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Method for the prediction of the effective dose equivalent to the crew of the International Space Station

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Abstract

This paper describes a methodology for assessing the pre-mission exposure of space crew aboard the International Space Station (ISS) in terms of an effective dose equivalent. In this approach, the PHITS Monte Carlo code was used to assess the particle transport of galactic cosmic radiation (GCR) and trapped radiation for solar maximum and minimum conditions through an aluminum shield thickness. From these predicted spectra, and using fluence-to-dose conversion factors, a scaling ratio of the effective dose equivalent rate to the ICRU ambient dose equivalent rate at a 10 mm depth was determined. Only contributions from secondary neutrons, protons, and alpha particles were considered in this analysis.

Measurements made with a tissue equivalent proportional counter (TEPC) located at Service Module panel 327, as captured through a semi-empirical correlation in the ISSCREM code, where then scaled using this conversion factor for prediction of the effective dose equivalent. This analysis shows that at this location within the service module, the total effective dose equivalent is 10–30% less than the total TEPC dose equivalent. Approximately 75–85% of the effective dose equivalent is derived from the GCR. This methodology provides an opportunity for pre-flight predictions of the effective dose equivalent and therefore offers a means to assess the health risks of radiation exposure on ISS flight crew.
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Keywords: Effective dose equivalent; ISS; Predictive model; GCR; Trapped radiation; PHITS

1. Introduction

In preparation for missions to the International Space Station (ISS), a radiation dose assessment is performed to ensure that the crew will not exceed mission/career dose limits. The ISSCREM (International Space Station Cosmic Radiation Exposure Model) was recently developed as a possible assessment tool (El-Jaby, 2012; El-Jaby et al., 2013a,b) for radiation exposure prediction from galactic cosmic radiation (GCR) and trapped radiation sources, which correlated dose equivalent rate data as collected

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onboard the ISS with a tissue equivalent proportional counter (TEPC) (NASA, 2011) located at Service Module panel 327 (SM-327).

The ISSCREM model takes into account the physical phenomena occurring in low-Earth orbit that influence the radiation exposure. The GCR model relates the TEPC daily dose equivalent rate to the cutoff rigidity due to geomagnetic shielding as interpolated from ISS orbit vectors. The trapped radiation model correlates the TEPC dose equivalent rate to the mean daily atmospheric density over all ISS orbit crossings of the South Atlantic Anomaly (El-Jaby, 2012; El-Jaby et al., 2013a,b). This approach is able to reproduce the dose equivalent that would be measured by the TEPC at SM-327 from both GCR and trapped proton exposures to within ±10% and ±20%, respectively, on a daily and cumulative mission basis (El-Jaby, 2012; El-Jaby et al., 2013a,b).

The dose equivalent is an operational quantity that is useful for mission planning, whereas there is a need to assess the health and safety of space-crew due to a protection quantity that considers the relative increase in stochastic health effects from radiation exposure. The effective dose equivalent,[5] E, given in Sieverts (Sv), is used to estimate this risk and is given by the product of the absorbed dose equivalent in tissue t, H_t in Sv, and the corresponding tissue weighting factor w_t, summed over all tissue types.

$$E = \sum_t w_t H_t \tag{1}$$

In this work, a conversion factor of the ambient-to-effective dose equivalent is developed to convert a dose equivalent from GCR and trapped radiation sources (as provided by ISSCREM) into a corresponding effective dose equivalent. This analysis is considered for years 2000, 2007, 2009, and 2010 in order to compare with other published estimates of the effective dose from post-flight analysis of measured data. The spectral contribution of heavy ions to the GCR component of the total effective dose equivalent is further studied to assess its significance on the resulting secondary spectra.

2. Methodology

The predicted dose equivalent from the TEPC as fit in ISSCREM, H_{TEPC}, is converted into an effective dose equivalent, E, using the conversion factor f as given by Eq. (2).

$$E = f H_{\mathrm{TEPC}} \tag{2}$$

The conversion factor is approximated by the ratio of the effective-to-ambient dose equivalent, $E/H^*(10)$, summed over all particle types including neutrons (n), protons (p), alpha particles (α), exotic particles (EP) (such as muons, pions and kaons), and heavy ions (HI). This analysis is done to account for the secondary particles produced by the interaction of primary GCR and trapped radiation ions with the shielding of the ISS.

$$f = \sum_{i:\mathrm{n,p,\alpha,EP,HI}} \frac{E_i}{H^*(10)_i} = \sum_{i:\mathrm{n,p,\alpha,EP,HI}} \frac{\int \left(\frac{d\phi}{dE}\right)_i e_i dE}{\int \left(\frac{d\phi}{dE}\right)_i h_i dE} \tag{3}$$

In Eq. (3), $H^*(10)$ is the ambient dose equivalent at 10 mm depth inside an ICRU (International Commission on Radiation Units and Measurements) sphere, $d\phi/dE$ is the differential particle flux in units of particles $\mathrm{s^{-1}\,cm^{-2}\,MeV^{-1}}$, h is the fluence-to-ambient dose equivalent conversion factor in pSv $\mathrm{cm^2}$, and e is the fluence-to-effective dose equivalent conversion factor in pSv $\mathrm{cm^2}$.

The ICRU ambient dose equivalent is a standardized unit of dose equivalent wherein the radiation field depositing the dose is aligned and expanded onto the ICRU sphere (ICRP, 2007). This quantity permits comparison of different exposures to a common reference point in a tissue analog which is essential for determining the effectiveness of a given radiation quality in depositing dose (ICRP, 2007). Equation (3) assumes that H_{TEPC} is equivalent to $H^*(10)$, however, in the development of the Predictive Code for Aircrew Radiation Exposure (PCAire), the response of a TEPC detector similar to that used aboard the ISS was shown to have an over-response of approximately 15% for photons and neutrons as compared to the ambient dose equivalent (Lewis et al., 1999, 2002). To date, the response of the ISS TEPC as compared to an ambient dose equivalent has not been done. In addition, the TEPC aboard the ISS is of a different design from that used in aircrew studies and, therefore, it will have a slightly different response. Furthermore, at ISS altitudes the radiation environment is different than at commercial aircraft altitudes. As such, the assumption that H_{TEPC} is equivalent to $H^*(10)$ is utilized as a first order approximation.

Fluence-to-ambient dose equivalent conversion factors, h, are only available for protons, neutrons (Sato et al., 2011a) and alpha particles (EXPACS, 2012[6]). Although conversion factors for the fluence-to-effective dose equivalent, e, are available for all heavy ions (Sato et al., 2009, 2010), Eq. (3)currently can only be evaluated with a summation over neutrons, protons, and alpha particles. Fig. 1 illustrates the conversion factors, h, and Fig. 2 illustrates those for e, specifically for neutrons, protons, and alpha particles.

3. Transport simulations

The proton, neutron, and alpha distributions inside the ISS were simulated using the Particle and Heavy-Ion Transport code System (PHITS) (Niita et al., 2011; Sato

[5] Effective dose equivalent is used here to refer to the linear energy transfer (L) quality factors $Q(L)$ based effective dose. This approach can be distinguished from the currently recommended ICRP effective dose which is based on radiation weighting factors w_r.

[6] Alpha particle fluence-to-ambient dose equivalent conversion factors utilized in (EXPACS, 2012) made available through private communication from Dr. T. Sato, Japan Atomic Energy Agency.

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