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Variation of space radiation exposure inside spherical and hemispherical geometries

Z.W. Lin [a,b,*], Y. Baalla [c], L.W. Townsend [d]

[a] Department of Physics, East Carolina University, C-209 Howell Science Complex, Greenville, NC 27858-4353, USA
[b] National Space Science and Technology Center, University of Alabama in Huntsville, Huntsville, AL 35805, USA
[c] The University of Tennessee Space Institute, Tullahoma, TN 37388, USA
[d] Department of Nuclear Engineering, University of Tennessee at Knoxville, Knoxville, TN 37996, USA

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ABSTRACT

We calculate the space radiation exposure to blood-forming organs everywhere inside a hemispherical dome that represents a lunar habitat. We derive the analytical pathlength distribution from any point inside a hemispherical or a spherical shell. Because the average pathlength increases with the distance from the center, the center of the hemispherical dome on the lunar surface has the largest radiation exposure while locations on the inner surface of the dome have the lowest exposure. This conclusion differs from an earlier study on a hemispherical dome but agrees with another earlier study on a spherical-shell shield. We also find that the reduction in the radiation exposure from the center to the inner edge of the dome can be as large as a factor of 3 or more for the radiation from solar particle events while being smaller for the radiation from galactic cosmic rays.

1. Introduction

In human space missions, astronauts will be exposed to space radiation from both galactic cosmic rays (GCR) and solar particle events (SPE). This can occur both in flight and in habitat. The galactic cosmic rays are constantly present and consist of energetic particles such as protons and heavy ions. On the other hand, solar event particles are less energetic but can have a very high flux in a short period of time. Consequently, solar particle events are the main concern for space radiation protection in short missions and galactic cosmic rays need to be also considered for missions of long durations such as a lunar base or a trip to the Mars.

It is therefore useful to study how the radiation exposure varies inside a spacecraft and inside a habitat. There have been earlier studies that address the variation of the radiation exposure inside habitats on the lunar surface or on the surface of Mars as well as inside spacecraft modules (Celnik et al., 1965; Nakache, 1965; Nealy et al., 1988; Simonsen and Nealy, 1991; Wilson et al., 1991, 1995). For example, Nealy et al. (1988) concluded that the maximum dose inside a half-buried sphere on the lunar surface occurs at a position above the center of the sphere, and Wilson et al. (1995) concluded that the exposure is maximum in the center of a spherical-shell shield and decreases as one approaches the walls since the average thickness increases as the wall is approached. These previous studies thus suggest that the position of the maximum dose in a spherical-shell shield is different from that in a hemispherical shield.

In this study we derive the analytical pathlength distributions for any point inside a hemispherical shield as well as a spherical shield, and then investigate the variation of dose inside both geometries. Using the results from one-dimensional radiation transport calculations, we calculate the radiation exposure inside a three-dimensional domed lunar habitat for several typical space radiation environments including solar particle events and galactic cosmic rays. We also consider a spherical shell in space as the simplest representation of a spacecraft and study how the radiation exposure inside depends on locations inside the shell.

2. Methods

The deterministic radiation transport that was used in earlier studies assumes the straight-ahead approximation, i.e., nuclear fragments do not change their directions relative to the direction of the projectile nucleus. The radiation transport gives the dose–depth relationship, $H(t)$, which represents the dose equivalent in

* Corresponding author at: Department of Physics, East Carolina University, C-209 Howell Science Complex, Greenville, NC 27858-4353, USA. Tel.: +1 252 328 2941; fax: +1 252 328 6314.
E-mail address: linz@ecu.edu (Z.W. Lin).

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blood-forming organs (BFO) behind a slab material of thickness t under a unidirectional radiation. The radiation exposure at an observation point X inside a three-dimensional object, under the same radiation environment but now isotropic in directions, is then given by (Shinn et al., 1990)

$$H_X = \int H(t) f_X(t) \mathrm{d}t,$$

where $f_x(t)$ represents the isotropic pathlength distribution function of the object at the observation point X. A pathlength is the length through the object material along a line from the observation point to the exterior of the object. It is easy to see that, under the straight-ahead approximation, the exposure at the center of a spherical shell of thickness t_s is the same as $H(t_s)$, the exposure behind a slab of thickness t_s under a unidirectional radiation.

We consider three choices for the space radiation environment: a solar minimum GCR environment, the Feb. 1956 SPE to represent a hard SPE environment, and the Aug. 1972 SPE to represent a soft SPE environment. The solar minimum GCR environment came from the Cosmic Ray Effects on MicroElectronics (CREME) model (Adams et al., 1981), and the corresponding ion and ion-group spectra are shown in Fig. 6 in Simonsen and Nealy (1991). The dose–depth relationships $H(t)$ for lunar regolith slabs are taken from Nealy et al. (1988) and Simonsen and Nealy (1991). In this study we first consider a hemispherical dome, i.e., a half-buried spherical shell, on a flat lunar surface to represent a lunar habitat. The shell is made of simulated lunar regolith that has a density of $\rho_{\mathrm{Regolith}} = 1.5\ \mathrm{g/cm^3}$ and a composition consisting of 52.7% SiO_2, 19.8% FeO, 17.5% Al_2O_3, and 10.0% MgO in weight fractions (Nealy et al., 1988; Simonsen and Nealy, 1991). The shell has an inner radius of $R_1 = 750$ cm and a thickness of $t_s = 50$ cm. We also consider an aluminum spherical shell with an inner radius of 160 cm and a thickness of 10 cm as the simplest representation of a spacecraft.

The BFO dose equivalent values as a function of the thicknesses of lunar regolith slabs (Nealy et al., 1988; Simonsen and Nealy, 1991) are shown in Fig. 1 for the SPE and GCR environments, where the dose equivalent is in the unit of cSv for SPE environments and cSv/year for the GCR environment. We have parameterized these dose–depth values for our calculations of the radiation exposure in spherical and hemispherical geometries. The dose–depth parameterizations for the solar minimum GCR, the hard SPE (HSPE), and the soft SPE (SSPE) environments are given, respectively, by

$$\begin{aligned} H_{\mathrm{GCR}}(t) &= 30\,\mathrm{e}^{-0.11t} + 28\,\mathrm{e}^{-0.004t}, \\ H_{\mathrm{HSPE}}(t) &= 32\,\mathrm{e}^{-0.11t} + 27\,\mathrm{e}^{-0.015t}, \\ H_{\mathrm{SSPE}}(t) &= 300\,\mathrm{e}^{-0.2t} + 6\,\mathrm{e}^{-0.045t}, \end{aligned} \qquad (1)$$

where t is in the unit of cm.

3. Results

The pathlength through a spherical or hemispherical shell from an inside observation point X along a given direction can be written as

$$\begin{aligned} t_X(\theta,\phi) = {} & \sqrt{R_2^2 - r_X^2 + r_X^2(\sin\theta_X \sin\theta \cos\phi + \cos\theta_X \cos\theta)^2} \\ & - \sqrt{R_1^2 - r_X^2 + r_X^2(\sin\theta_X \sin\theta \cos\phi + \cos\theta_X \cos\theta)^2}, \end{aligned} \qquad (2)$$

where $R_2 = R_1 + t_s$ represents the outer radius of the shell and t_s is the thickness of the shell. As shown in Fig. 2, with the origin of the coordinate system at the center of the sphere, r_x and θ_x represent the spherical coordinates of the observation point X inside the spherical shell, while θ and ϕ represent the direction that points to the radiation particles that will go through X. The total dose at the observation point is independent of its azimuthal angle ϕ_x, thus we have taken $\phi_x = 0$ in deriving Eq. (2).

For isotropic radiation environments, the exposure at an observation point X inside a spherical shell is then given by

$$H_{X,\mathrm{sphere}} = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} H(t_X(\theta,\phi)) \sin\theta \, \mathrm{d}\theta/(4\pi).$$

For a hemispherical dome on a flat lunar surface, the Moon blocks half of the solid angle below the horizon, i.e., $H(t_x(\theta,\phi)) = 0$ for $\theta \in [\pi/2, \pi]$ with $\theta = \pi$ pointing towards the center of the Moon. Therefore for a hemispherical dome on the lunar surface the exposure at an inside observation point X is given by

$$H_{X,\mathrm{hemisphere}} = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi/2} H(t_X(\theta,\phi)) \sin\theta \, \mathrm{d}\theta/(4\pi).$$

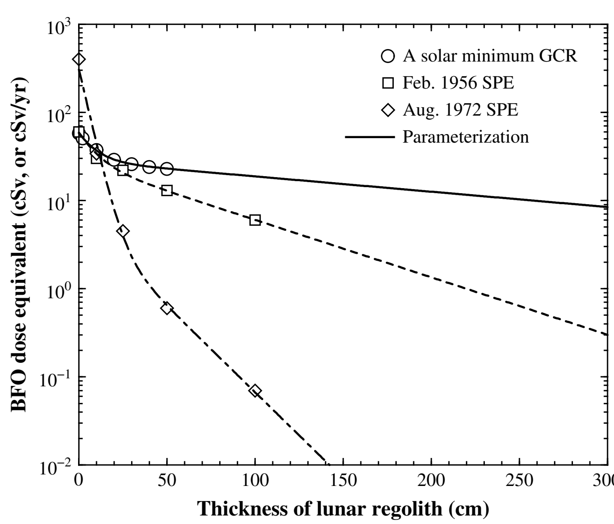

Fig. 1. The BFO dose equivalent as a function of the lunar regolith thickness for three different space radiation environments.

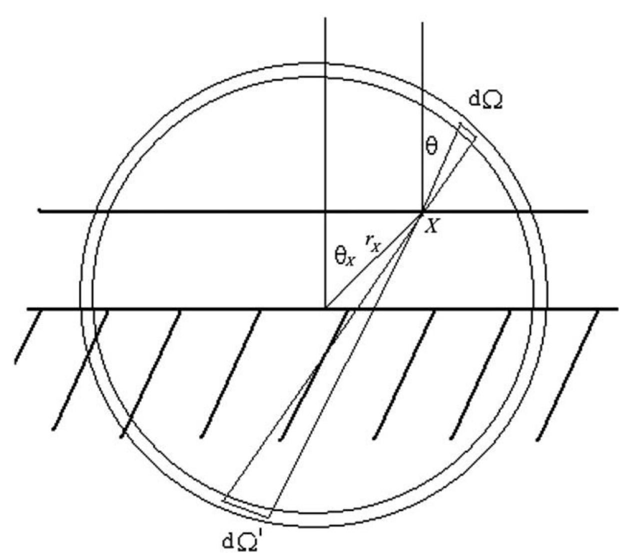

Fig. 2. Illustration of the solid angle elements in a half-buried spherical shell on a flat surface.