

THE X-/GAMMA-RAYS, PROTON AND ALPHA PARTICLES SHIELDING PROPERTIES FOR TUNGSTEN OXIDE POLYMER COMPOSITES

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Abstract

In this work, the uncharged and charged ionizing radiation shielding properties for tungsten oxide polymer composites amount 9 samples were studied. The uncharged ionizing radiation such as X-rays and gamma-rays shielding properties were simulated at the tube voltages of 40-120 kVp and the energy range of 59.6-1,332 keV, respectively. The mass attenuation coefficients (μ_m), half value layer (HVL), and mean free path (MFP) values were discussed for both-rays. The charged ionizing radiation such as proton and alpha particles were determined mass stopping power (MSP), and projected range (PR) in the kinetic energy range of 10 keV-10 MeV. The results found that the increasing energy for X-rays and gamma-rays, the μ_m decreased while HVL and MFP increased. Whereas, increasing tungsten oxide content, the μ_m increased while HVL and MFP decreased. Also, the HVL was compared with some shielding materials. The result found that the tungsten oxide polymer composites had better X-rays and gamma-rays shielding properties compared to some shielding materials. In addition, the increasing amount of tungsten oxide improved proton and alpha particles shielding. It indicated that the tungsten oxide polymer composites had the ability to shield X-rays and gamma-rays, proton and alpha particles and can be applied as ionizing radiation shielding materials.

Keywords: Ionizing radiation shielding; Polymer composites; Tungsten oxide

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Introduction

To diagnose and treat a wide range of illnesses, different radiations are currently employed in medicine. X-rays, for example, are used in general imaging laboratories at tube voltages of 40-150 kVp, while gamma rays are used for nuclear medicine imaging examinations at energies of 140, 364, and 511 keV (Afkham *et al.*, 2020). The use of the special characteristics of radionuclides and stable nuclides to diagnose and treat human anatomy, physiology, and biochemical status is known as nuclear medicine (Love and Palestro, 2016; Ge *et al.*, 2020; Pellico *et al.*, 2021). Isotopes utilized in nuclear medicine release radiation that is distinct in that it is non-directional, high energy, and transmittance. Therefore, medical professionals cannot manipulate isotope characteristics artificially (Yin *et al.*, 2021). This leads to damage to cell tissue, chromosomes, and possibly genetic modification (Kamiya *et al.*, 2015; Tharmalingam *et al.*, 2017; Lumniczky *et al.*, 2021).

In general, radiation is attenuate by materials which has high density and high atomic number (Majunatha *et al.*, 2019). Lead is the most commonly used radiation shielding material in medical institutions due to it has high atomic number and density. Therefore, lead aprons are a type of apparel that may effectively screen radiation workers from exposure (Çetin *et al.*, 2016; Sayyed *et al.*, 2019a). Lead, however, is poisonous and detrimental to the environment as well as human health. Additionally, lead-containing clothing intended for radiation shielding weights 3.15-3.45 kg. Users are physically burdened by this and medical personnel's range of motion is restricted. Thus, new radiation shielding materials are required to replace the lead that is now employed to guard nuclear medicine staffs from X-rays and gamma-rays.

Polymer composites with tungsten oxide are expected to be used to shield electron radiation in space. This group of polymers is the most promising binder for composites for aerospace radiation

shielding applications (Cherkashina, 2020). As tungsten (W) has high atomic number (74) and density (19.25 g/cm³), lighter than lead and environmentally friendly. It means that the application of polymer composites and tungsten oxide is less burdensome (Singh *et al.*, 2017; Akman *et al.*, 2019; AbuAlRoos *et al.*, 2020).

In this context, polymer composites tungsten oxide was simulated the uncharged and charged ionizing radiation. The uncharged ionizing radiation such as X and gamma-rays properties were simulated using FLUKA Monte Carlo code at tube voltages of 40-120 kVp and the energy range of 59.6-1332 keV, respectively. The charged ionizing radiation such as proton and alpha particles were evaluated using SRIM program at kinetic energy range 10 keV-10 MeV. The characteristics that needed to be examined were the mass attenuation coefficient (μ_m), half value layer (HVL) and mean free path (MFP) for X and gamma-rays. While mass stopping power (MSP) and projected range (PR) for proton and alpha particles were discussed.

Materials and Methods

The chemical compositions and density of the polymer composites tungsten oxide to simulation for 9 samples are shown in Table 1 (Cherkashina, 2020).

The Uncharged Ionizing Radiation

FLUKA (FLUKtuierende KAskade) code is favors used in particle-nuclear sciences. It is mainly in high energy experimental physics and engineering shielding. In this work, the FLUKA Monte Carlo code version 4-3.3 which schematic set up for simulate X and gamma-rays were exhibited in Figures 1 and 2. The simulation for linear attenuation coefficients (μ) of samples can be follows in equation (Issa *et al.*, 2018; Almuqrin *et al.*, 2021):

Table 1. Chemical composition and density of polymer composites tungsten oxide

Samples	Weight Fraction of Elements (wt%)					Density (g/cm ³)
	C	N	O	H	W	
PCW0	68.11	7.57	21.62	2.70	-	1.43
PCW1	61.30	6.81	21.53	2.43	7.93	1.61
PCW2	54.49	6.05	21.44	2.16	15.86	1.77
PCW3	47.68	5.30	21.33	1.89	23.80	1.99
PCW4	40.86	4.55	21.25	1.62	31.72	2.23
PCW5	34.06	3.78	21.15	1.35	39.66	2.57
PCW6	27.24	3.03	21.06	1.08	47.59	3.05
PCW7	20.43	2.27	20.96	0.82	55.52	3.46
PCW8	13.62	1.51	20.87	0.54	63.46	4.35

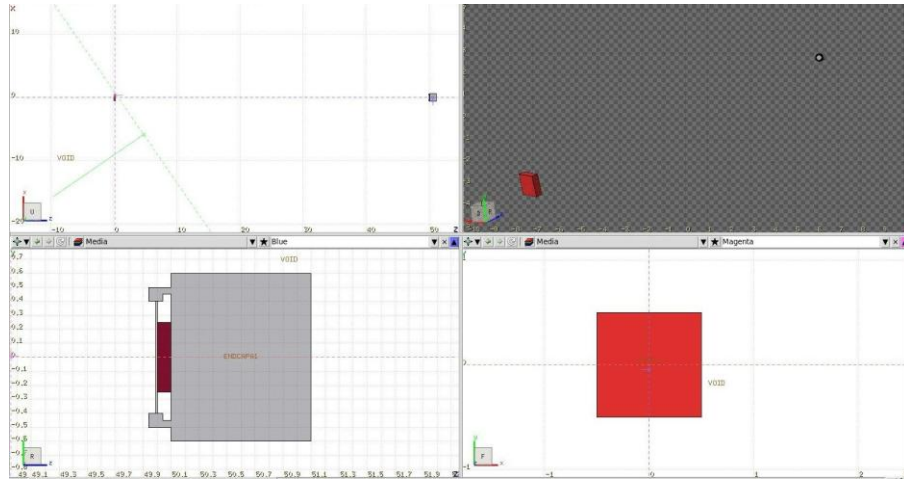


Figure 1. The schematic set up to simulate X-rays

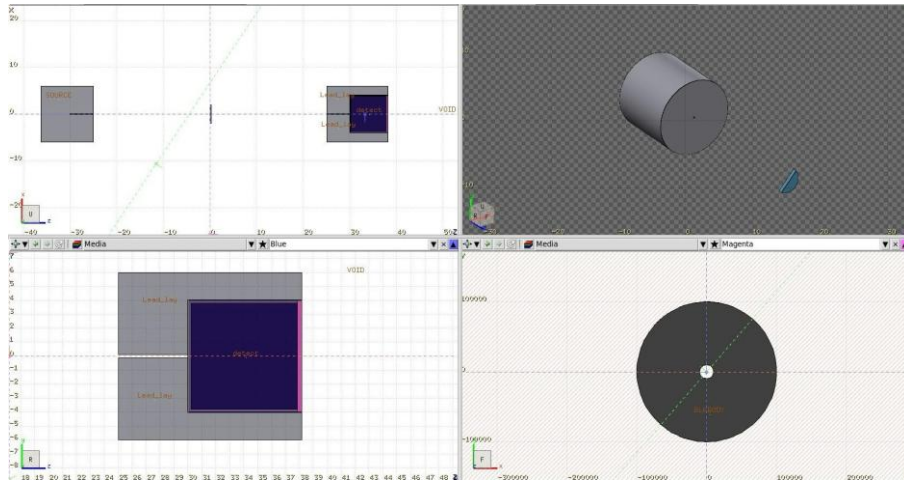


Figure 2. The schematic set up to simulate gamma-rays

$$I = I_0 e^{-\mu x} \quad (1)$$

where x is the sample thickness, I and I_0 are the gamma-ray intensity passed through with and without shielding material, respectively.

The μ_m , which express the interaction likelihood of X and gamma-rays with medium, can be found using the following equation (Kumar, 2017, Kaewjaeng *et al.*, 2021a):

$$\mu_m = \ln\left(\frac{I_0}{I}\right) \left(\frac{1}{\rho x}\right) \quad (2)$$

Equation (3) was utilized to evaluate the relative deviations (RD(%)) for μ_m values between

the FLUKA code and the XCOM program (Akyildirim *et al.*, 2020):

$$RD(\%) = \left(\frac{\mu_m(XCOM) - \mu_m(FLUKA)}{\mu_m(XCOM)} \right) \times 100. \quad (3)$$

Equation (4) can be used to calculate the HVL, which is defined as the sample thickness that causes the intensity of X and gamma rays to decrease to half of their initial value (Kursun *et al.*, 2023; Sriwongsa *et al.*, 2024):

$$HVL = \frac{0.693}{\mu}. \quad (4)$$

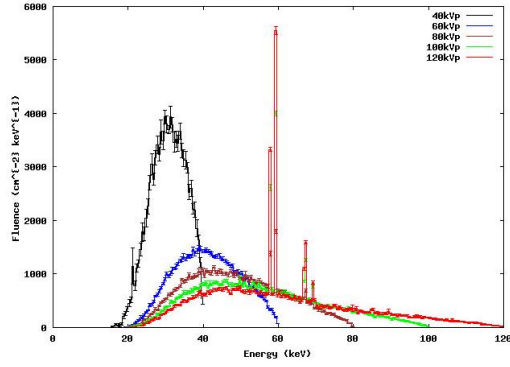


Figure 3. The X-rays spectrum at 40, 60, 80, 100, and 120 kVp

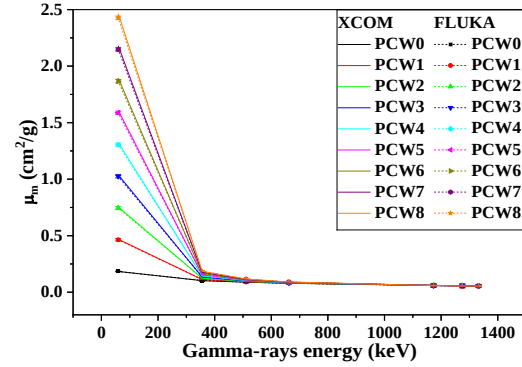


Figure 5. The μ_m with gamma-rays energy of samples

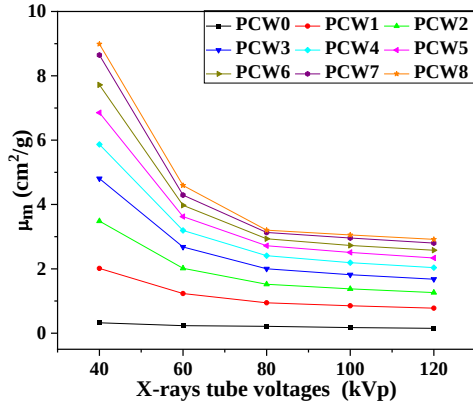


Figure 4. The μ_m with X ray energy of samples

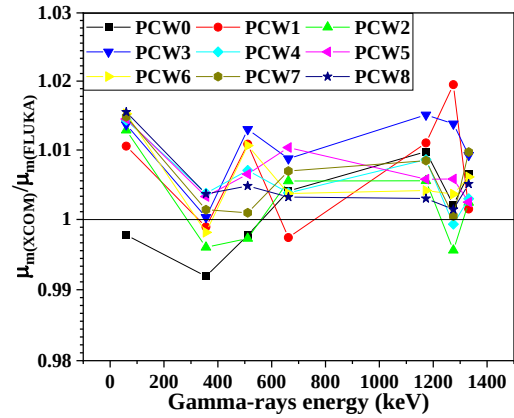


Figure 6. Ratios of μ_m values from FLUKA and XCOM

In an attenuator medium, the average distance between two successive X-rays and gamma-rays interactions, as represented by Equation 5, is known as the mean free path (MFP) (Kursun *et al.*, 2023; Sriwongsa *et al.*, 2024):

$$\text{MFP} = \frac{1}{\mu} \quad (5)$$

The Charged Ionizing Radiation

The heavy charged particles (proton and alpha particles) interactions with materials are very important for investigation and detection according to the Bethe-Bloch method. The MSP and PR of proton (H^{1+}) and alpha (He^{2+}) particles of samples were simulated using SRIM-2013 software program. MSP is a strong feature because it refers to decrease of kinetic energy (E_k) when passing through a certain density of samples, while PR is a concept that used to define the expected depth to which H^{1+} or He^{2+} will penetrate up to rest in an absorber material which small value is excellent

H^{1+} and He^{2+} shielding samples (Ravangvong *et al.*, 2022; Subedi *et al.*, 2023).

Results and Discussion

X and Gamma-Rays Shielding Properties

The μ_m values from FLUKA code for X-rays at tube voltages of 40-120 kVp and the X-rays spectrum can exhibited in Figure 3. The μ_m values from FLUKA code compared with XCOM program for gamma-rays at energy range 59.6-1332 keV of polymer composites tungsten oxide were exhibited in Figures 4 and 5. The μ_m for X and gamma-rays in the samples clearly rose as the WO_3 contents grew increased in accordance with density and chemical composition. Furthermore, the main process and probability interaction at the energy ranges processes caused the μ_m values to drop with increasing energy (Sriwongsa *et al.*, 2023, Sayyed *et al.*, 2019b).

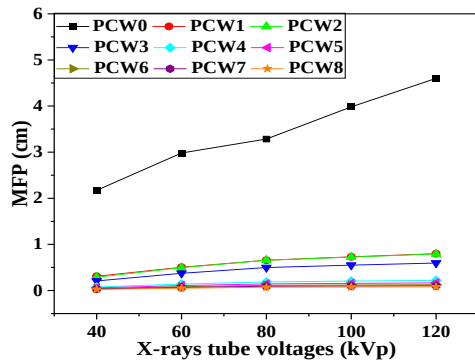


Figure 7. The MFP with X-rays tube voltages of samples

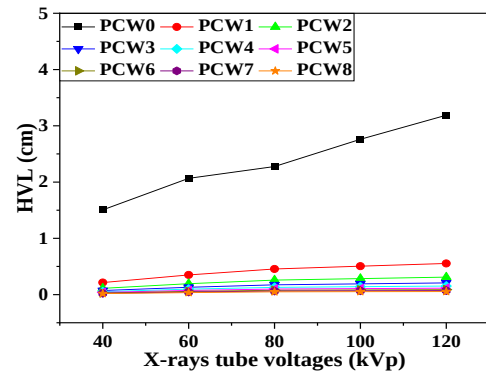


Figure 9. The HVL with X-rays tube voltages of samples

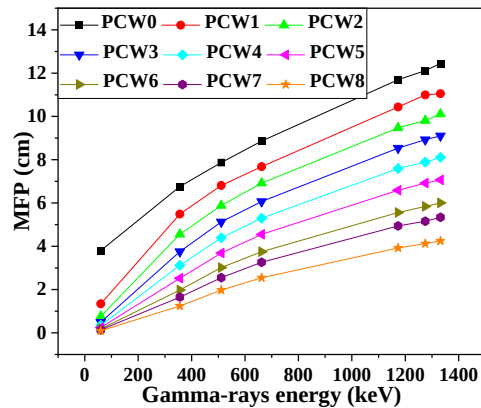


Figure 8. The MFP with gamma-rays energy of samples

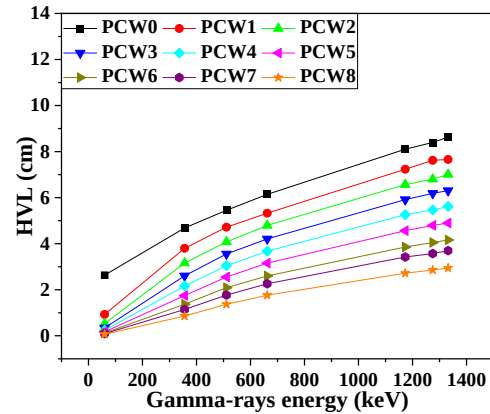


Figure 10. The HVL with gamma-rays energy of samples

The RD(%) for μ_m values of gamma-rays from the FLUKA code and XCOM program was exhibited in Equation (3). It was discovered that a value for W_0 to W_8 ranged from -0.82% to 0.91%, -0.44% to 1.27%, 0.03% to 1.49%, -0.07% to 1.41%, 0.25% to 1.43%, -0.18% to 1.50%, 0.05% to 1.46%, and 0.30% to 1.53%, respectively. When the μ_m values from both simulations are examined in Figure 6, it can be shown that the FLUKA simulation produced somewhat lower results than XCOM. Numerous other researchers have reported findings that are comparable to this (Akyildirim *et al.*, 2020, Sriwongsa *et al.*, 2024). The XCOM code is the standard theory used to analyze radiation shielding properties, so FLUKA's small RD(%) may be ascribed to the code's geometric reproducibility and the accuracy of the model physics (Akyildirim *et al.*, 2020, Sriwongsa *et al.*, 2024).

The MFP and HVL of samples for X-rays and gamma-rays are shown in Figures 7-10. The trends

of MFP and HVL values of samples decreased and increased with increasing WO_3 content and energy, respectively. These results indicated that the MFP and HVL values were depended on the density of samples and a small thickness was used for high X and gamma-rays energies attenuation (Kaewjaeng *et al.*, 2021a; 2021b; Mukamil *et al.*, 2022).

The HVL values of samples were compared with commercial window glass, red brick, concrete, X-rays window for X-rays at energy 120 kVp while commercial window glass, ordinary concrete and hematite-serpentine for gamma-rays at energy 662 keV as exhibited in Figures 11 and 12. The HVL of PCW3-PCW8 samples have been found better than commercial window glass, red brick, concrete and X-rays window for X-rays while PCW5-PCW8 samples found better than commercial window glass, ordinary concrete and hematite-serpentine. It indicated that these samples can be developed for X and gamma-rays shielding medium (Kaewjaeng *et al.*, 2021a; 2021b, Mukamil *et al.*, 2022).

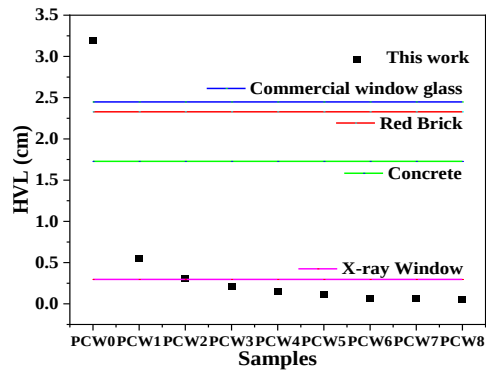


Figure 11. The comparative HVL of samples with some materials at 120 kVp X-rays tube voltages

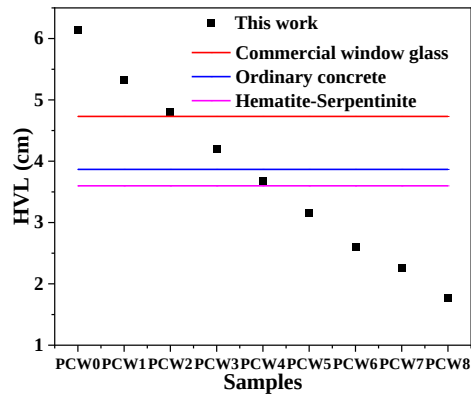


Figure 12. The MFP with gamma-rays energy of samples

Mass Stopping Power (MSP) and Projected Range (PR)

The MSP is a value used to discuss the rate of particles' losses of kinetic energy (E_k) when passing through medium per unit mass thickness. While the PR is a quantity used to explain the number of particles that can penetrate the thicknesses of sample. The MSP and PR values are low indicated that medium is excellent particles shielding. Figure 13 illustrated the MSP for H^{1+} and He^{2+} particles with E_k ranging at 10 keV-10 MeV. It found that MSP values for H^{1+} and He^{2+} increased with increasing E_k until the highest values at 0.08 MeV and 0.65 MeV for H^{1+} and He^{2+} , respectively. After that, these values decreased. These events are varied inversely with the square of velocity (v^2) and directly with ion charge. In addition, MSP value of He^{2+} higher than H^{1+} because of the higher electrical charge and lower velocity of He^{2+} compared with H^{1+} (Ravangvong *et al.*, 2022).

The PR value for H^{1+} and He^{2+} with E_k as exhibited in Figure 14. The results shown that PR

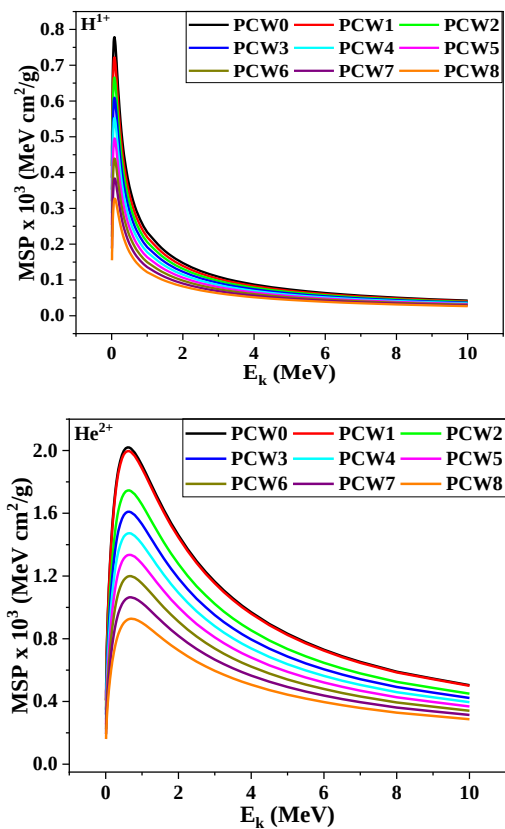


Figure 13. MSP values for H^{1+} and He^{2+} particles with E_k of samples

values of both H^{1+} and He^{2+} particles increased with increasing E_k and the PR value of H^{1+} had higher than He^{2+} at the same E_k . This difference is due to the variation in the rest masses of H^{1+} , and He^{2+} particles. The lower rest mass of H^{1+} compared to He^{2+} results in higher velocities for H^{1+} particles at the same energy. In addition, the PCW8 sample exhibits the shortest PR lengths for both H^{1+} and He^{2+} particles. This is attributed to the high contribution of WO_3 and the overall high density of the PCW8 sample. As a result, this sample may be developed into an H^{1+} and He^{2+} shielding material (Ravangvong *et al.*, 2022).

Conclusions

This study investigated X-rays, gamma-rays, protons and alpha particles shielding properties of polymer composites tungsten oxide. The X and gamma-rays shielding properties were simulated at the tube voltages of 40-120 kVp and the energy range of 59.6-1,332 keV, respectively. The values for shielding properties were explained on mass attenuation coefficient (μ_m), half value layer (HVL)

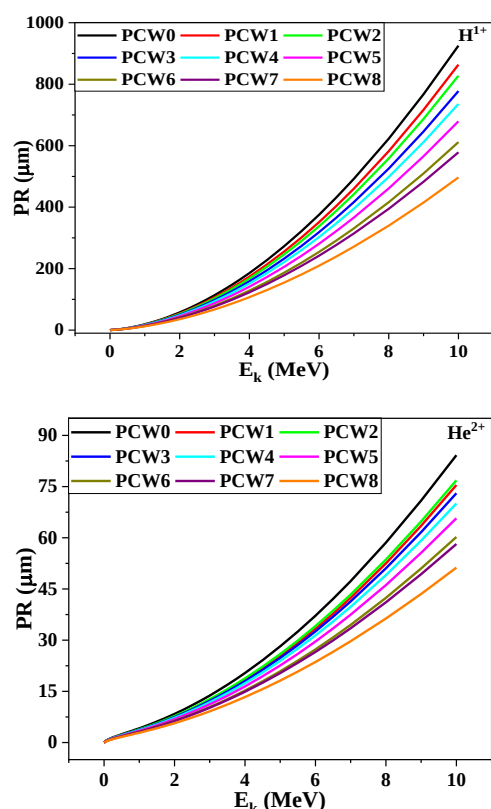


Figure 14. PR values for H^{1+} and He^{2+} particles with E_k of samples

and mean free path (MFP) as simulated using FLUKA code. The protons and alpha particles shielding properties were discussed on mass stopping power value (MSP), and projected range value (PR) which determined using SRIM program. The μ_m , HVL and MFP values for X and gamma-rays found that PCW8 sample had the maximum μ_m values and minimum HVL and MFP. The comparison of HVL value with some materials for X and gamma-rays at energy 120 kVp and 662 keV, respectively. They found that PCW3-PCW8 samples were better than commercial window glass, red brick, concrete and X-rays window for X-rays while PCW5-PCW8 samples found better than commercial window glass, ordinary concrete and hematite-serpentine. The protons and alpha particles shielding properties particles at energy ranging 10 keV-10 MeV were discussed on MSP and PR values. It found that PCW8 sample had the lowest values which reflected that this sample is excellent protons and alpha particles shielding. These results indicated that polymer composites tungsten oxide have potential to be developed for X and gamma-rays, protons and alpha particles shielding materials.

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