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A review on neutron shielding performance of nano-composite materials

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▸ ***Review article***

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ABSTRACT

Neutron sources employed in different applications in both medicine and industry. Due to the harmful effects of neutron particles on living organisms, radiation shields have played a vital role in radiation protection against neutrons. In recent decade, numerous investigations conducted on the design and fabrication of nanocomposites as more efficient shielding materials against fast and thermal neutrons. A range of different nanoparticles for a spectrum of neutron energies investigated. However, there is no comprehensive review concerning the shielding properties on these newly proposed shielding materials against neutrons. The current review is an attempt to gather the information provided by the published papers in this regard. The neutron attenuation of nanocomposites and their ordinary counterparts discussed and compared. In addition, the effect of influential parameters, including particle size, neutron energy, particle type, and materials composition analyzed.

***Keywords**: Nanomaterials, shielding, thermal neutron, fast neutron, radiation protection.*

INTRODUCTION

Shielding against neutrons has been a great challenge for application of neutron sources in industry and medicine. Exposure to neutron radiation is particularly hazardous for human health and can cause irreversible damages to vital organs (1). The biological consequences of exposure to neutron radiation are considerably greater than exposure to an equivalent amount of absorbed radiation dose from beta, gamma, and X-ray radiation (2). Neutrons widely produced and used in fission reactors as well as other industries. On the other hand, in some cases, the neutrons considered as the byproduct of the interaction of other ionizing radiations such as protons and photons with materials. Thus, its industrial and medical usage has necessitated higher degree of shielding strategies against neutrons as a hazardous radiation to human health. For instance, high-energy neutrons can be produced in particle accelerators and high-energy photon beams by (γ, η) interactions. Exposure to neutron radiation is considered highly harmful for human health because of higher linear energy transfer (LET) of neutrons compared to photons and electrons which can cause more irreversible damages to vital organs (3). Thus, shielding against neutrons plays a critical role in establishing a safe working condition for personnel as well as people living around the nuclear reactor facilities.

From physical point of view, neutrons have no electrical charge and interact with the nuclei of materials via different ways. Neutrons interaction with nuclei occurs via elastic and inelastic scattering, neutron capture, nuclear spallation, and nuclear fission. While, photons interact mostly with orbital electrons and ionization of target atoms occurs following interaction through Photoelectric, Compton, and Pair production phenomena. Consequently, the types of materials favored for neutron shielding are quite different compared to materials which are appropriate for gamma/X-rays shielding (4). In other words, composites which contain high atomic number materials such as Barium (Ba), Lead (Pb) and Bismuth (Bi) are utilized to absorb gamma or X-rays, while materials which contain low atomic number elements such as Hydrogen (H), Lithium (Li), Carbon (C), Boron (B) and Aluminum (Al) are preferred in absorbing neutron particles (3). Neutrons exhibit a sophisticated absorption cross section pattern in terms of neutron energy and atomic number of absorber due to their interactions with nuclei. Furthermore, in terms of kinetic energy, neutrons are categorized mainly into several groups(5) tabulated in table 1.

Table 1. Neutron energy distribution ranges.

	Cold neutrons	Thermal neutrons	Epithermal neutrons	Cadmium neutrons	Epi-Cadmium neutrons	Slow neutrons	Intermediate neutrons	Fast neutrons
Neutron Energy (eV)	0.0 - 0.025	0.025	0.025-0.4	0.4 – 0.5	0.5 – 1	1-10	10-1000	> 1 MeV

In general, low atomic number elements(6) with high scattering cross sections (the probability of neutron-target interaction) are found to be suitable for neutron attenuation and shielding(7). Polyethylene and paraffin are often applied as basic materials for shielding of small size sources, while for larger sources concretes and water are recommended shielding materials (8). In space industry as well as nuclear protection devices more flexible and light materials such as polymers doped by elements, including B, Li, Samarium etc. are needed(9). However, for establishing bunkers used for particle accelerator facilities, high-density concretes containing both high atomic number material and boron-enriched materials to block both photons and neutrons has been recommended (10,11).

In recent years, the application of more efficient materials and composites for radiation shielding has attracted a considerable attention of many radiation and nanotechnology scientists (12,13). Traditionally, composites containing micron-sized fillers are still most widely employed in radiation shielding(14,15). However, since a higher weight fraction (wt %) of micro-sized fillers was necessary to achieve efficient neutron absorption, the application of micro-sized fillers in neutron shields negatively influenced the weight of the composite and its fabrication(16). Several experimental and simulation studies have demonstrated the application of nanoparticles (NPs) as hopeful method to design new nano-composite radiation shields(17,18). They found that the shielding properties of nano-composites largely depended on the type of NPs, size of NPs, NPs concentration, radiation energy and epoxy type (19).

Looking at the electronic resources it seems that no systematic review study done in this field. On the other hand, there are some discrepancies and disagreements among published articles concerning the effect of neutron energy, properties of NPs in shielding power of newly proposed nano-composite materials. Thus, to clarify the issues, this study comprehensively reviewed and analyzed the published studies and tried to find reliable answers for observed differences between published articles.

Design of systematic review

This systematic review was designed on the basis of the standards set out in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) checklist (20).

Those articles that met the inclusion criteria were included in this study. The inclusion criteria were as follows: (a) the original, quantitative papers, review papers, protocols papers, thesis, meetings and ongoing papers; (b)

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the studies involved both simulation (such as Monte Carlo methods and Geant 4) and experimental procedures; (c) studies which investigated the effect of NPs as filler in the composite shield; (d) neutron radiation shielding not photon radiation was included. The exclusion criteria included (a) studies with unrelated abstracts; (b) studies with incomplete data; (c) conference paper; (d) letters to the editor; and (e) editorials.

A literature review performed to assess all available studies that involved the use of NPs as a neutron radiation shielding material in electronic databases, including PubMed/Medline, Embase, ProQuest, Scopus, Cochrane and Google Scholar based on Mesh key words and suitable synonyms in titles and abstracts. Two researchers (RM and EM) independently and separately performed literature search. Our search strategy in each database was established by the following terms: ((Neutron [Title/Abstract]) AND ((("shielding"[Mesh]) OR shielding material [Title/Abstract]) OR fast - thermal neutron [Title/Abstract] OR composite shield [Title/Abstract] OR epoxy resin [Title/Abstract] OR polymer composite shield [Title/Abstract]))) AND (((Nano-composites [Title/Abstract]) OR "Nano(18)particles "[Mesh]). Database search had no limitation in time, and our last update on search was in August 2019. To have a comprehensive search and to find possible relevant articles, manual search conducted on the reference list of articles in particularly review papers. The search was limited to articles published in English.

The results of systematic literature search from the database collected in Endnote X7. After removing duplicates, the articles selected independently by two in three stages. At first, the titles of all articles reviewed and articles that were not consistent with the objectives of the study excluded from the study. In the next steps, the abstract and the full text of the articles considered, and the full texts of relevant articles that involved inclusion criteria and methodological quality assessment, identified and included. For each eligible study, one reviewer extracted the data and then a second reviewer checked the results. Any inconsistencies were resolved through discussion and by consulting a third reviewer. After the final selection of studies, the required information extracted and summarized. The total articles presented as a flow chart for the selection of the included studies (figure 1).

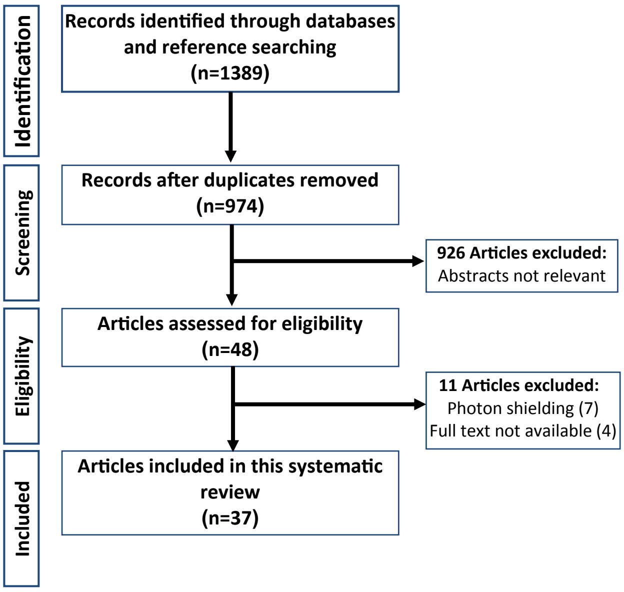

Figure 1. PRISMA flow chart diagram.

Shielding properties of nano-materials against thermal neutrons

In order to capture moderated/thermalized neutrons, composite shielding materials are commonly dispersed with elements having high cross sections for neutron capture such as boron, gadolinium, cadmium and lithium as fillers (21). In addition, these fillers are capable of reducing the dose of low energy gamma rays originated from (η, γ) interaction. Among all these materials, Gadolinium has the highest thermal neutron absorption cross section but it is expensive (1). Moreover, Cadmium is a toxic material with high neutron cross section. Among these elements, boron has an excellent absorbing power for thermal neutrons and neutron capture by boron produces only stable products. Boron with a large cross section of 760 barn for thermal neutrons is used frequently in the composition of different mixture and materials(22). Overall, Boron and its derivatives have good mechanical and chemical stability as well as high neutron capture cross sections which make them the mostly used materials in neutron shielding (23,24).

There are several studies on the introduction of new nano-composites or nano-filled materials for neutron shielding (10,25-29). In most of these investigations, multiple factors have been analyzed including: (1) size of filler particle, (2) concentration of filler (fraction of weight), (3) composite's thickness, (4) energy of neutron beams, (5) neutron attenuation coefficient and (6) half and tenth values. Among the materials used for shielding, composites loaded with ultra-dispersed particles provided high shielding ability against thermal neutrons. The studies show that the interaction probability between thermal neutrons and the particles increases as the particle size decreases. In this regard, the employment of nano-sized particles would find a superior place among the fillers used for enhancement of shielding property of material against thermal neutrons (10,12,25,29-32). Moderation length of thermal neutrons in nano-structured materials closely related to absorption and scattering cross section of neutrons by individual nucleus. Material porosity and the density of nuclei (atoms) of the moderator material has a great impact on the neutron moderation length (33). Artem *et al.* indicated that the size of the ultra-dispersed particles (like Nano particles) do not greatly influence the neutron moderation length. However, they concluded that the moderator material in the form of ultra-dispersed particles could be effective for shielding of neutrons with lower energies (0.0-0.025 eV)(33). Kim *et al.* (34) added nano- and micro-B_2O_3 with two different sizes of 200-300 μm and 0.1-1 μm to poly vinyl alcohol (PVA). They showed that the macroscopic thermal neutron absorption cross section for Nano-fillers was 12% and 13.3% higher than larger particles for the weight concentration of 1 and 2.5%, respectively.

Studies have shown that adding nano-materials to polymers increases their tensile and flexural strength as well as temperature durability (35-38). Application of nano-sized boron and its derivatives as fillers in shielding materials and studying its features relative to micro-sized particles has been one of the interesting topics in both experimental and simulation studies(39). For instance, Galehdari *et al.* studied the thermal neutron attenuation efficiency and mechanical properties of light weight hybrid sandwich panels incorporating three different particles (Boron Nano-powder, Gd NPs and Boron Carbide NPs) as possible construction materials for neutron shielding (38). Figure 2 shows that thermal neutrons (energy ~0.025 ev) was absorbed effectively more than 50% by epoxy boron nano-powder 3 wt% compared to neat epoxy. In addition, the results demonstrated that boron Nano-powders provides highest thermal neutron shielding efficiency than the other sandwich composites (Gd and Boron Carbide powders). The advantage of nano-powder attributed to smaller size of particles and relatively higher dispersion ability of nano-powder into resin matrix.

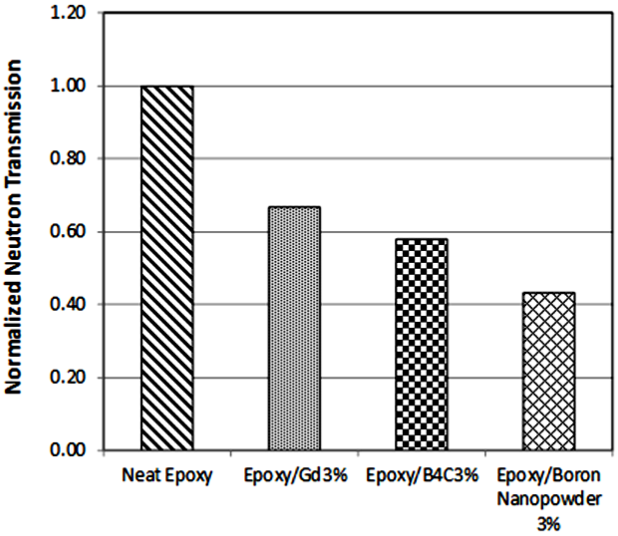

Figure 2. Neutron transmission for different epoxy based materials (The graph was redrawn based on the provided by the study of Galehdari and Kelkar (21)).

Boron carbide (B_4C) is a cheap ceramic material that has been extensively studied as one of the promising neutron absorber materials. Besides, B_4C contains ^{10}B which has a high cross section for thermal neutron (about 3,838 barns) (22,26,39,40). Soltani *et al.* (29) conducted an experimental and MC simulation investigation on the effect of particle size and weight percentages of Boron carbide on the thermal neutron shielding properties of high density polyethylene (HDPE) loaded with B_4C as a light weight composite. In their study, different weight percentages of Boron carbide 1, 2, and 5 wt% (micron size of Boron carbide ~1μm) and nano size of less than 50 nm have been designed to compare the effect of size and weight percentage of filler in shielding of thermal neutrons. The results of experimntal measurement was shown in figure 3.

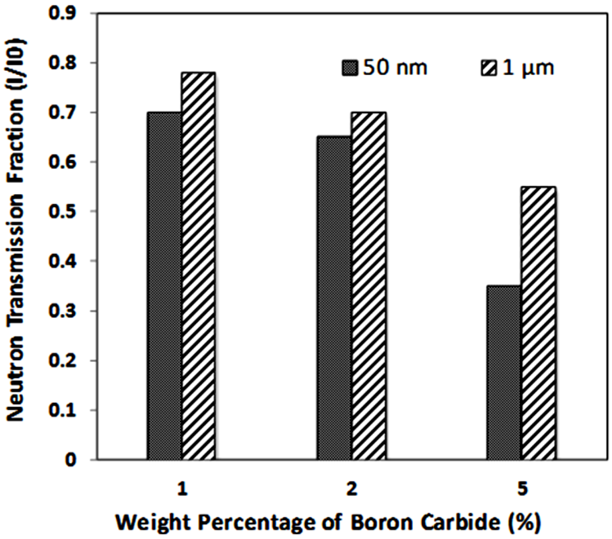

Figure 3. Comparing neutron transmission fraction versus weight percentage of boron carbide for filler size of 50 nm and 1 μm (The graph was prepared based on the data extracted from (29).

They showed that adding 5% boron nano-sized filler resulted in about 40% higher macroscopic absorption corss section relative to micro-sized filler. Furthermore, the superiority of nano-sized composite increased with weigth percentage of filler. For HDPE with B_4C (1%,2%), the simulation results revealed that the neutron transmission fraction decreased about 25% with reduction in B_4C particle size from 1μm to 50 nm, but, in experimental measurment for B_4C (1% and 2% wt) 7.79 and 8.7% reduction was observed relative to pure polymer. Considering this large disagreement, we believe that the differenece between experiments and simulations, specially in low filler contents of 1-2%, comes from uncertinities associated with experimental measurments where such subtle differences in neutron attenuation can be obscured. Furthermore, the homogeneity of distribution of filler inside the base material could be another influecing parameter in experimental measurements. Figure 4 shows the schematic representation of simulated geometery of nanocomposite containing NPs homogenously distributed inside HDPE matrix.

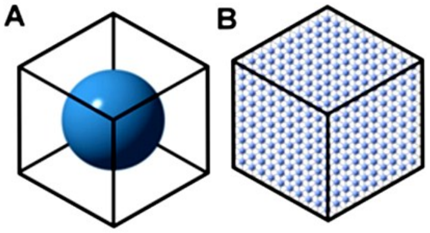

Figure 4. The schematic representation of geometry simulated by Monte Carlo code. **(A)** A single lattice cell surrounded by matrix in a composite. **(B)** The whole composite filled with lattice elements containing Nano- or micro-particles.

The higher attneuation of NPs was ascribed to higher surface to volume (S/V) ratio of nano-particles relative to micrparticles and they recommended using B_4C in nano size form to achieve higher performance in shielding agianst thermal neutrons. In a similar investigation, Kim *et al.* (41) studied the enhancement of thermal neutron attenuation of HDPE composites by adding nano-powder of boron carbide (B_4C) and boron nitride (BN) compared to their microparticle counterparts. Among the studied particles boron nitride had higher shielding effect compared to boron carbide. Also, micro boron nitride had better shielding effect relative to nano boron carbide. The results showed that neutron attenuation of studied nanocomposite was dependent on particle size for thermal neutrons (~0.025 eV). Additionally, neuton absorption of the HDPE nanocomposites was 20% higher than those composites doped with microparticles at the same densities both in experiment and MC simulation. This study indicated that thermal neutron attenuation was not only dependent on the size of the boron compound filler in the polymer, but also on the the mass density of composites. It can be concluded that nanometer range was the most effective paricle size range for neuron radiation shielding. Moreover, it is summarized that althogh B_4C and BN/HDPE nanocomposites display geater shielding effect for thermal

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neutrons compared to their micro-sized counterparts, but reducing the size of particles less than 500 nm in nanocomposites does not make a significant improvement in thermal neutron attenuation.

In figure 5, we have gathered the MC simulation data provided from two recent studies (29, 24) and have compared them with each other. In this figure, the effect of particle size from 0.01 µm to 100 µm on neutron transmission has been depicted.

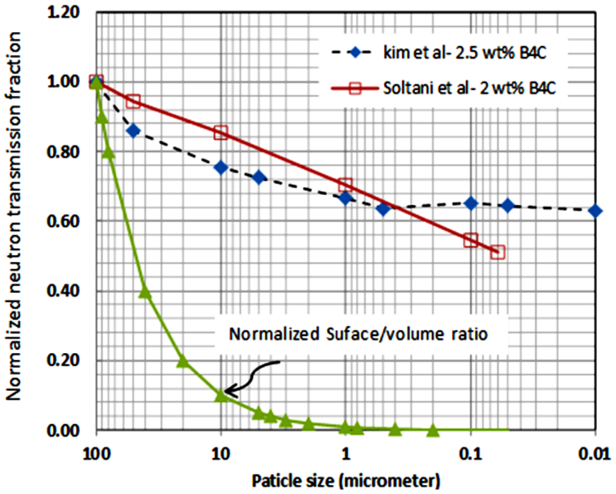

Figure 5. The thermal neutron transmission versus particle diameter (µm) from two independent Monte Carlo simulation studies by Kim et al. and Soltani *et al.* (40 and 29). In addition, the data shown with line and triangles exhibits the S/V ratio that normalized to the S/V ratio of a particle with diameter of 100 µm. (The graph drawn based of the data provided by two different studies and the calculations of the current study).

The maxium transmittence has been considered for particles with 100 µm and other data was normalized to its value. Also, to analyze the effect of S/V on transmittence, the curve of S/V ratio has been superimposed on the same graph assuming that the maximum transmittence happens for larget particle size of 100 µm. From the results of kim *et al.* (24), it can be assumed two distinct parts on the graph. In the first part from 100 µm to about 1 µm, there is a markdely markedly decrease in transmitted nuetrons by decrease in particle size. However, in the second part, i.e., nano-size range from 500 nanometer to 0.01 µm , no significant variation was found for the number of transmited nuetron with reduction in particle size. As it can be seen in figure 5, the finding of kim *et al.* (24) about particle size is a little bit different from the study of Soltani *et al.* (29) To be more precise, in the case of kim *et al.* (24) an approximately exponential relationship was found between neutron transmission and logarithm of particle size, while in the results of Soltani *et al.* an approximately linear relationship between log of particle size and neutron transmision was seen. Figure 5 also shows the relationship between log of particle size and normalized S/V to 100 µm. As the figure 5 shows the S/V ratio decreases exponentially with increasing in particle size. Thus, if the superiosity of nano to micro only ascibed to S/V ratio, there should be close agreement between S/V ratio curve and two prevoiuly mentioned MC studies in terms of neutron transmission and particle size. However, we see that both MC studies do not follow the S/V curve and there is a steep fall-down with particle size for S/V curve. As a result, it can be suggested that S/V is not the only effective parameter in higher absorption of neutrons by NPs and other influencing parameters such as particle atomic composition, mass density, absoption and scattering characteristics of compostion are effective in nano-composites attenuation coefficients. Also, it should be noted that the filling effect of NPs in porous region of a composite structer is prominant comapred to micro-sized fillers. It is worth noting that the higher filling effect of nanopartiles compared to micropartiles leads to using lower weight percentage of nanoparticle in the fabrication of light weight shielding materials. In this regard, Koops (42) evaluated the effect of particle size on shielding properties of suitable neutron absorbing composites and compared the result with recent experimental findings. They theoretically showed that nano-filler functions better than larger sized particles with less weight penalty. It means that adding nanometer-sized filler to composites will increase shielding effect and keeps the weight of absorber in its minimum value which is very critical parameter in aerospace and aeronautics applications.

In an attemp to design a novel nano-compaosite to provide dual shielding effect against both photons and neutrons, Zhou *et al.* (27) produced a shield composed of bismuth and borate nano-fillers for simultaneous thermal neutron and gamma rays. One sample was produced using Bi_2O_3 and B_2O_3 mixure with the same mole ratio of Bismuth and Boron atoms relative to the other sample which was fabricated using $Bi_6B_{10}O_{24}$ NPs. The particle size was 200 nm on average. Their results showed that the nanoparticle-based shield had better performance in low energy photons (less than 400 keV) relative to the mixture. But, for thermal neutrons, there was no difference between two samples. It was in agreement with the results of Kim *et al.* (24) where they showed that reducing particles size from 500 nm does not change the transmission significantly.

Rezaeian *et al.* (25) indicated that the addition of nanoclay to the polymer matrix leads to an improvement in the mechanical and thermal properties of the resultant nanocomposite. In this study, neutron-shield materials of polyethylene, borated polyethylene and nano-composites of epoxy/clay/B4C and epoxy/ clay/B4C/carbon fiber were employed to investigate the effectiveness of the neutron shielding nanocomposites in comparison with liquid neutron shield (ethylene glycol mixed with water) for a dual-purpose cask (DPC) of Bushehr's Water Reactor, nuclear-power-plant spent fuels. According to their results, in the case of the DPC with the neutron-shield material made of borated polyethylene and epoxy/clay/ B4C, the dose rates from the neutron sources were reduced by 55% and 17.5%, respectively. Also, the overall dose rates were reduced by 16% and 11%, respectively, for borated polyethylene and epoxy/clay/B4C in comparison with ethylene glycol mixed with water. In this case, we should keep in our mind that epoxy-based nano-composites had better mechanical and physical properties to be employed as a shielding material in nuclear facilities. However, their attenuation properies was lower compared to ethylene glycol and borated polyethylen. On the other hand, it should be added that water could be used as an effective neutron shield because of its high hydrogen content but it does not have the ability for absorption of secondary gamma rays which are the byproduct of water/ neutron interaction.

For thermal neutron shielding, dual or multiple NPs should be employed to absorb both neutrons and capture gamma rays which are the byproduct of thermal neutron absorption. For example, in a study (28) the shielding properties of two different filler materials, including B_4C and PbO in epoxy nano-composites for high energy neutron were investigated. Nano-composites and micro-composites made of B_4C (5-10-20 wt%) with particle sizes of 500 nm and 30 µm and PbO of 300 nm and 10 µm (5-10-20 wt%) were used as filler materials. In fact, B_4C particles were used for absorption of thermal neutrons while PbO particles were responsible for attenuating gamma radiations. For thermal neutron, the results revealed that the linear attenuation coefficients of B_4C micro- and nano-composite against neutrons was very similar in all used concentration of filler. Additionally, doubling the wt% of filler caused almost 20% increase in attenuation coeffiecint of B_4C loaded nanocompsites. Also, for gamma radiation and Nano- and micro-composites made of PbO similar results were found. In other words, no particle size effect was found for both neutron and gamma rays. The result of this study was in contrast with the results of previously mentioned studies which reported a considerable difference in neutron and gamma absorption between nano- and microparticles. It is hard to find the exact reasons for such a great disagreement. However, we think that the study of Lee *et al.* was focused primarily on the methods of nano-composite preparation by ultrasonic dispersion approach and the precision of the attenuation measurement was not stringent enough to reveal the minute differences between Nano-and micro-states. Also, the particle size for NPs was 500 nm which is not comparable with NPs with size less than 100 nm which was used in other studies.

Shielding properties of nano-materials against fast neutrons

In general, for fast neutrons (energy >0.1

MeV), scattering interactions including elastic and inelastic types are more likely than capture interactions. Hydrogenous materials such as polyethylene, water, plastics and concretes moderate fast and intermediate energy neutron via inelastic scattering. Neutron absorbing materials such as boron derivatives absorb produced thermalized neutrons. These materials have a very high neutron absorption cross-section and generate low energy secondary photon radiation after the absorption process. In this regard, Mortazavi *et al.* (32) designed and fabricated high-density borated polyethylene nano-composites as fast neutron shields. In this study, neutron attenuation of borated polyethylene shields containing 2% and 5% weight percentage of Boron NPs compared to the pure polyethylene. The results showed that borated polyethylene nano-composite, which included 5 wt% boron has the highest attenuation both in experiment and simulation. However, it is worth mentioning that polycarbonate films were used to measure the attenuation of neutrons from an Am-Be neutron source. Thus, we think that the accuracy of measurement by this type of dosimeter was not sufficient to reveal the small differences of nano-composite with 2% boron content.

In protection against high energy neutrons originated from radioactive elements, gamma radiations also emitted from the source. In addition, gamma rays might be produced from fast neutron via inelastic interactions with matter. Furthermore, secondary gamma radiation produced by thermalized neutron interaction with atoms of the matter must considered. Clearly, for a source generating mixed rays including fast neutron radiations and gamma rays, such as (^{239}Am-Be)(27) both high atomic number atoms for fast neutron thermalization and gamma attenuation as well as low atomic number materials for thermal neutron shielding are required. Moreover, to have more effective shielding nano-composites, the mass density of blended NPs should be as close with each other as possible, which could simultaneously attenuate both gamma and neutron beams. Because it has shown that, a large discrepancy between the densities of two materials causes considerable negative effect on their compatibility and dispersion, which reduces their mechanical and physical performance(27). In this regard, neutron shielding properties of H-BN/Gd2O3/HDPE ternary nano-composites were studied by Irim *et al.* (12). In this investigation, Hydrogen based HDPE and gadolinium oxide nanoparticle (~100 nm) were used to thermalize fast neutrons (4.5 MeV) via elastic and inelastic scattering and then hexagonal boron nitride NPs (~100 nm) captured the resultant thermal neutrons. Furthermore, gadolinium oxide nano-particle (~100 nm) applied in order to attenuate 4.4 MeV gamma radiations, which were the byproduct of (α, n) capture reaction and 2.2 MeV gamma radiations originated from capture reaction during high-energy neutron moderation. This study has considered gadolinium oxide nanoparticle as a gamma shielding material but the results showed that increase of gadolinium oxide concentration from 1 wt% to 2 wt% leads to neutron shielding enhancement. Besides, addition of 3 wt% Gd_2O_3 to neat polyethylene caused improvement of mass attenuation coefficient up to 52% due to the increase in neutron radiation-filler interaction.

The use of concrete as a neutron shielding material has been taken into account in different studies on neutron radiation shielding (43). Concrete is one of the most appropriate and commonly used materials in shielding against fast neutrons (44,45). Concrete contains some elements such as hydrogen, carbon, etc., that makes it suitable for fast nuetron modrating and shielding (46) and its higher density makes it suitable for secondary gamma absorption. Heavy concretes are shielding materials used in radiation therapy bunkers, nuclear medicine departments and nuclear power stations which are obtained from addition of heavy natural aggregates such as barite, hematite, etc. to the ordinary concrete (47,48). A study indicated the effectiveness of a concrete containing of boron carbide fillers depends on the concentration of B_4C added to the mixture and on the size of the fillers (44,47). High density concretes containing sufficient moderating materials are more

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suitable for shielding of fast neutrons. The ordinary concrete loaded with micro and NPs was investigated to examine its shielding properties against fast neutrons (100-3000 keV) [(10)]. In this simulation study the ordinary concrete was loaded with PbO_2,Fe_2O_3,WO_3, and H_4B micro and NPs. The results showed that the attenuation coefficients of NPs was higher than micro-particles for neutron in all doped concretes. According to the results, the concerete loaded with nano-sized materials had relative higher attenuation about 7% relative to microparticles for neutrons. However, adding NPs to the ordinary conceret increased its neutron attenuation up to 14% for 100 keV neutrons. It should be noticed here that neutron attenuation enhancement by NPs decreased slightly by increasing neutron energy from 100 keV to 3000 keV. The data was shown in figure 6.

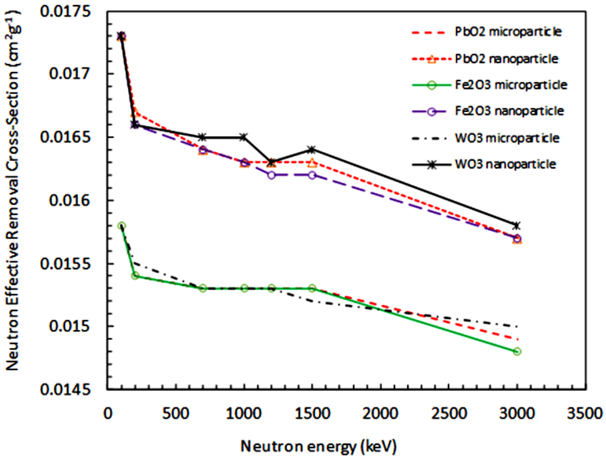

Figure 6. Variation of neutron effective removal cross section in terms of neutron energy. The graph was depicted based on the data published in Mesbahi and Ghiasi (10).

The authors attributed the superiority of NPs to the higher surface/volume ratio of NPs. In other words, a simple surface calculation of particles shows that with reducing the radius of particles, the total surface of particles is increased for the same mass used in the composition of concerete (figure 5). Increased surface/volume ratio of composite beside more uniform distribution of NPs can approve increased attenuation for nanoparticle-loaded concretes.

Monte Carlo vurses experimental method

MC method has been used extensively in radiation physics for the estimation of various quantities. Generally speaking, it uses a statistical approach to transport photons, neutrons, and other particles to solve the radiation-related problems. There are several codes for MC simulation of ionizing radiation such as MCNP, EGS, FLUKA, etc.. However, the basic principles of this method can be found in the literature. This method as an effective tool in designation of nanocomposites has been used frequently in our reviewed studies. An important issue which should be adressed here is the reasons behind the differences reported between MC and experimentals studies. Figure 7 illustrates two different types of geometries that can be utilized for Monte Carlo simulations. In figure 7-A the NPs has been distributed in rows and columns where there are small tunnels between rows, which facilitate the transmission of neurons. In contrast, in the second configuration 7-B the tunnels have been blocked by NPs, consequently it can be theoretically assumed that the second configuration will attenuate more neutrons relative to first configuration.

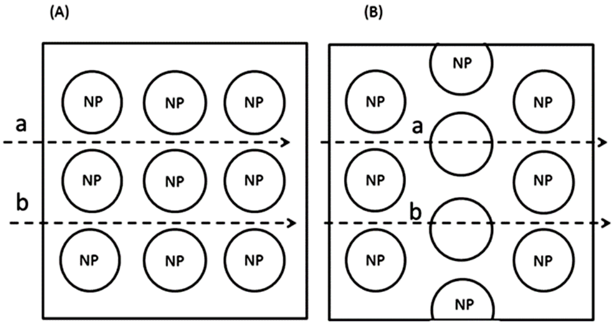

Figure 7. The schematic representation of nanoparticle distribution inside the polymer or concrete matrix. **(A)** The nanoparticles have been simulated in regular rows and columns where there are tunnels that allow neutron penetration with collisions. **(B)** The same nanoparticles have been dispersed in order to fill the tunnels between rows.

Moreover, it should be added here that most of MC simulations have used the first geometry (figure 7-A) for nanoparticle distribution inside the matrix [(49-52)]. We think the results of these simulations could be different from experimental measurement, because it is

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practically impossible to build such a homogenous and regular distribution for NPs. Therefore, the second geometry (figure 7-B) is more likely to resemble the actual fabricated nano-composites where the NPs are dispersed in an irregular pattern and the space between two adjacent NPs can be filled by other NPs. Consequently, it can be concluded here that a part of differences seen between MC and experimental studies goes back to the dissimilarities between real nanocomposite geometric configuration and the simulated geometry. Secondly, a constant diameter for NPs has been considered in MC studies where in the actual nanocomposite composition a range of diameters are employed. Thus, this could be a reason for the discrepancies observed between MC and experimental results. The third reason for disagreement between MC and experimental results originates from the existence of non-negligible uncertainty in the neutron flux or dose measurements by different dosimeters. In contrast, in MC studies the precision of calculation can go down to as low as 1% using higher number of neutron transportation history in a single simulation.

CONCLUSION

This review indicates that most of shielding materials doped with NPs including polymers and concretes, etc. exhibit higher neutron attenuation compared to fillers in μm scale or larger size particles. There are two important reasons to this observed advantage of nanoparticle-loaded shielding materials.

1) The higher S/V ratio for NPs enhances the probability of neutron interaction with NPs compared to micro-particles
2) The space between particles is more efficiently filled in application of NPs as fillers relative to micro-particles.

In short, we found that particle size plays a key role in the enhancement of neutron attenuation by different nano-shields. In other words, reducing the particle size from μm to nanometer increases the attenuation effect of composites. As we know that at least three types of radiation with different cross section of materials can be existed in neutron beams, including fast, thermal neutrons, and capture gammas, it is recommended to design multi-purpose nano-composites for fast neutron shielding. Because the fast neutron should be thermalized by, the first nano-filler and then the thermal neutron should be captured by second filler, which have higher cross section for interaction with thermal neutrons. In addition to neutron shielding NPs, there should be gamma-absorbing nano-materials, which are responsible for absorbing gamma rays that are the byproduct of neutron interactions with matter. Finally, the design and fabrication of multipurpose nano-composites for effective neutron shielding are recommended. Moreover, application of other highly neutron absorbing NPs such as boron carbide, samarium, gadolinium as a nano-filler in the composition of novel polymers and concretes are suggested.

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REFERENCES

1. Piotrowski T, Glinicka J, Glinicki MA, Prochoń P (2019) Influence of gadolinium oxide and ulexite on cement hydration and technical properties of mortars for neutron radiation shielding purposes. *Constr Build Mater, **195**: 583 -589*.
2. Galehdari AN and Kelkar A (2016) Characterization of Nanoparticle enhanced multifunctional sandwich composites subjected to space radiation. *International Mechanical Engineering Congress and Exposition* . November 2016, Arizona, USA.

3. Kaçal MR, Akman F, Sayyed MI, Akman F (2019) Evaluation of gamma-ray and neutron attenuation properties of some polymers. *Nuclear Engineering and Technology, **51(3)**: 818-824*.
4. Singh VP, Badiger NM, Vega-Carrillo HR (2015) Neutron kerma coefficients of compounds for shielding and dosimetry. *Ann Nucl Energy, **75**: 189-192*.
5. Carron NJ (2006) *An introduction to the passage of energetic particles through matter.* CRC Press; 2006.
6. Ueki K, Ohashi A, Nariyama N, *et al.* (1996) Systematic evaluation of neutron shielding effects for materials. *Nuclear science and engineering, **124(3)**: 455-464*.
7. Okuno K (2005) Neutron shielding material based on colemanite and epoxy resin. *Radiation protection dosimetry, **115(1-4)**: 258-261*.
8. Zhang X, Yang M, Zhang X, Wu H, Guo S, Wang Y (2017) Enhancing the neutron shielding ability of polyethylene composites with an alternating multi-layered structure. *Composites Science and Technology, **150**: 16-23*.
9. Chen S (2018) Polymer Based Nanocomposites as Multifunctional Structure for Space Radiation Shielding: A Study of Nanomaterial Fabrications and Evaluations. In: UWSpace; 2018.
10. Mesbahi A and Ghiasi H (2018) Shielding properties of the ordinary concrete loaded with micro- and nano-particles against neutron and gamma radiations. *Appl Radiat Isot, **136**: 27-31*.
11. Naseri A and Mesbahi A (2010) A review on photoneutrons characteristics in radiation therapy with high-energy photon beams. *Reports of Practical Oncology & Radiotherapy, **15**: 138-144*.
12. İrim ŞG, Wis AA, Keskin MA, *et al.* (2018) Physical, mechanical and neutron shielding properties of h-BN/Gd2O3/HDPE ternary nanocomposites. *Radiation Physics and Chemistry, **144**: 434-443*.
13. Malekzadeh R, Mehnati P, Sooteh MY, Mesbahi A (2019) Influence of the size of nano-and microparticles and photon energy on mass attenuation coefficients of bismuth–silicon shields in diagnostic radiology. *Radiological Physics and Technology*, *1-10*.
14. Hayashi T, Tobita K, Nakamori Y, Orimo S (2009) Advanced neutron shielding material using zirconium borohydride and zirconium hydride. *Journal of Nuclear Materials, **386**: 119-121*.
15. Wu Y, Zhang QP, Zhou D, Zhou Y-L, Zheng J (2017) Controlled synthesis of anisotropic lead borate crystals and its co-shielding of neutron and gamma radiations. *Journal of Alloys and Compounds, **727**: 1027-1035*.
16. Galehdari NA and Kelkar AD (2017) Effect of neutron radiation on the mechanical and thermophysical properties of nanoengineered polymer composites. *Journal of Materials Research, **32(2)**: 426-434*.
17. Mehnati P, Malekzadeh R, Sooteh MY (2019) Use of bismuth shield for protection of superficial radiosensitive organs in patients undergoing computed tomography: a literature review and meta-analysis. *Radiol Phys Technol, **12(1)**: 6-25*.
18. Cataldo F and Prata M (2019) Neutron radiation shielding with PUR composites loaded with B4C or graphite. *Fullerenes, Nanotubes and Carbon Nanostructures*, *1-7*.
19. Sakurai Y, Sasaki A, Kobayashi T (2004) Development of neutron shielding material using metathesis-polymer matrix. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **522(3)**: 455-461*.
20. Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine, **151 (4)**: 264-269*.
21. Park JS, Kim J, Yi SH (2017) Effects of Gadolinium in Fe based amorphous ribbons with high boron contents on the neutron shielding efficiency. *Ann Nucl Energy, **109**: 365-369*.
22. Sarıyer D, Küçer R, Küçer N (2015) Neutron shielding properties of concretes containing boron carbide and ferro – boron. *Procedia - Social and Behavioral Sciences,* **195**: 1752-1756.
23. Özdemir T and Yılmaz SN (2018) Hexagonal boron nitride and polydimethylsiloxane: A ceramic rubber composite material for neutron shielding. *Radiat Phys Chem, **152**: 93-99*.
24. Shtansky DV, Firestein KL, Golberg DV (2018) Fabrication and application of BN nanoparticles, nanosheets and their nanohybrids. *Nanoscale, **10(37)**: 17477-17493*.
25. Kim J, Jun J, Lee MK (2014) Particle size-dependent pulverization of b4c and generation of b4c/sts nanoparticles used for neutron absorbing composites. *Nuclear Engineering and Technology, **46(5)**: 675-680*.
26. Kipcak AS, Gurses P, Derun EM, Tugrul N, Piskin S (2013) Characterization of boron carbide particles and its shielding behavior against neutron radiation. *Energy Conversion and Management, **72**: 39-44*.
27. Zhou D, Zhang QP, Zheng J, Wu Y, Zhao Y, Zhou YL (2017) Co-shielding of neutron and γ-ray with bismuth borate nanoparticles fabricated via a facile sol-gel method. *Inorg Chem Commun, **77**: 55-58*.
28. Lee MK, Lee JK, Kim JW, Lee GJ (2014) Properties of B4C-PbO-Al(OH)3-Epoxy nanocomposite prepared by ultrasonic dispersion approach for high temperature neutron shields. *J Nucl Mater, **445(1-3)**: 63-71*.
29. Soltani Z, Beigzadeh A, Ziaie F, Asadi E (2016) Effect of particle size and percentages of Boron carbide on the thermal neutron radiation shielding properties of HDPE/B4C composite: Experimental and simulation studies. *Radiat Phys Chem, **127**: 182-187*.
30. Kaloshkin SD, Tcherdyntsev VV, Gorshenkov MV, Gulbin VN, Kuznetsov SA (2012) Radiation-protective polymer-matrix nanostructured composites. *J Alloys Compd, **536**: S522-S526*.
31. Kim J, Lee BC, Uhm YR, Miller WH (2014) Enhancement of thermal neutron attenuation of nano-B4C, -BN dispersed neutron shielding polymer nanocomposites. *J Nucl Mater, **453**: 48-53*.

32. Mortazavi SMJ, Kardan M, Sina S, Baharvand H, Sharafi N (2016) Design and fabrication of high density borated polyethylene nanocomposites as a neutron shield. *Int J Radiat Res,* ***14(4)****: 379-383*.
33. Artem'ev VA (2003) Estimate of neutron attentuation and moderation by nanostructural materials. *Atomic Energy,* ***94(4)****: 282-285*.
34. Jaewoo Kim YRU, MinKu Lee, Hee Min Lee, Chang Kyu Rhee (2008) Neutron shielding characteristics of nano-B2O3 dispersed Poly Vinyl Alcohol *Transactions of the Korean Nuclear Society Spring Meeting,* 641-642.
35. Saif MJ, Naveed M, Asif HM, Akhtar R (2018) Irradiation applications for polymer nano-composites: A state-of-the-art review. *Journal of Industrial and Engineering Chemistry,* ***60****: 218-236*.
36. Stawarz S, Witek N, Kucharczyk W, Bakar M, Stawarz M (2018) Thermo-protective properties of polymer composites with nano-titanium dioxide. *Int J Mech Mater*. ***15:*** *585-599.*
37. Sabri JH, Hameed Alsarraf A, Hadi Mahdi K (2019) A Comparative Study for Micro and Nano shield of (PbO) composite for gamma Radiation. *Energy Procedia,* ***157****: 802-814*.
38. Galehdari NA and Kelkar AD (2016) Characterization of nanoparticle enhanced multifunctional sandwich composites subjected to space radiation. Paper presented at: ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)2016; Phoenix, Arizona, USA, November 11–17, 2016.
39. Li X, Wu J, Tang C, *et al.* (2019) High temperature resistant polyimide/boron carbide composites for neutron radiation shielding. *Composites Part B: Engineering,* ***159****: 355-361*.
40. Kara Ü, Tekin HO, Calik A, Akkurt I (2015) Performance of boron-carbide as radiation shielding. *ACTA PHYS POL A,* ***128(2)****: 335-336*.
41. Kim J, Lee BC, Uhm YR, Miller WH (2014) Enhancement of thermal neutron attenuation of nano-B4C, -BN dispersed neutron shielding polymer nanocomposites. *J Nucl Mater,* ***453(1)****: 48-53*.
42. Koops L (2013) Size effects on the efficiency of neutron shielding in nanocomposites – a Full-Range Analysis. *International Journal of Nanoscience,* ***12(3)****: 135*.
43. Mesbahi A (2012) Does concrete composition affect photoneutron production inside radiation therapy bunkers? *Japan Radiological Society,* ***30****: 162–166*.
44. DiJulio DD, Cooper-Jensen CP, Llamas-Jansa I, Kazi S, Bentley PM (2018) Measurements and Monte-Carlo simulations of the particle self-shielding effect of B4C grains in neutron shielding concrete. *Radiat Phys Chem,* ***147****: 40-44*.
45. Mesbahi A, Alizadeh G, Seyed-Oskoee G, Azarpeyvand AA (2013) A new barite–colemanite concrete with lower neutron production in radiation therapy bunkers. *Ann Nucl Energy,* ***51****: 107-111*.
46. Kharita M, Yousef S, AlNassar M (2011) Review on the addition of boron compounds to radiation shielding concrete. *Progress in Nuclear Energy - Prog Nucl Energy,* ***53****: 207-211*.
47. Mesbahi A and Shirazi A (2011) Photoneutron production and backscattering in high density concretes used for radiation therapy shielding. *Ann Nucl Energy,* ***38****: 2752–2756*.
48. Mesbahi A and Mahdavi SR (2011) Photoneutron and capture gamma dose calculations for a radiotherapy room made of high den sity con crete. *Nuclear Technology & Radiation Protection,* ***26:*** *147-152.*
49. Park J, Suh H, Woo SM, Jeong K, Seok S, Bae S (2019) Assessment of neutron shielding performance of nano-TiO2-incorporated cement paste by Monte Carlo simulation. *Prog Nucl Energy,* ***117****: 103043*.
50. Tekin HO, Singh V, Kara Ü, Manici T, Altunsoy Guclu E (2016) Investigation of Nanoparticle Effect on Radiation Shielding Property Using Monte Carlo Method. *Celal Bayar Üniversitesi Fen Bilimleri Dergisi,* ***12(2)****: 195-199.*
51. Tekin HO, Singh VP, Manici T (2017) Effects of micro-sized and nano-sized WO3 on mass attenauation coefficients of concrete by using MCNPX code. *Appl Radiat Isot,* ***121****: 122-125*.
52. Tekin HO, Sayyed MI, Issa SAM (2018) Gamma radiation shielding properties of the hematite-serpentine concrete blended with WO3 and Bi2O3 micro and nano particles using MCNPX code. *Radiat Phys Chem,* ***150****: 95-100*.