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Comparative Study of Neutrons Shielding Coefficents in Different Doped Composites

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Abstract

In present article, three coefficients of the interaction of fast neutrons with matter are calculated and they are the fast neutrons Removal cross-sectional Σ_{NR}, the mean free path (mfp) and the half- value thickness layer ($x_{1/2}$) for many composites employing two empirical via Excell2012, for choosing the proper protective shields for the fast neutrons. In the light of present calculations , the proper shield in terms of having a protection property for removal cross section of fast neutrons is borate glass doped with 15 % of lutetium oxide Lu_2O_3 content whose values were 0.161606 cm^{-1} and 0.152979 cm^{-1} respectiely according to the equations of James and Zoller, and in the second place is the glass sample at 10 % of Lu_2O_3 content and the lowest value for the removal cross section of fast neutrons is pure polyethylene , which has a value (Σ_R)of 0.069091 cm^{-1} and 0.064655 cm^{-1} .According to the equations of James and Zoller. As far as the best material in terms of the lowest value of the mean free path and the Half value layer are concerned, it was **is** borate glass sample doped with 15 % of Lu_2O_3 content relative to the compounds studied in the current study. All the current results are reasonable agreement with the previous studies, except for the element hydrogen.

Keywords: Glass - free path – fast neutron -shield -Lutetium.

1- Introduction

There is an invisible enemy that constantly threatens the human beings animals ,operation of electronics that is nuclear ionizing radiation. From sea level to outer space, ionizing radiation is virtually everywhere. At sea level and even more at aircraft altitudes, atmospheric neutrons, originating from the interaction of cosmic rays with the atmosphere, constantly bombard electronic devices. Alpha, emitted by radioactive contaminants in the chip materials, are another major threat in terrestrial applications. In space, satellites and spacecraft can be hit by highly energetic particles such as protons, electrons, and heavier particles, due to radiation belts, solar activity, and galactic cosmic rays. Finally, man-made radiation in environments such as nuclear power plants or highenergy physics experiments can expose devices to extreme amounts of radiation.ionizing radiation [1]. Neutron shielding is a very complex issue ,this is due

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to the wide range of energies that neutron have .

In many studies [2-8], different composite materials materials are tested within neutron shielding capabilities. In the present investigation , calculations were made for a group of materials using the equations of James and Zoller through the use of software Excel 2012.The calculations included the neutron shielding coefficients such as the mean free path, the half value layer and the fast neutron removal cross section and compared these results with others.

2-Methods and materials

2-1 -Neutron removal cross sections Σ_R

The term ($\boldsymbol{\Sigma_R}$)is defined as the occurrence probability of a first collision which removes that neutron from its uncollided fast group .The dominant interaction mechanism for fast neutrons is elastic scattering[9]. Neutron has a complex resonance structure that changes with its energies. The neutron attenuation factors are further complicated by the amount of hydrogen material embadded into the shields of the fast neutrons via the slowing down property they are possess; therefore, the value of $\Sigma_R$is empirically calculated for each shield material as a coefficient of removal [10]. From the current study, several empirical equations have been applied for the purpose of calculating the mass removal cross section. Zoller equation [11 - 12], it is defined as:

$$\frac{\Sigma_R}{\rho}\left(\frac{cm^2}{g}\right)=\frac{0.19}{Z^{0.743}}\ldots for Z\leq 8 \qquad (1)$$

$$\frac{\Sigma_R}{\rho}\left(\frac{\mathrm{cm}^2}{\mathrm{g}}\right)=\frac{0.125}{\mathrm{Z}^{0.565}}\ldots\mathrm{for}\quad \ldots.\mathrm{Z}>8 \qquad (2)$$

Among the equations used for compounds and mixtures is the James Wood equation [13]

$$\frac{\Sigma_R}{\rho}\left(\frac{cm^2}{g}\right)=\frac{0.206}{(A\,Z)^{1/3}} \qquad (3)$$

For the above equations A, Z, ρ represent the density, the atomic and mass number of each of the elements constituting the composed material, with respect to the calculation of Σ_R, it can be calculated for a mixture of a number of elements according to the following equation [11]

$$\Sigma_R=\sum_i W_i\left(\frac{\Sigma_R}{\rho}\right)_i \qquad (4)$$

Where W_i , ρ , $\frac{\Sigma_R}{\rho}$ is the partial density in units of (*g/cm*$^{-3}$), the density and the mass neutron removal cross-sectional of the element (*i*), . The partial density of the compound element (*i*) this can be calculated as follows[13]:

$$W_i=(\rho)_{sam}w_i \qquad (5)$$

Here $(\rho)_{sam}$ is the density of the sample under study and the removal cross-sectional of the composite material containing (i) elements is defined by equation [11]:

$$\left(\frac{\Sigma_R}{\rho}cm2/g\right)_C=\sum_{i=1}^{n}w_i\left(\frac{\Sigma_R}{\rho}\right)_j \qquad (6)$$

Where $\left(\frac{\Sigma_R}{\rho}\right)_j$ stand for the mass neutron removal cross-sectional of element (*j*) .

2-2- Mean Free path ($\boldsymbol{mfp}$)

The"mean free path " idea stand for the mean distance traveled by a particle between two successive collisions inside a material .The mean free path mathematicaly is defined as[14].

$$mfp(cm)=\frac{1}{\Sigma_R} \qquad (7)$$

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This idea is of a great importance when making shielding calculations.

2-3 -Half Value Layer $x_{1/2}$

The half value - layer ($x_{1/2}$) fundamentally represent is the thickness of a homogeneous absorber that attenuates the narrow beam intensity I(0) to one-half (50 %)

of the original intensity.The value of ($x_{1/2}$) is an important property that determines whether a material sample acts adequately as a shielding material [15] .

$$x_{\frac{1}{2}}(cm) = \frac{0.693}{\Sigma} \qquad (8)$$

The concept of the value (HVL) is very useful when making rapid and approximate shielding calculations. For example, the value of a layer of thickness equal to unity of a material indicates that it reduces the radiation intensity to half of its original value, and two layers of half thickness reduce the intensity to a quarter of its original value and so on .

All the equations from (1) to (8) do not included any effect on the electrons present in each element for which the shielding properties are calculated, and this is in fact the result of the neutron being an uncharged particle and the electron being charged With a negative charge, the two particles do not interact with each other electromagnetically, as well as the large amount of the neutron mass compared to the mass of the electron, which is approximately 1840 times, which means that there is no significance interaction between them, even if that happens.

3- Results and discussion

Tables (1, 2 ,3and 4) and figures (1, 2 ,3and 4) represent the values of neutron removal cross-sectional area $\left(\frac{\Sigma_R}{\rho}\right)$ for pure poly ethyline and boronated polyethyline with 1% and 5.45% and 30% respectively obtained using the James equations J and Zoller's equation Z, which are resulted by application of the equations from (1) to (6) as econd best composite shield is 0.088503 and 0.081553 cm-1 according to james and Zoller equation as well as these compared values less than the values of the neutron removal cross section [16]. These values of Σ_R are depend largely on the molecular structure and density of the composed material. By noting these tables , that there is a good agreement for all components, except of hydrogen, and this effect may be regard to value for the optional arbitrary constant, and the special bases to which both the mass (A) and atomic (Z) numbers of element of a substance were exponential to the target material in the two equations used. It should be noted that the effect of light elements (with a low mass number) on the total values $\Sigma_R(cm^{-1})$ for the composite materials (despite its low density compared to other elements) most affecting than heavy elements specifically the element hydrogen, where the mass of the hydrogen nucleus is approximately one atomic unit and is approximately equivalent to the neutrons mass.

Therefore, when a neutron collides with the hydrogen nucleus, an elastic collision results in the elastic neutron scattering from the light elements. A large part of the kinetic energy of a neutron, as an average in a single scattering process. Specifically, for scattering from hydrogen, the average energy loss is half of the initial neutron energy, thus, the scattering of fast neutrons by hydrogen essentially acts as an effect absorption or removal reaction because the neutron, is removed from the energy region of the fast neutrons by a single scattering event [16]. Therefore, this becomes clear by substituting in the mass number of hydrogen A = 1 and using $\theta > \frac{\pi}{2}$ in the equation [18]:

$$\frac{E}{E_0} = \left[\frac{\cos\theta + (\cos^2\theta + A^2 - 1)^{\frac{1}{2}}}{(A+1)}\right]^2 \qquad (9)$$

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The scattering energy is always equal to zero, the neutron scatters with the hydrogen nucleus (proton) at angles from $\theta = 0$ to $\theta = \frac{\pi}{2}$ and from observing the tables mentioned, we note that the decrease in the percentage of hydrogen will lead to a decrease in the value of Σ_R and vice versa .With regard to polyethylene doped with boron by 5%, as shown in Table (3). We note that the boron that is added operates to increase the total density, and this is due to the large absorption cross-sectional value of the boron element, which is equal to (760 barn), this in turn works to absorb Gamma ray photons generated from the interactions of the neutron with hydrogen [9].

Table (1) Comparison of calculated and measured values [16] Fast neutron removal section for pure polyethylene ($\rho = 0.92$ g/cm^3)

Element	Partial Density ρ (g cm^{-3})	Σ_R/ρ (cm^2 g^{-1}) J	Σ_R/ρ (cm^2 g^{-1}) Z	Σ_R/ρ (cm^2 g^{-1}) Ref.[16]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[16]
H	0.132200	0.206000	0.190000	0.598000	0.027233	0.025118	0.079056
C	0.787800	0.053133	0.050187	0.050200	0.041858	0.039537	0.039548
Total					0.069091	0.064655	0.118603

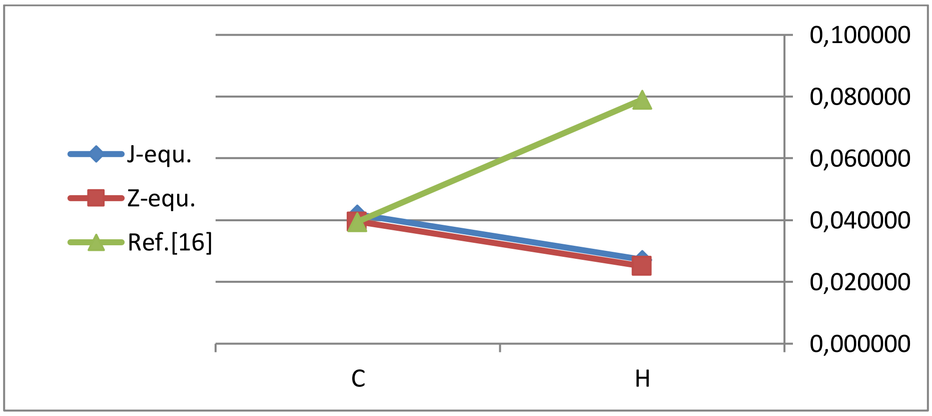

Figure (1) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [16] fast neutron removal section of pure polyethylene ($\rho = 0.92$ g / cm^3)

Table (2) Comparison of calculated and measured values [16] Fast neutron removal section for polyethylene doped by 1% boron ($\rho = 1.7$ g/cm^3)

Element	Partial Density ρ (g cm^{-3})	Σ_R/ρ (cm^2 g^{-1}) J	Σ_R/ρ (cm^2 g^{-1}) Z	Σ_R/ρ (cm^2 g^{-1}) Ref.[16]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[16]
H	0.099280	0.206000	0.190000	0.598000	0.020452	0.018863	0.059369
B	0.017000	0.057708	0.057467	0.057500	0.000981	0.000977	0.000978
C	0.306340	0.053133	0.050187	0.050200	0.016277	0.015374	0.015378
O	0.813110	0.044359	0.040528	0.040500	0.036069	0.032954	0.032931
Na	0.003230	0.035792	0.032250	0.034100	0.000116	0.000104	0.000110
Mg	0.002380	0.034397	0.030702	0.033300	0.000082	0.000073	0.000079
Al	0.423980	0.032303	0.029345	0.029300	0.013696	0.012442	0.012423
Si	0.004420	0.031226	0.028142	0.025200	0.000138	0.000124	0.000111
S	0.000340	0.028717	0.026096	0.027700	0.000010	0.000009	0.000009

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Ca	0.026010	0.024966	0.023005	0.024300	0.000649	0.000598	0.000632
Fe	0.000340	0.020660	0.019836	0.021400	0.000007	0.000007	0.000007
Sr	0.001700	0.015955	0.016008	0.016000	0.000027	0.000027	0.000027
Total Σ_R (cm^{-1})					0.088503	0.081553	0.122055

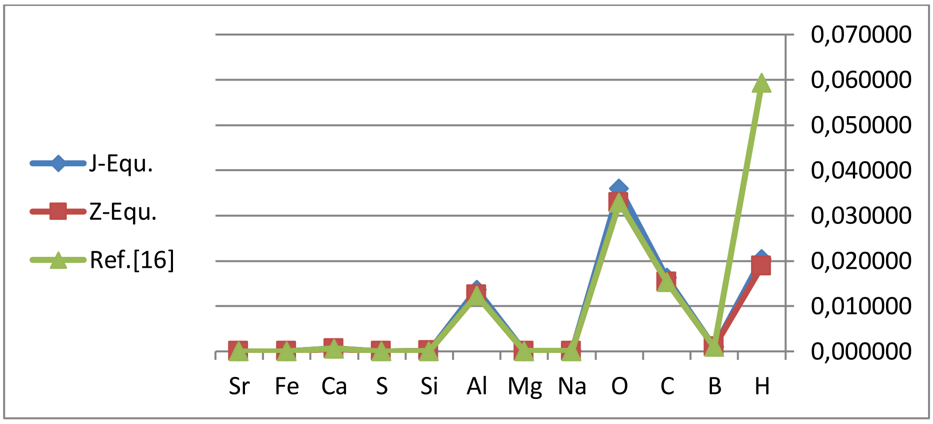

Figure (2) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [16] fast neutron removal section of polyethylene doped by 1% boron ($\rho = 1.7$ g / cm^3)

Table (3) Comparison of calculated and measured values [16] Fast neutron removal section for polyethylene doped by 5.45% boron ($\rho = 1.6$ g/cm^3)

Element	Partial Density ρ (g cm^{-3})	Σ_R /ρ (cm^2 g^{-1}) J	Σ_R /ρ (cm^2 g^{-1}) Z	Σ_R /ρ (cm^2 g^{-1}) Ref.[16]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[16]
H	0.091520	0.2060	0.190000	0.598000	0.018853	0.017389	0.054729
B	0.087200	0.05770	0.057467	0.057500	0.005032	0.005011	0.005014
C	0.415360	0.05313	0.050187	0.050200	0.022069	0.020845	0.020851
O	0.635040	0.04435	0.040528	0.040500	0.028170	0.025737	0.025719
Na	0.003680	0.03579	0.032250	0.034100	0.000132	0.000119	0.000125
Mg	0.012160	0.03439	0.030702	0.033300	0.000418	0.000373	0.000405
Al	0.190720	0.03230	0.029345	0.029300	0.006161	0.005597	0.005588
Si	0.021920	0.03122	0.028142	0.025200	0.000684	0.000617	0.000552
S	0.002080	0.02871	0.026096	0.027700	0.000060	0.000054	0.000058
Ca	0.133920	0.02496	0.023005	0.024300	0.003343	0.003081	0.003254
Fe	0.001440	0.02066	0.019836	0.021400	0.000030	0.000029	0.000031
Sr	0.008480	0.01595	0.016008	0.016000	0.000135	0.000136	0.000136
Total Σ_R (cm^{-1})					0.085088	0.078987	0.116462

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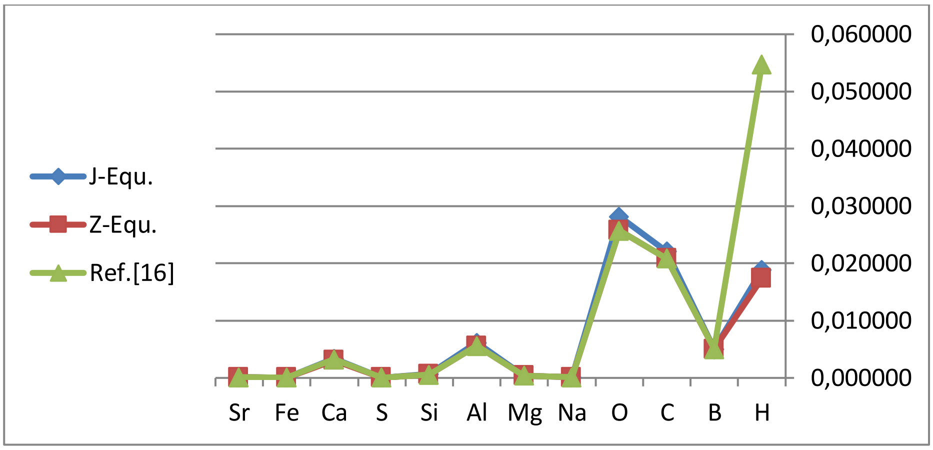

Figure (3) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [16] fast neutron removal section of polyethylene doped by 5.45% boron (ρ = 1.6 g / cm^3) .

Table (4) Comparison of calculated and measured values [16] Fast neutron removal section for polyethylene doped by 30% boron (ρ = 1.19 g/cm^3)

Element	Partial Density ρ (g cm^{-3})	Σ_R /ρ (cm^2 g^{-1}) J	Σ_R /ρ (cm^2 g^{-1}) Z	Σ_R /ρ (cm^2 g^{-1}) Ref.[16]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[16]
H	0.104244	0.206000	0.190000	0.598000	0.021474	0.019806	0.062338
B	0.357000	0.057708	0.057467	0.057500	0.020602	0.020516	0.020528
C	0.721140	0.053133	0.050187	0.050200	0.038316	0.036192	0.036201
O	0.000238	0.044359	0.040528	0.040500	0.000011	0.000010	0.000010
Si	0.000476	0.031226	0.028142	0.025200	0.000015	0.000013	0.000012
Fe	0.000476	0.015955	0.019836	0.021400	0.000008	0.000009	0.000010
Total Σ_R (cm^{-1})					0.080425	0.076523	0.119098

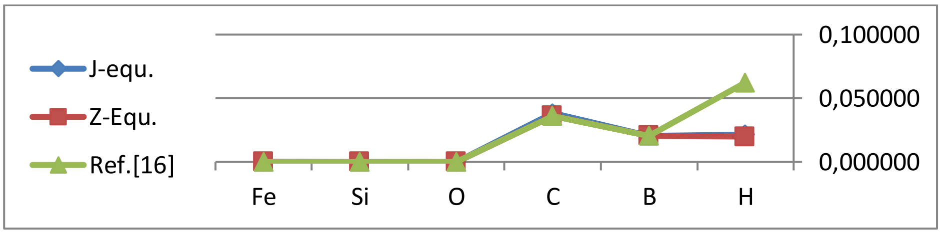

Figure (4) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [16] fast neutron removal section of polyethylene supported by 30% boron (ρ = 1.19 g / cm^3).

The calculations borate Glass doped with Lu_2O_3

$$xLu_2O_3Li_2O(80-x)B_2O_3$$

Where x=5,10,15% of tables (5,6 and 7) and figures (5,6 and 7) represent the neutron removal cross-sectional values ($\frac{\Sigma_R}{\rho}$) for borate glass systems. The values of Σ_R for of glass smple doped with 15% of Lu_2O_3 content are greater than that other composites material and by applying the equation [19-20]:

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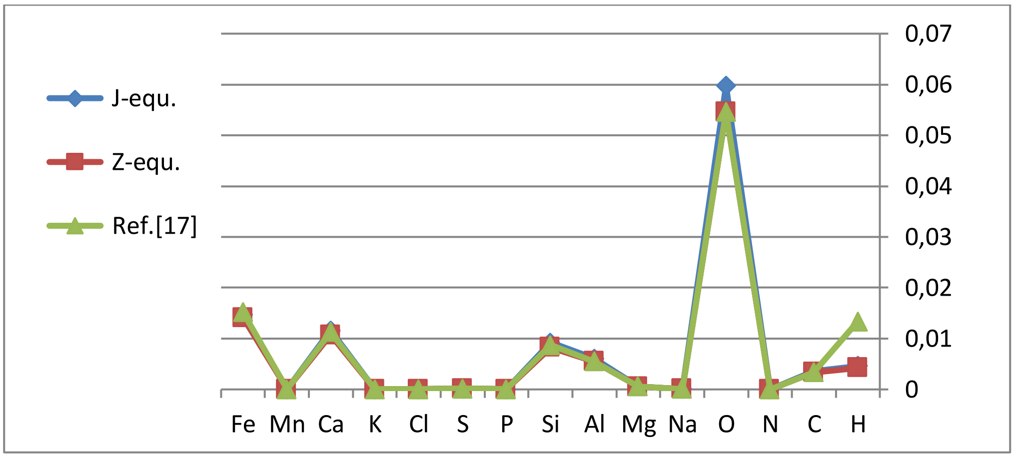
$$Error = \left|\frac{standard - cal.}{cal}\right| \times 100\% \qquad (10)$$

With error 2.85% for James equation and 2.63% for Zoller equation and this effect can be explained as a result of the increase in mass density ($3.44 g/cm^3$) due to the addition of the 15% fraction weight of some Lu_2O_3 of to glass , this make the separation distances between atoms closer and thus increase the property of attenuation through the increasing number of frequented interactions represented by elastic collisions and inelastic collisions of fast neutrons per unit time and per unit distance within glass .



Fig(5) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [20] for the fast neutron removal section of glass smple at 5% of Lu_2O_3 content.

Table (5) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [20] for the fast neutron removal section of glass smple at 5 % of Lu_2O_3 content.

Element	Partial Density ρ (g cm^{-3})	Σ_R /ρ (cm^2 g^{-1}) J	Σ_R /ρ (cm^2 g^{-1}) Z	Σ_R /ρ (cm^2 g^{-1}) Ref.[20]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[21]
Li	0.4	0.07796402	0.083995	0.080000	0.031186	0.033598	0.033000
B	0.63	0.057708415	0.057467	0.060000	0.036356	0.036204	0.036000
O	1.57	0.044359377	0.040528	0.040000	0.069644	0.063629	0.063000
Lu	0.12	0.010517631	0.011245	0.010000	0.001262	0.001349	0.001000
Total Σ_R (cm^{-1})					0.138448	0.133432	0.133000

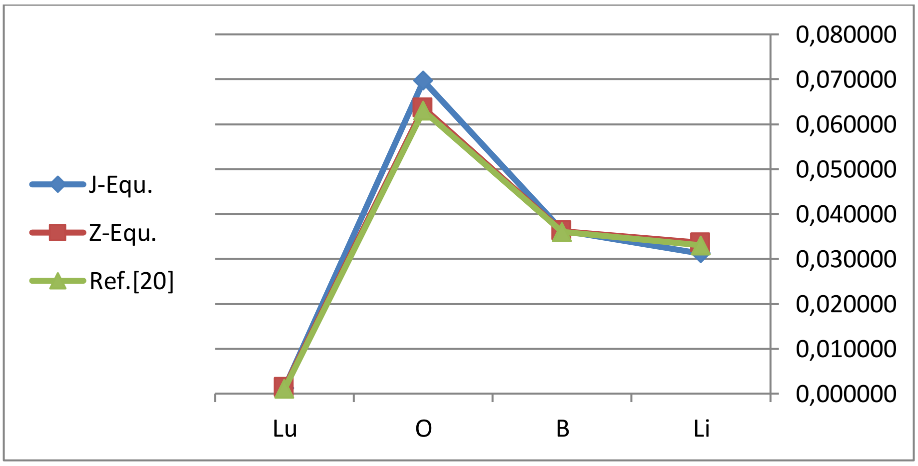


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Figure (6) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [21] for the fast neutron removal section of glass smple at 5 % of Lu_2O_3 content

Table (6) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [21] for the fast neutron removal section of glass smple at 10 % of Lu_2O_3 content

Element	Partial Density ρ (g cm^{-3})	Σ_R/ρ (cm^2 g^{-1}) J	Σ_R/ρ (cm^2 g^{-1}) Z	Σ_R/ρ (cm^2 g^{-1}) Ref.[20]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[21]
Li	0.47	0.077964	0.083995	0.080000	0.036643	0.039478	0.039000
B	0.69	0.057708	0.057467	0.060000	0.039819	0.039652	0.039000
O	1.73	0.044359	0.040528	0.040000	0.076742	0.070114	0.069000
Lu	0.28	0.010518	0.011245	0.010000	0.002945	0.003149	0.003000
Total Σ_R (cm^{-1})					0.156149	0.149244	0.150000

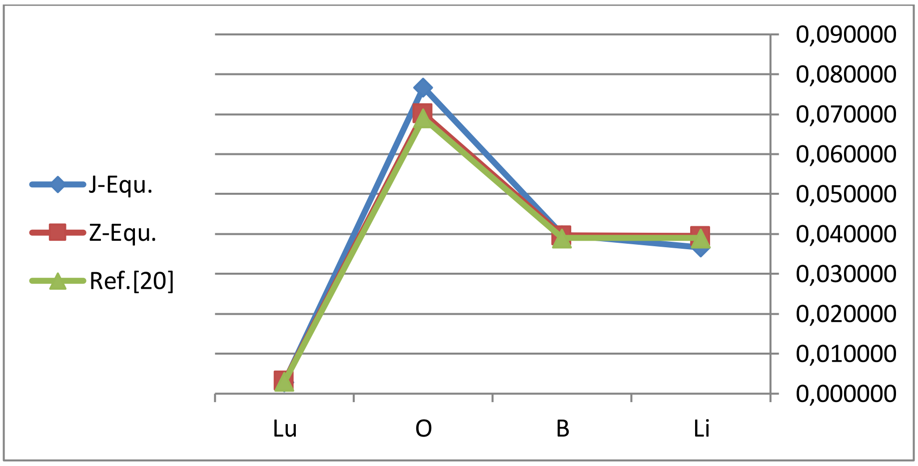

Figure (6) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [21] for the fast neutron removal section of glass smple at 10 % of Lu_2O_3 content

Table (7) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [21] for the fast neutron removal section of glass smple at 15 % of Lu_2O_3 content

Element	Partial Density ρ (g cm^{-3})	Σ_R/ρ (cm^2 g^{-1}) J	Σ_R/ρ (cm^2 g^{-1}) Z	Σ_R/ρ (cm^2 g^{-1}) Ref.[20]	Σ_R (cm^{-1}) J	Σ_R (cm^{-1}) Z	Σ_R (cm^{-1}) Ref.[21]
Li	0.5	0.077964	0.083995	0.080000	0.038982	0.041997	0.042000
B	0.69	0.057708	0.057467	0.060000	0.039819	0.039652	0.039000
O	1.76	0.044359	0.040528	0.040000	0.078073	0.071330	0.071000
Lu	0.45	0.010518	0.011245	0.010000	0.004733	0.005060	0.005000
Total Σ_R (cm^{-1})					0.161606	0.152979	0.157000

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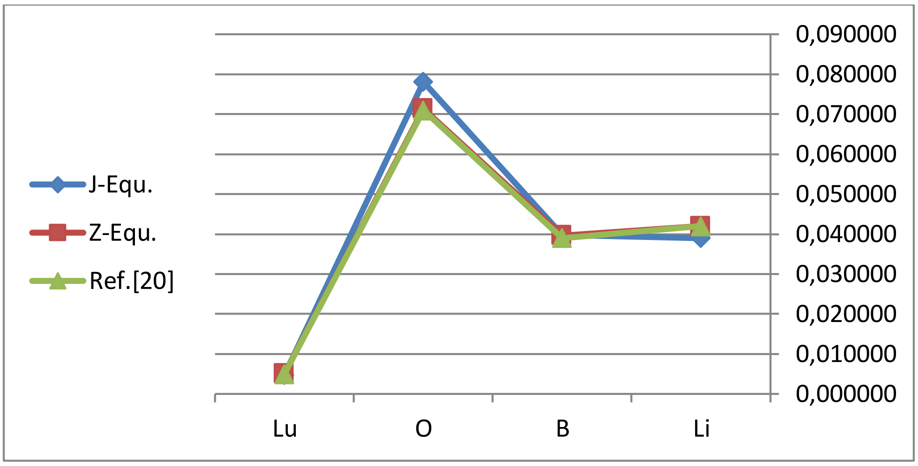

Figure (7) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured [21] for the fast neutron removal section of glass smple at 15 % of Lu_2O_3 content

By application eq.(7) we get the values of free path (Table 8), we find that the optimum value of the attenuation path for fast neutrons by using the James Wood and Zoller equations was for the glass sample at 15 % of Lu_2O_3 content, which amounts to (6.187879367 cm and 6.536828889 cm). Then the glass sample at 10% of Lu_2O_3 content, which according to the results obtained by using James and Zoller emperical equations:(6.404157922 cm and 6.700451078 cm). These results indicate that the best medium for attenuate the neutral radiation of fast neutrons is the mixture of Lu_2O_3.

In other words, the fast neutrons that entered

$$xLu_2O_3Li_2O(80-x)B_2O_3$$

into it is subjected to the least number of elastic and inelastic collisions per unit distance within the depth of the material until it is removed from the neutron beam. We note (table 8)that the worst value of the attenuation distance of thermal neutrons is for the pure polyethylene, which amounted to (14.473665 cm and 15.4667 cm) .

Table (8) Comparison of the values calculated by the James Wood J and Zoller Z equations with the measured values of a number of previous studies of the free path rate of fast neutrons in several Hydrogenous composite materials.

Composite material	λ (cm) J-equation present study	λ (cm) Z-equation present study	λ (cm) calculated By
pure polyethylene	14.473665	15.4667	8.431489 Ref.[16]
polyethylene doped by 1% boron	11.299052	12.26196	8.193027 Ref.[16]
polyethylene doped by 5.45% boron	11.752538	12.660312	8.58649 Ref.[16]
polyethylene doped by 30% boron	12.4339446	13.067966	8.396446 Ref.[16]
Borate glass	7.222915597	7.494481917	7.518796992

with 5 % Of Lu_2O_3			Ref.[20]
Borate glass with 10 % Of Lu_2O_3	6.404157922	6.700451078	6.666666667 Ref.[20]
Borate glass with 15 % Of Lu_2O_3	6.187879367	6.536828889	6.369426752 Ref.[20]

By applying eq.(8) we obtain the best value of the half-thick layer(HVL) required (Table 9) to attenuate the fast neutrons to half intial value is the botate glass sample at 15 % of Lu_2O_3 content material, which reached (4.288200401 cm and 4.53002242 cm) according to the results of the James Wood and Zoller equations respectively, it was found that the glass sample at 10% of Lu_2O_3 content is the second largest HVL required to attenuate thermal neutrons, and its values was (4.43808144 cm and 4.643412597 cm) according to the results of the James Wood and Zoller equations. It is noted from Table (8) that the lowest value is for the half- value layer needed to attenuate the fast neutron beam was that of pure polyethylene (10.03223 cm and 10.7207 cm), and in the second order was polyethylene reinforced by 30% boron, where its values were (8.6185536 cm and 9.058025 cm) according to the results of the James Wood and Zoller equations, it is noted from the tables mentioned that the values of $(x_{1/2})$ decrease as the density of the composed material increases, and the reason is due to the increase in the vicinity of the interfacial distances between atoms and molecules, which works to further hinder the progress of neutrons into the depth of the material In other words, the number of collisions per unit time increases per unit distance within the shielding material.

Table (10) Comparison of the calculated and measured values for the values of the thickness of the half layer $x_{1/2}$ (cm) fast neutrons for a number of substances.

Composite	$x_{1/2}$ (cm) J-present study	$x_{1/2}$ (cm) Z-present study	$x_{1/2}$ (cm) calculated By
pure polyethylene	10.03223	10.7207	Ref.[16] 5.8442634
polyethylene supported by 1% boron	7.831906	8.499346	Ref.[16] 5.678974
polyethylene supported by 5.45% boron	8.146238	8.77546	Ref.[16] 5.95170
polyethylene supported by 30% boron	8.6185536	9.058025	Ref.[16] 5.819973
5 % Borate glass with Of Lu_2O_3	5.005480509	5.193675968	Ref.[20] 5.210526316
Borate glass	4.43808144	4.643412597	Ref.[20]

with 10 % Of Lu_2O_3			4.62
15 % Borate glass with Of Lu_2O_3	4.288200401	4.53002242	Ref.[20] 4.414012739

4 - Conclusions

we found that the most suitable material according to having a shielding property for fast neutrons as a removal cross-sectional is is glass sample doped with 15% of Lu_2O_3 content whose values were 0.161606 cm^{-1} and 0.152979 cm^{-1} ,according to James equations and Zoller. Secondly, was the is the borate glass sample doped with 10% of Lu_2O_3 content while the minimum value for the shielding of fast neutrons was pure polyethylene , which has a value (Σ_R)of 0.069091 cm^{-1} and 0.064655 cm^{-1} according to the James and Zoller equations. The current study also showed that the most suitable shielding elements that works best to remove fast neutrons when interacting is hydrogen(atomic mass of hydrogen equals to that of neutron and Lu_2O_3 (due to their high molecular weight) .The values of $\Sigma_R(cm^{-1})$ are a function of the chemical composition and the density of the sample.The selection of any material as a protective shield from thermal neutrons depends mainly on the values of the macroscopic cross-sectional $\Sigma_R(cm^{-1})$, which in turn is based on the values of the fraction by weight of the elements included in its composition.The greatest value of the cross-sectional for removing fast neutrons $\Sigma_R(cm^{-1})$ for any composite material is an indication that it contains the largest percentage by weight of light elements such as hydrogen.

5 – References

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