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Elastic Rubber Composites as Shield against Photons and Neutrons

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ABSTRACT

A synthetic, ethylene-propylene-diene terpolymer monomer (EPDM) rubber reinforced with carbon–black (N-220) as a filler with the addition of different concentrations of lead powder (0–500 phr), was developed to be used as a radiation shielding against γ - rays. Experimental studies on the influence of γ-radiation on the target samples were carried out using ^{137}CS (E^{γ} = 0.662 Mev) and (^{60}Co with energies of 1.172 Mev and 1.332 Mev). The attenuation coefficient and HVL were improved by two ways; one way by increasing the concentration of lead powder at constant thickness and the other by increasing the thickness of the composite samples at a constant concentration of lead powder. A high attenuation coefficient and HVL was obtained for 400phr lead (μ=0.0852 and 0.141 cm^{-1} for Eγ = 0.662, and 1.172 Mev respectively). Good results were also obtained for HVL when using 400phr lead (HVL= 8.137, 4.915, and 5.627 cm for Eγ = 0.662, 1.172, and 1.332 Mev respectively). For testing the moderating fast neutron emitted from ^{239}Pu–^{9}Be, samples containing 100, 200, and 300 phr lead and 25 phr borax were used. The results showed good enhancement/improvement in the values of the total macroscopic cross section. As a result of using the X.com program, it was found that the values of the linear and mass attenuation coefficients were in a good agreement with the experimentation values for uniform and collimated beams. However, this could not be confirmed for heterogeneous beams.

1. INTRODUCTION

In our world where more than 3000 nuclear power plants have been established, the use of radiation in various shapes for different purposes and the growing threat of nuclear terrorism put all organisms at a biological risk [1]. Ionizing radiation has adverse effects on human health and life, as well as on the surrounding environment [2]. Over-exposure to γ-rays may affect radiation users and the public in several ways such as nausea, vomiting, fatigue, diarrhea, headache, skin burns, and death [3].

To reduce the risk of excessive γ-rays exposure, high-quality γ-rays shielding materials are required. Materials that contain a large atomic number in addition to high density are considered among the most recommended candidate materials to achieve this purpose due to their high probability of interactions and large energy transfer with γ-rays. Lead-containing materials are the most common materials used in the field of radiation protection [4]. It is reported that there are different functional materials that are applied for radiation shielding applications. Polymer composites represent one type of these functional materials and many

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researchers are interested in such a branch of material science [5, 6]. The most dangerous and difficult to shield are neutrons and γ-rays due to their high penetrability and energy [7]. Ethylene-propylene-diene terpolymer monomer (EPDM) is one of the general-purpose synthetic rubber, and it is among the fastest-growing elastomer in applications in recent years [8].

Lead is a highly toxic material, which makes its use difficult and dangerous. Heavy concrete is another promising material for radiation protection [9, 10]. However, moisture variation in concretes makes it difficult to predict radiation protection [11]. Much research is devoted to the development of glass-based radiation shielding materials [12-18]. The degradation of EPDM by γ- radiation has been extensively studied. EPDM has radiation resistance up to 2100 kGy [19].

Neutron sources are very often used in industry, the neutrons have a relatively higher radio-biological effect (RBE) and dose weighting factor, compared to other types of ionizing radiation [20]. EPDM contains ethylene and propylene, containing a high amount of hydrogen, so it can be used as neutron shielding material with the addition of boron compounds. It was found that 50 phr of paraffin wax can moderate fast neutrons at a small distance to reduce its energy. Borax is efficient in either absorbing or slowing down fast neutrons into thermal neutrons.

Designing shielding systems for neutron absorption is one of the most challenging tasks. Most materials will readily absorb thermal neutrons, boron elements absorb thermal neutrons with the emission of charged particles and gamma rays of low energy, $E\gamma = 0.48$MeV but for slow neutrons, in most materials ,the radioactive capture reaction or (n,γ) reaction occurs and produces one or more (5 to 10MeV) secondary γ-photons. These γ-photons represent a source that requires a heat absorber and further shielding. Therefore, it is preferable not to use more than 25phr of borax to avoid increasing the number of photons produced [21]. Boron is nearly unique in its ability to absorb thermal neutrons, producing γ-rays. For this reason, boron and boron compounds are often used in concrete and rubber to increase the probability of neutron capture without producing secondary capture γ-rays of high energy [22].

The aim of the present study is devoted to preparing ethylene-propylene-diene terpolymer (EPDM) rubber composite reinforced with carbon black (CB- N 220), loading with lead powder of different concentrations (0 to 500 phr), to be used as a radiation shielding against γ-rays. To use the main composite as a fast neutron moderating material, borax (powder) was added with different concentrations (0 to 100 phr). A fixed concentration of borax (25phr) with different lead concentrations (100, 200 and 300phr) was prepared to investigate the effect of lead on fast neutron (emitted from ^{239}Pu – ^{9}Be source) moderation.

2. EXPERIMENTAL WORK

2.1. Sample Preparation

EPDM rubber composites used in the current study were prepared using the master-batch technique. In this technique all fixed ingredients are mixed with the raw rubber material, the master-batch is divided into equal parts, and these parts are impregnated with different loadings of lead powder 25, 50, 100, 200, 400, and 500 phr to study its impact on the shielding of γ- rays. Moreover, A second group was prepared by adding a fixed phr of borax (25phr) with different percentages of lead (100, 200, and 300 phr). All fixed ingredients and lead powder (variable) and/or borax powder (25 phr) were mixed by a compressive method under a temperature of 153 ºC and pressure 4Mpa, the prepared mix was compressed in the form of a circular disk with a diameter of 10 cm and 4 mm thick.

2.2. Exposure to γ - Sources

An experimental study of the effect of γ – radiation on the studied samples was carried out using the following radioisotopes sources:

a- Isotope source of γ-radiation ^{137}Cs (E γ = 0.662 Mev)

b- Isotope source of γ-radiation ^{60}Co, considering two energy peaks of ^{60}co with energies of 1.172 Mev and 1.332 Mev).

The measurements were carried out using two conditions:

(1) mono-energetic beam of γ rays (a narrow geometry without considering the scattered radiation) where the two sources of γ rays (^{137}Cs and ^{60}Co) were used separately. The

scheme of the experiment in the conditions of a narrow beam is shown in Fig.(1).

(2) The two sources of γ rays are used together i.e the beam of γ rays is not mono energetic. The detection of γ - radiation was made up by Scintillation detector. The NaI crystal has the dimensions 5" × 5" with energy resolution 8%.

The shielding material used in the present work was a synthetic, ethylene- propylene-diene terpolymer (EPDM) rubber reinforced with carbon–black (N-220) as a filler, cured by sulfur with the addition of zinc oxide and steric acid as activator and Z.K to accelerate the vulcanization process, (Table 1). Table (2) shows the ingredients for samples with different phr of lead without borax, while Table (3) shows the ingredients of the samples containing 25 phr of borax and different phr of lead powder.

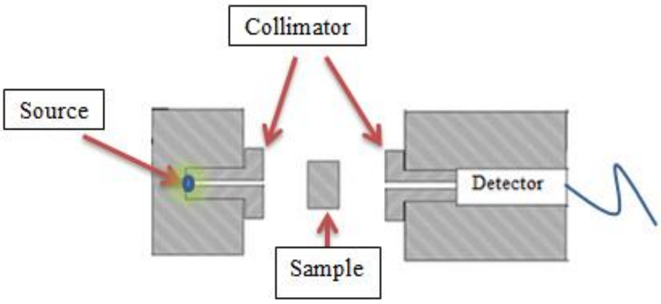

Fig. (1): Schematic of experiment in the geometry of a "narrow" beam of γ-radiation

The two types of γ- ray sources used in the current work are ^{60}Co and ^{137}Cs. Cobalt emits two gamma photons with energies of 1.173 and 1.332 MeV respectively, and it has a half lifetime of 5.27 years, while Cesium emits only one gamma photon with an energy of 0.66 MeV, and it has a half lifetime of 30.719 years.

Table (1): The ingredients of the EPDM rubber composite samples

Material	Role	Amount (phr)
EPDM	Rubber base	100 phr
carbon – black (N – 220)	Reinforcement (filler)	50 phr
Paraffin Oil	Softener (plastizer)	50 phr
Steric acid	Activator	2 phr
ZnO	accelerator	50 phr
Z.K	accelerator	3 phr
Sulfur	Curing agent	3 phr
Series (1)	Radiation shielding	Lead powder: Variable (0,25,50,75,100,200,300,400 , 500)
Series (2)	Neutron moderation	Variable: Lead powder (100 , 200 , 300) borax (25phr)

Table (2): The ingredients of the EPDM rubber composite with zero borax and various lead powder concentration

	EPDM (borax, lead)								
Ingredients phr	(0,0)	(0,25)	(0,50)	(0,75)	(0,100)	(0,200)	(0,300)	(0,400)	(0,500)
EPDM	100	100	100	100	100	100	100	100	100
Stearic Acid	2	2	2	2	2	2	2	2	2
Carbon black N220	50	50	50	50	50	50	50	50	50
Processing oil (paraffin oil)	50	50	50	50	50	50	50	50	50
Zinc oxide	5	5	5	5	5	5	5	5	5
Z.k	3	3	3	3	3	3	3	3	3
Sulfur	3	3	3	3	3	3	3	3	3
Lead powder	0	25	50	75	100	200	300	400	500
Borax	0	0	0	0	0	0	0	0	0

Table (3): Ingredient of the sample with 25phr borax and varies lead powder (100, 200, 300 phr)

	EPDM(borax, Lead)		
Ingredients Phr	(25, 100)	(25, 200)	(25, 300)
EPDM	100	100	100
Stearic Acid	2	2	2
Carbon black N 220	50	50	50
Paraffin oil	50	50	50
Zink oxide	5	5	5
Z.k	3	3	3
Sulfur	3	3	3
Lead powder	100	200	300
Borax	25	25	25

The current research consists of three practical parts:

(1) The first part focuses on theoretical and experimental calculations of linear attenuation coefficients and mass attenuation coefficients using XCOM for EPDM rubber composite with 25, 50, 75, and 100 phr lead as shielding materials.

(2) In the second part, the attenuations of γ-radiation for the prepared samples (EPDM/ 0, 25, 50, 75, 100, 200, 400 and 500 phr lead) at different thicknesses (0.5 to 4 cm) were examined using γ-rays were the two sources of γ rays are used together. In this case, the linear attenuation coefficient and half value thickness were calculated experimentally (without XCOM), because the beam and γ rays is not mono-energetic with high scattered condition. Experimental studies were performed for the composite samples for the three energies emitted from ^{137}Cs, ^{60}Co.

(3) In the third part, the effects of borax and lead on the moderation of the fast neutron were investigated.

2.3. Fast Neutron Source

^{239}Pu - ^{9}Be was used as a Fast Neutron Source (FNS), at the Developing Nuclear Techniques Lab, Nuclear Research Center, Egyptian Atomic Energy Authority.

A 5 Ci PuBe source and neutron–gamma spectrometer with a detector of stilbene scintillator (40 × 40 mm^2) were used to measure the transmitted spectra of the fast neutron and the total γ-rays transmitted from EPDM rubber composite.

The total γ-ray flux contains the primary γ-rays emitted from the source, and secondary γ-rays resulting from the inelastic scattering of fast neutrons besides the radioactive capture of slow neutrons. The radiation source is installed in a lead collimator, with an opening diameter of 10 mm, to produce a narrow fine beam to be convenient for measurement processes. Moreover, the detector was placed 400 mm away from the radiation source to achieve an appropriate count rate for the detector.

3. THEORETICAL ASPECTS

When γ-rays pass through the matter (see Figure (2)), they undergo attenuation primarily by Compton, photoelectric, and pair production interactions. The relation between the original intensity of the beam I$_o$ and the intensity transmitted through an absorber of thickness t is given by:

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

μ: is the linear attenuation coefficient for the absorbing material (cm^{-1})

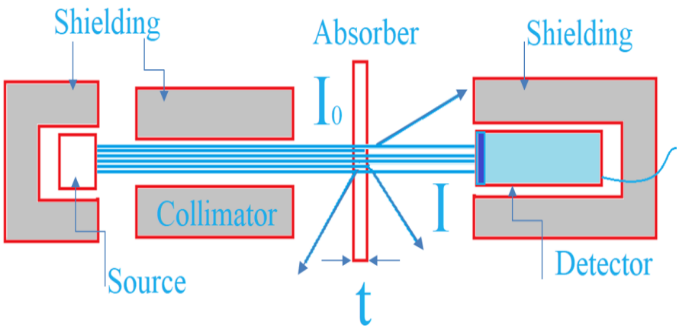

Fig. (2): The effect of absorber (shielding material) of thickness t on the attenuation of γ - rays

The linear attenuation coefficient (μ) depends on the absorber density (ρ) gm/cm^3 which can be variable; therefore it is a common practice to use the mass attenuation coefficient [23, 24]:

$$\mu_m = \frac{\mu}{\rho} \quad cm^2 gm^{-1} \tag{2}$$

The half-value layer (*HVL*) of the absorbing material is defined as that thickness $x_{1/2}$ which will decrease the initial intensity by half.

$$I_{HVL} = \frac{I_0}{2} \tag{3}$$

$$X_{1/2} = \frac{\ln 2}{\mu} \tag{4}$$

The Buildup Factor is a correction factor used to account for the observed increase in irradiative transmission through shielding material due to the scattered radiation. Buildup factors are dependent on the energy of the primary radiation, the composition of the shielding material, and the thickness of the shielding material.

$$\frac{I}{I_0} = B(t, E_\gamma)\exp(-\mu t) \tag{5}$$

It should be taken into account that both the attenuation coefficient and the *HVL* of rubber composite shielding material are functions of γ-photons energy. The degree of attenuation of γ-rays depends on the number of atoms per unit volume – the shield thickness and photon energy, in other words, on macroscopic cross-sections and material density [25-27].

To tackle the attenuation of neutrons inside any medium is a very complicated problem because there are many factors that must be considered to study this attenuation, e.g., the neutron source geometry, the energy spectrum of the emitted neutrons, the changes in the neutron energy inside the medium, the elemental constituents of the medium, etc. To simplify the problem in this work the attenuation of neutrons was studied by considering a neutron beam passes through a bulk of matter, the intensity in the beam will decrease gradually due to nuclear reactions that remove neutrons from the beam. For fast neutrons, the predominant reactions are the scattering, besides some reactions such as (n, p), (n, α), or (n, 2n) are possible. For slow or thermal neutrons, the primary cause of their removal is the (n, γ) reaction. The attenuation law is given by equation (6)

$$I = I_0\, exp - \Sigma_t x = I_0 \exp(-N_0 x) \tag{6}$$

Where Σ_t is total macroscopic cross-section and related to the microscopic cross section by the following relation:

$$\Sigma_t = n\,\sigma_t = \sum_{i=1}^{n} N_i\,\sigma_i = N_1\,\sigma_1 + N_2\,\sigma_2 + \cdots + N_n\,\sigma_n \tag{7}$$

This equation is due as most materials are composed of several elements, and because most elements are composed of several isotopes.

The probability of a particular reaction occurring between a neutron and a nucleus is called the microscopic cross-section. This cross-section will vary with the energy of the neutron. The macroscopic cross-section is the probability of a given reaction occurring per unit travel of the neutron, i.e.

$$\Sigma\, macroscopic\ neutron\ cross - section = \sum_{i=1}^{n} Microscopic\ neutron\ cross - section\ (cm^2) \times atomic\ density\ \left(\frac{atoms}{cm^3}\right)$$

The macroscopic cross-sections (Σ) represent the effective target area that is presented by all the nuclei contained in 1 cm^3 of the material (1/cm). The inverse of the macroscopic cross-section (cm^{-1}) is the mean free path (the average distance traveled by a neutron before interaction).

$$\lambda = \frac{1}{\Sigma} \tag{8}$$

4. RESULTS AND DISCUSSION

4-1 γ rays Attenuation Coefficients

Table (5): The theoretical (XCOM program) and experimental values of the linear attenuation coefficient and mass attenuation coefficient for EPDM/lead composites (two sources separately)

EPDM/25 phr lead

Energy	cps (free)	cps (with sample)	linear attenuation cm^{-1}	mass attenuation (exp.)	mass attenuation XCOM cm^2/g	Deviation
0.66	198.2	191.5	0.0860	0.0847	0.0858	1.3001
1.172	38.05	37.1	0.0632	0.0623	0.0633	1.6143
1.332	34.98	34.16	0.0593	0.0584	0.0591	1.2036

EPDM/50 phr lead

Energy	cps (free)	cps (with sample)	linear attenuation cm^{-1}	mass attenuation (exp.)	mass attenuation XCOM cm^2/g	deviation
0.66	198.2	190.4	0.10037	0.0859	0.0858	-0.0415
1.172	38.05	36.95	0.07334	0.0627	0.0633	0.8992
1.332	34.98	34.01	0.07030	0.0601	0.0591	-1.6837

75 phr lead

Energy	cps (free)	cps (with sample)	linear attenuation cm^{-1}	mass attenuation (exp.)	mass attenuation XCOM cm^2/g	deviation
0.66	198.2	189.7	0.10958	0.0861	0.0858	-0.2607
1.172	38.05	36.83	0.0815	0.0640	0.0633	-1.0600
1.332	34.98	33.94	0.0755	0.0593	0.0591	-0.1821

EPDM/100 phr lead

Energy	cps (free)	cps (with sample)	linear attenuation cm^{-1}	mass attenuation (exp.)	mass attenuation XCOM cm^2/g	deviation
0.66	198.2	188.97	0.1192	0.0852	0.0858	0.7717
1.172	38.05	36.71	0.0896	0.0640	0.0633	-1.1394
1.332	34.98	33.85	0.0821	0.0586	0.0591	0.8483

N.B: XCOM is a computer program and data base which can be used to calculate photon cross-sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, in any element, compound or mixture, at energies from 1 keV to 100 GeV.

The theoretical calculated values using X.COM program give a good agreement with the experimental values.

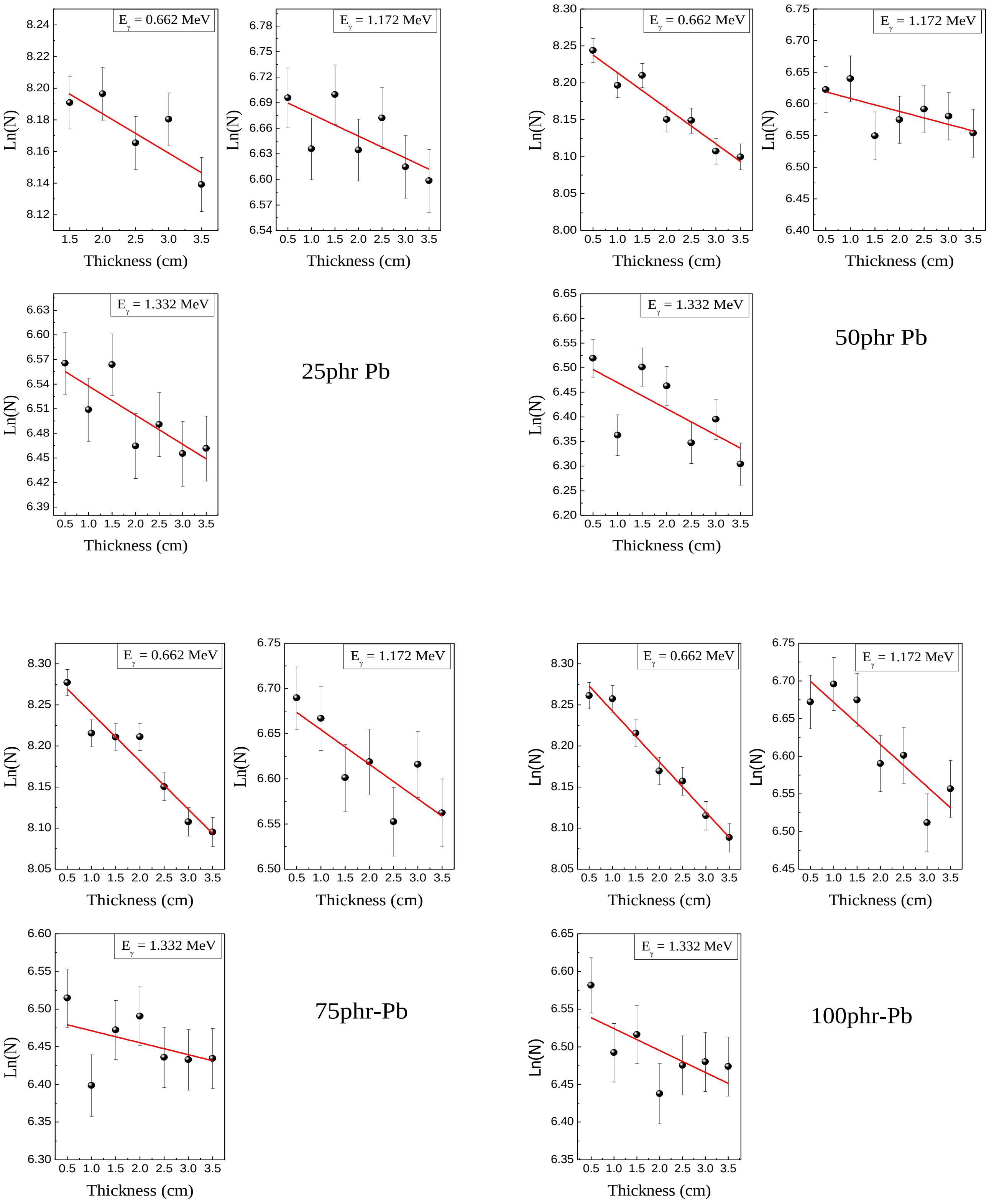

Fig. (3): The attenuation curve (Ln(N)vs. thickness) for the EPDM rubber composite containing 25, 50, 75, and 100 phr lead, for Eγ = 0.660, 1.172, and 1.332 Mev

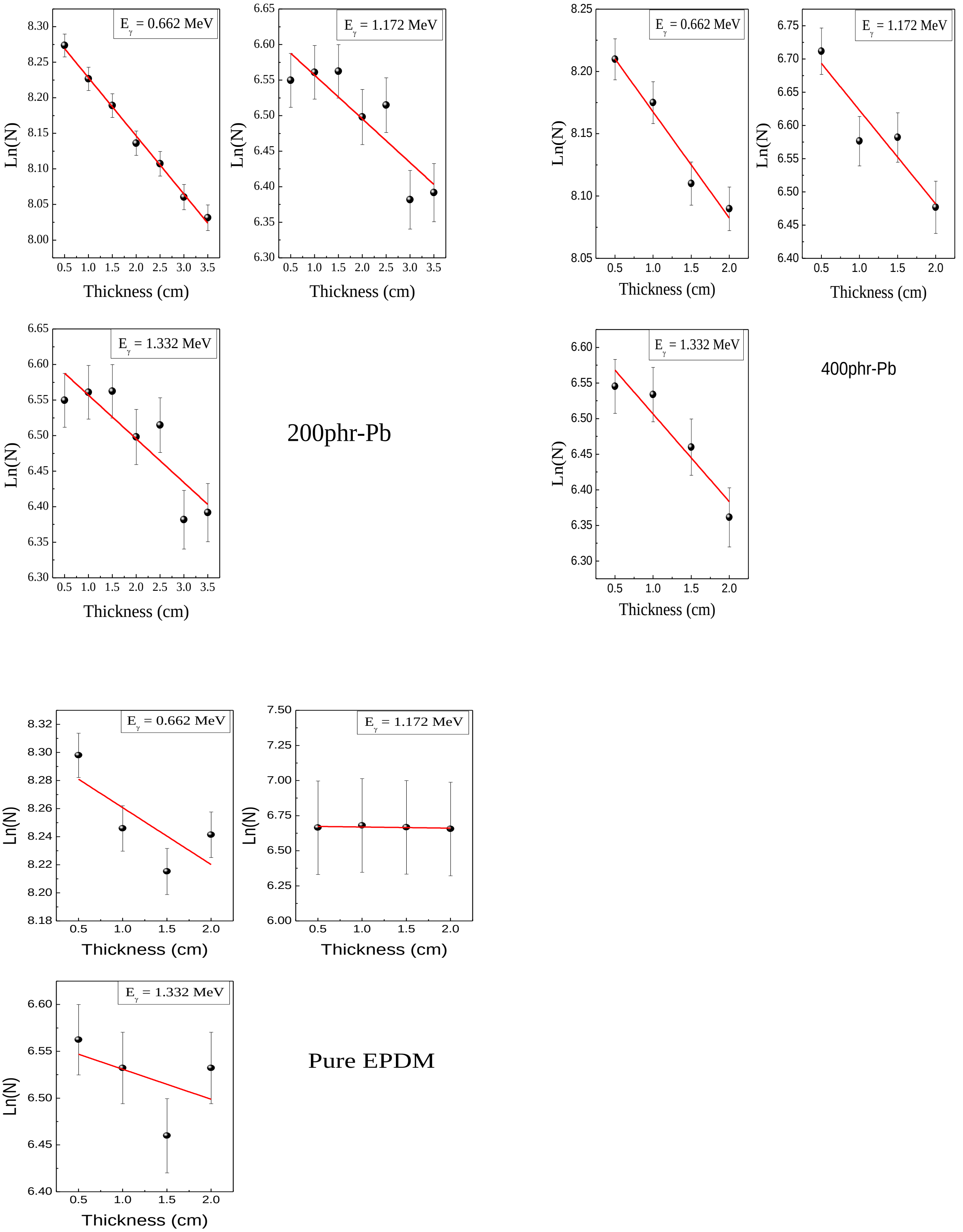

Fig. (4): The attenuation curve (Ln(N) vs. thickness) for the EPDM rubber composite containing, 200, 400 ,and 0 phr lead, for Eγ = 0.660, 1.172, and 1.332 Mev

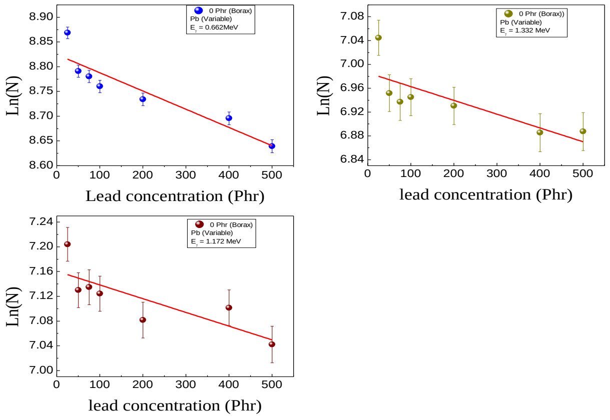

Fig. (5): γ-rays attenuation (Ln N) versus lead concentration (25, 50, 75, 100, 200, 400, and 500 phr) for Eγ = 0.660, 1.172, and 1.332 Mev

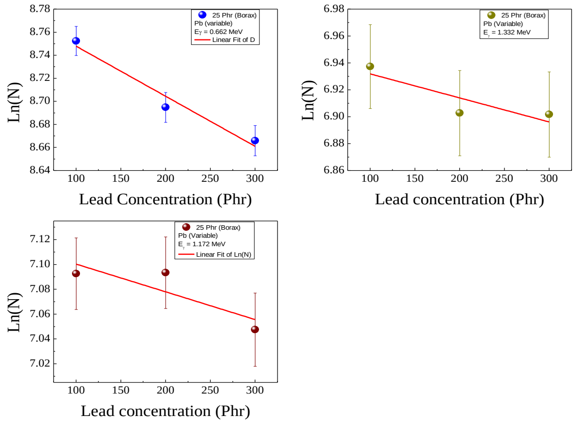

Fig. (6): γ-rays attenuation (Ln N) versus lead concentration (100, 200, and 300 phr lead and 25 phr borax) for Eγ = 0.660, 1.172, and 1.332 Mev

Table (6): The attenuation coefficients and HVL for EPDM/lead composites for Eγ = 0.660, 1.172, and 1.332 Mev*

Lead concentration phr	For ^{137}Cs (Eγ = 0.66 Mev)		For ^{60}Co (Eγ = 1.172 Mev)		For ^{60}Co (Eγ = 1.332Mev)	
	μ(cm^{-1})	HVL	μ(cm^{-1})	HVL	μ(cm^{-1})	HVL
25	0.0237	29.197	0.0206	26.762	0.0158	43.87
50	0.0481	14.417	0.0259	26.804	0.0208	33.32
75	0.0586	11.828	0.0382	18.126	0.0363	19.10
100	0.0614	11.282	0.0560	12.386	0.0514	13.49
200	0.0818	8.473	0.0615	11.276	0.0615	11.28
400	0.0852	8.137	0.1410	4.915	0.1232	5.63

The effect of the addition of Pb powder to EPDM rubber composites on the attenuation of γ-rays emitted from ^{137}Cs (Eγ = 0.660 Mev) and ^{60}Co (Eγ = 1.172 and 1.332 Mev) has been investigated for heterogeneous and broad beam (Fig 3 to 6). The results of the attenuation tests of EPDM and EPDM loaded with different phr of lead are given in Table 6.

[*] The two sources (^{137}Cs, ^{60}Co) are placed together without collimation (broad and heterogeneous beam).

It was observed that the attenuation properties of the EPDM rubber composites increase as the concentration of the lead powder increases. The result showed that a high attenuation coefficient was obtained for 400phr lead [μ = 0.0852 cm^{-1} for Eγ = 0.662 Mev, μ = 0.1410 cm^{-1} for Eγ = 1.172 Mev and μ = 0.1232 cm^{-1} for Eγ = 1.332 Mev]. Moreover, the effect of the thickness on the attenuation of γ-radiation, for a given fixed Pb concentration has been investigated. The result showed that the attenuation increases with increasing the thickness of each of the lead concentrations, and good values for HVL were obtained [HVL = 8.137 cm for Eγ = 0.662 Mev, HVL = 4.915 cm for Eγ = 1.172 Mev and HVL = 5.627 cm for Eγ = 1.332 Mev at 400 phr lead].

The attenuation properties of pure host EPDM rubber composites (0phr lead) are weak. In Figures (3 , 4), some points deviate below the straight line of the attenuation curves, at higher energies, which can be attributed to the high scattering of photons and hence escapes from detection. This, in turn, will decrease the observed count. At higher energies of γ-rays the occurrence of pair production will be enhanced and hence increase the observed count. This deviation decreases as the lead concentration increases due to increasing the average density of the sample (as shown in Fig. (4) for 200 and 400phr lead). Fig. (5) shows that as the concentration of lead increases the attenuation increases at a constant thickness of 2 cm, for the samples containing 25, 50, 75, 100, 200, and 400 phr lead. The same behavior is shown in Fig. (6) for the samples containing 100, 200, and 300 phr lead with 25phr borax.

4.2 Fast neutron measurements

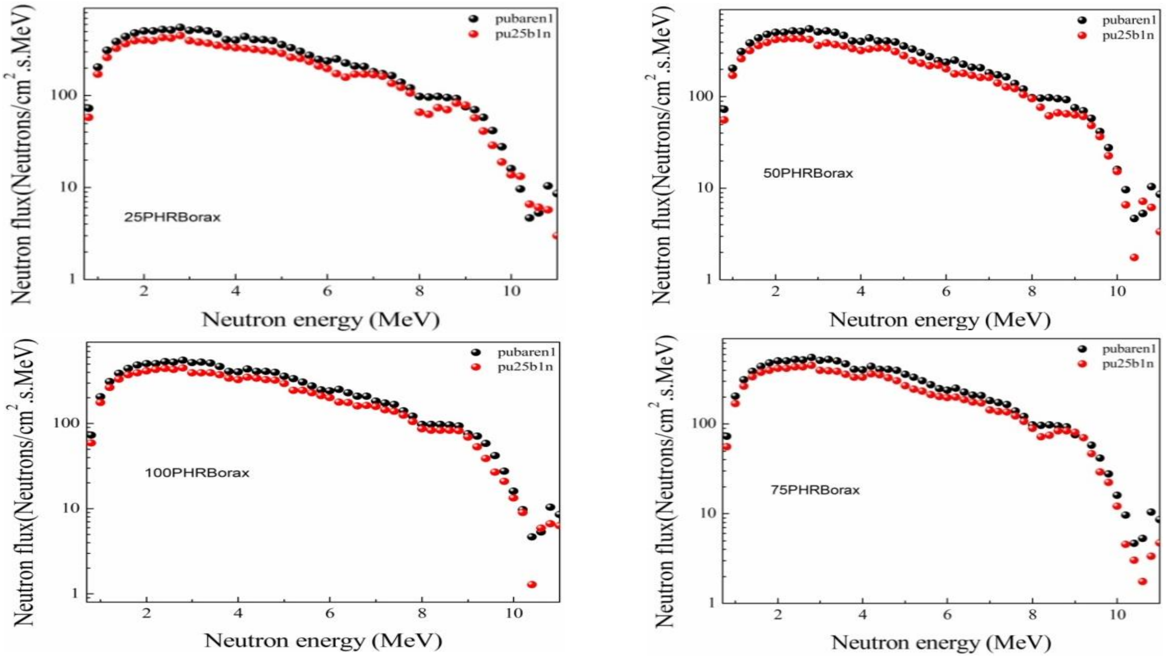

Fig. (7): Fast neutron fluxes measured for the samples containing 25, 50,75, and 100 phr borax respectively

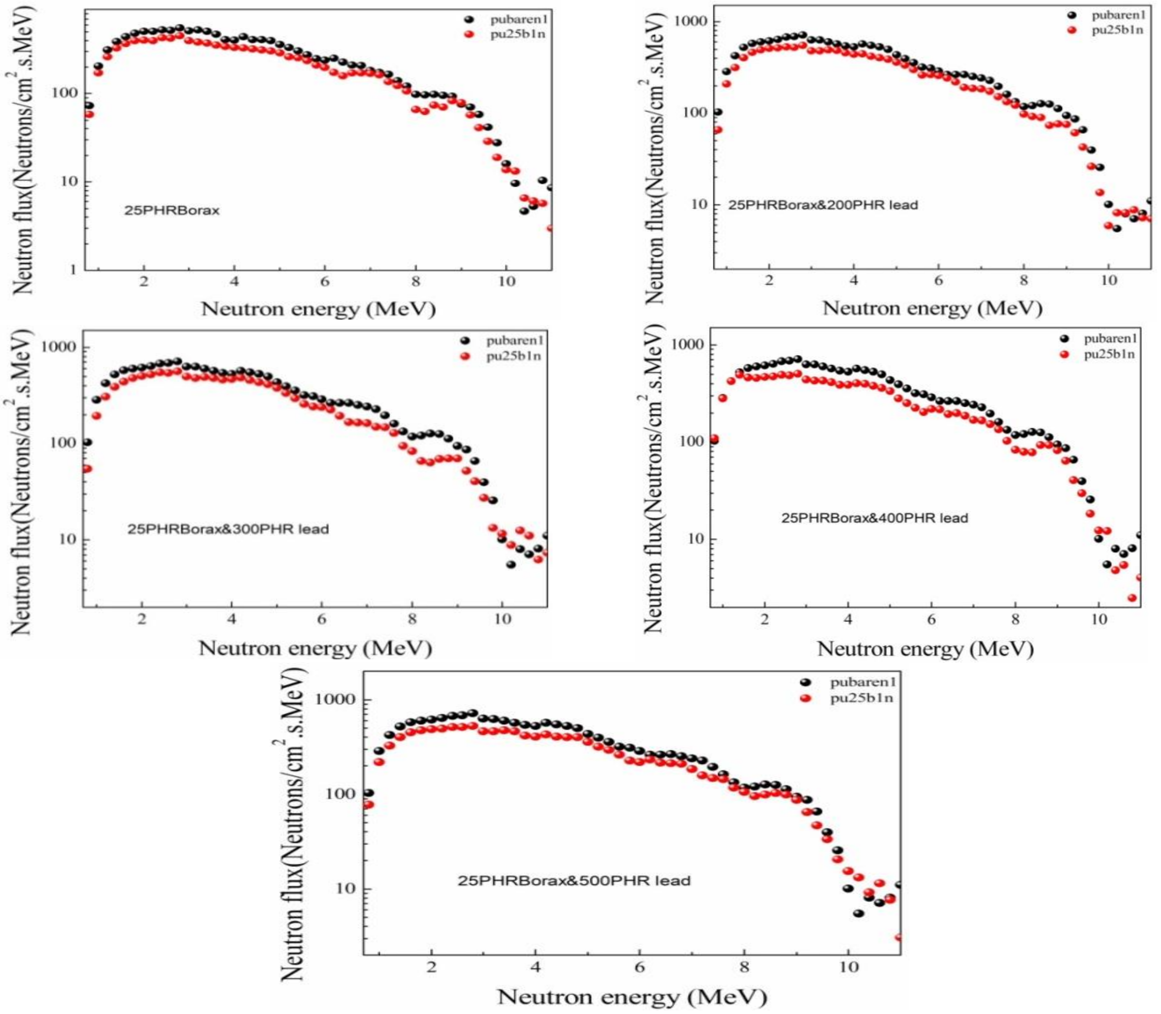

Fig. (8): Fast neutron fluxes measured for the samples containing 25 phr borax and 100, 200, 300, 400 phr lead, and 50 phr borax/400 phr lead

Figures (7 and 8) shows a relation between the transmitted neutron fluxes and their energy distributions, where PuBe source was used as a fast neutron source with energy range 0.8 to 11 Mev for fast neutrons and from 0.47 to 8.3 Mev for γ-rays. Using the multi–channel analyzer, the integral fast neutron and γ-ray counts were recorded for 100 sec using operating voltage of 1900V. The measured transmitted radiation of fast neutrons was carried out through a fixed sample thickness of 2 cm for all measurements. The test includes different groups of samples. The first group was of EPDM rubber composite loaded with different loadings of borax (25, 50, 75, and 100 phr), while the second group was of a fixed load of borax (25 phr) with different loads of lead (100, 200, 300, and 400 phr). Another sample containing 50 phr borax loaded with 400 phr lead was tested to illustrate the effect of increasing borax on absorbing a large number of slow neutrons, but this process showed an increase of the emitted γ-ray. The spectrum of neutron source (bare spectrum) and the transmitted one from the sample were integrated to obtain the incident intensity.

The initial intensity (Io), transmitted intensity (I) and the attenuation coefficient for γ-rays (emitted from the neutron source and the secondary gamma) were calculated for all the samples. In addition, the macroscopic cross-section was also calculated from the obtained fast neutron data. The layouts of fast neutron spectra, for the investigated EPDM rubber of 2 cm thickness with the different loads of lead and borax, were almost the same and had similar profiles like the preliminary neutron spectrum of PuBe source (bare).

As shown in Table (7-a), the result showed good values for the attenuation coefficient, and it increases by increasing the borax concentration. It is expected that as the borax concentration increase, a large amount of γ–rays are emitted due to the slow neutron capture with borax in the form of (n, γ) reaction

The values of macroscopic cross-section given in Table (7-b).

Table (7 -a): Incident and transmitted γ- rays photons and their calculated attenuation coefficient of EPDM/borax rubber composite

Borax Concentration (phr)	Total Gamma counts (Counts/100sec)	Initial intensity	Relative intensity	Attenuation Coefficient
0	5380	5737	1.0664	0.03212
25	5098	5737	1.1253	0.05904
50	5095	5737	1.1260	0.05934
75	5037	5737	1.1390	0.06506
100	5022	5737	1.1424	0.06655

Table (7-b): Incident and transmitted neutron fluxes and their calculated macroscopic cross section for EPDM/borax rubber composite

Borax Concentration (phr)	Total fast neutron counts	Initial intensity	Relative intensity	Macroscopic cross section
0	12000	13300	1.1083	0.0514
25	10600	13300	1.2547	0.1135
50	10600	13300	1.2547	0.1135
75	10700	13300	1.243	0.1088
100	10800	13300	1.2315	0.1041

Table (8-a): Incident and transmitted γ- rays photons and their calculated γ- rays attenuation coefficient of EPDM/lead/borax rubber composite

Lead / Borax Concentration (phr)	Total Gamma counts (Counts/100s)	Initial intensity	Relative intensity	*Attenuation Coefficient*
0/0	5389	9055	1.6803	0.2595
25/100	5807	9055	1.5593	0.2221
25/200	5747	9055	1.5756	0.2273
25/300	5670	9055	1.5970	0.2341
25/400	5714	9055	1.5847	0.2302
50/400	5870	9055	1.5426	0.2167

From Table (8-a) it is noticed that there is no considerable effect on the attenuation of γ-rays despite increasing the concentration of lead due to the capture of slow neutrons.

Table (8-b): Incident and transmitted neutron fluxes and their calculated attenuation coefficient for EPDM/lead/borax rubber composite

Lead/Borax Concentration (phr)	Total fast neutron counts	Initial intensity	Relative intensity	Macroscopic cross-section
25/100	12300	14000	1.1382	0.0647
25/200	12300	14000	1.1382	0.0647
25/300	12300	14000	1.1382	0.0647
25/400	12300	14000	1.1382	0.0647
50/400	12900	14000	1.0853	0.0409

According to the data obtained from Figures 7 and 8, it was observed that at a low energy range of 1.5 to 2.5 Mev, there is an evident increase in the flux intensity of fast neutrons at all spectra for all samples. These high neutron fluxes emanated from the fission of plutonium and the (n, 2n) reaction with Be nuclei are more significant due to the large size of the used PuBe source in the measurements [28, 29]. On the other side, there is a remarkable shortage in the ratio of fast neutron fluxes at the energy range of 3 to 4 Mev which can be ascribed to the high attenuation at this definite energy (effective removal cross-section) unlike the 3-4 Mev for which a high flux of fast neutrons can be observed at the energy range of 4 to 5 Mev for all samples, indicating a decrease of the effective removal cross–section. This high flux can be attributed to the radiation source itself. As a result of the ^{9}Be (α,n) ^{12}C reaction for higher energy alpha particles has occurred [30]. The Q value for this reaction is 5.7 Mev. The α particles created from the fast neutron reaction (n, α), while the highest effective removal cross-section is evaluated at energy from 5 to 11 Mev except at 9 Mev is also a result of the PuBe source itself as a result of the ^{9}Be (α,n) ^{12}C reaction for higher energy alpha particles as in the case of 4-5 Mev, and the reaction (n, 2n) for fast neutrons.

The result showed also good values for the total macroscopic cross-section (0.06473 cm^{-1}) for samples containing 25 phr borax and 100, 200, 300 phr lead. Samples containing borax only showed a total macroscopic cross-section of 0.11346 cm^{-1}.The EPDM host composite also gives a good value for a macroscopic cross-section of 0.07708 cm^{-1}.

5. CONCLUSIONS

In the present work, a group of composite based on EPDM rubber with different ingredients and carbon black was prepared (host composite) using the two-roll method. Shielding against ionizing radiation was studied using two scenarios, the first using a heterogeneous and non-collimated radiation beam, and for the other scenario, a homogeneous and collimated beam was used.

For the first scenario, the results showed that the increase in the lead content (from 0phr, 25, 50, 75,100, 200, 300, 400, and 500phr) improved the γ - ray shielding properties of EPDM rubber composites with the highest attenuation in 500phr lead.

The EPDM rubber composite loaded with 25, 50, 75, 100 phr borax, and the samples with a 25 phr borax and 100, 200, 300, 400 phr lead, were used to investigate their ability in moderating the fast neutrons to thermal neutron. The results indicatd that the attenuation of γ-rays increased with increasing of the borax contents, while the number of neutrons also increases. The rubber composite containing 25 and phr borax showed the maximum valves for the total macroscopic cross-section. The optimum concentrations of lead powder and borax powder which give good results for γ rays attenuation and moderate fast neutrons at the same time are 25 phr borax and 300 phr lead.

X.com program was used to confirm the experimentally calculated values of the linear and mass attenuation coefficients. It was found that the uniform and collimated beam scenario give a good agreement with the experimental values, which is not verified for the heterogeneous case.

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Declarations

Compliance with Ethical Standards

Conflict of interest:

The authors declare that they have no conflict of interest, and all co-authors have approved the contents of this manuscript and submission.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the present study.

Data availability and Materials

The authors confirm that the data supporting the findings of the present study are available within the article. However, the original collected data are available by contacting the corresponding author.

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Author contributions

All authors have contributed, discussed the results and approved the final manuscript.

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