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AN EVALUATION OF ENERGY-INDEPENDENT HEAVY ION TRANSPORT COEFFICIENT APPROXIMATIONS

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ABSTRACT

Utilizing a one-dimensional transport theory for heavy ion propagation, evaluations of typical energy-independent transport coefficient approximations are made by comparing theoretical depth-dose predictions to published experimental values for incident 670 MeV/necleon ^{20}Ne beams in water. Results are presented for cases where the input nuclear absorption cross sections, or input fragmentation parameters, or both, are fixed. The lack of fragment charge and mass conservation resulting from the use of Silberberg-Tsao fragmentation parameters continues to be the main source of disagreement between theory and experiment.

INTRODUCTION

As the era of the Space Transportation System progresses toward the development of a permanently manned Space Station, possible lunar bases and manned Mars missions, long-term exposure of astronauts and spacecraft equipment to large fluences of galactic heavy ions indicates a need to investigate methods of shielding from these high-energy ions. Because of significant, technological barriers, active radiation shielding methods involving electromagnetic fields do not appear to offer viable alternatives to bulk, passive shielding methods in the near future (To 83). To properly evaluate passive

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shield requirements, a comprehensive theory describing the interaction and propagation of galactic heavy ions, and their subsequent reaction products, in the spacecraft structure and inhabitants is required. In previous work (Wi 84), an energy-dependent transport theory for heavy-ion beams was presented and comparisons with an experimental Bragg average ionization curve were made. The agreement between theory and experiment was excellent when the Silberberg-Tsao fragmentation parameters (Si 77) were renormalized to conserve fragment mass and charge. Because of excessive computer resource requirements, however, a fully energy-dependent transport calculation for the complete galactic heavy ion radiation spectrum is impractical. Typically, galactic cosmic ray shielding calculations (Le 83; Wi 86a) utilize energy-independent approximations for the input transport coefficients in order to reduce the required computer resources. In the work described herein, typical energy-independent approximations are used in the fully energy-dependent transport theory and the resultant depth-dose predictions compared with published experimental values for incident 670 MeV/nucleon ^{20}Ne beams in water in order to assess the levels of inaccuracy introduced by these input approximations.

DEPTH-DOSE EXPRESSIONS

From before (Wi 84), the transport equation in the straigh-ahead approximation and neglecting target secondary fragments is written as

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E}\,\tilde{S}_j(E) + \sigma_j(E)\right]\Phi_j(x,E) = \sum_{k>j} m_{jk}(E)\sigma_k(E)\Phi_k(x,E) \tag{1}$$

where $\Phi_j(x,E)$ is the flux of ions of type j with atomic mass A_j at x moving along the x-axis at energy E in units of MeV/nucleon, $\sigma_j(E)$ is the corresponding macroscopic nuclear absorption cross section, $\tilde{S}_j(E)$ is the specific stopping power (change in E per unit distance), and $m_{jk}(E)$ is the fragmentation parameter of ion j produced in collision by ion k. The transport equation (1) is solved by the method of characteristics using an iterative procedure. The resultant series is

$$\Phi_j (x,E) = \sum_{\alpha=0}^{\infty} \Phi_j^{(\alpha)} (x,E) \tag{2}$$

where $\alpha = 1, 2, 3, \ldots,$ denotes the various generations of reaction products, and $\alpha = 0$ is the primary beam. Equation (2) can be used to evaluate the dose as

$$D(x) = \sum_j \int_0^{\infty} dE\ S_j(E)\ \Phi_j(x,E) \tag{3}$$

where a water density of 1 g/cm^3 is assumed. Expressions for the doses due to primary, secondary, and tertiary ions are given in equations (9), (12) and (15) of our previous work (Wi 84) and are not repeated here. The previous calculations used fully energy-dependent values for the transport coefficients $S_j(E)$, $\sigma_j(E)$, and $M_{jk}(E)$. The experimental and calculated doses for 670 MeV/necleon ^{20}Ne beams in water are reproduced in Fig. 1. The curve labelled ST denotes the calculation using the Silberberg-Tsao fragmentation parameters (Si 77) augmented by the light fragment production cross sections of Bertini (Be 68). The curve labelled VR denotes the calculation using the renormalized fragmentation parameters which conserve fragment mass and charge. The multiplicative renormalization factor is

$$F = [(Z_p A_p)/(Z_s A_s)]^{1/2} \tag{4}$$

where Z_s and A_s are the total fragment charge and mass obtained from the semiempirical formulae (Si 77), and Z_p and A_p are the incident projectile ion charge and mass. Typical differences between theory and experiment before the Bragg peak are 1-3% for the VR calculations and up to 20% for the ST calculations. Beyond the Bragg peak the differences are ~25% for the VR calculation and nearly a factor of 3 for the ST calculation.

INPUT PARAMETER APPROXIMATION RESULTS

Nuclear Absorption Cross Sections

Typical galactic cosmic ray transport calculations utilize energy-independent absorption cross sections, σ_{ij}, obtained from some form of the Bradt-Peters parameterization (Br 50)

$$\sigma_{ij} = \pi r_o^2 \left(A_i^{1/3} + A_j^{1/3} - \delta\right)^2 \tag{5}$$

where r_o and δ are energy-independent parameters which have been fitted to a particular set of cross section data and A_i and A_j are the mass numbers of the colliding nuclei. While certainly adequate for high energies where the cross sections are nearly asymptotic, significant differences exist (To 86), at energies below 2 GeV/nucleon, between experimental data/detailed theoretical formalisms and the values predicted by equation (5).

To test the sensitivity of the dose predictions to the absorption cross section energy dependence, the σ_{ij} were fixed at their 2 GeV/nucleon values, which are representative of the asymptotic results obtained from equation (5). The input fragmentation parameters used in the calculations were the fully energy-dependent ones. The results are displayed in Fig. 2 as the ratios of calculated to experimental doses. For the renormalized fragmentation parameter predictions (label VR) the calculated dose is underestimated by

< 10% before the Bragg peak and by up to 35% beyond the Bragg peak. For the unrenormalized fragmentation parameters (label ST) the calculated dose is underestimated by up to 33% before the Bragg peak and by almost a factor of 4 beyond the Bragg peak.

Nuclear Fragmentation Parameters

Aside from the use of energy-independent absorption cross sections, another possible simplification to the heavy ion transport problem is the use of energy-independent fragmentation parameters. To test this approximation, dose calculations for the ^{20}Ne beam in water were performed using fragmentation parameters m_{jk} fixed at the values applicable to the incident beam energy of 670 MeV/nucleon. The absorption cross sections were fully energy-dependent. The results are displayed in Fig. 3 as the ratios of calculated to experimental doses. For the VR fragmentation parameters, the calculated dose is within 3% of the experimental dose in the region before the Bragg peak and generally within 10% beyond the Bragg peak. For the ST fragmentation parameters, the calculated dose underestimates the experimental dose by up to 20% before the Bragg peak and by a factor of two beyond it. Thus, as long as fragment charge and mass are conserved, the use of energy-independent fragmentation parameters may be reasonable. Recently, an energy-independent fragmentation model, which conserves fragment charge and mass without renormalization, has been developed (Wi 86b) for use in heavy ion transport studies and will be incorporated into the existing transport codes in the near future.

Fragmentation Parameters and Nuclear Absorption Fixed

Finally, we test the sensitivity of the transport calculations to the combined use of energy independent fragmentation parameters and nuclear absorption cross sections. The fragmentation parameters were fixed at their values for an incident energy of 670 MeV/nucleon and the nuclear absorption cross sections were fixed at the asymptotic values for 2 GeV/nucleon incident beam energy. The results for 670 MeV/nucleon ^{20}Ne in water are displayed in Fig. 4 as the ratio of calculated to experimental dose as a function of absorber depth. In the region before the Bragg peak, the VR calculation underestimates the dose by up to 13% whereas the ST calculation underestimates by up to 35%. Beyond the Bragg peak, the doses are underestimated by $<$ 28% for the VR calculation and by factors of 2-3 for the ST calculation.

Stopping Power

For all calculations performed in this parameter study, the fully energy-dependent stopping powers obtained by summing the electronic and nuclear contributions according to the methods described elsewhere (Wi 84) are used. Results obtained with a simplified power law range-energy relation are presented elsewhere (Wi 86a) and will not be discussed in this work.

CONCLUSIONS

Utilizing energy-independent transport coefficient approximation, depth-dose calculations for 670 MeV/nucleon ^{20}Ne beams in thick water absorbers have been performed and comparisons to experimental data made. The results indicate that the accuracies of the predicted doses are least affected by the use of the energy-independent fragmentation parameters, if they are renormalized to conserve charge and mass. The typical error is less than 10% if fully energy-dependent absorption cross sections are used. The use of energy-independent absorption cross sections resulted in dose underestimates of up to 35% for the calculations utilizing renormalized fragmentation parameters.

Clearly, however, the lack of charge and mass conservation in the Silberberg-Tsao fragmentation parameters introduces the most significant errors into the calculations. Without renormalizing these parameters to conserve fragment mass and charge, the predicted doses underestimate the measured doses by 20-40% before the Bragg peak and by a factor of 2-4 after the Bragg peak. Finally, it should be emphasized for radiation protection studies that care must be exercised in interpreting these results. Because of significant differences in radiobiological equivalences (RBE) for the various components of the mixed radiation field in the absorber, large errors in biological dose predictions may exist even though reasonable agreement with the experimental Bragg curve is obtained. Hence, it is imperative that transport theories be capable of providing accurate predictions of the radiation field composition and not just approximate estimates of the total physical dose.

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Figure Captions

Figure 1.- Energy deposition in water by 670 MeV/nucleon ^{20}Ne ions. Fully energy-dependent calculations using Silberberg-Tsao (ST) and renormalized (VR) fragmentation parameters are displayed. Also displayed are experimental results from Lawrence Berheley Laboratory. The dose relative to zero absorber is displayed on the ordinate.

Figure 2.- Ratio of calculated to experimental doses, as a function of depth in water, for a 670 MeV/nucleon ^{20}Ne beam. The calculations utilized energy-dependent renormalized (VR) and unrenormalized (ST) Silberberg-Tsao fragmentation parameters, and energy-independent nuclear absorption cross sections. For reference, the Bragg peak location is labelled (BP).

Figure 3.- Ratio of calculated to experimental doses, as a function of depth in water, for a 670 MeV/nucleon ^{20}Ne beam. The calculations used energy-independent renormalized (VR) and unrenormalized (ST) Silberberg-Tsao fragmentation parameters. The nuclear absorption cross sections were fully energy-dependent. For reference, the Bragg peak location is labelled (BP).

Figure 4.- Ratio of calculated to experimented doses, as a function of depth in water, for a 670 MeV/nucleon ^{20}Ne beam. The calculations used both energy-independent nuclear absorption cross sections, and Silberberg-Tsao (ST) and renormalized (VR) fragmentation parameters. For reference, the Bragg peak location is labelled (BP).

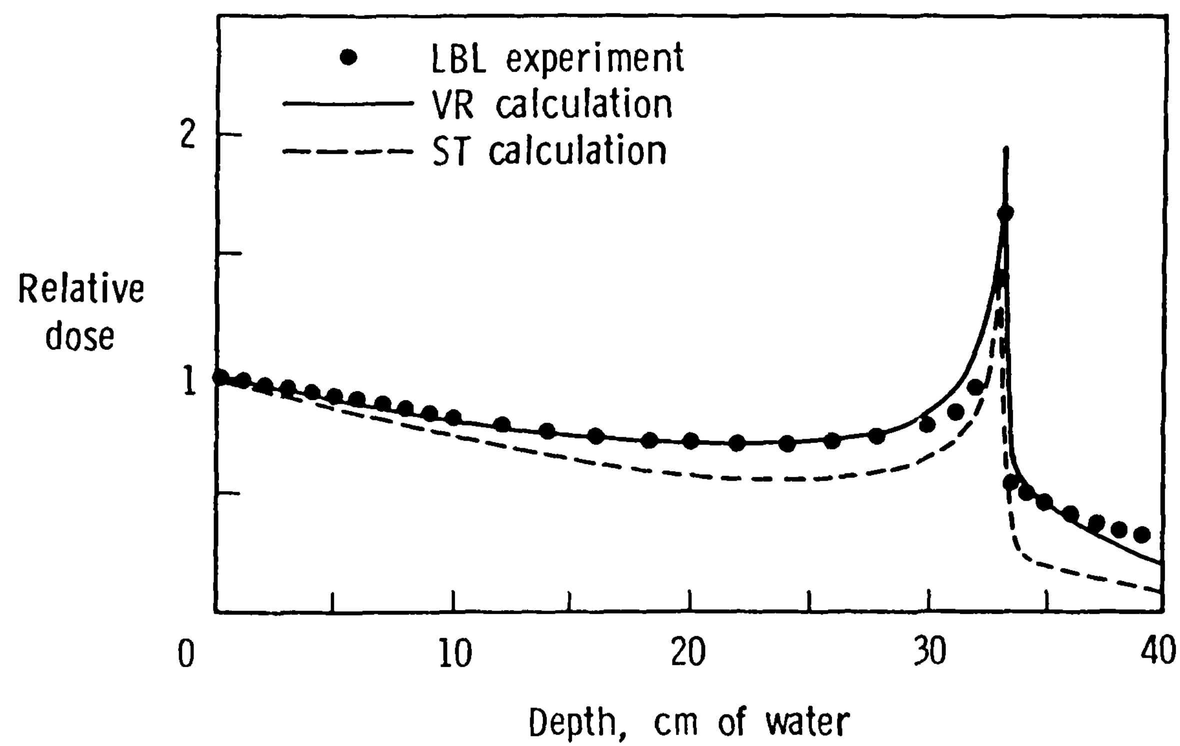

Figure. 1 – Townsend/Wilson
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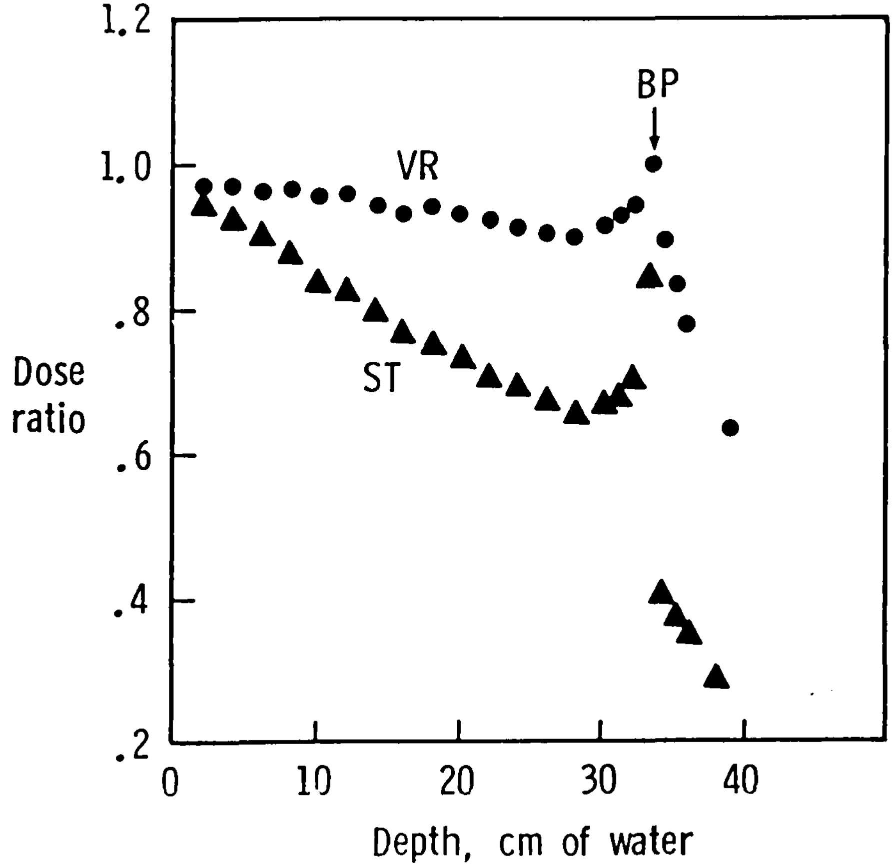

Figure 2.- Townsend/Wilson
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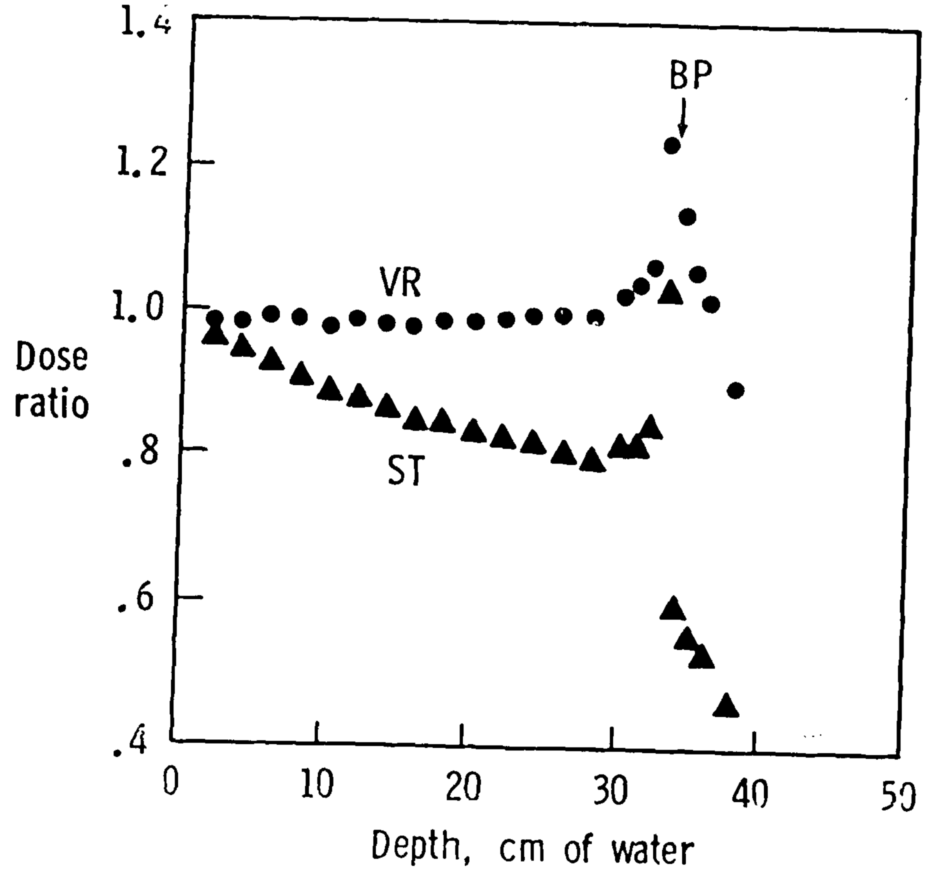

Figure 3.- Townsend/Wilson
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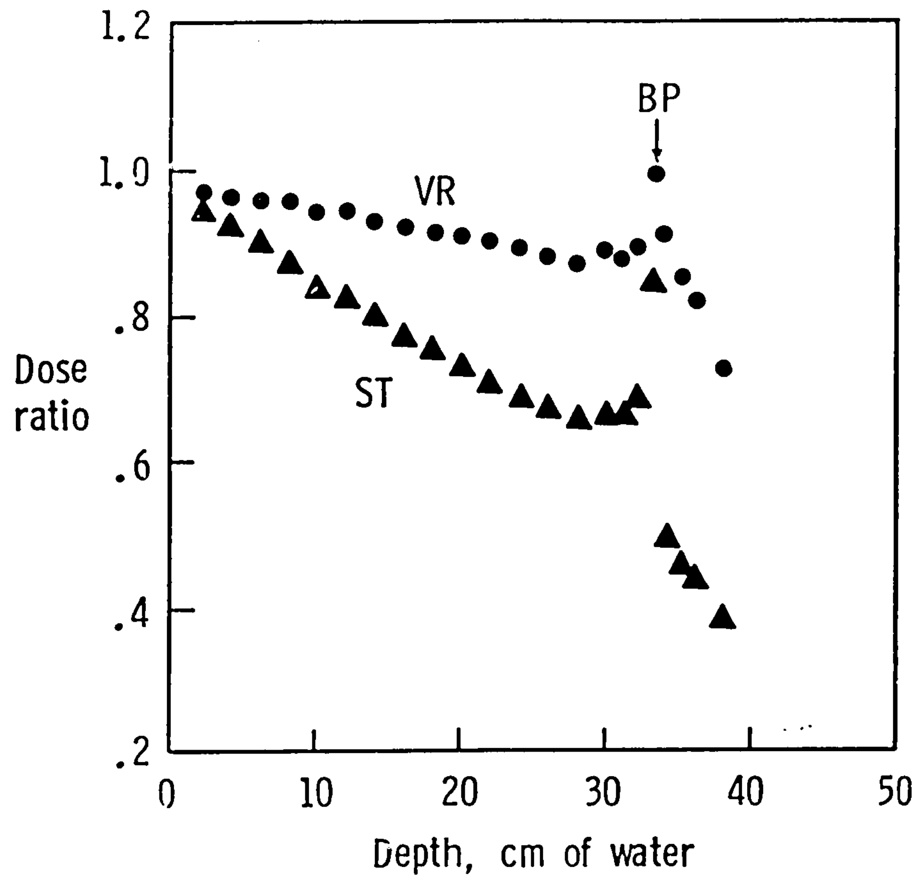

Figure 4.- Townsend/Wilson
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