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Shielding performance of honeycomb and foam structures in a magnetic field against spatial high-energy electron radiation

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ABSTRACT

Shielding against spatial high-energy electron radiation is essential to the success of space exploration. Honeycomb and foam systems, combined with a magnetic field, were proposed to shield against spatial high-energy electrons given the immense mass and large amount of secondary X-rays of a passive shield and the demand for a high-intensity magnetic field of an active method. The shielding capabilities of several structures were investigated using the Monte Carlo method. The influences of magnetic flux density and hollow cube size on shielding property were studied by simulating energy deposition in a Chinese male reference phantom. Results showed that the honeycomb and foam systems enhanced the shielding capability against high-energy electrons and reduced the penetration of secondary X-rays. The effective dose in the male phantom decreased with increasing magnetic flux density. The proposed structures exhibited excellent shielding capabilities with a small hollow cube. In addition, the foam structure performed better than the honeycomb structure. Thus, the presented systems may be used for space radiation protection in a high-energy electron environment.

1. Introduction

When crossing the Van Allen radiation belt, a spacecraft will inevitably encounter high-energy charged particles, including electrons and protons [1]. Moreover, during a long-term space mission, a spacecraft will experience a spatial high-energy charged particles environment. For example, Jupiter systems have nearly 5×10^5 $cm^{-2}{\cdot}s^{-1}$ electrons with 20 MeV as reported by the Galileo interim radiation electron model [2]. An extreme high-energy electron environment causes aerospace equipment failure [3] and radiation damage in astronauts [4]. Therefore, protection against high-energy electron radiation should be studied for future space programs.

To reduce the damage caused by high-energy electrons, the National Aeronautics and Space Administration and the European Space Agency have been conducting studies on high-energy electron shielding in the past decades [5–7]. Metal and polymer materials have been extensively used as passive shielding configurations against high-energy electrons [8–11]. To enhance shielding capability using a passive method, the interactions between electrons and matter should be reinforced by increasing the mass thickness of a shield. Consequently, the amount of secondary X-rays significantly increases because of the bremsstrahlung effect [12] and immense mass is required to achieve reasonable radiation exposure values [13]. For these reasons, alternatives to passive method have been investigated throughout the years; among the presented approaches, the active magnetic radiation shield system is one of the most interesting [14]. This system can deflect charged particles away from a spacecraft in a magnetic field via Lorentz force [15]. However, an active method requires a wide range of magnetic field with a magnetic flux density of several tesla (T), which is difficult to implement in engineering applications [16].

In the current study, honeycomb and foam systems, which consist of passive and active systems, were proposed to shield against spatial high-energy electrons in a magnetic field. The electrons in the vacuum cube of the honeycomb and foam structures are evidently deflected by a magnetic field, thereby resulting in re-interaction between electrons and matter. Consequently, these structures do not only enhance shielding capability, but also reduce magnetic flux density requirements. Moreover, compared with aluminum (Al)/vacuum with a multilayer configuration [17], the honeycomb and foam structures exhibit excellent mechanical properties [18,19]. In this study, we compared the shielding

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capability of the honeycomb and foam systems with those of conventional shielding methods using the Monte Carlo method. We also studied the influences of magnetic flux density and hollow cube size on shielding capability by calculating the effective dose in a male reference phantom.

In this work, we mainly investigated the shielding performance against 20 MeV electrons and their resultant secondary gamma/X-ray in space. And the realistic space environment in Jupiter systems, which includes electrons, protons, sulfur, will be studied in the next process. In addition, this configuration should be incorporated into a larger system to cover the major component of human and electronic risk in space environment.

2. Methods

To investigate the electron shielding performance of the honeycomb and foam structures, the Monte Carlo package Geant4 (version 10.01) was used in this study. This package includes simulations of electron transportation and electron interaction with matter in a magnetic field [20]. The reference physics list, QBBC, which contains standard electromagnetic and hadronic physics processes, was adopted to simulate particle interaction in space [21].

2.1. Theoretical models

Six configurations, namely, H-0, H-1, F-0, F-1, Al-0, and Al-1, were studied in this work. Al was selected as the shielding material because as a non-magnetic material, it has nearly the same magnetic permeability as that of vacuum, and thus, its effect on magnetic field distribution is negligible. The geometric models of the honeycomb, foam, and conventional passive shielding structures are shown in Fig. 1. We have not modeled a real foam but a regular grid to approximate a foam, without complex geometric model and numerous material compositions. The parameters of the shielding configurations are listed in Table 1. The honeycomb, which consisted of an outer cube (Al) and an inner cube (vacuum), was used in H-0 and H-1. The foam, which comprised an outer cube (Al) and several inner cubes (vacuum), was used in F-0 and F-1. The pure Al layer was used in Al-0 and Al-1. In addition, two thin Al layers (0.2 cm thick) were set on both ends of the honeycomb and the foam, and the size of the outer cube (parameter a) was 0.75 cm. H-0, H-1, F-0, F-1, and Al-0 were set with the same quality.

As shown in Fig. 1, a 45 cm × 45 cm radiation field with 20 MeV electrons was used to perpendicularly irradiate the six shielding configurations that measured 45 cm × 45 cm. A magnetic field was distributed throughout the entire shielding configuration along the +*x*-axis. The number of histories was set to 1×10^7 for all cases to enable simulation throughput and to be reasonably well assured that the tallies are stable but may not be converged.

2.2. Dose evaluation

The influences of magnetic flux density and hollow cube size (parameter a in Fig. 1) on shielding capacity were investigated. Magnetic flux density was set from 0 T to 1.6 T. The detailed parameters of the honeycomb and foam structures are listed in Table 2. As shown in Fig. 2, a 198 cm × 126 cm electron field with 20 MeV electrons was applied perpendicularly to irradiate the shielding structure along the +*y*-axis. A Chinese male reference phantom [22], which was designed using a polygonal mesh surface for flexibility and to achieve realistic results, was placed 50 cm away from the shielding structure. Considering the geometry construction precision and the calculation speed in the Monte Carlo code used in this study, the phantoms were voxelized with a resolution of 0.56 × 0.56 × 0.56 cm^3. After voxelization, the height and weight of male phantom are 170 cm and 63 kg, and the phantom sizes are 106 × 64 × 300 (N). We scored the energy deposition in 49 major tissues and organs to calculate effective dose.

The effective dose, *E*, is determined as the gender averaged and tissue or organ weighted summation of the equivalent doses.

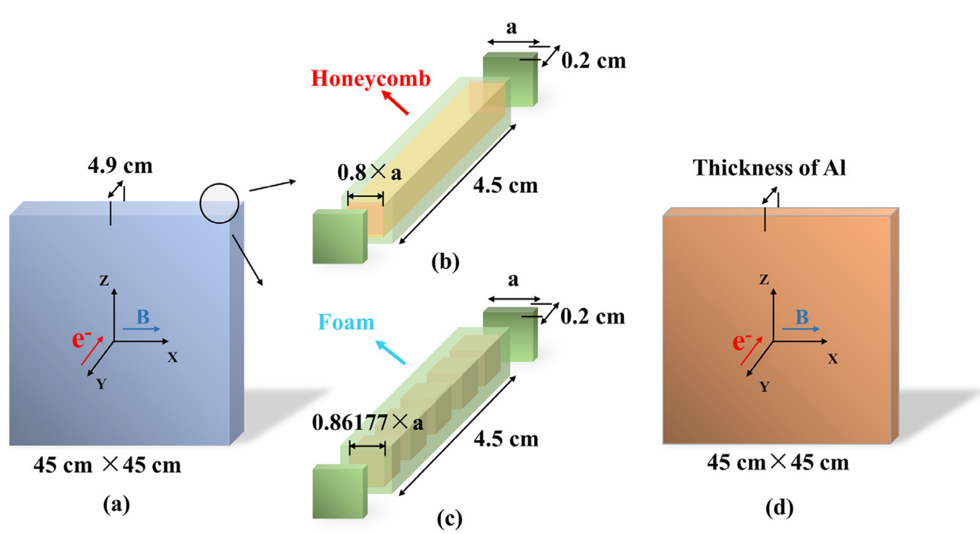

Fig. 1. Geometric models of the (a) honeycomb and foam system, (b) honeycomb structure, (c) foam structure, and (d) pure Al.

Table 1
Parameters of the six configurations.

Configuration	H-0	H-1	F-0	F-1	Al-0	Al-1
Type	Honeycomb	Honeycomb	Foam	Foam	Pure Al	Pure Al
Thickness (mm)	2 + 45 + 2	2 + 45 + 2	2 + 45 + 2	2 + 45 + 2	20.2	31
Magnetic flux density (T)	0	1	0	1	0	0