

IMPROVED SPACECRAFT MATERIALS FOR RADIATION SHIELDING

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Introduction

Solar particle events and galactic cosmic rays have the potential of producing serious radiation health effects in astronauts in the Human Exploration and Development of Space (HEDS) enterprise^{1,4}. Solar particle events (SPEs) consist mainly of modest energy protons (below a few hundred MeV). Galactic cosmic rays (GCR) consist of high energy particles comprised mainly of protons but also include multiply charged ions (nuclei of chemical elements) through U with only small contributions above Ni. The SPE protons of 30 to 120 MeV are most important to astronaut exposures and fluence levels above 10^8 p/cm² will limit astronaut activity on rare occasions for a period of several hours to few days. A storm shelter from such events must be provided⁵. The GCR pose an ever-present low level background radiation and have great penetrating power through shield materials. The GCR ions of high charge and energy (HZE) are few in number but dominate the estimated cancer risk to astronauts in deep space^{3,4,6}. The intensity of these ions must be reduced while holding secondary radiations to a minimum within the spacecraft interior where the astronaut spends most of his time^{7,8}. Unlike the provision of a SPE storm shelter, shielding required against GCR is needed at all times during the mission and greatly impacts mission costs as the shielding of such a large living/work area requires a large mass of material⁸. Of course, the provision of such a large mass for GCR shielding tends to mitigate the SPE storm shelter requirement. The GCR HZE transmission characteristics of shield materials are poorly understood and the estimated excess Mars mission cost⁸ for shielding against the GCR due to uncertainty in shield estimates is between \$10B and \$30B. Thus, the provision of shielding from the GCR HZE particles at minimum mission cost is a critical element of the HEDS enterprise. Unless there are cost effective means developed to protect the astronaut, there will be no HEDS missions beyond the geomagnetic field⁹.

The insufficient understanding of HZE particle induced risk to astronauts is a basic challenge to shield material studies at this time. Cancer induction is related to mutational events in the cell which have been studied in mammalian cell systems as a guide to the effectiveness of HZE particle cancer induction^{10,11}. There also exist data from HZE induction of hardierian gland tumors in mice for which models have been derived¹². These radiobiological models will be used as indicators for the rate of cancer risk attenuation as a function of materials selection and thickness¹³. The second challenge in seeking optimum shielding materials is that models for the nuclear interaction processes (fragmentation and secondary particle production cross sections) required for shield evaluation are not entirely developed and validated⁸. Therefore, laboratory testing of material transmission characteristics is an essential component of any materials development program. In the testing area, it is impossible to test all materials against all ions in the GCR environment due to the large number of ion types and their broad energy spectrum. Testing is limited to a few dominant ions at the most important energies. Sixty percent of the astronaut cancer risks are from the ions of C, O, Mg, Si, and Fe (with an added 30 percent from the other HZE ions and only about 8 percent from GCR protons)¹⁴. These five dominant ions will be the focus of laboratory testing in the most important energy range between 500 MeV per nucleon and 2000 MeV per nucleon. Such

transmission tests require a complex diagnostic apparatus to identify the particles transmitted through or produced in the shield material¹⁵. A unique test apparatus has been developed and operated for NASA by the Lawrence Berkeley National Laboratory for use at the Brookhaven National Laboratory (BNL) AGS accelerator facility (a unique facility within the US able to simulate the GCR HZE ion beams found in space)^{15,17}. Some components produced in an external shield material are themselves biologically damaging (e. g., neutrons) and multilayered neutron absorbing materials may show advantage^{7,18}. A neutron shield testing facility and computational procedures are now available at Langley for the optimization of neutron absorption properties.

In the execution of this proposal, we will first examine current and developing spacecraft materials and evaluate their ability to attenuate adverse biological mutational events in mammalian cell systems and reduce the rate of cancer induction in mice harderian glands as a measure of their protective qualities. The HZETRN code¹⁹ system will be used to generate a database on GCR attenuation in each material. If a third year of funding is granted, the most promising and mission-specific materials will be used to study the impact on mission cost for a typical Mars mission scenario as was planned in our original two year proposal at the original funding level. The most promising candidate materials will be further tested as to their transmission characteristics in Fe and Si ion beams to evaluate the accuracy of the HZETRN transmission factors⁸. Materials deemed critical to mission success may also require testing as well as materials developed by industry for their radiation protective qualities (e.g., Physical Sciences Inc.) A study will be made of designing polymeric materials and composite materials with improved radiation shielding properties as well as the possible improvement of mission-specific materials.

Shielding Methodology

The specification of the interior environment of a spacecraft and evaluation of the effects on the astronaut is at the heart of the radiation protection problem. The Langley Research Center has been developing such techniques^{2,8}. The relevant transport equations are the linear Boltzmann equations for the flux density $\phi_j(\mathbf{x}, \Omega, E)$ of type j particles as

$$\Omega \cdot \nabla \phi_j(\mathbf{x}, \Omega, E) = \sum_k \int \sigma_{jk}(\Omega, \Omega', E, E') \phi_k(\mathbf{x}, \Omega', E') d\Omega' dE' - \sigma_j(E) \phi_j(\mathbf{x}, \Omega, E) \quad (1)$$

where $\sigma_j(E)$ and $\sigma_{jk}(\Omega, \Omega', E, E')$ are the media macroscopic cross sections. The $\sigma_{jk}(\Omega, \Omega', E, E')$ represent all those processes by which type k particles moving in direction Ω' with energy E' produce a type j particle in direction Ω with energy E . Note that there may be several reactions which produce a particular product, and the appropriate cross sections for equation (1) are the inclusive ones. The total cross section $\sigma_j(E)$ with the medium for each particle type of energy E may be expanded as

$$\sigma_j(E) = \sigma_{j,at}(E) + \sigma_{j,el}(E) + \sigma_{j,r}(E) \quad (2)$$

where the first term refers to collision with atomic electrons, the second term is for elastic nuclear scattering, and the third term describes nuclear reactions. The microscopic cross sections and average energy transfer are ordered as follows:

$$\sigma_{j,at}(E) \sim 10^{-16} \text{ cm}^2 \text{ for which } \Delta E_{at} \sim 10^2 \text{ eV} \quad (3)$$

$$\sigma_{j,el}(E) \sim 10^{-19} \text{ cm}^2 \text{ for which } \Delta E_{el} \sim 10^6 \text{ eV} \quad (4)$$

$$\sigma_{j,r}(E) \sim 10^{-24} \text{ cm}^2 \text{ for which } \Delta E_r \sim 10^8 \text{ eV} \quad (5)$$

This ordering allows flexibility in expanding solutions to the Boltzmann equation as a sequence of physical perturbative approximations. It is clear that many atomic collisions ($\sim 10^6$) occur in a centimeter of ordinary matter, whereas $\sim 10^3$ nuclear coulomb elastic collisions occur per centimeter. In contrast, nuclear reactions are separated by a fraction to many centimeters depending on energy and particle type. Special problems arise in the perturbation approach for neutrons for which $\sigma_{j,at}(E) \sim 0$, and the nuclear elastic process appears as the first-order perturbation.

As noted in the development of equation (1), the cross sections appearing in the Boltzmann equation are the inclusive ones so that the time-independent fields contain no spatial (or time) correlations. However, space- and time-correlated events are functions of the fields themselves and may be evaluated once the fields are known^{20,21}. Such correlations are important to the biological injury of living tissues. For example, the correlated release of target fragments in biological systems due to ion or neutron collisions have high probabilities of cell injury with low probability of repair resulting in potentially large relative biological effectiveness (RBE) and quality factor²². Similarly, the passage of a single ion releases an abundance of low energy electrons from the media resulting of intense fields of correlated electrons near the ion path.

The solution of equation (1) involves hundreds of multi-dimensional integro-differential equations which are coupled together by thousands of cross terms and must be solved self-consistently subject to boundary conditions ultimately related to the external space environment and the geometry of the astronaut's body and/or a complex vehicle. In order to implement a solution one must have available the atomic and nuclear cross section data. The development of an atomic/nuclear database is a major task in code development.

Transport Coefficients

The transport coefficients relate to the atomic/molecular and nuclear processes by which the particle fields are modified by the presence of a material medium. As such, basic atomic and nuclear theories provide the input to the transport code data base. It is through the nuclear processes that the particle fields of different radiation types are transformed from one type to another. The atomic/molecular interactions are the principal means by which the physical insult is delivered to biological systems in producing the chemical precursors to biological change within the cells. The temporal and spatial distributions of such precursors within the cell system governs the rates of diffusive and reactive processes leading to the ultimate biological effects. The transport coefficients are developed under a related project described in a separate paper in these proceedings²³.

Transport Solution Methods

The solution to equation (1) can be written in operational form as $\phi = G \phi_B$ where ϕ_B is the inbound flux at the boundary, and G is the Green's function which reduces to a unit operator on the boundary. A guiding principle in radiation-protection practice is that if errors are committed in risk estimates, they should be overestimates. The presence of strong scattering terms in equation (1) provides lateral diffusion along a given ray. Such diffusive processes result in leakage near boundaries. If ϕ_Γ is the solution of the Boltzmann equation for a source of particles on the boundary surface Γ , then the solution for the same source on Γ within a region enclosed by Γ_0 denoted by $\phi_{\Gamma_0}(\Gamma)$ has the property

$$\phi_{\Gamma_0}(\Gamma) = \phi_\Gamma + \epsilon_\Gamma \quad (7)$$

where ϵ_Γ is positive provided Γ_0 completely encloses Γ . The most strongly scattered component is the neutron field for which an 0.2 percent error results for infinite media in most practical problems². Standard practice in space radiation protection replaces Γ as required at some point on the boundary and along a given ray by the corresponding Γ_N evaluated for normal incidence on a semi-infinite slab. The errors in this approximation are second order in the ratio of beam divergence and radius of curvature of the object², rarely exceed a few percent for space radiations, and are always conservative. The replacement of Γ by Γ_N as a highly accurate approximation for space applications has the added advantages that Γ_N is the natural quantity for comparison with laboratory simulations and has the following properties: If Γ_N is known at a plane a distance x_0 from the boundary (assumed at the origin), then the value of Γ_N at any plane $x \geq x_0$ is

$$G_N(x) = G_N(x - x_0) G_N(x_0) \quad (8)$$

Setting $x = x_0 + h$, where h is small and of fixed-step size gives rise to the marching procedures of HZETRN.

Evaluation Of Shield Effectiveness

Our prior survey of current and developing spacecraft materials will be updated and ordered according to hydrogen content per unit mass and then number of electrons per unit mass as an indicator of shielding effectiveness. The HZETRN code system will be used to evaluate the transmission of GCR through each material as a function of the material's areal density (a parameter related to total shield mass) and the rate of attenuation of adverse biological effects using four bioresponse models (cancer risk using LET-dependent quality factors, Harderian gland tumors in mice, neoplastic transformation in mice cells, and mutations in hamster cells). The materials will then be ordered according to their effectiveness per unit mass in reducing the biological hazard. Since aluminum is a current standard material for spacecraft construction, special emphasis will be given to the relative benefit of various aluminum alloy systems and aluminum matrix composites. The most promising aluminum based material systems, polymer systems, and the most promising polymer composite systems will be used in target testing at the BNL AGS facility. The targets will be prepared by the Materials Division of Langley Research Center for laboratory testing of their shield material's transmission characteristics.

Materials Database

The choice of materials will be guided as follows. Since aluminum alloys are still the primary construction technology in the space program, we will study the effects of added alloy components as to their protective qualities. For example, the Cu additive to aluminum alloy will lessen the shielding effectiveness whereas Al-Li alloy systems will have improved shielding characteristics. Aluminum metal matrix composites are favorable depending on the fiber used and boron fibers in particular may show some advantage since they absorb low energy neutrons which are always produced as a secondary reaction product. However, the boron fibers with tungsten cores need careful evaluation as the tungsten will be a strong source of secondary radiations. Neat polymers have already shown important advantages in their radiation protection properties and can be ordered in their protective abilities according to their hydrogen content although there has been little laboratory testing. The use of *in situ* polymer manufacturing and regolith composites will be examined as a mission cost effective means of habitat construction. Polymer matrix composites could be an important alternative to many aluminum based structures with anticipated improved radiation protective properties. We will examine the effects of fiber choice on protective properties as well as of polymer content. The protective value of the fibers are expected to be ordered from least effective to most effective as glass, graphite, boron, Kevlar, and polyethylene fibers. In addition, materials identified as part of mission critical elements, such as inflatable lay-ups, regolith augmentation, and consumables, will be evaluated. Materials available for habitat construction on the Martian surface will be examined. All of the materials will be quantified as to their protective abilities and trade studies in the third year will be made on the most promising materials to evaluate their effect on mission costs in the context of current uncertainty in HZE cancer risks factors.

Preliminary Transmission Characterization Tests

Water and polyethylene both satisfy the requirements of good shielding properties (High electron density and large nuclear cross section per unit mass) and have been used as targets in a number of different measurements. We discuss the 510 MeV/nucleon ^{56}Fe ion beams on CH_2 target measurements.

Transmission of Fe ions in polyethylene

The fragmentation of 510 MeV/nucleon ^{56}Fe in polyethylene was measured¹⁶ and compared¹⁷ to transmission properties based on the NUCFRG2 nuclear fragmentation model²⁴ in figure 1. The agreement between data and model is good, but the model's underprediction of the heavy fragment yield indicated that it could be improved, particularly in its treatment of nuclear structure effects. Also, in this case the uncertainties in both data and model were

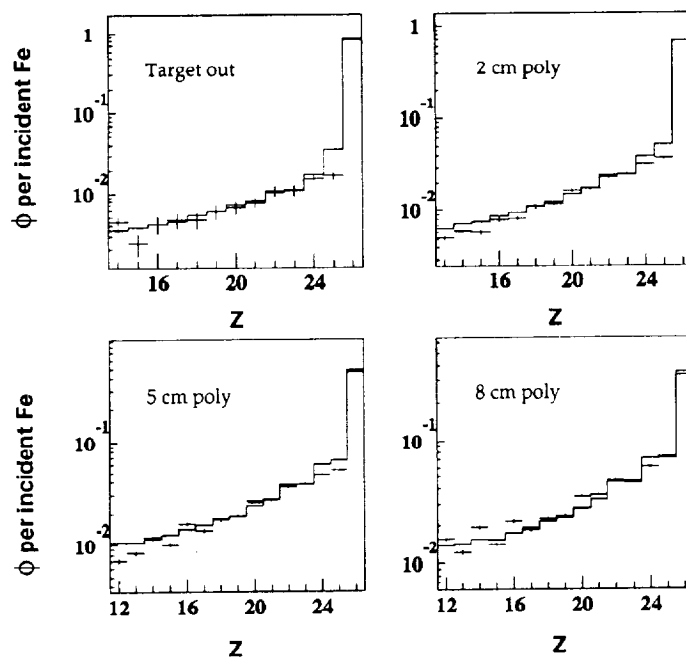


Figure 1. Comparison of measured fragment production by 510 MeV/nucleon ^{56}Fe in CH_2 with a model calculation (solid line histogram), as described in the text and in ref. [24].

small enough that the effects of higher order fragmentation could be studied. It was found that at least two generations of fragments must be included for the model transmission functions to accurately reproduce the data².

Validation Testing

The validity of the predicted transmission properties will be tested in the Fe and Si ion beams at the BNL AGS accelerator in the first two years. Added beam testing with C, O, and Mg beams may be accomplished in the third year. Detection systems to measure projectile fragmentation are typically of small to moderate size, depending upon the angular range covered. Figure 2 is a schematic of a detector configuration which our group has used to measure the fragmentation of 1.08 GeV/nucleon ^{56}Fe in a variety of materials at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS)¹⁶. A series of solid state detectors record the energy deposited by charged particles traversing them. Convoluting the energy losses in two or more detectors makes it possible to calculate the particle's charge and energy. The solid state detector stack was augmented by plastic scintillation counters to measure the time of flight between two points. This information is needed to supplement the energy loss information in the case of the lighter charged particles.

Each individual particle event seen by the detector system is recorded during the accelerator test and off line analysis codes are used to extract information about the transmitted particle composition. Some correction to the data is required to account for multiple scattering effects for which particles are lost from the detector system.

The interactions of the high energy ions produce very penetrating secondary neutrons in the shield materials for which special inner layers of neutron absorbing materials may be placed. A fast neutron testing laboratory has been established at Langley to validate the absorption properties of materials.

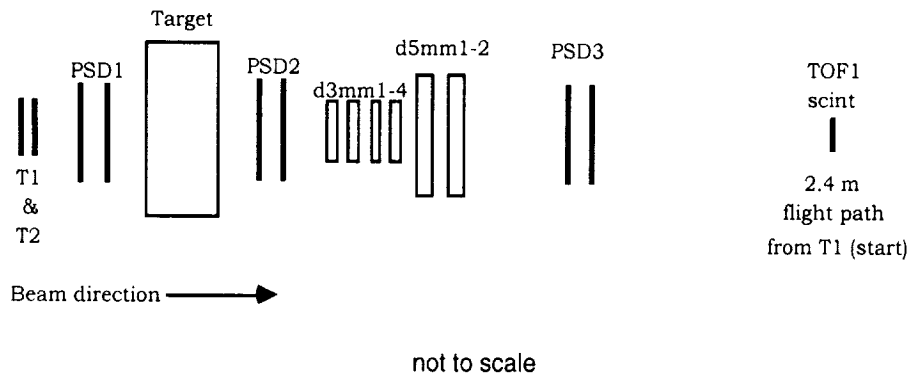


Figure 2. Detectors used to measure fragmentation cross sections and fragment fluences from 1.08 GeV/nucleon ^{56}Fe incident on a variety of targets. The detectors include plastic scintillation counters (T1, T2, TOF1), position sensitive solid state detectors (PSD1,2,3) and 3 and 5 mm solid state energy loss detectors (d3mm1-4, d5mm1-2).

Mission Trade Studies

Mission trade studies will be performed using the developed materials data base of the radiation properties of current and developing spacecraft materials as well as mission-specific materials. The most current Mars mission scenarios and transfer vehicle configurations will be used to assess the impact of material selection on crew safety and mission cost. The calculated and experimentally validated radiation transmission properties will be used to generate a figure of merit for each of the selected materials relative to aluminum. A methodology to incorporate the “figure of merit” results, including cancer risk using quality factors and the three bioresponse models, will be developed to establish a design procedure for the trade studies. The launch mass savings, obtained through judicious material selection, will then be evaluated for a Mars mission where parasitic shield requirements for GCR may become mission prohibitive. In addition, the effectiveness of the shield design strategy in reducing the biological effects of the GCR environment incurred by crew members will be evaluated. The remaining uncertainty associated with HZE transmission properties and bioresponse models will be included in the trade study analysis to address their impact on mission cost. By establishing a design procedure at the conceptual phase of mission development to incorporate radiation-efficient materials, based on experimentally validated transmission properties and current bioresponse models, the potentially negative impact of shielding requirements on mission go/no-go decisions can be resolved.

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