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Coupled neutron transport for HZETRN

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ABSTRACT

Exposure estimates inside space vehicles, surface habitats, and high altitude aircrafts exposed to space radiation are highly influenced by secondary neutron production. The deterministic transport code HZETRN has been identified as a reliable and efficient tool for such studies, but improvements to the underlying transport models and numerical methods are still necessary. In this paper, the forward–backward (FB) and directionally coupled forward–backward (DC) neutron transport models are derived, numerical methods for the FB model are reviewed, and a computationally efficient numerical solution is presented for the DC model. Both models are compared to the Monte Carlo codes HETC-HEDS, FLUKA, and MCNPX, and the DC model is shown to agree closely with the Monte Carlo results. Finally, it is found in the development of either model that the decoupling of low energy neutrons from the light ion transport procedure adversely affects low energy light ion fluence spectra and exposure quantities. A first order correction is presented to resolve the problem, and it is shown to be both accurate and efficient.

1. Introduction

Radiation exposure guidelines are a primary concern for the design of personal shielding, spacecraft, instrumentation, and mission planning. Consequently, there is significant interest in developing computational tools that allow shield analyses not only in simplified geometries, but in more complex final design models as well (Wilson et al., 2003). The deterministic transport code HZETRN (Wilson and Badavi 1986; Wilson et al., 1991, 2003, 2006; Cucinotta, 1993; Shinn et al., 1991), developed at NASA Langley Research Center has emerged in recent years as a reliable and efficient tool for such studies. It has shown reasonable accuracy in deep space galactic cosmic ray (GCR), solar particle event (SPE), and low earth orbit (LEO) simulations when compared to either Monte Carlo results or experimental data (Wilson et al., 2005). However, such verification and validation has revealed a deficiency in the low energy neutron transport procedure (Shinn et al., 1994). HZETRN utilizes the straight ahead approximation in which all fragments are assumed to propagate in the same direction as the projectile. The assumption is accurate for high energy charged particles but breaks down for low energy neutrons which are produced nearly isotropically (Alsmiller et al., 1965). This is significant for heavily shielded space vehicles, surface habitats, and high altitude aircraft where secondary neutron production is important in exposure calculations (Getselev et al., 2004).

Several neutron transport models have been developed for HZETRN, with recent efforts focused on identifying an optimal bi-directional neutron transport model and solution method. The terms model and method are used extensively throughout this paper; model is used to refer to the set of governing transport equations, while method is used to refer to the analytic or numerical techniques used to solve a model. Heinbockel et al. (2000) and Clowdsley et al. (2000a,b) developed the forward–backward (FB) neutron transport model. It assumes that low energy neutrons can be split into forward and backward components, and multiple reflections from forward to backward (or vice versa) can be ignored. Feldman (2003) expanded on the work of Heinbockel and Clowdsley by developing the directionally coupled forward–backward (DC) neutron transport model. It also assumes that low energy neutrons can be split into forward and backward components, but multiple reflections are accounted for in the governing transport equations. The numerical methods used for each model were significantly different as well.

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Heinbockel et al. (2000) and Clowdsley et al. (2000a,b) used a multigroup method for solving the FB model. Multigroup methods have a long history in nuclear reactor theory and assume that fluences or cross sections are constant over small regions, or groups, of the energy spectrum (Marchuk and Lebedev, 1986). Marchuk and Lebedev (1986) gives a more general description of this method. Feldman (2003) used a collocation technique along with first order finite differencing for the DC model. Collocation and finite differencing methods use polynomial expansions of the solution to transform a differential equation into a system of linear equations (Deuflhard and Bornemann, 2002). In this case, the system was sufficiently large that it had to be solved numerically. Deuflhard and Bornemann (2002) and Demmel (1997) give more detailed descriptions of these numerical methods.

Recently, Slaba et al. (2006), Slaba (2007) and Heinbockel et al. (2007) developed three methods for solving the FB model which they called the collocation method, the fixed-point series method, and Wilson's method. The latter two methods are both based on Neumann series solutions wherein each term of the series solves a simple set of equations related to the original model. The work allowed for intensive verification of the multigroup method, and the collocation method was identified as the most accurate and computationally efficient (Slaba, 2007). Slaba (2007) also indicated that a combination of the methods could be used to obtain a computationally efficient Neumann series solution to the DC model.

Finally, despite all of the attention given to neutron transport models and methods, accurately coupling these models back into HZETRN remained unresolved. The impact of such a coupling has not been previously studied in detail and must be examined if any of the neutron transport models are to be used in design studies.

In this paper, we first give a summary of the neutron transport models and methods developed thus far and present an efficient method for solving the DC model. Comparisons are made between the FB and DC models and the Monte Carlo codes HETC-HEDS (Gabriel et al., 1995; Townsend et al., 2005), FLUKA (Fasso et al., 2003, 2005), and MCNPX (Briesmeister, 2000; MCNPX 2.6.0 Manual, 2008). The impact of decoupling low energy neutrons from the light ion transport procedure in HZETRN is also examined, and a first order correction is presented. Fluence spectra and dose quantities are given to exhibit the accuracy of the proposed correction.

2. HZETRN description

The one-dimensional Boltzmann transport equation for charged and neutral particles with the continuous slowing down and straight ahead approximations is given as (Wilson et al., 1991)

$$B\left[\phi_j\right] = \sum_k \int_E^\infty \sigma_{jk}(E,E')\phi_k(x,E')\mathrm{d}E' \tag{1}$$

with the linear differential operator

$$B\left[\phi_j\right] \equiv \left[\frac{\partial}{\partial x} - \frac{1}{A_j}\frac{\partial}{\partial E}S_j(E) + \sigma_j(E)\right]\phi_j \tag{2}$$

where ϕ_j is the fluence of type j ions at depth x with kinetic energy E (AMeV), A_j is the atomic mass of a type j particle, $S_j(E)$ is the stopping power of a type j ion with kinetic energy E, $\sigma_j(E)$ is the total macroscopic cross section for a type j particle with kinetic energy E, and $\sigma_{jk}(E,E')$ is the macroscopic production cross section for interactions in which a type k particle with kinetic energy E' produce a type j particle with kinetic energy E. Macroscopic cross sections are obtained by multiplying the corresponding microscopic cross section by the target particle mass density (Wilson et al., 1991). Hereafter, it is assumed that all cross sections are macroscopic whether it is explicitly written or not.

Wilson and Badavi 1986; Wilson et al. (1991, 2003, 2006; Cucinotta, 1993; Shinn et al., 1991) obtained approximate solutions to equation (1) by introducing the scaled quantities

$$\psi_j(x,r) = \nu_j S_p(E)\phi_j(x,E) \tag{3}$$

$$s_{jk}(r,r') = S_p(E)\sigma_{jk}(E,E'), \tag{4}$$

where $S_p(E)$ is the proton stopping power, r is the residual proton range

$$r = \int_0^E \frac{\mathrm{d}E'}{S_p(E')}, \tag{5}$$

and the scaling parameter $\nu_j = Z_j^2/A_j$. For neutrons, ν is taken as unity in fluence scaling relations and zero in range scaling relations. This will be explained in more detail shortly. Equation (1) is now given in terms of the variables x and r as

$$\left[\frac{\partial}{\partial x} - \nu_j\frac{\partial}{\partial r}S_p(E) + \sigma_j(r)\right]\psi_j(x,r) = \sum_k \frac{\nu_j}{\nu_k}\int_r^\infty s_{jk}(r,r')\psi_k(x,r')\mathrm{d}r', \tag{6}$$

which can be inverted using the method of characteristics (Haberman, 1998) and written as the Volterra type integral equation (Wilson et al., 2006)

$$\psi_j(x,r) = e^{-\varsigma_j(r,x)}\psi_j(0,r+\nu_j x) + \sum_k \frac{\nu_j}{\nu_k}\int_0^x \int_{r+\nu_j x'}^\infty e^{-\varsigma_j(r,x')} s_{jk}(r+\nu_j x',r')\psi_k(x-x',r')\mathrm{d}r'\mathrm{d}x', \tag{7}$$

with

$$\varsigma_j(r,x) = \int_0^x \sigma_j(r+\nu_j t)\mathrm{d}t. \tag{8}$$

Note that ν_j in equation (3) and ν_j/ν_k in equation (6) are both fluence scaling relations, and $\nu_n = 1$ in both cases to provide a nontrivial scaling (see equation (3)). Conversely, wherever ν appears as the argument of a fluence or cross section in equations (7) and (8), it is a range scaling relation and $\nu_n = 0$. This convention is taken to reflect the absence of atomic interactions in neutron transport ($S_n(E) \equiv 0$).

From here, the problem is split into two parts: heavy ions ($A > 4$) and light particles ($A \le 4$). For heavy ions, it is noted that projectile fragments have energy and direction very near that of the projectile, while target fragments are produced nearly isotropically with low energy and travel only a short distance before being absorbed. This approximate decoupling of target and projectile fragments is discussed in detail by Wilson et al. (1991) and suggests that heavy target fragments can be neglected in the heavy ion transport procedure (their contribution to dose is approximately accounted for after the transport procedure). The production cross section can now be recast as

$$s_{jk}(r,r') = \sigma_{jk}(r)\delta(r-r'). \tag{9}$$