Acta Astronautica 144 (2018) 254–262

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Radiation production and absorption in human spacecraft shielding systems under high charge and energy Galactic Cosmic Rays: Material medium, shielding depth, and byproduct aspects

Joseph Barthel [*,1], Nesrin Sarigul-Klijn [2]

Space Engineering Research and Graduate Program (SpaceED), Mechanical and Aerospace Engineering Department, University of California, Davis, Davis, CA, 95616-5294, USA

ARTICLE INFO

Keywords:
Galactic cosmic rays (GCRs)
Solar particle events (SPEs)
Spacecraft shielding
Human safety
Electronics protection
Effective dose
Linear energy transfer (LET)

ABSTRACT

Deep space missions such as the planned 2025 mission to asteroids require spacecraft shields to protect electronics and humans from adverse effects caused by the space radiation environment, primarily Galactic Cosmic Rays. This paper first reviews the theory on how these rays of charged particles interact with matter, and then presents a simulation for a 500 day Mars flyby mission using a deterministic based computer code. High density polyethylene and aluminum shielding materials at a solar minimum are considered. Plots of effective dose with varying shield depth, charged particle flux, and dose in silicon and human tissue behind shielding are presented.

1. Introduction

The radiation environment of space consists of electromagnetic radiation and charged particles that have been accelerated to high velocities. The charged particles come from two major sources, Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR). Of the two, GCR are a chronic source of high energy radiation and may cause health risks to humans exposed to them for long periods of time [1], while the levels of damage caused by SPE may vary drastically with the strength, duration, and location of the solar event. GCRs are mostly light-to-heavy nuclei that have been stripped of electrons and accelerated in large magnetic fields of black holes or other galactic phenomena to energies from 100 MeV to over 1 TeV [2]. These nuclei are made up of most elemental nuclei from hydrogen to iron that have a positive charge due to electron stripping and comprise the majority of harmful radiation for humans and electronics in space. In addition, two rings of energetic particles trapped by Earth's magnetic field create a dynamic and severe environment called Van Allen belts affecting spacecraft orbiting Earth or on missions beyond Earth. Van Allen Belts start at altitudes in the order of 700 km with an inner/outer zone of 3700 km/27,000 km with the effects extending to about 50,000 km. The percentage of time in the Van Allen radiation belts is very low for new proposed concepts such as HERO [3]–less than 1% of each orbit. As a comparison, Molniya constellation satellites orbit in 12 h highly elliptical 500 km perigee by 39,900 km apogee orbits that are inclined 63.4° to the equator [4]. These satellites fly directly through the heart of the radiation belts while providing communication services for Russia. Sirius Satellite Radio flies a Tundra orbit, which is a 24 h highly elliptical geosynchronous orbit also at an inclination of 63°. It also flies directly through the heart of the radiation belts. Despite the new proposals designed to minimize flight through Van Allen Radiation Belts, spacecraft shielding is still essential to protect human and extend the life of electronics.

Charged particles are typically described by their energy per nucleon (MeV/u) and high-speed nuclei of charge greater than 2 (nuclei with more protons than helium) are referred to as HZE ions (High charge (Z) and Energy). HZE ions stripped of their electrons permeate free space and can travel large distances in material, sometimes breaking apart before being stopped, causing cascading showers of lighter nuclei split off from the original radiation. HZE ions can have energies upwards of 1 GeV which makes them difficult to stop in shielding material, and have been studied as significant potential risk factors to humans on long-duration space missions [5–12].

Studies have attempted to determine the minimum amount of shielding required to keep humans safe for a long-duration mission using

---

* Corresponding author.
E-mail addresses: josephmbarthel@gmail.com (J. Barthel), nsarigulklijn@ucdavis.edu (N. Sarigul-Klijn).

[1] Graduate Researcher, SpaceED and Ph.D. degree candidate in Mechanical and Aerospace Engineering.

[2] Professor and Director of SpaceED, 2132 Bainer Drive, 530.752.0682.

https://doi.org/10.1016/j.actaastro.2017.12.040
Received 16 August 2017; Received in revised form 6 December 2017; Accepted 27 December 2017

Nomenclature

SPE	Solar Particle Event
GCR	Galactic Cosmic Rays
HZE	High Charge and Energy
PEL	Permissible Exposure Levels
HDPE	High-Density Polyethylene
LET	Linear Energy Transfer
ICRP	International Commission on Radiological Protection
HZETRN	High charge (Z) and Energy TRaNsport computer code

Permissible Exposure Levels (PELs) that are given in overall total dose [13]. If HZE ions are found to be more hazardous than previously thought, more shielding may be required to insure the safety of humans within spacecraft.

2. Theory on shielding from charged particles

As GCR is comprised almost exclusively of charged particles, many of which being HZE ions, it is essential to understand the fundamentals of how charged particles interact with matter to effectively protect humans and electronics. Passive shielding can be an effective way to block or break down certain particle types and energies, but there are limitations.

2.1. Bethe-Bloch formula

The ability of a passive shielding material to stop incoming charged particles is based on its mass stopping power, *S,* which is given by the Bethe-Bloch equation,

$$\frac{S}{\rho} = -\frac{dE}{\rho dx} = 4\pi N_A {r_e}^2 m_e c^2 \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right] \tag{1}$$

where $\frac{dE}{dx}$ is energy change per length of shielding, ρ is the density of the material, N_A is Avogadro's number, r_e is the electron radius, m_e is electron mass, c is the speed of light, Z is the number of electrons in the material, A is the number of atoms in the material, z is the incoming radiation's charge, $\beta = v/c$ where v is the particle's velocity, I is the mean excitation potential of the passive shielding, δ is a density correction due to shielding from remote electrons by close electrons (giving a reduction of energy loss for high energies), and C is a shell correction term (important at very low energies) [14].

Important to note is that the stopping power is proportional to the inverse square of the incoming particle's velocity, and the square of its ion charge z. For the shielding material, the stopping power is proportional to its density, ρ, and to the ratio of number of electron to atoms Z/A. This means the best material for stopping incoming radiation is one with high density and a high charge per atom count, which occur in materials with lowest atomic numbers. High-density polyethylene (HDPE), with polymer chains made of CH_4, and water (H_20) are commonly chosen radiation shielding materials for their densities, 0.97 g/cm^3 and 1 g/cm^3 respectively, and proportionally low numbers of neutrons. Electron plasmas would be ideal however are much more difficult to sustain and utilize for shielding.

2.2. Bragg curves

The energy loss rate of a charged particle traveling through a material changes as it loses energy as shown by the Bethe-Bloch equation's $1/\beta^2$ term. Due to the random nature of interactions between any single incoming particle and the material it travels through, it is more useful to look at the energy loss of a beam of particles through the material instead of a single particle's path.

As a beam of charged particles enters a material, generally it will lose energy via frequent inelastic Coulomb interactions with electrons. Interactions with the target material's nuclei can occur through repulsive Coulomb elastic scattering with the nucleus and non-elastic nuclear interactions that can create secondary particles, though these are much less frequent [14]. A heavy ion breaking apart in material medium results in projectile fragments with an energy and direction very similar to the original heavy ion's. If the target material fragments from the interaction, the fragments are isotropic and low in energy, which results in subsequent absorption over relatively short distances [15].

The Linear Energy Transfer (LET) that results from inelastic Coulomb interactions with electrons is known as a Bragg curve, and can be seen for a hydrogen ion beam in Fig. 1 for energy levels of 55, 103, 205 and 250 MeV. The curve shape follows the Bethe-Bloch equation with energy loss proportional to z^2/β^2 until the particle beam is stopped.

HZE ions lose energy through the same inelastic Coulomb interactions, and if they do not have interactions with the target material's nuclei will be stopped in a shorter distance due to energy loss being proportional to *Z,* number of electrons in the material. Since the HZE ions can break apart via nuclear interactions when they do interact with the target material's nuclei, the shape of the Bragg curve no longer exclusively increases until the peak, as seen in Fig. 2.

The range for energy transfer in material is much shallower for HZE than similar energy levels of hydrogen ions (Fig. 3). For iron ions up to 1 GeV the range in water for LET would be slightly under 300 mm.

3. Radiation environment

GCRs comprise the majority of the radiation danger to humans during a long-duration mission and dose limits have been set for maximum

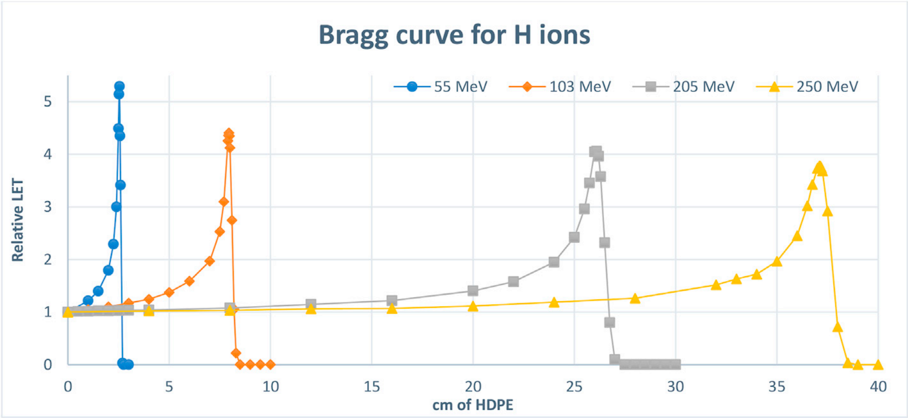

Fig. 1. The relative linear energy transfer of a beam of hydrogen ions (protons) traveling in HDPE. Energy loss follows the Bethe-Bloch equation until the beam loses its kinetic energy. (Experimental data from https://www.bnl.gov/nsrl/userguide/bragg-curves-and-peaks.php retrieved on Oct 21, 2016).