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Effectiveness of using Polyethylene and 5% Borated Polyethylene for Radiation Shielding in Spacecraft

Md Akhlak Bin Aziz[1], Md. Fazlul Huq[2], Zahid Hasan Mahmood[3] and Khorshed Ahmad Kabir[2]

[1]The University of Manchester, Department of Nuclear Science and Technology
School of Physics and Astronomy, Manchester M13 9PL, UK

[2]Department of Nuclear Engineering, University of Dhaka, Dhaka–1000, Bangladesh

[3]Department of Electrical and Electronic Engineering, University of Dhaka, Dhaka–1000, Bangladesh

E-mail: fazlul.huq@du.ac.bd

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ABSTRACT

Polyethylene composites are good absorbers of low energy neutrons that can find applications as structural material inside spacecraft. Polyethylene and 5% borated polyethylene fabricated using conventional polymer processing techniques were evaluated for radiation shielding properties. Count rate variation of thermal neutrons was observed experimentally by placing sheets of polyethylene and 5% borated polyethylene of variable thickness in between an Americium-Beryllium source and He-3 detector and then compared with simulation results obtained by modelling the experimental setup using Monte Carlo n-Particle (MCNP) code version 4c. MCNP results verified the experimental findings that showed 5% borated polyethylene provides much improved radiation shielding compared to neat polyethylene.

Keywords: Polyethylene, Borated Polyethylene, Radiation Shielding, Thermal Neutrons.

1. Introduction

Human space exploration was enhanced with the advancement of the International Space Station (ISS) before which Human Exploration and Development of Space (HEDS) was mostly limited to low earth orbit (LEO) [1]. Radiation shielding of manned spacecraft is now becoming increasingly important both for distant missions and near earth missions such as to the International Space Station [2]. Protecting both the astronauts and the equipment from radiation hazards is one of the highest priorities set by the space agencies including NASA [3].

Travelling to different planets will take the astronauts outside the van Allen belts and expose them to an increased radiation environment that will include galactic cosmic rays (GCRs) and solar energetic particle (SPE) events. Missions to Mars had to satisfy the radiation tolerance criteria [4] and are still being questioned [5]. Integrating proper shielding materials in the spacecraft design to form habitat shields and radiation 'storm' shelter can ensure radiation protection. Incorporating such shielding materials can get complex due to spacecraft limitations [6, 7]. Space solar radiation is composed of galactic cosmic rays and solar energetic particles [10]. Solar energetic particles are mostly low energy protons [8] and neutrons. Apart from safeguarding against biological damage, neutrons must also be shielded to prevent secondary emission of gamma rays. Galactic cosmic rays are composed of elements from hydrogen to nickel and have energy spectra from 10 MeV to millions of MeV [9]. Materials having low atomic numbers, particularly those with high hydrogen content break down GCR into less damaging particles producing less secondary particles [11].

In the current research, the effect of using such materials with high hydrogen content like polyethylene and 5% borated polyethylene have been tested to shield neutrons that can further cause secondary gamma emissions. Polyethylene and 5% borated polyethylene were tested both experimentally and using MCNP version 4c and then the results were compared to suggest the better one.

2. Related Works

In 1991 NASA identified polyethylene as a useful structural polymer for spacecraft shielding from Galactic Cosmic Ray. Forming high-density fiber with polyethylene matrix and bonding the resulting composite face sheets to form polyethylene sheets still remained a challenge [14]. It was shown later in 2001 that use of aliphatic/aromatic hybrid polymers is an improvement to pure aliphatic system and materials like Carbon nanotubes with high hydrogen content enhanced radiation protection [15]. In 2008 it was observed that adding Boron to composites like nitrides gave significant improvement in results. Only 2wt% born nitride showed much improved radiation shielding than 100% polyethylene [10]. Before being utilized for evaluating mechanical and radiation shielding properties, boron nitride powder surfaces fabricated using polymer processing techniques were functionalized to improve interfacial adhesion. Novel ultra light structures were later tested for the attenuation of gamma rays and thermal neutrons and it was observed that borated water attenuated most, followed by water and metals [13]

3. Methods

3.1 Experiment

To study the effectiveness of polyethylene and 5% borated polyethylene for neutron shielding, an experiment was carried out with an Americium-Beryllium source taken inside a water tank. Polyethylene and 5% borated polyethylene sheets of variable thickness were placed in between the He-3 detector and the water tank. Figure 1 shows the cross-section of the experimental setup.

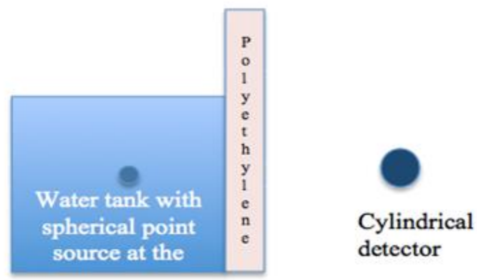

Fig. 1: Cross-section of the experimental setup used.

The Americium-Beryllium point source of activity 1.25 x 106 neutrons/second was placed at the center of the water tank of dimensions 118×59×70 cm3. The cylindrical He-3 detector of diameter 5 cm and length 105 cm was placed 60 cm away from the source and was used to detect thermal neutrons. Polyethylene sheets of each 2 cm thickness were placed one by one beside the water tank and corresponding shielding effects were observed using the He-3 detector. Then the entire experiment was repeated with 5% borated polyethylene instead of polyethylene.

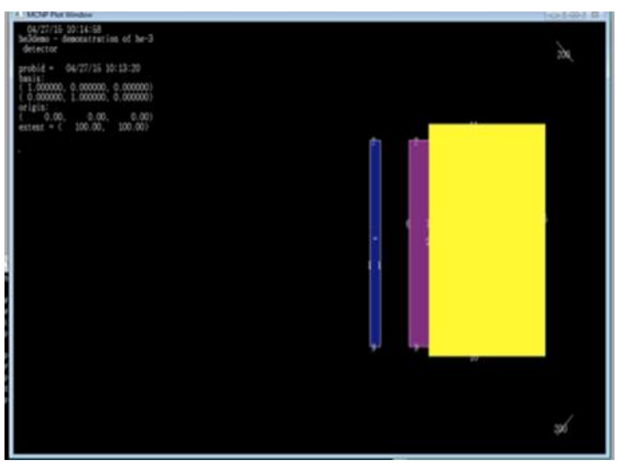

Fig. 2: MCNP geometry plot bird's eye view

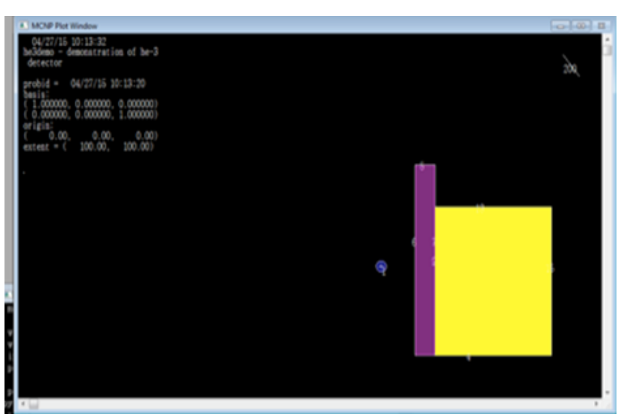

Fig. 3: MCNP geometry plot cross-sectional view

3.2 Modeling

To validate the results, they were compared with Monte Carlo n- Particle (MCNP) code simulation outputs. The same experimental setup or the geometry was modeled using MCNP and the results were compared with the corresponding simulation outputs. Figure 2 and 3 show the MCNP geometry modeled for the simulations.

4. Results

4.1 Experimental results

Figure 4 shows the experimental results of count rate and their corresponding distances for 100% polyethylene.

With an increase in the thickness of polyethylene, there is an initial rise in count rate. This is because the polyethylene moderated the neutrons and increased the chances of neutrons being detected (as the detector has a higher cross section for moderated neutrons). With further increase in the moderator thickness, the count rate declined. The maximum count rate is at a thickness of 6 cm and the count rate falls after that. The decline was due to hydrogen capture and also because with increased material the scattering increased and the neutrons were not detected in the solid angle covered by the detector.

Figure 4 also shows the experimental results of count rate and their corresponding distances for 5% Borated polyethylene.

From figure 4 it is observed that with increase in 5% borated polyethylene thickness, there is a decrease in the count rate. It is unlike the case of polyethylene where count rate increases first and then decreases. This is because the boron in the 5% borated polyethylene that has very high thermal neutron microscopic absorption cross-section of 767 barns absorbed the neutrons thermalized by polyethylene [14]. But the decrease is small because there is only 5% boron in the polyethylene. A greater percentage of boron could have led to a sharper fall in the count rate.

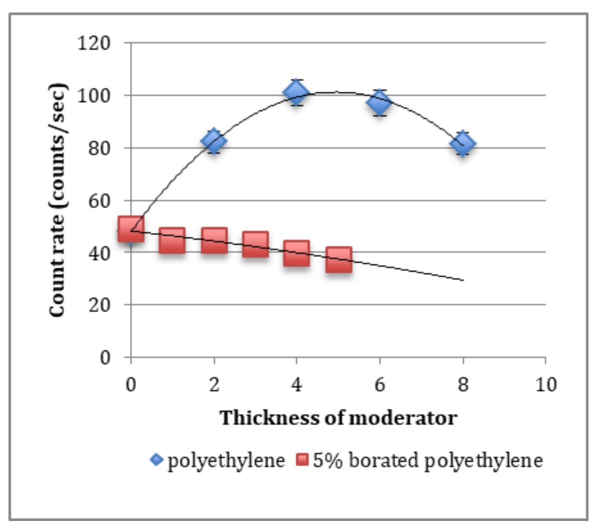

Fig. 4: Experimental output showing count rate variation of detected neutrons with polyethylene thickness (cm) and with 5% borated polyethylene thickness (cm).

4.2 Simulation results

Figure 5 shows simulation results of the count rate versus thickness graphs of polyethylene and 5% borated polyethylene using the geometry plots of MCNP.

The shape of the output for polyethylene is similar to the experimental output but the magnitude of the count rates is different. Like the experimental output, with an increase in the thickness of polyethylene, there is an initial rise in count rate. The neutrons got moderated by polyethylene that increased their chance of being detected. Further increase in the moderator thickness caused hydrogen capture and scattering which slowly decreased the count rate. The magnitude of count rate differs from the experiment because the exact condition in the lab could not be replicated by MCNP. Neutrons were reflected and scattered by the concrete walls, ceiling, floor, humans inside the lab etc. back to the detector that increased the experimental count rate.

For 5% borated polyethylene, it was observed that with increase in thickness the count rate increases a little but drops off sharply from a thickness of 6 cm.

Initially the increase was due to moderation of the neutrons by the polyethylene. With further increase in thickness the count rate fell more sharply compared to polyethylene. This fall in count rate is because of the presence of boron that has very high microscopic absorption cross-section. Boron absorbs the neutrons thermalized by the polyethylene.

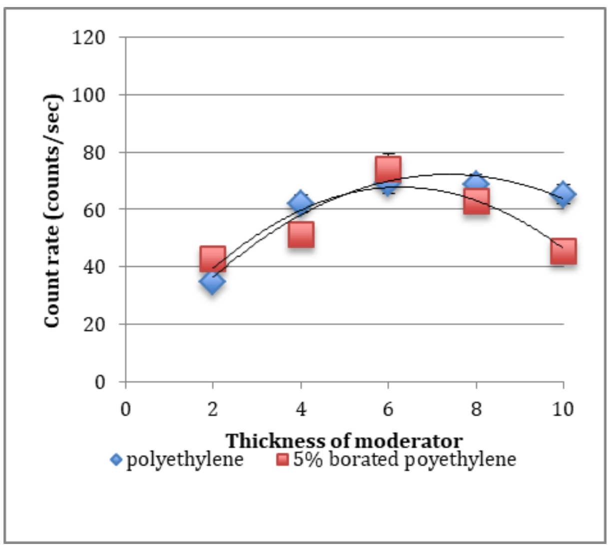

Fig. 5: MCNP output showing variation of count rate of incident neutrons with polyethylene thickness (cm) and 5% borated polyethylene thickness (cm).

5. Discussions

The results of polyethylene show that after an initial rise in count rate shielding of neutrons starts from a thickness of 6 cm. But effective shielding that is drop in count rate from the level without any shielding starts at thickness much higher than 10 cm. Therefore, polyethylene can be used as a shielding material inside spacecraft only if a thickness of much greater than 10 cm shields can be accommodated. Polyethylene starts shielding neutrons only after the hydrogen content increases to a certain extent leading to hydrogen capture. Before that instead of blocking neutrons, polyethylene moderates fast neutrons and increases thermal neutron counts that may ultimately lead to secondary emission of harmful gamma rays.

Experimental results show that there is a linear decrease in count rate with increase in thickness of 5% borated polyethylene. Simulation results also show that effective shielding can be obtained from a thickness of 10 cm. As a result, even with smaller thickness of 5% borated polyethylene a greater shielding can be obtained than with neat polyethylene. Therefore, 5% borated polyethylene can find useful applications as radiation shielding material inside spacecraft. Moreover, there is an optimum thickness of polyethylene where the count rate of thermal neutrons is maximum. In applications like submarines, moderator and shielding material choice has many constraints like weight, volume etc. In such application or other applications where polyethylene can be used as moderator, this optimum thickness can be utilized to fix the moderator thickness so that the thermal neutron intensity is enhanced.

It has already been shown that 2 wt% boron nitride composite showed much improved radiation shielding than neat polyethylene [10]. Addition of boron to 5% will enhance shielding. But continuous increase in boron will not be very much advantageous if the neutrons do not reach thermal energies [10]. Ratio of boron can be increased further keeping in balance with moderation by the hydrogen content. Researches by NASA show liquid hydrogen remains the optimal shielding material [12] but it is recommended to explore new multifunctional materials with greater hydrogen content than polyethylene [12]. Novel ultra-light structure based on open cell foams of borated water also gives good thermal neutron shielding [13]. Polyethylene based materials do not produce secondary long-lived or high-energy gamma emitting progeny. With similar shielding properties and only 1/3 density of its competitor aluminium [10], polyethylene is more widely used as a shielding material. With better results than polyethylene as shown, 5% borated polyethylene is more vocal than polyethylene for usage as low energy neutron shielding material in and around nuclear reactors and more importantly in spacecraft.

6. Conclusions

Neutron sources in outer space can be of variable energies. Polyethylene effectively shields thermal neutrons but for variable energies it effectively shields neutrons after a thickness greater than 10 cm. At thickness of less than 6 cm it acts as a moderator and increases the concentration of thermal neutrons. But 5% borated polyethylene shields effectively with increasing thickness. In 5% borated polyethylene, the sufficient amount of polyethylene present moderates the neutrons and the boron with high absorption coefficient absorbs the moderated neutrons. As a result, 5% borated polyethylene will provide better results than neat polyethylene for shielding neutrons inside spacecraft.

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