IMPROVED SPACECRAFT MATERIALS FOR RADIATION PROTECTION
Shield materials optimization and testing

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The cost effectiveness of shielding against galactic cosmic rays (GCR) could influence a go/no-go decision for the developing HEDS enterprise since excess shield costs for deep-space missions are estimated to be greater than $10B (NASA CP-3360, 1995). Methods by which radiation shielding is optimized need to be developed and materials of improved shielding characteristics identified and validated. The Microgravity Materials Program through its 98-HEDS-04 Research Announcement has called for research to support "Enhanced human radiation protection through the development of light weight soft goods with high radiation protection characteristics." The GCR are very penetrating and the energy absorbed by the astronaut behind the shield is nearly independent of shield composition and even the shield thickness. However, the mix of particles in the transmitted beam changes with shield material composition and thickness. This results in part from the breakup of the high-energy heavy ions of the GCR which make contributions to biological effect out of proportion to their deposited energy. So the mixture of particles in the radiation field changes with shielding and 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. Thus, one is faced with choosing materials which may protect a given tissue against a given effect but leave unchanged or even increase the risk of other effects in the same tissue or increase the risks to other adjacent tissues of a different type in the same individual. The optimization of shield composition will then be tied to a specific tissue and risk to that tissue. Such peculiarities arise from the complicated mixture of particles, the nature of their biological response, and the details of their interaction with material constituents. This is a radical departure from prior shield design experience. As our understanding of the biological effects in specific astronaut tissues is improved, control of the most adverse effects can be specified as dictating a particular material composition for addressing the most important tissues and effects in those tissues, while minimizing adverse biological effects in the same and adjacent tissues.

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Aside from the understanding of the biological response to specific components, one also needs an accurate understanding of the radiation emerging from the shield material. This latter subject has been a principal element of this project. In the past ten years our understanding of space radiation interactions with materials has changed radically, with a large impact on shield design. For example, the NCRP in its Report No. 98 (1989) estimated that only 2.5 g/cm^2 of aluminum would be required to meet the 500 mSv limit for the exposure of the blood forming organs (this limit is strictly for LEO but can be used as a guideline for the Mars mission analysis). The current estimates require aluminum shield thicknesses above 50 g/cm^2 , which is impractical for the Mars Reference Mission. In such a heavily shielded vehicle, the neutrons produced throughout the vehicle also contribute significantly to the exposure and this demands greater care in describing the angular dependence of secondary particle production processes. This has been the focus of much of the last year's activity and has resulted in improved neutron prediction capability. These new methods have also improved our understanding of the surface environment of Mars. The Mars 2003 NRA HEDS related surface science requirements were driven by the need to validate predictions on the upward flux of neutrons produced in the Martian regolith and bedrock made by the codes developed under this project. The codes used in the surface environment definition are also being used to look at *in situ* resources of the Mars Reference Mission for the development of construction materials of Martian surface facilities. For example, synthesis of polyimides and polyethylene as binders of regolith for developing basic structural elements has been studied and targets built for accelerator beam testing of radiation shielding properties. Preliminary mechanical tests have been promising.

Several materials have been identified (using the criteria reported by this project at the last conference) as potentially important for future shielding materials. These are liquid hydrogen, hydrogenated nanofibers, liquid methane, LiH, Polyethylene, Polysulfone, and Polyetherimide (in order of improving shield performance). Some of the materials are multifunctional and are required for other onboard systems. We are currently preparing software for trade studies with these materials relative to the Mars Reference Mission as required in the project's final year.

At the beginning of this project, the shield design technology was at Technology Readiness Level (TRL) 3-4. The laboratory testing with relevant particle types has provided valuable data for model improvements and database validation. Future improvements will be more evolutionary than revolutionary as interaction models are relatively mature, which was not the case a few years ago and as confirmed by the blind test conducted by the LBNL group (Phys. Rev C56:388; 1997). Future improvements are expected to be incremental. An opportunity for comparison with flight measurements on a large 2219 aluminum alloy structure allowed us to rapidly move the TRL to include level 6-7 elements in the project. The use of the tissue equivalent proportional counter (TEPC) with its broad spectral capability and the time resolved methodologies allows testing of codes and databases for both trapped proton spectra and galactic cosmic rays. This comparison added to the evidence that the pions may be the next most important component to add to the current technology, and consequently a low energy database for pion production has been prepared. The addition of higher energy multi-pion processes is in progress and will be funded out of another program. Only modest improvements to the exposure field are expected for spacecraft but the enhanced model may play a more important role for the Mars surface. Additional testing of the codes and database will take place on ISS in the near future. As a final note, the identification of polyethylene as a relatively efficient shield material under this project has resulted in an on-going activity with JSC for the augmentation of the ISS design to reduce the cancer risks of the astronauts in ISS operations.