Optimized Shielding for Space Radiation Protection

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Abstract. Future deep space mission and International Space Station exposures will be dominated by the high-charge and -energy (HZE) ions of the Galactic Cosmic Rays (GCR). A few mammalian systems have been extensively tested over a broad range of ion types and energies. For example, C3H10T1/2 cells, V79 cells, and Harderian gland tumors have been described by various track-structure dependent response models. The attenuation of GCR induced biological effects depends strongly on the biological endpoint, response model used, and material composition. Optimization of space shielding is then driven by the nature of the response model and the transmission characteristics of the given material.

KEYWORDS: Human exploration, Galactic Cosmic Radiation, Shielding materials

1. Introduction

Methods by which radiation shielding is optimized need to be developed and materials of improved shielding characteristics identified and validated. As the mixture of particles in the radiation field changes with added shielding, the control of risk contributions from dominant particle types is critical to reducing the hazard to the astronaut. The risk of biological injury for a given particle type depends on the type of biological effect and is specific to cell or tissue type [1,2,3]. The optimization of shield composition will then be tied to a specific tissue and risk. Such peculiarities arise from the complicated mixture of particles, the nature of their biological response, and the details of their interaction with material constituents.

Shielding optimization also requires an accurate understanding of the way in which the shield material interacts with the radiation field. Our understanding of this interaction has changed radically in the past ten years. For example, the NCRP estimated

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that only 2 g/cm^2 of aluminum [4] would be required to meet the annual 500 mSv limit for the exposure of the blood forming organs while current estimates require above 50 g/cm^2. The neutrons produced throughout such a heavily shielded vehicle also contribute significantly to the exposure and this demands greater care in describing the angular dependence of secondary particle production and transport processes [5].

Many of the materials must meet other mission requirements (strength, thermal, hardness…) vary widely in composition and in radiation shielding properties (e.g., polymeric composites vs. metallic structures). A large fraction of the protective properties come from materials chosen for other requirements and early entry of radiation constraints and a multifunctional design process is required for design optimization.

2. Methodologies

The types and energy distributions of particles transmitted through a shield material requires the solution to the Boltzmann transport equation with boundary conditions related to the external space radiation environment. The flux density $\phi_j(x,\Omega,E)$ of type j particles at spatial location x, moving in direction Ω with energy E is given [6] as

$$\Omega \bullet \nabla \phi_j(x,\Omega,E) = \sum \int \sigma_{jk}(\Omega,\Omega',E,E') \ \phi_k(x,\Omega',E') \ d\Omega' \ dE' - \sigma_j(E) \ \phi_j(x,\Omega,E) \qquad (1)$$

where $\sigma_j(E)$ is the macroscopic cross section (*i.e.*, probability per g/cm^2) for removal of j particles of energy E, $\sigma_{jk}(\Omega,\Omega',E,E')$ are the macroscopic cross sections for various atomic and nuclear processes adding j particles of energy E in direction Ω including spontaneous disintegration. In general, there are hundreds of particle fields $\phi_j(x,\Omega,E)$ with several thousand cross-coupling terms $\sigma_{jk}(\Omega,\Omega',E,E')$. Since the atomic, nuclear elastic and reactive cross sections are ordered as $1:10^{-5}:10^{-8}$, solutions to the Boltzmann equation are expanded as a sequence of physical perturbative approximations. Special problems arise in the perturbation approach for neutrons that lack significant atomic processes [5].

The double differential particle production and fragmentation cross sections $\sigma_{jk}(\Omega,\Omega',E,E')$ of equation (1) are separated into an isotropic term and a remainder as

$$\sigma = \sigma_{iso} + \sigma_F \qquad (2)$$

where the remainder σ_F consists of only forward directed secondary particles and σ_{iso} is dominated by the lower energy particles produced in the reaction. Equation (1) can likewise be separated into two parts for which σ_F appears only in equation (1) with solution ϕ_F and a second equation in which σ_{iso} appears in equation (1) but with source terms from coupling to the ϕ_F field through σ_{iso}. Equation (1) for ϕ_F can be solved with a marching procedure [6]. There remains the evaluation of the terms σ_{iso} of equation (1); especially the low-energy neutron transport solved using multigroup methods [7]. Finally, it should be noted that this procedure assumes the use of only *inclusive cross sections, i.e.,* reactions of the type A+B $\rightarrow$ X + unobserved particles, where X is the particle contributing to the flux and includes all of the multiple particle events. Correlated events such as exclusive reaction channels are functions of the particle fields and can be evaluated once the fields are known.

3. Biology and Shielding

The relative probability of cancer lethality has been estimated by various international learned organizations, mainly using data obtained from the careful study of atomic bomb survivors performed by the Radiation Effects Research Foundation in Hiroshima. Extrapolation to occupational radiation exposure delivered by particles of different linear energy transfer (LET) is usually accomplished by means of a "quality factor" Q that multiplies the absorbed dose (measured in J/kg, or Gray) to obtain a common risk scale, measured in Sievert. The dependence of Q on LET, Q(L), defined by the ICRP [8] has been generally accepted as the standard for radiation protection. The relationship between cancer lethality in humans and the relative biological effectiveness (RBE) of high-LET ions for inducing biological endpoints accessible to laboratory experimentation has not been established; its understanding is one of the critical problems of radiation research. Nevertheless, RBE(L) data have been used as guidance in the definition of Q. Laboratory data show that RBE depends, in addition to LET, on the track width as predicted by Schaefer [9] soon after the discovery of such ions in space and later quantified by Katz [10]. Models to quantify RBE have been developed for several mammalian systems for which sufficient data exist [11-13].

The solution to equation (1) can be written in terms of the Green's function $G(\rho,\sigma,\boldsymbol{x})$ as, $\Phi(\rho,\boldsymbol{x}) = G(\rho,\sigma,\boldsymbol{x})\ \Phi_B(\Gamma)$, where $\Phi(\rho,\boldsymbol{x})$ is a vector array representation of the particle fields at location $\boldsymbol{x}$ within the shield. The shield material is represented by the vector of material compositional densities ρ and array of associated cross sections σ with the boundary condition related to the space source of radiation given by $\Phi_B(\Gamma)$ at the boundary Γ. The particle fields at $\boldsymbol{x}$ are related to a biological effect ef occurring in a biological system s with probability $R_{s,ef}$ as

$$I_{s,ef}(\rho,\boldsymbol{x}) = \Sigma\, R_{s,ef}\, \Phi(\rho,\boldsymbol{x}) = \Sigma\, R_{s,ef}\, G(\rho,\sigma,\boldsymbol{x})\ \Phi_B(\Gamma) \tag{3}$$

where the summation is over all particle types and energies and $I_{s,ef}(\rho,\boldsymbol{x})$ is the net effect observed at x due to the sum of all components of the radiation field. The same approach can be applied to conventional whole body (b) fatal cancer risk (fc) if $I_{b,fc}(r,\boldsymbol{x})$, is approximated by $R_{b,fc} = k\ Q(L)\ L$ where k is the fatal cancer risk coefficient. The materials aspect of the shield design problem is then to find a composition given by the vector of material component densities ρ which will minimize the injury $I_{s,ef}(\rho,\boldsymbol{x})$ for a minimum mass of material about $\boldsymbol{x}$. The optimization process depends on the cross sections of the material components σ and the nature of the matrix response function $R_{s,ef}$. The contributions of various charge groups within a 5 g/cm^2 aluminum shield at solar minimum to biological injury according to risk estimated by use of the quality factor (dose equivalent), the Harderian gland tumor model, and C3H10T1/2 cell survival and transformation endpoints are shown [3] in Fig. 1. The importance of various contributions depends on the risk model used. Furthermore, the relative importance depends on the specific biological endpoint as seen in comparing the survival and transformation endpoints of C3H10T1/2 cells. We compare the shield attenuation of dose equivalent $H(x)$ related to fatal cancer risks with cell transformation $T(x)$ as a function of shield thickness x in Fig. 2. It is interesting to note that many materials can more or less efficiently reduce the dose equivalent while the cell transformation only admits to reduction behind low atomic number materials with high hydrogen content.

4. Optimization Methods

A large fraction of the shielding on human rated vehicles is from the basic structure and onboard systems [2]. Their contribution to shielding as well as any

additional shielding can be optimized in one of three ways: (1) addition of bulk material surrounding the entire habitat; (2) change of elements constituting the structure (e.g., materials with a high ratio of atomic electrons to nuclear protons and neutrons to maximize stopping relative to nuclear interactions); and, (3) redistribution of materials to enhance shielding of locations, such as sleeping quarters, where humans will spend a substantial portion of their time. Unless radiation constraints are incorporated at an early stage of the design, shielding improvements may only be achieved at considerable cost in additional weight of the structure (for example, a 5,500 kg vault was added to Skylab requiring additional support structures). Clearly, optimum solution of radiation constraints requires improved methods of design. Since the basic structure and onboard systems provide much of the shielding, the optimization of spacecraft shielding is inherently a multidisciplinary design process.

5. Future Materials Research

Required materials research must develop multifunctional material properties for use in system optimization procedures. Optimum radiation protective materials are needed to finish out deficiencies in the shield design at minimum mass and costs.

Multifunctional materials optimization. Radiation shield optimization requires an evaluation of materials and making appropriate choices at each step of the design process. Many choices will be driven by design requirements resulting in less than perfect shield materials. The shield performance of candidate materials for each specific application needs to be characterized to allow optimum choices in the design process. New materials for specific applications need to be developed with enhanced shielding characteristics. For example, polymeric composites are preferable to aluminum alloys. We have proposed developing sound absorbing materials that are efficient radiation shields for use in crew areas. Recent advances in hydrogen storage in graphite nanofibers may have a large impact (3-6 times better than aluminum) on radiation safety in future spacecraft design [14].

Optimum protective materials. The requirements for a high performance shield material is to maximize the number of electrons per unit mass, maximize the nuclear reaction cross section per unit mass, and minimize the production of secondary particles [1,2]. Thus, the transmitted LET spectra of hydrogen shows almost universal attenuation

above a few keV/μ resulting in good attenuation of biological effects independent of biological model used. On the other hand, materials with less hydrogen content such as water experience attenuation only above 20 keV/μ [1]. The maximum performance is for liquid hydrogen which we use to define the maximum performance limit of any material as shown in Fig. 3. It is a challenge to materials research to develop materials approaching these high performance levels.

6. Concluding Remarks

It is clear from past experience that a great price has been paid in reaching off-optimum solutions to protection problems. This has resulted from the inefficient computational procedures for shielding estimates. As our knowledge of biological response improves and as our ability to efficiently solve shielding design issues with available high-speed computational procedures, we can think in terms of optimized designs utilizing multifunctional materials which will improve safety and lower mission costs. We stand at the threshold of radically improved designs for human exploration.

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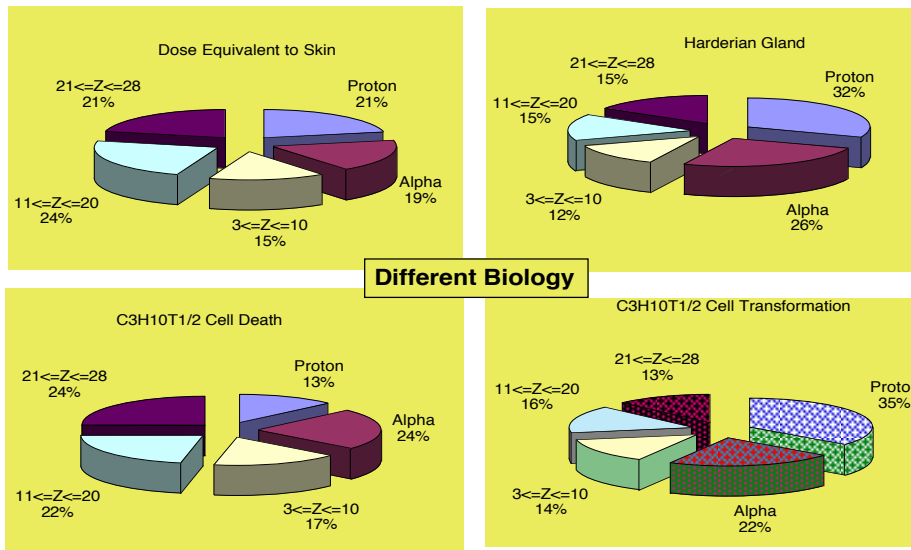
Fig. 1. Contributions from different GCR charge groups in different risk models for the skin with 5 g/cm^2 of aluminum shielding.

(a) Dose equivalent (b) Cell Transformation
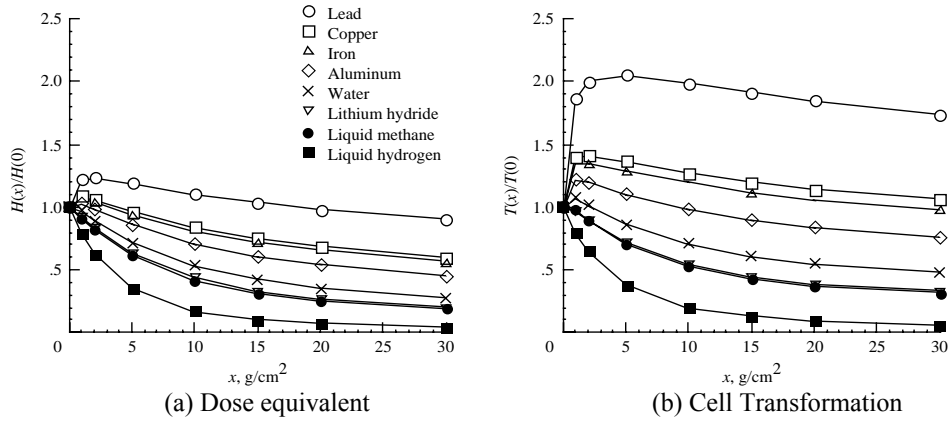
Fig. 2. Attenuation of dose equivalent H(x) and cell transformation T(x) in a one year exposure
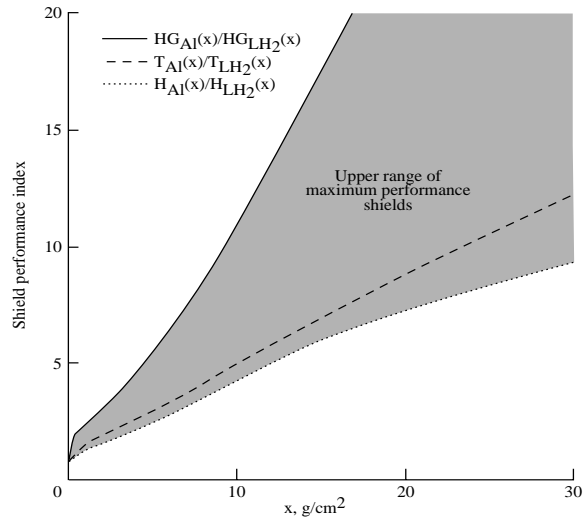within several shield materials.

Fig. 3. Maximum shield performance factors relative to aluminum using various
biological within several shield materials.