Life Sciences in Space Research 7 (2015) 90–99

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

Neutron yields and effective doses produced by Galactic Cosmic Ray interactions in shielded environments in space

Lawrence H. Heilbronn [a,*], Thomas B. Borak [b], Lawrence W. Townsend [a], Pi-En Tsai [a], Chelsea A. Burnham [a], Rafe A. McBeth [b]

[a] Department of Nuclear Engineering, University of Tennessee, Knoxville, TN 37996-2300, United States
[b] Department of Environmental and Radiological Health Sciences, Colorado State University, Ft. Collins, CO 80523-1618, United States

ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 8 October 2015
Accepted 8 October 2015

Keywords:
Neutron spectra
Neutron Effective dose
GCR Monte Carlo simulation

ABSTRACT

In order to define the ranges of relevant neutron energies for the purposes of measurement and dosimetry in space, we have performed a series of Monte Carlo transport model calculations that predict the neutron field created by Galactic Cosmic Ray interactions inside a variety of simple shielding configurations. These predictions indicate that a significant fraction of the neutron fluence and neutron effective dose lies in the region above 20 MeV up to several hundred MeV. These results are consistent over thicknesses of shielding that range from very thin (2.7 g/cm^2) to thick (54 g/cm^2), and over both shielding materials considered (aluminum and water). In addition to these results, we have also investigated whether simplified Galactic Cosmic Ray source terms can yield predictions that are equivalent to simulations run with a full GCR source term. We found that a source using a GCR proton and helium spectrum together with a scaled oxygen spectrum yielded nearly identical results to a full GCR spectrum, and that the scaling factor used for the oxygen spectrum was independent of shielding material and thickness. Good results were also obtained using a GCR proton spectrum together with a scaled helium spectrum, with the helium scaling factor also independent of shielding material and thickness. Using a proton spectrum alone was unable to reproduce the full GCR results.

1. Introduction

The National Aeronautics and Space Administration (NASA) has identified radiation monitoring as a critical technology within the agency's Space Technology Roadmaps (Hurlbert et al., 2012). Within that framework, the development of compact, low-mass, low-power charged particle and neutron spectrometers that can be used for missions beyond LEO (low Earth orbit) is identified as a major challenge. The agency has set a goal of 2017 for the testing of newly developed radiation monitors, and as such it is critical to identify at this time what ranges of particles, energies, and flux to which these monitors must respond. In particular, it is critical to identify the key components of the neutron spectrum which must be measured, because the size, weight and cost of a neutron dosimeter are directly related to the neutron energies to which the instrument can measure.

Most of the neutron instrumentation flown in space has been responsive to low energy neutrons, from thermal energies up to 10 or 20 MeV. Badhwar et al. (2001) reviewed the neutron instruments and dosimeters flown on shuttle missions through 2000, including activation foils, track detectors, nuclear emulsions, passive dosimeters (TLDs) and Bonner spheres. More detailed information on these instruments may be found in Benton and Benton (2001). The reported range of neutron energies from these systems extends up to 14 MeV, with doses and dose equivalents reported for neutron energies up to 10 MeV. Those results were extended beyond 10 MeV either through model calculations of the neutron spectra or through using a simple exponential spectrum beyond that limit. Calculations reported in that paper predicted that 50% of the dose equivalent was above 10 MeV. The HEND (Mitrofanov et al., 2002) and LEND (Mitrofanov et al., 2008) detectors, which use a combination of ^{3}He counters, moderators, absorbers, and stilbene scintillators, measure neutrons from thermal energies up to 15 MeV, primarily for the purpose of finding subsurface hydrogen at Mars and the Moon. Another neutron instrument designed to find surface hydrogen on the Moon, the Lunar Prospector Neutron Spectrometer (Feldman et al., 1998), was designed to measure neutrons up to 1 MeV.

Bubble detectors (Lewis et al., 2012; Smith et al., 2013) have been used for neutron dosimetry and spectrometry in space, with

* Corresponding author.
E-mail address: lheilbro@utk.edu (L.H. Heilbronn).

http://dx.doi.org/10.1016/j.lssr.2015.10.005
2214-5524/

responses for some detectors reported out to energies of 300 MeV. The Radiation Assessment Detector (RAD) aboard the Mars Science Laboratory has characterized the neutron environment on Mars between energies of 8 and 740 MeV (Köhler et al., 2014), and to date represent the highest neutron energies directly measured in space.

There are essentially no neutrons in the primary space radiation environment. Instead, neutrons in space are created by GCR interactions with spacecraft, human, and habitat materials. As a GCR particle interacts with a target nucleus, the breakup of $Z > 1$ GCR particles releases neutrons generally in the forward direction (along the direction of the incoming GCR ion) and with high energies. The interaction also deposits a large amount of energy into the target nucleus, and as a result neutrons are released from the target. Those neutrons are generally isotropic in their angular distribution and have energies below 20–30 MeV. The overlap region between the GCR ion and the target nucleus also releases intermediate energy neutrons distributed at all angles. The multiplicity of neutrons from these interactions depends on the mass of the GCR ion and target nucleus, as well as the thickness of the shield. As such, the nature of the neutron energy spectrum depends greatly on the type of material and the thickness of the material, as well as the primary radiation environment incident upon those materials.

This study investigates the energy dependence in neutron spectra and neutron effective dose produced by Galactic Cosmic Rays (GCR) interactions in various thicknesses of two materials: aluminum and water. Using the transport model PHITS (Niita et al., 2010), the neutron yield (number of neutrons per incident GCR particle) as a function of neutron energy was calculated to determine (1) what fraction of the neutron spectrum lies within particular ranges of neutron energy, (2) what fraction of the neutron effective dose lies within particular energy neutron energy ranges, and (3) what fraction of the neutrons are produced by each ion species in the GCR. Determination of the fraction of neutron yield and neutron effective dose within particular regions of neutron energy will provide guidance on what neutron energy ranges are of importance for dosimetry instrumentation in space-based applications.

The baryonic component of the incident GCR field is complex, composed of atomic nuclei ranging from $Z = 1$ to $Z = 26$ (with the greatly reduced fluences above $Z = 26$ not considered here), and with energies between 10 MeV/nucleon and several TeV/nucleon (NCRP, 1989). Protons make up 87% of that component, with He nuclei making up 12%, and $Z > 2$ ions making up the remaining 1%. Those percentages can vary slightly with solar activity and solar cycle. Although the HZE component ($Z > 2$ component) makes up a small fraction of the baryonic fluence, previous calculations (Walker et al., 2013) have shown its contribution to the neutron yield cannot be neglected. As a result, GCR Monte Carlo transport model calculations require a complex source term and, in turn, can become time intensive in order to generate the desired statistical accuracy from some of the rarer components of the GCR field. In order to determine if the complexity of the source term could be reduced, the simulations were also used to study if a simplified GCR spectrum could be used for transport model calculations of GCR-induced neutron production, saving calculation time and effort. The simplification techniques considered here include (1) using a weighted GCR proton spectrum (weighting the overall normalization) to represent the entire GCR spectrum, (2) keeping the proton and He spectra unchanged but replacing interactions of all GCR HZE with a single HZE species, and (3) keeping the proton spectrum unchanged and weighting the He spectrum to represent the entire contribution from $Z \geq 2$ ions. Similar methodologies have been employed in previous studies of neutron production in Earth's atmosphere (O'Brien et al., 1992; Clem et al., 2004, 2003; Roesler et al., 2002), but none of those studies were compared with calculations that employed the full GCR spectrum. As such, the accuracy of the neutron flux resulting from calculations using those simplification techniques cannot be known. By determining the neutron energy spectrum produced by interactions from the individual components of the GCR separately, it is possible to investigate if a there is a reliable methodology that can use a simplification technique across different shielding scenarios that will accurately reproduce the neutron spectrum generated by the entire GCR spectrum.

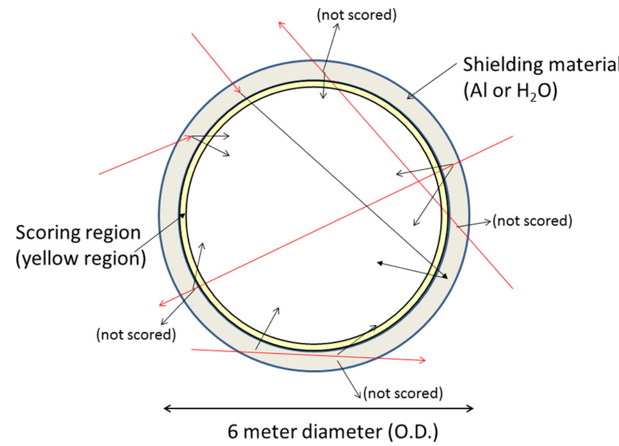

Fig. 1. GCR ions (red arrows) are isotropically incident upon a spherical shell of either Al or water. Interactions of GCR in the shielding can produce neutrons (black arrows) anywhere in the shielding and in any direction. Only neutrons entering the yellow scoring region from the shielding material are tallied in the calculation. All neutrons shown in the diagram except those noted are scored. The outside diameter of the shell is six meters. The inside diameter varies (see Table 1). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2. Calculation method

A simple geometry using large, 6-meter outer diameter spherical shells of varying thicknesses was used to simulate GCR transport through the shielding materials. Fig. 1 shows a schematic of the geometrical setup, with an isotropic distribution of GCR ions (red arrows) incident upon the shielding material. Interactions of GCR within the shielding material produce neutrons (shown with black arrows) that can be produced in any direction. Only neutrons that move from the shielding into the scoring region (shown with the yellow shell just inside the shielding material) are included in the neutron energy spectrum present inside the shielding. This includes neutrons that backscatter into the scoring region. The tally used in the PHITS calculation was "f-curr", which scores the neutron current moving forward from one surface (shielding wall) into another surface (scoring region shown in yellow in Fig. 1).

The choice of a scoring region just inside the shell was made in order to maximize the number of neutrons being scored and decrease the time needed to accrue sufficient statistics. In order to investigate whether or not the location of the scoring region led to a bias in the measured neutron yields other than in the overall magnitude, the calculations were also run using a small scoring region placed in the center of the shell (not shown in Fig. 1). For those calculations, any neutrons entering a 50-cm diameter sphere located in the center were scored. Because of the time involved with the simulations, the inner 50-cm diameter sphere calculations were performed for one set of shell thicknesses instead of the entire range of thicknesses.

Two separate shielding materials were used in the calculations. In one set of simulations, aluminum was chosen as the shielding material due to its common use in spacecraft and other structures in space. For reference, a similar calculation of neutron production