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Calculation of Shielding Parameters of Fast Neutrons for Some Composite Materials

Ahmed Fadhil Mkhaiber*, **Salwah Kareem Dawood**
Department of Physics, College of Education (Ibn Al-Haitham), University of Baghdad, IRAQ
*Correspondent author email: ahmfad27@gmail.com

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Abstract

In this paper ,Shielding parameters of fast neutrons likes removal cross section , half thickness, and mean free path were calculated for polymer composite which consisted of paraffin wax as basic material (P) with various reinforced materials [Boron (B), Boron trioxide (B_2O_3), Iron(III) oxide (Fe_2O_3), Tungsten (W), Kaolin (Clay)] with different reinforced concentration (5, 15, 25, 35, 45) % weight percentage . Results have been shown that, with increasing the reinforced materials concentrations, removal cross section increases while half thickness and mean free path decreased.

Keywords: Shielding materials, removal cross section, fast neutron, half value layer, and mean free path.

الخلاصة

تم في هذا البحث حساب معلمات توهين النيوترونات السريعة مثل المقطع العرضي للازالة ، سمك النصف ومعدل المسار الحر لمتراكبات بوليميرية والتي تحتوي على شمع البرافين كمادة اساس مع مواد تدعيم مختلفة (بورون B، ثلاثي اوكسيد البورون B_2O_3، ثلاثي اوكسيد الحديد Fe_2O_3، تنكستن W، طين الكاؤولين Clay) وبتراكيز مختلفة (٥، ١٥، ٢٥، ٣٥، ٤٥)% نسبة وزنية. أظهرت النتائج انه مع زيادة تركيز مادة التدعيم فان المقطع العرضي للازالة يزداد، بينما يقل كل من سمك النصف ومعدل المسار الحر.

Introduction

Ionizing radiation is very dangerous to human health, such as neutrons, so it was necessary to assess these risks and determine the level of exposure to this radiation and to develop the technologies to protect against this radiation [1]. Neutron shielding is complex because neutrons interact with matter only through nuclei, so they do not stop easily through matter, and can travel large distances through most materials without scattering or absorbing. This means that the neutrons have a high penetrability ability, which makes them dangerous both in terms of material or radiation [2]; the interaction of neutrons with the matter is described by some parameters such as removal cross-section (Σ_R), mean free path, half thickness [3]. So the shielding system is designed to reduce the radiation dose and slow the neutrons [4]. In this study, various materials [Boron(B), Boron trioxide (B_2O_3), Iron(III) oxide (Fe_2O_3), Tungsten (W), Kaolin (Clay)] with different concentrations (5 ,15 ,25, 35 ,45)% weight percentage have been added to paraffin wax to determine the suitability of these materials for use as shields against neutrons.

Materials and Methodologies

Neutron particles are neutral [5] and since they does not carry a charge that has the ability to penetrate nuclei [6], its interaction with the material differs from that of the photons [7]. The main reaction mechanism with nuclei is through scattering (elastic and inelastic) and absorption. In elastic scattering interactions, the neutron interacts with the nucleus, which is normally stable and subject to the laws of maintaining momentum and energy. In the other hand, the inelastic scattering interactions, leaves the nucleus in excited state after the reaction and it is followed by the return of the excited nucleus to the ground stable state, through the emission of gamma rays[8]. As for the absorption reactions, the neutron is absorbed and captured by the nucleus, so the nucleus is converted into an unstable radioactive nucleus, and the nucleus get rid of the excess energy to return to stability by emitting gamma rays[9] .

The removal cross sections of fast neutrons (Σ_R)

The fast neutron attenuation is described by removing the cross section (Σ_R) where it represents the probability of the reaction of the neutron which is subject to collision first [10] [11] in the case of compounds or mixtures it is given by the following relationship [12]:

$$\Sigma_R = \sum_i \rho_i \, (\Sigma_R/\rho)_i \qquad (1)$$

Where ρ_i is partial density. Σ_R/ρ is mass removal cross section, which can be calculated for any compound or mixture by the following experimental equation [6]:

$$\frac{\Sigma_R}{\rho} = 0.206\, A^{-1/3} Z^{-0.294} \quad (\mathrm{cm^2/g}) \qquad (2)$$

Where A: is the atomic weight, Z: atomic number

Half Thickness ($X_{½}$)

The thickness of the material needed to reduce the intensity of incident neutrons to its half original value and is given by the following equation [9] [13]:

$$½\ (\mathrm{cm}) = 0.693/\Sigma \qquad (3)$$

Σ: removal cross section of fast neutron, Mean free Path (λ): the distance rate that the neutron travels without interactions and is given by the following equation [14] [15]:

$$\lambda\ (cm) = 1/\Sigma \qquad (4)$$

Results and Discussion

Removal cross sections of fast neutrons

Mass macroscopic cross section (Σ_R/ρ) and removal cross section of fast neutron (Σ_R) have been calculated using the equations (2), (1) respectively for various shields and different concentrations. As shown in Tables (1-6). One can be observed from these tables that the total cross section depends on the type and density that of the elements composing shields, the contribution of light elements to the determination of the total cross section values of neutron removal is of great importance if compared with heavy material especially hydrogen, where hydrogen has the highest mass cross section compared to other elements, also increasing the weight ratio of hydrogen will contribute to increasing the removal cross section of fast neutron (Σ_R).

These Tables show that the high concentration of hydrogen and boron in the chemical composition of the mixture [P (Paraffin) +B (Boron)] compared to the rest of the mixtures, which explains why this mixture has the greatest value of the total cross-sectional, and the mixture [P(Paraffin) +W(Tungsten)] has the lowest value of the total cross sectional because it contains the tungsten which has the lowest value of the mass cross section, so attenuation of fast neutrons using the mixture (P+B) is better than the other mixtures as shown in Figure 1. It is also evident from this figure that the total cross-sectional values of the mixture containing Iron trioxide and clay (kaolin) have convergent values which give the possibility of replacing iron trioxide with by (Kaolin) where it is more abundant and cheaper.

Table 1: Values of Fast Neutrons Effective Removal Cross-Section for Pure Paraffin Wax.

Groups	Concentration	Element	Σ_R/ρ(cm²g⁻¹)	Fraction by Weight	Partial Density (g/cm³)	Σ_R (cm⁻¹)
P	0%	C	0.053	0.852	0.809	0.043
		H	0.205	0.147	0.140	0.028
Total Σ_R						0.071
		B	0.058			
		W	0.010			
		O	0.044			
		Fe	0.020			
		Al	0.032			
		Si	0.031			

Table 2: Values of Fast Neutrons Effective Removal Cross-Section for Paraffin Wax + Boron Composite.

	Concentration	**Element**	**Fraction by Weight**	**Partial Density (g/cm^3)**	**Σ_R (cm^{-1})**	**Total Σ_R**
P+B	5%	C	0.810	0.793	0.042	0.073
		H	0.140	0.137	0.028	
		B	0.050	0.049	0.003	
	15%	C	0.724	0.755	0.040	0.076
		H	0.126	0.131	0.027	
		B	0.150	0.156	0.009	
	25%	C	0.639	0.713	0.038	0.079
		H	0.111	0.124	0.025	
		B	0.250	0.279	0.016	
	35%	C	0.554	0.664	0.035	0.083
		H	0.096	0.115	0.024	
		B	0.350	0.420	0.024	
	45%	C	0.469	0.608	0.032	0.088
		H	0.081	0.105	0.022	
		B	0.450	0.583	0.034	

Table 3: Values of Fast Neutrons Effective Removal Cross-Section for Paraffin Wax + W Composite.

	Concentration	**Element**	**Fraction by Weight**	**Partial Density (g/cm^3)**	**Σ_R (cm^{-1})**	**Total Σ_R**
P+W	5%	C	0.810	0.807	0.043	0.072
		H	0.140	0.140	0.029	
		W	0.050	0.050	0.001	
	15%	C	0.724	0.803	0.043	0.073
		H	0.126	0.139	0.029	
		W	0.150	0.166	0.002	
	25%	C	0.639	0.796	0.042	0.074
		H	0.111	0.138	0.028	
		W	0.250	0.312	0.003	
	35%	C	0.554	0.789	0.042	0.075
		H	0.096	0.137	0.028	
		W	0.350	0.498	0.005	
	45%	C	0.469	0.778	0.041	0.077
		H	0.081	0.135	0.028	
		W	0.450	0.747	0.008	

Table 4: Values of Fast Neutrons Effective Removal Cross-Section for Paraffin Wax + Boron trioxide Composite.

	Concentration	**Element**	**Fraction by Weight**	**Partial Density (g/cm^3)**	**Σ_R (cm^{-1})**	**Total Σ_R**
P+B_2O_3	5%	C	0.810	0.793	0.042	0.073
		H	0.140	0.138	0.028	
		B	0.015	0.015	0.001	
		O	0.034	0.0338	0.001	
	15%	C	0.724	0.758	0.040	0.075
		H	0.126	0.131	0.027	
		B	0.047	0.0488	0.003	
		O	0.103	0.108	0.005	
	25%	C	0.639	0.717	0.038	0.077
		H	0.111	0.124	0.026	
		B	0.078	0.087	0.005	
		O	0.172	0.193	0.009	
	35%	C	0.554	0.670	0.036	0.080
		H	0.096	0.116	0.024	
		B	0.109	0.132	0.008	
		O	0.241	0.292	0.013	
	45%	C	0.469	0.615	0.033	0.083
		H	0.081	0.107	0.022	
		B	0.140	0.183	0.011	
		O	0.310	0.407	0.018	

Table 5: Values of Fast Neutrons Effective Removal Cross-Section for Paraffin Wax + Iron(III) oxide Composite.

	Concentration	Element	Fraction by Weight	Partial Density (g/cm³)	Σ_R (cm⁻¹)	Total Σ_R
P+Fe_2O_3	5%	C	0.810	0.802	0.043	0.073
		H	0.140	0.139	0.029	
		Fe	0.035	0.035	0.001	
		O	0.015	0.015	0.001	
	15%	C	0.724	0.784	0.042	0.074
		H	0.126	0.136	0.028	
		Fe	0.105	0.114	0.002	
		O	0.045	0.049	0.002	
	25%	C	0.639	0.763	0.041	0.076
		H	0.111	0.132	0.027	
		Fe	0.175	0.209	0.004	
		O	0.075	0.090	0.004	
	35%	C	0.554	0.738	0.039	0.078
		H	0.096	0.128	0.026	
		Fe	0.245	0.326	0.007	
		O	0.105	0.140	0.006	
	45%	C	0.469	0.705	0.037	0.081
		H	0.081	0.122	0.025	
		Fe	0.315	0.473	0.010	
		O	0.135	0.203	0.009	

Table 6: Values of Fast Neutrons Effective Removal Cross-Section for Paraffin Wax + Clay ($Al_2Si_2O_9H_4$).

	Concentration	Element	Fraction by Weight	Partial Density (g/cm³)	Σ_R (cm⁻¹)	Total Σ_R
P+$Al_2Si_2O_9H_4$	5%	C	0.810	0.794	0.042	0.073
		H	0.141	0.139	0.028	
		O	0.028	0.027	0.001	
		Al	0.010	0.010	0.001	
		Si	0.011	0.011	0.001	
	15%	C	0.724	0.761	0.040	0.074
		H	0.128	0.134	0.028	
		O	0.084	0.088	0.004	
		Al	0.031	0.033	0.001	
		Si	0.033	0.034	0.001	
	25%	C	0.639	0.722	0.038	0.076
		H	0.115	0.130	0.027	
		O	0.139	0.157	0.007	
		Al	0.052	0.059	0.002	
		Si	0.054	0.061	0.002	
	35%	C	0.554	0.676	0.036	0.077
		H	0.102	0.124	0.025	
		O	0.195	0.238	0.011	
		Al	0.073	0.089	0.003	
		Si	0.076	0.093	0.003	
	45%	C	0.469	0.623	0.033	0.080
		H	0.088	0.117	0.024	
		O	0.251	0.334	0.015	
		Al	0.094	0.125	0.004	
		Si	0.098	0.130	0.004	

The relationship between the fast neutrons removal cross section and the concentration of the reinforcement materials was drawn as shown in Figure 2. It is clear from the figure that the values of the removal cross-section increase with the increasing of this can be explained, when concentration of the reinforcement materials increase. In increasing the concentration, the weighted fraction of the added elements will increase. Therefore, the contribution of each element in determining the value of the total cross sections will be increased for all mixtures.

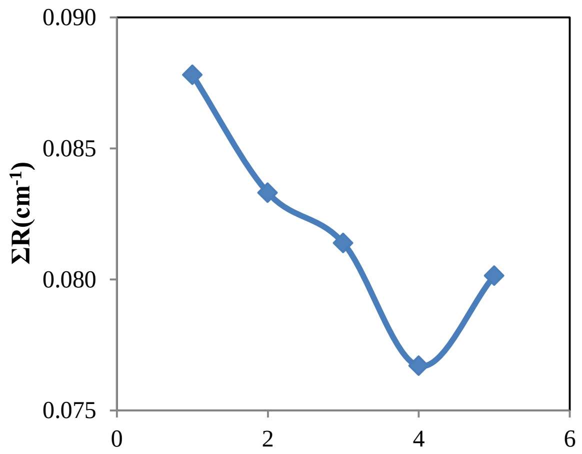

Figure 1: Fast neutrons effective removal cross section as a function of type of the reinforcement material at the concentration of 45% for all composite.

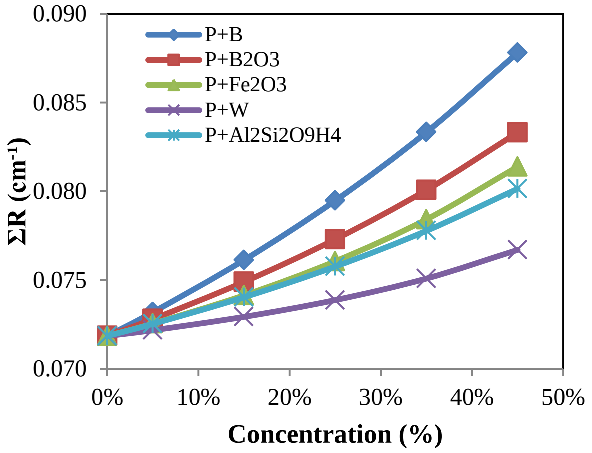

Figure 2: Fast neutrons effective removal cross section as a function of concentration for all composite.

Half value layer ($X_{1/2}$)

Table 7 shows the values of the thickness of the half value at the different concentrations for all the mixtures. The relationship between the thickness of the half value and the concentration of the additive was drawn as shown in Figure 3. It is observed from this figure, that when reinforcement materials increases, the thickness needed to attenuate the neutrons intensity to its half value is decreased. This is due to the relationship between the total cross-section and the increase in the concentration of the reinforcing material.

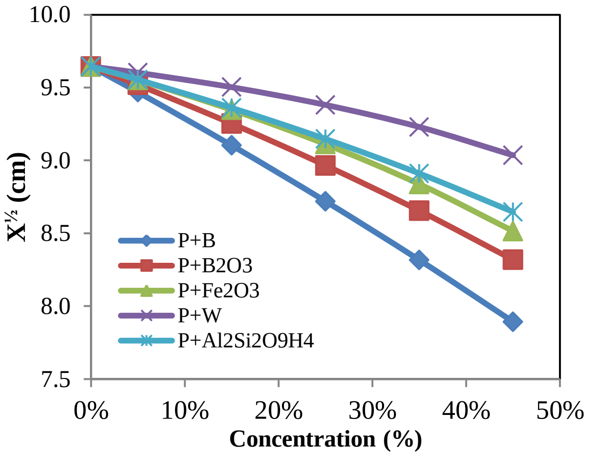

Figure 3: Half value layer as a function of concentration for all composite.

Mean free Path (λ)

Table 8 shows the values of the mean free path at different concentrations, and the Figure 4 shows the relationship between mean free path and concentration of the reinforcement material. It is clear from the figure that the mean free path decreases with increasing of concentration. This is due to an increase in density of the shields with an increase in the concentration, of reinforcing materials where the distance traveled by the neutron inside the shield decreases.

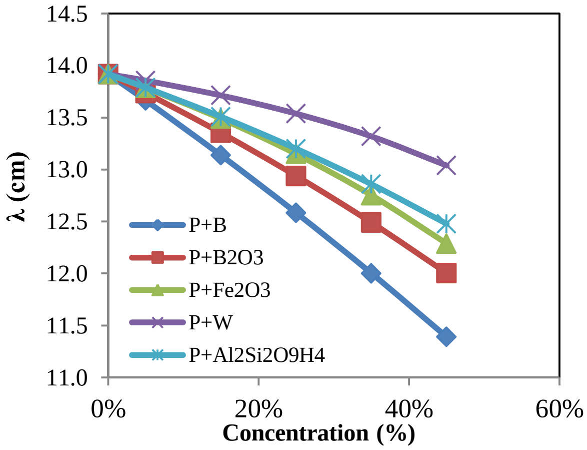

Figure 4: Mean free path as a function of concentration for all composite.

Table 7: Half value layer for Fast Neutron at different Concentration of reinforcement material.

Concentration	**P+B**	**P+W**	**P+B_2O_3**	**P+Fe_2O_3**	**PS+$Al_2Si_2O_9H_4$**
0%	9.645	9.645	9.645	9.645	9.645
5%	9.469	9.602	9.519	9.552	9.555
15%	9.103	9.502	9.253	9.347	9.361
25%	8.720	9.381	8.966	9.112	9.147
35%	8.317	9.230	8.655	8.838	8.911
45%	7.893	9.035	8.318	8.515	8.647

Table 8: Mean Free Path for Fast Neutron at different Concentration of reinforcement material.

Concentration	**P+B**	**P+W**	**P+B_2O_3**	**P+Fe_2O_3**	**PS+$Al_2Si_2O_9H_4$**
0%	13.918	13.918	13.918	13.918	13.918
5%	13.663	13.855	13.736	13.784	13.787
15%	13.136	13.712	13.352	13.488	13.507
25%	12.582	13.537	12.938	13.148	13.199
35%	12.001	13.318	12.489	12.753	12.858
45%	11.389	13.038	12.003	12.287	12.478

Conclusions

The results showed that the values of the attenuation coefficient of neutrons increased by increasing the concentration of the reinforcement materials. This is due to the increase of the cross sections of neutron radiation reactions with increasing concentration.

The selection of materials for fast neutron shielding requires knowledge of the macroscopic cross sections of the used materials. The results show that the total cross section depends on the density and chemical composition of the shielding materials. The shields containing boron in their composition are more effective for attenuation of fast neutrons.

This study shows that there is a great affinity between the values of neutron attenuation coefficients between iron trioxide and clay, which gives the possibility of replacing iron trioxide by clay because it is more abundant, cheaper and lighter.

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