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3DHZETRN: Shielded ICRU spherical phantom

John W. Wilson [a], Tony C. Slaba [b,*], Francis F. Badavi [a], Brandon D. Reddell [c], Amir A. Bahadori [c]

[a] Old Dominion University, Norfolk, VA 23529, USA
[b] NASA Langley Research Center, 2 West Reid St., Mail stop 188E, Hampton, VA 23681-2199, USA
[c] NASA Johnson Space Center, Houston, TX 77004, USA

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ABSTRACT

A computationally efficient 3DHZETRN code capable of simulating High (H) Charge (Z) and Energy (HZE) and light ions (including neutrons) under space-like boundary conditions with enhanced neutron and light ion propagation was recently developed for a simple homogeneous shield object. Monte Carlo benchmarks were used to verify the methodology in slab and spherical geometry, and the 3D corrections were shown to provide significant improvement over the straight-ahead approximation in some cases. In the present report, the new algorithms with well-defined convergence criteria are extended to inhomogeneous media within a shielded tissue slab and a shielded tissue sphere and tested against Monte Carlo simulation to verify the solution methods. The 3D corrections are again found to more accurately describe the neutron and light ion fluence spectra as compared to the straight-ahead approximation. These computationally efficient methods provide a basis for software capable of space shield analysis and optimization.

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1. Introduction

Early space radiation shield code development relied on Monte Carlo (MC) methods (Alsmiller, 1967; Lambiotte et al., 1971) and made important contributions to the space program. Due to intensive computational requirements, MC methods utilized restricted one-dimensional problems leading to imperfect representation of appropriate boundary conditions (Alsmiller et al., 1972; Pinsky et al., 2001; Armstrong and Colburn, 2001; Foelsche et al., 1974). Even so, intensive computational requirements for MC codes remained, and shield evaluation was made near the end of the design process in greatly simplified geometry to enhance computer efficiency (Armstrong and Colburn, 2001; Wilson et al., 2002). Resolving shielding issues at the end of the design cycle had a negative impact on the design, since resolving issues early could have minimized shield augmentation requirements and associated launch costs. This is especially true in post-launch augmentation, as was done for the International Space Station (ISS) (Shavers et al., 2004). Furthermore, added shielding at the end of the design process could require de-scoping mission objectives, as instruments and equipment may be removed to meet launch requirements, as was done on the Viking Project.

Improved spacecraft shield design requires early entry of radiation constraints into the design process to maximize performance and minimize costs. As a result, NASA has been investigating high-speed computational procedures to allow shield analysis to be part of the preliminary design concepts following through to the final design, allowing shield optimization procedures (Wilson et al., 2003a, 2004a, 2004b). For the last several decades, NASA has pursued deterministic solutions of the Boltzmann equation allowing field mapping within the ISS in tens of minutes (Wilson et al., 2007) using standard finite element method geometry common to modern engineering design practice (Qualls et al., 2001, Wilson et al., 2003a, 2004a). Ray tracing procedures in complicated geometry hinders the application of MC methods to such engineering models. Even so, deterministic methods have relied on the straight-ahead approximation, resulting in the HZETRN code with loosely defined impact on model uncertainty (Wilson and Khandelwal, 1974); yet, it handily facilitated the ISS design augmentation for which no other code was capable. Recently, a 3D version of HZETRN has been developed in simple geometry (homogeneous sphere) with improved convergence criteria and verification of 3D effects using MC methods (Wilson et al., 2014a).

Herein, the homogeneous media limitation will be removed from the solution methodology, and MC codes are used again to verify the solution methods in simple geometry. The restriction to slab and spherical objects will be maintained to allow efficient MC simulations for verification purposes. The next step in this

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* Corresponding author. Tel.: +1 757 864 1420.
E-mail address: Tony.C.Slaba@nasa.gov (T.C. Slaba).

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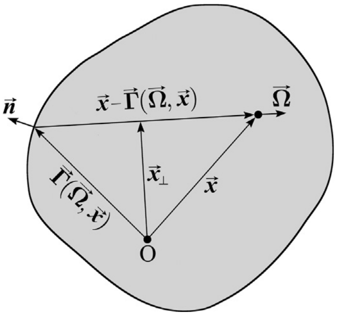

Fig. 1. Geometric relations of quantities useful in solving Eq. (1). The symbol $\vec{n}$ is a unit normal vector.

development will be to use more complex geometric models so that simple mapping of the present methodology into more realistic applications can be studied. In the present report, the current status of transport code development will be briefly reviewed with emphasis on extending these developments into a generalized 3D version of the HZETRN code. These advances will use available MC codes, Geant4 (Agostinelli et al., 2003), FLUKA (Fasso et al., 2005; Battistoni et al., 2007), and PHITS (Sato et al., 2006, 2013) to judge the veracity of these developments, especially with regard to their 3D aspects.

2. Deterministic code development

The relevant transport equations are the linear Boltzmann equations derived on the basis of conservation principles (Wilson et al., 1991) for the flux (or fluence) density, $\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)$, of a j type particle in the continuous slowing down approximation (CSDA) in which atomic processes are described by the stopping power, $S_j(E)$, for each ion type j (vanishes for neutrons, $j=n$) as

$$\mathbf{B}\big[\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)\big] = \sum_k \int_E^\infty \int_{4\pi} \sigma_{jk}\big(E,E',\boldsymbol{\Omega},\boldsymbol{\Omega}'\big)\phi_k\big(\boldsymbol{x},\boldsymbol{\Omega}',E'\big)d\boldsymbol{\Omega}'dE', \tag{1}$$

where the differential operator on the left hand side is defined as

$$\mathbf{B}\big[\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)\big] \equiv \boldsymbol{\Omega}\cdot\nabla\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E) - \frac{1}{A_j}\frac{\partial}{\partial E}\big[S_j(E)\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)\big] + \sigma_j(E)\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E), \tag{2}$$

and solved subject to a boundary condition over the enclosure of the solution domain as shown in Fig. 1. In Eqs. (1) and (2), $\sigma_j(E)$ and $\sigma_{jk}(E,E',\boldsymbol{\Omega},\boldsymbol{\Omega}')$ are the media macroscopic cross sections and include nuclear elastic and reactive processes. One obstacle to solving Eq. (1) is the need to evaluate the integral $d\boldsymbol{\Omega}'$ at arbitrary locations within the media and development of computational methods to efficiently handle this limitation. The approach to a practical solution of Eq. (1) is to develop a progression of solutions from the simple to increasingly complex, allowing early implementation of high-performance computational procedures and establishing a converging sequence of approximations with established accuracy criteria and means of verification and validation.

The first step leading to the lowest order solution reduces the evaluation by introducing the straight-ahead approximation as guided by the nucleon transport studies of Alsmiller et al. (1965) using MC methods in which the differential cross sections were approximated as

$$\sigma_{jk}\big(E,E',\boldsymbol{\Omega},\boldsymbol{\Omega}'\big) = \sigma_{jk}\big(E,E'\big)\delta\big(\boldsymbol{\Omega}-\boldsymbol{\Omega}'\big). \tag{3}$$

Numerical marching procedures were developed to solve the transport equation under the straight-ahead approximation, resulting in the HZETRN code. A corresponding nuclear fragmentation model, NUCFRG2, was also developed for HZETRN, and the verification and validation processes utilizing the NUCFRG2 database as described elsewhere (Wilson et al., 1987a, 1987b, 2005, 2006). This approximation produced dose and dose equivalent results to be within the statistical uncertainty of the MC result obtained using the fully angle dependent cross sections in slab geometry (Alsmiller et al., 1965; Wilson et al., 1991) providing a verification process.

Space flight validation of HZETRN has been limited largely to low Earth orbit (LEO), containing both trapped particle and attenuated galactic cosmic ray (GCR) components. The two primary limitations in the LEO trapped environmental models AP8MIN and AP8MAX as discussed by Wilson et al. (2003b) is the assumption that the trapped particles are isotropic (resulting from the omnidirectional fluence description) and poor representation of the dynamic behavior that have been scaled according to a semi-empirical methodology (Wilson et al., 2003b). These omnidirectional models, in conjunction with GCR representations of Badhwar et al. (2001a), have been relatively successful in describing the radiation environment aboard the highly maneuverable shuttle spacecraft based on the area monitor records wherein anisotropies tend to be averaged. Such models have been found to be less accurate in the formation flying of the ISS, mainly oriented in the local horizontal plane along the velocity vector as was demonstrated elsewhere using the ISS area monitor records and the ISS six-degree of freedom trajectory data (Hugger et al., 2003; Wilson et al., 2005; Nealy et al., 2006; Slaba et al., 2011a, 2013).

A dynamic and anisotropic trapped proton environmental model was subsequently developed and validated for orbit averaged quantities for future use in LEO shield design and operations (Badhwar, 1997; Wilson et al., 2003b, 2005). These environmental AP8 and AE8 models are placed in a suitable form for evaluation of the incident radiation on the bounding surface of the six-degree of freedom motion of an orbiting spacecraft for shield evaluation (Wilson et al., 2005). To test the dynamic behavior, shuttle TLD data from 1983 to 2000 were used, giving good coverage for nearly two solar cycles. With the use of a normalization procedure intended to represent environmental model uncertainty, Badhwar (1997) and Badhwar et al. (1996, 2001a, 2001b) showed that the root mean square error of both observed and calculated dose and dose equivalent rates were within 15%. The normalization procedure is based on scaling the model trapped proton contribution to the available TLD measurements. Recent validation studies by Slaba et al., (2011a, 2013) did not utilize normalization procedures and focused entirely on the GCR component of the LEO environment. Those studies revealed larger dose differences up to 40 percent (up to 13 percent for dose equivalent) if pion production and the associated electromagnetic cascade were not included, as was the case in most of the previous validation efforts. More recently, an updated dynamic and anisotropic trapped proton model, AP9, has been made available and preliminary validation comparisons have shown reduced uncertainties (Badavi, 2014). These comparisons highlight the usefulness of HZETRN within the straight-ahead approximation in many cases, but further improvement is still necessary.

It is clear that the straight-ahead approximation provides accurate dosimetric results and a good approximation to the particle fluence in many circumstances (Badhwar et al., 1995; Badhwar, 1997). One limitation of the straight-ahead approximation is near the front boundary where the calculated neutron fluence vanishes (unless neutrons are part of the external radiation environment such as the neutron albedo Wilson et al., 2005). This results from the straight-ahead approximation and can be improved by em-