energy photons. A thickness of 2 cm clay is adequate to shield 1 MBq source of Am-241 source down to 0.0528 μSv/hr. For X-ray of 150 kVp, the calculated HVL is 0.9335 cm for the clay, which is lower compared to 2.23 cm, from the literature data. Photons below 60 keV of the 150 kVp X-ray spectra were significantly attenuated, and the calculated dose rate reduced by 80%. For photons above 150 keV, the clay may need to be doped with a higher Z element to improve its photon-shielding efficiency. Consequently, clay (1.99 g cm^{-3}) shielding material with an affordable thickness of 2 cm is adequate for our purpose as a non-lead shielding for X-ray laboratory (150 kVp) where the average X-ray energy is ~50 keV.

Conflict of interest

The authors declare that they have no conflict of interest.

Statement of human and animal rights

This article does not contain any studies with human participants and animal performed.

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