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# Analytical-HZETRN model for rapid assessment of active magnetic radiation shielding

S.A. Washburn [a,*], S.R. Blattnig [b], R.C. Singleterry [b], S.C. Westover [c]

[a] *Aerospace Engineering Sciences, University of Colorado at Boulder, Boulder, CO 80309-0431, USA*
[b] *NASA Langley Research Center, Hampton, VA 23681-2199, USA*
[c] *NASA Johnson Space Center, Houston, TX 77058-3696, USA*

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## Abstract

The use of active radiation shielding designs has the potential to reduce the radiation exposure received by astronauts on deep-space missions at a significantly lower mass penalty than designs utilizing only passive shielding. Unfortunately, the determination of the radiation exposure inside these shielded environments often involves lengthy and computationally intensive Monte Carlo analysis. In order to evaluate the large trade space of design parameters associated with a magnetic radiation shield design, an analytical model was developed for the determination of flux inside a solenoid magnetic field due to the Galactic Cosmic Radiation (GCR) radiation environment. This analytical model was then coupled with NASA's radiation transport code, HZETRN, to account for the effects of passive/structural shielding mass. The resulting model can rapidly obtain results for a given configuration and can therefore be used to analyze an entire trade space of potential variables in less time than is required for even a single Monte Carlo run. Analyzing this trade space for a solenoid magnetic shield design indicates that active shield bending powers greater than ~15 Tm and passive/structural shielding thicknesses greater than 40 g/cm$^2$ have a limited impact on reducing dose equivalent values. Also, it is shown that higher magnetic field strengths are more effective than thicker magnetic fields at reducing dose equivalent.

*Keywords:* Space radiation; Radiation exposure; Dose equivalent; Active shielding; Magnetic shielding; GCR

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## 1. Introduction

Radiation exposure remains one of the most challenging problems facing long-term, deep-space, human exploration missions. The hazards associated with long-term or chronic exposure to Galactic Cosmic Radiation (GCR) and acute exposure from Solar Particle Events (SPEs) threaten the feasibility of such missions (Townsend, 2005a; Durante and Cucinotta, 2011). Since these forms of radiation consist primarily of charged particles, one promising solution is the use of active radiation shielding. There are several general classes of active shielding (Townsend, 2005b), some of which include the use of magnetic fields. These designs take advantage of the Lorentz force, created by a charged particle moving through the magnetic field, which can be used to divert harmful radiation away from the crew. Although many technical advances need to be made in order to make these shields a reality (Townsend, 2005b; Spillantini, 2010), they hold the promise of potentially being able to reduce the radiation exposure received by astronauts to acceptable levels, at a significantly lower mass penalty than passive shielding only designs.

One of the techniques for assessing the effectiveness of such designs is the use of Monte Carlo analysis to determine crew radiation exposure. Unfortunately, Monte Carlo analysis is a lengthy and computationally intensive process. Days, or even weeks, can be required to analyze a single configuration, and this limits the ability to effectively evaluate a large trade space of design variables. This trade

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* Corresponding author. Tel.: +1 650 773 8561.
*E-mail address:* scott.a.washburn@colorado.edu (S.A. Washburn).

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space generally includes three primary variables: magnetic field strength, magnetic field thickness, and passive/structural shielding mass. A broad analysis of these variables would allow designers to select configurations suited to specific mission goals, including mission radiation exposure limits, duration, and destination.

This paper presents a rapid method to evaluate the active magnetic shielding trade space. This is accomplished by first developing an analytical model for the flux inside a solenoid magnetic field. The flux results are then coupled to the NASA High-Charge and Energy (HZE) radiation transport code, HZETRN (Wilson et al., 1995; Slaba et al., 2010a, 2010b), to account for passive shielding and structural mass effects. This method allows for the rapid evaluation of radiation exposure, specifically dose equivalent, over the trade space of variables so that a general design focus may be selected before continuing with more detailed and intensive modeling techniques.

Magnetic radiation shields generally fall into two design categories: toroidal, with the magnetic field lines curling around the habitat structure, and solenoidal, with the magnetic field lines running parallel to the central axis of the habitat. The analytical portion of this model was developed by focusing on the solenoidal design; however, these principles can be modified and applied to the toroidal case. By analyzing the solenoid design for a large range of magnetic field strengths, magnetic field thicknesses, and passive/structural shielding mass, some of the basic characteristics of such a design can be observed.

## 2. GCR flux

The Badhwar-O'Neill 2010 (BO'10) GCR model (O'Neill, 2010) is used in the current analysis to compute the ambient radiation field in deep-space. The BO'10 model provides the GCR energy spectrum from 1 MeV/n to $10^6$ MeV/n for elements with $Z = 1$ through $Z = 94$. This study only takes into account elements with $Z = 1$ through $Z = 28$, since the resulting dose equivalent for elements with $Z$ greater than 28 provides a negligible contribution to the total dose equivalent (Simpson, 1983). The model output is the differential flux, given units of particles-m$^{-2}$-s$^{-1}$-sr$^{-1}$-MeV/n$^{-1}$, and is assumed to be isotropic. The GCR model output used in this analysis is based on a solar modulation parameter value of 481 MV, corresponding to the 1977 solar minimum. This solar minimum results in one of the highest known GCR environmental exposures (Badhwar et al., 1994), providing a design basis for the shielding analysis. Periods of increased solar activity, such as at a solar maximum, would result in reduced exposure values. SPEs are not considered in this analysis since studies have shown that active shielding which is sufficient to reduce GCR dose will also effectively reduce SPE exposures (Wilson et al., 1997).

## 3. Charged particle motion in a magnetic field

The motion of charged particles as they pass through a magnetic field is governed by the Lorentz force equation, given by

$$\vec{F} = q\vec{v} \times \vec{B}, \tag{1}$$

where $q$ is the particle's charge, $v$ is the particle's velocity, and $B$ is the magnetic field strength. This force affects particle motion perpendicular to the magnetic field lines, while the velocity component parallel to the magnetic field remains unaffected. Since the high energy particles which comprise the GCR flux can have kinetic energies in the GeV/n range, relativistic equations must be utilized. The Lorentz force results in the particle's motion in the plane perpendicular to the magnetic field being circular. The equation for the radius of curvature of a charged particle in a magnetic field, which is also known as the Larmor radius or gyroradius (Griffiths, 1999), is given by

$$r_L = \frac{\gamma m_0 v_\perp}{qB}, \tag{2}$$

where $\gamma$ is the Lorentz factor, $m_0$ is the particle's rest mass, and $v_\perp$ is the particle's velocity component perpendicular to the magnetic field.

Eq. (2) demonstrates that as the energy, and therefore velocity, of a given particle increases, its Larmor radius will also increase, making the particle more difficult to deflect. Additionally, a higher magnetic field strength, $B$, results in a smaller Larmor radius, causing greater deflection of a given particle.

## 4. Analytical-HZETRN model development: infinite cylinder

### 4.1. Analytical component

In order to simplify the complex calculations for determining the GCR flux inside a magnetic field, an infinitely long, cylindrically shaped, solenoid magnetic field is examined using the following assumptions:

(1) the field is uniform in magnitude, and
(2) the field is confined to the boundaries of the cylindrical geometry, as shown in Fig. 1a.

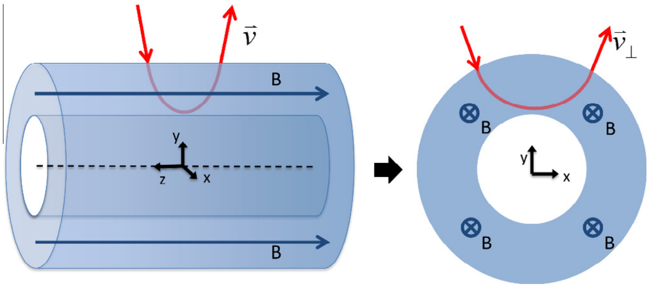

Fig. 1a. Infinite cylinder model and cross section.