

Onboard Radiation Shielding Estimates for Interplanetary Manned Missions

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The main focus of space related shielding design is to protect operating systems, personnel and key structural components from outer space and onboard radiation. This paper summarizes the feasibility of a lightweight neutron radiation shield design for a nuclear powered, manned space vehicle. The Monte Carlo code MCNP5 is used to determine radiation transport characteristics of the different materials and find the optimized shield configuration. A phantom torso encased in air is used to determine a dose rate for a crew member on the ship. Calculation results indicate that onboard shield against neutron radiation coming from nuclear engine can be achieved with very little addition of weight to the space vehicle. The selection of materials and neutron transport analysis as presented in this paper are useful starting data to design shield against neutrons generated when high-energy particles from outer space interact with matter on the space vehicle.

***KEYWORDS: space radiation, radiation shielding, MCNP, space
nuclear reactors***

1. Introduction

The prospect of manned space missions outside Earth's orbit is limited by the travel time the crew would spend in space. The chemical rockets currently used in the space program have no hope of propelling a manned vehicle to a far away location (like travel to Mars or even Jupiter and Pluto) due to the enormous mass of fuel that would be required. Several new propulsion designs have been theorized that could allow a manned vehicle to travel very large distances and return home safely [1 - 4]. The use of nuclear technology for such an advanced propulsion system is obviously advantageous due to the large energy capacity of nuclear fuel. However, the radiation emitted from nuclear propelled engines on board the ship is required to be attenuated to the levels allowable for to the crew and estimated travel time. Land based reactor systems use a great deal of stainless steel and concrete for radiation shielding. These materials are far too heavy to send into orbit and use in a space vehicle. This paper evaluates the possibility of constructing a radiation shield from lightweight materials that will provide safe protection for the crew and low neutron radiation doses for the duration of a long term space flight. This same analysis will be used later to determine the shield against neutrons generated when high-energy particles from outer space interact with materials in space vehicle.

2. Computational Models

The Monte Carlo code MCNP5 was used to evaluate the neutron flux distribution through several shield configurations. The selection of shield materials is based on the following criteria: to use a reflector to redirect the incident neutrons, to use elastic scattering collisions to lower the energy, and then remove slowed-down neutrons from the system with a strong but light absorber material. In first step of optimization we analyzed the effect of material spatial position in the shield and how the overall attenuation responds to different orientation of the materials. Once we selected the best combination and thickness of each of material constituents in the shield, we proceeded with the shield design for a given neutron flux intensity and energy spectrum, and calculated the dose on a phantom torso placed at 1m from the neutron shielded source.

2.1 Optimization of the Radiation Shield Configuration

Firstly we analyzed how the orientation of the specially selected materials would affect the overall shield arrangement and efficiency of these materials to achieve low doses and low weight of the shield. We use a slab 0.9m long with a cross-sectional area of 1m². Since the design of the space propulsion system is not known, we have selected the intensity of incident neutron beam to be 10¹² n/cm²s and assumed all neutrons are monoenergetic having energy of 14 MeV. These two values although selected arbitrarily do represent the highest expected neutron intensity and neutron energy for the possible engine types (fusion, antimatter or fission based, or the combination of those). The thickness of all materials at first was selected to be 30cm. The choice of materials was based on their density and neutron cross sections. Table 1 summarizes the materials we selected for shielding design, [5]

Table 1 Selected shielding materials [5]

Material	Density (kg/m ³)	Components	Atomic Fraction
AS4 / 3502 graphite/epoxy composite	1.578	C-natural	0.737823
		H-1	0.214368
		O-16	0.022268
		N-14	0.020364
		N-15	0.000076
		S-natural	0.005102
Li ⁶ CO ₃ – loaded polyethylene	1.08	H-1	0.527656
		C-natural	0.295406
		O-16	0.100132
		Li-6	0.076806
B ¹⁰ – loaded polyethylene	0.92	H-1	0.624741
		C-natural	0.310296
		B-10	0.064963

All materials containing hydrogen spread the neutron population over broad range of energies due to large energy loss per single collision event. The additives such as boron

or lithium reduce the neutron population in low energy region because of the strong affinity toward neutron absorption as shown in “Figure 1.” The Li-6 loaded polyethylene (Li⁶ PE) has an absorption peak around 300 keV higher than the B-10 loaded polyethylene (B¹⁰ PE). The graphite/epoxy composite has good reflective properties at high energies (>10 MeV), [5].

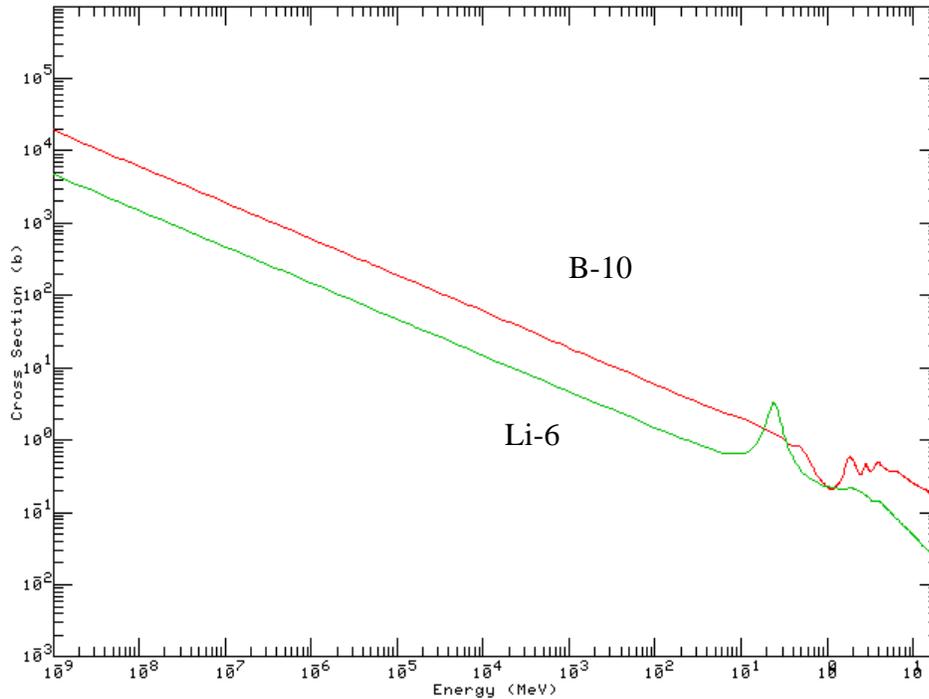


Fig. 1: Absorption cross section for B-10 and Li-6 [8]

Table 2 lists the arrangement of these materials as we used to find the most promising combination in terms of shield efficiency, and its weight. The material listed first is the one closest to the neutron source.

Table 2 Shield Material Configurations

Configuration 1	Epoxy Composite / Li ⁶ PE / B ¹⁰ PE
Configuration 2	Li ⁶ PE / Epoxy Composite / B ¹⁰ PE
Configuration 3	B ¹⁰ PE / Li ⁶ PE / Epoxy Composite

It was presumed that Configuration 1 would give the best shielding properties. It makes sense to have the reflector first because anything that gets reflected away from the shield doesn't have to be stopped by the shield. Also, the Li⁶ PE absorbs higher energy neutrons than the B¹⁰ PE so it should be placed nearer to the shield. The main difference imposed by the material placement was in the flux shape out of the shield. The carbon content of the composite material is a good moderator however it absorbs no neutrons so

the soft flux is increased. On the other hand, the polyethylene materials are good in moderating and absorbing neutrons. It should be noted that the composite material is a good reflector for high energy neutrons; however below $\sim 600\text{keV}$ these properties are nearly nonexistent. This means that having the composite material after one of the other components is a waste of space. This was seen in the transmitted flux of Configuration 2 and being several orders of magnitude higher than the other configurations as shown in “Figure 2.”

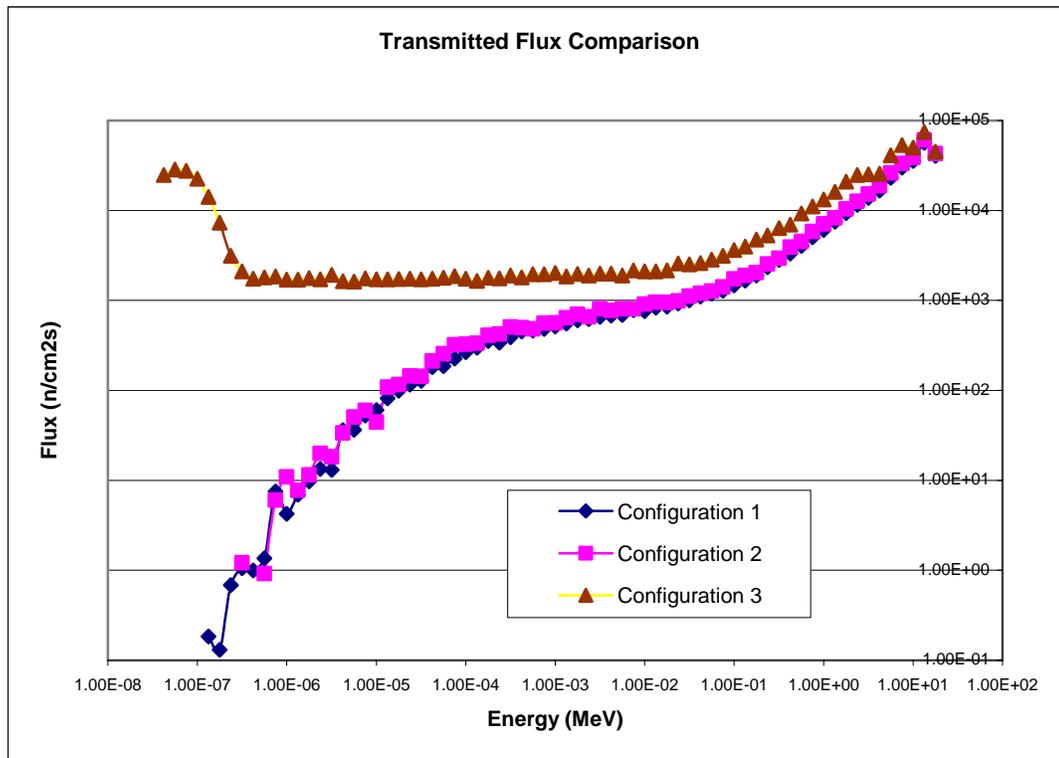


Fig. 2: Transmitted flux comparison of three neutron shield configurations

2.2 Flux Attenuation Optimization

After we understood the best arrangement of materials, we used that to design a shield that would provide best possible protection from an incident flux of $10^{12}\text{n/cm}^2\text{s}$ 14MeV neutrons using lightweight materials. The materials used are described in Table 3. Regular polyethylene is added as a moderator and the aluminum serves as the reflector. The components are sandwiched together in the order as listed, with a layer of polyethylene between the reflector and the Li^6PE . “Figure 3” shows a schematic of the shield. The total length of the shield is 1.5m. A region of air is added after the shield. The neutron flux spatial and energy distribution through this shield is given in “Figure 4.” From this figure we can see how the neutron flux changes through the shield components. The near side of the figure is the farthest from the neutron source. The polyethylene material drives the flux into the low energy regions (0.1 eV). The B^{10}PE and Li^6PE continue this trend but also remove low energy neutrons. This explains the “humps” in flux distribution, “Figure 4.” The reason for the large drop in flux between the last two

sections is that the last section is B¹⁰ PE 50cm thick. “Figure 5” shows the overall transmitted flux distribution out of the shield. These values are used to compute the radiation dose.

Table 3. Shield Components

Material	Density (g/cm ³)	Components	Atomic Fraction
Aluminum	2.7	Al-27	0.995
		Cu-63	0.005
Li ⁶ CO ₃ – loaded polyethylene	1.08	H-1	0.527656
		C-natural	0.295406
		O-16	0.100132
		Li-6	0.076806
Polyethylene	0.91	H-1	0.667954
		C-natural	0.332046
B ¹⁰ – loaded polyethylene	0.92	H-1	0.624741
		C-natural	0.310296
		B-10	0.064963

The overall shield weight per unit area is 1,580 kg/m². This area is dependent on the size of the reactor because only the side of the reactor facing the crew needs this much protection. If the reactor is only 0.5m² on the side facing the crew, the shield will not need to be as big if the side is 2m².

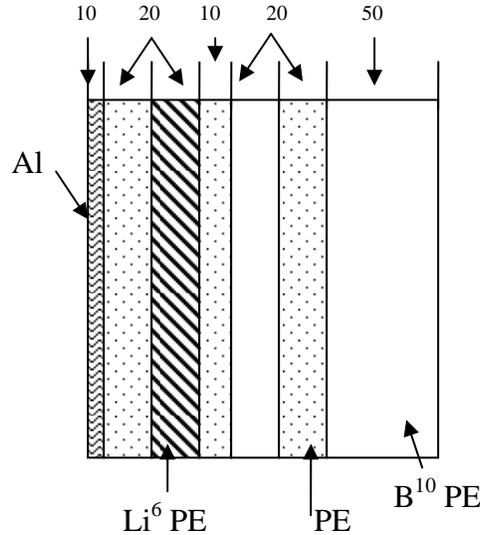


Fig. 3: Schematic of the radiation shield (for materials in Table 3). Thicknesses given in centimeters

3. Neutron Radiation Doses

The dose calculation was performed using the internal functions of MCNP, [6]. The phantom as we modeled in this stage of work, represents only a human torso and is

not detailed, though dimensions and weight of the torso are reasonably selected (the phantom is a box, 0.6m tall, 0.4m wide and 0.225m deep).

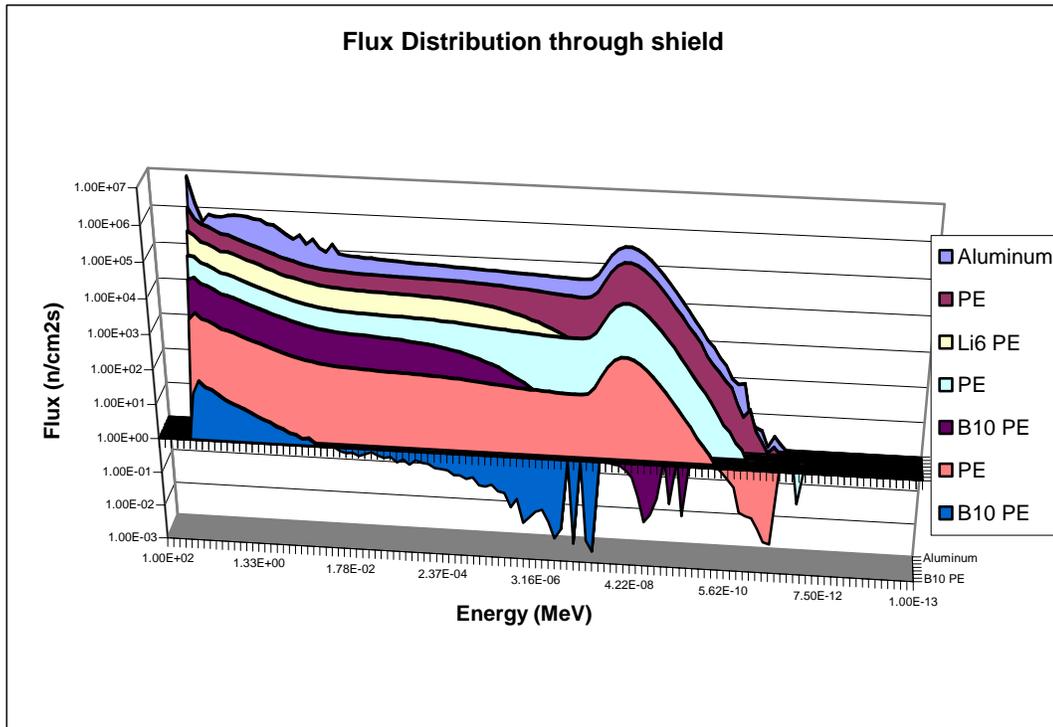


Fig.4: Flux distribution through the radiation shield (MCNP)

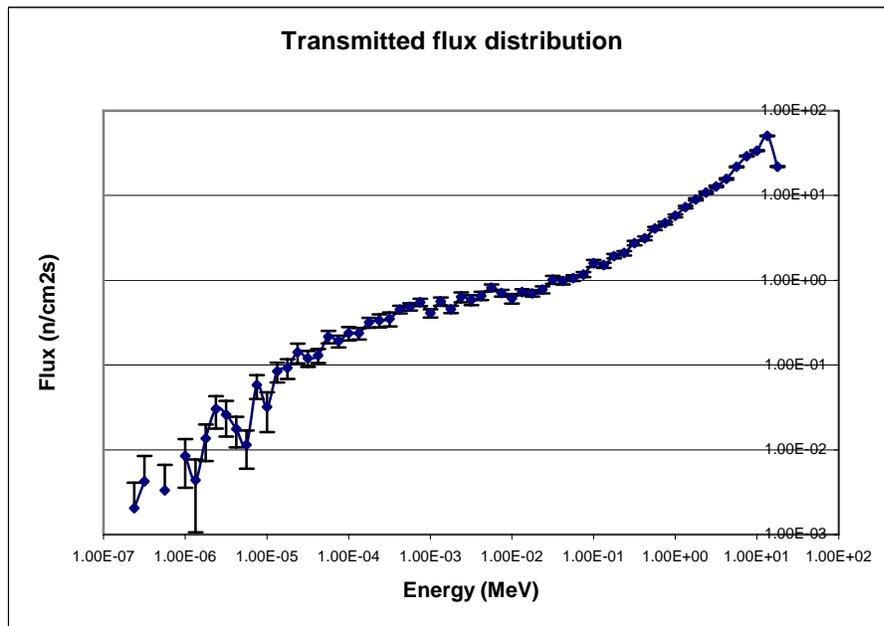


Fig.5: Transmitted flux distribution at back edge of shield (right side of Figure 1)

The dose received by the phantom at 1m from the shield was calculated to be 69mR/hr. This is promising considering the simplicity of the model we applied in this stage of optimization. In addition we did not take into account the effects of any of structural components that will exist between the nuclear engine and crew and thus additionally attenuate the radiation intensity. Also, based on current theoretical designs it is unlikely that the crew will be within a few meters of the reactor during operation, [5]. NASA recommendation, following NCRP guidelines, suggests that astronauts should not receive more than 50 Rem for the duration of a trip, [7]. This means that if a crew member were to be in front of the shield for more than an hour they would go over their allowable limit. However, as previously stated, current theoretical designs have crew members as far from the reactor as possible for the duration of reactor operation. Changing some of the shield components should reduce the flux even more, for instance utilizing the resonance absorption properties of dysprosium. Though they are much denser than the polyethylenes used here, small amounts of these materials could prove very useful. Heat removal from the shield is not analyzed yet. This consideration remains for future studies.

4. Conclusion

If nuclear power is to be used in space travel new shield designs must be developed. The luxury of using concrete and steel on land is not available due to the extremely high cost per pound of launching material into space. Lightweight materials must be utilized to keep the overall mass of a radiation shield low and crew protection at a maximum. Many lightweight materials exist with excellent shielding properties that make such a shield feasible. Our preliminary study showed that onboard neutron shield can be successfully designed adding very little weight to the vehicle and still assuring low radiation doses.

This is our first step in space shielding design and optimization based on an assumed neutron flux intensity and simple computer model. The main focus of our future work will be to develop the model to include shielding from galactic cosmic radiation. In addition more complex models are planned to be used in order to include onboard ship layout, an accurate human phantom that will allow dose calculations at specific bodily organs, and galactic radiation interactions with the space vehicle materials.

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