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RADIATION TRANSMISSION PROPERTIES OF *IN-SITU* MATERIALS

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INTRODUCTION

The development of a permanent human presence in space is a key element of NASA's strategic plan for the Human Exploration and Development of Space (HEDS). The habitation of the International Space Station (ISS) is one near-term HEDS objective; the exploration and settlement of the moon and Mars are long-term goals of that plan. Achieving these goals requires maintaining the health and safety of personnel involved in such space operations at a high level, while at the same time reducing the cost of those operations to a reasonable level.

Among the limiting factors to prolonged human space operations are the health risks from exposure to the space ionizing radiation environment. In order to keep the risk of radiation-induced cancer at acceptable levels, it is necessary to provide adequate shielding from the ionizing radiation environment. The cost of transporting shielding materials to the moon or Mars is prohibitive. One cost-effective method of providing adequate shielding in those environments is to utilize local, *in-situ* materials. Simple techniques may involve covering a transported habitat with local regolith, or using water found on Mars (and recently found on the moon) to augment shielding. Novel shielding techniques are being developed which combine local regolith with resin binders to construct structural materials for use in the building of habitats. The presence of water and a carbon dioxide atmosphere on Mars holds some promise as building blocks in the manufacturing of resin binders.

As the mass of shielding increases, radiation dose decreases. However, as the shielding mass increases, calculations predict (1-3) that the percentage of the dose from neutrons increases, due in part to the high penetrabilities of neutrons. For moderately thick (40 - 50 g/cm²) shields on lunar and Martian bases, approximately 50% or more of the dose could come from neutrons. A recent workshop (4) conducted at the Johnson Space Center concluded that the dose from neutrons in the ISS could comprise 30 to 60 percent of the total dose. As evident from these predictions, the production of neutrons is an important consideration in the design and development of shielding to be used in various mission scenarios.

Because of the relatively short lifetimes of free neutrons, they are not present in space radiation. Essentially all neutrons in the radiation field are secondary neutrons produced by interactions of primary trapped, Galactic Cosmic Ray (GCR) and Solar Particle Event (SPE) particles in shielding materials and human tissue. The spectrum of primary particles covers a mass range from protons to

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iron, and covers a range in energy from 50 MeV/nucleon to energies of a few TeV/nucleon. As such, the ability of any calculation to accurately predict the dose from neutrons depends on that calculation's ability to accurately model the production and transport of neutrons generated from an enormous range of interactions. Development and verification of model calculations depend upon a relevant experimental data base of neutron-production cross sections, neutron-interaction cross sections, and thick-target neutron yields.

Much of the experimental data base needed for the development of radiation transport models comes from experiments conducted at ground-based particle accelerators. Particle accelerators do not produce beams that simulate the entire GCR or SPE spectrum at any one time; however, they produce beams of GCR-like particles where the mass, charge, energy, direction, and number of particles interacting in the target is known to a high degree of precision and accuracy. Ground-based experiments that measure secondary neutron production provide highly detailed information in regards to neutron spectra over a large range in neutron energy and angle. Because of these features, the data resulting from such experiments are used to examine the details of physical processes of neutron production (such as nucleon evaporation from target and projectile remnants, breakup of the overlap region between projectile and target, and final-state interactions) which must be incorporated by transport models. These data, then, are of critical importance to the development of models that will ultimately be used to predict risk in complex radiation and shielding environments in space.

The ground-based experiments that are relevant to neutron transport can be divided into three categories: neutron-production cross-section measurements, thick-target neutron-yield measurements, and neutron-interaction cross-section measurements. Cross-section experiments measure neutron spectra created by a projectile at one specific energy, with no contributions from secondary interactions in the target. As stated above, cross-section measurements provide information on the details of the physical processes that produce neutrons in projectile-target interactions. Thick-target measurements refer to experiments where the target is thick enough such that secondary interactions produce a measurable effect on the neutron yield outside the target. Secondary interactions include both neutron production from secondaries interacting with target nuclei and neutron-flux attenuation due to neutron interactions with target nuclei. In addition to the effect of secondary interactions, thick-target measurements also sample primary projectile-target interactions over a large range of projectile energies, as opposed to interactions at one energy in cross section measurements.

The research presented here is a theoretical and ground-based experimental study of neutron production from interactions of GCR-like particles in various shielding components. An emphasis is placed here on research that will aid in the development of *in-situ* resource utilization. The primary goal of the program is to develop an accurate neutron-production model that is relevant to the NASA HEDS program of designing technologies that will be used in the development of effective shielding countermeasures. A secondary goal of the program is the development of an experimental data base of neutron production cross sections and thick-target yields which will aid model development.

I. Model Development

Comparisons of proton-induced neutron yields and cross sections with High Energy Transport Code (HETC) (5) and Bertini (6) intranuclear cascade model calculations have been made over a wide variety of systems (7-12) with incident proton energies similar to those found in space. Generally, the HETC and Bertini calculations do a good job of matching spectral shapes, and do an excellent job of reproducing the magnitudes of the cross sections for interactions with very heavy elements (W, Pb, U). However, the agreement deteriorates for lighter nuclei, where the calculations overestimate the production by a factor of two for low-energy ($E = 20$ MeV) neutrons (10). For all targets, HETC underestimates the yields at large angles for neutrons above 10 MeV, and underestimates the high-energy yield (above 100 MeV) at forward angles. Note that these observations were made on calculations using the version of HETC that was available between 1989 and 1993. No comparisons with that data have been made with later versions of HETC, and those comparisons may be worth investigating. Zucker, *et al.*, report (13) that LAHET calculations (which they report are similar to the 1996 version of HETC) of their 800-, 1000-, 1200-, and 1400-MeV data sets overestimate the data by 10 to 20 percent.

Boltzmann-Uehling-Uhlenbeck (BUU) calculations have been compared with thick-target neutron yields (14). The BUU calculations do a good job of fitting the data at large angles, both in magnitude and shape. However, at forward angles the BUU calculations either over-predict or under-predict the yield, depending on the angle. This may be due in part to the fact that forward-angle spectra from BUU calculations are sensitive to the cutoff density used to determine whether or not a particle has been emitted. Even though the BUU calculation misses the magnitude of the forward angle spectra, it does a fairly good job in reproducing the shape of those spectra. In comparing calculations with thick-target yields, any discrepancy between data and calculation does not necessarily indicate a problem with the calculated cross sections used as input because the problem may lay with the methodology used in applying those cross sections to produce thick-target yields.

BUU and intranuclear cascade model calculations have varying degrees of success in matching experimental data. The discrepancies between those models and data may suggest that uncertainties may still be large (on the order of 50%) when calculations are made of the neutron fluence behind shielding and tissue in space-related activities. Much of that uncertainty is due to the lack of relevant nuclear data to compare to, but it is also clear that improvements can be made in modeling neutron production. The neutron production model under development in this work is based on an abrasion-ablation fragmentation model (15,16). In the abrasion (knockout) step, the portions of the projectile and target nuclear volumes that overlap are sheared away by the collision. The remaining projectile piece, moving at velocities essentially the same as the pre-collision velocity, is highly excited and decays by gamma and particle emission. This step is called the ablation stage. Improvements to the existing model will include the decay of the overlap region and the decay of the target remnant.

II. Experimental Neutron Data (Ground-Based)

A variety of neutron cross-sections and thick-target yields have been measured from systems applicable to the general problem of radiation transport in space-related activities (see Ref. [4] and references contained therein). The data includes thick-target neutron yields measured from heavy-ion reactions in this project (14,17).

To get an idea of the neutron energies that may be important to consider in terms of crew risk assessment, the neutron yields reported (8) for 256-MeV protons stopping in Al (20-cm long, 54 g/cm²) have been integrated over the angular range from 30 to 150 degrees. Table I lists the percentage of the total flux (above 0.5 MeV) contained within a specific range of neutron energy for several ranges of energy, along with the percentage of total dose-equivalent. Roughly half of the neutron flux (51%) is below 5 MeV, with 29% of the flux above 20 MeV. However, when considering the dose equivalent, the percentages shift towards higher neutron energies; roughly half (52%) of the dose equivalent is above 20 MeV. This evaluation most likely underestimates the relative importance of neutrons above 20 MeV in space environments because (1) data below 30 degrees, where much of the high-energy neutron flux is contained, is not considered, and (2) although 256 MeV is near the peak of the GCR proton energy distribution, the majority of the GCR proton flux is above 256 MeV. Proton interactions at higher energies will increase the yield of high-energy neutrons relative to the low-energy yield.

Table 1. Percentages of the total neutron flux and total neutron dose equivalent from 256-MeV protons stopping in Al, for the ranges of neutron energy.

Energy range (MeV)	% Neutron flux	% Dose-equivalent
0.5 - 1	13%	6%
1 - 5	38%	28%
5 - 10	13%	9%
10 - 20	7%	5%
20 - 50	9%	12%
50 - 100	13%	25%
100 - 200	6%	13%
>200	1%	2%

An analysis of the heavy-ion data suggests that the neutron multiplicity from interactions in one system can be deduced from the measured multiplicity in another system (at the same projectile energy per nucleon) using the following relationship:

$$\frac{M(\text{system1}, T > T_0)}{M(\text{system2}, T > T_0)} = \frac{\sigma(\text{system2})}{\sigma(\text{system1})} \times \left(\frac{(A_{\text{tgt1}})^{1/3} + (A_{\text{proj1}})^{1/3}}{(A_{\text{tgt2}})^{1/3} + (A_{\text{proj2}})^{1/3}} \right)^{a(T_0)}$$

where $M(\text{system1}, T > T_0)$ and $M(\text{system2}, T > T_0)$ are the neutron multiplicities of system 1 and system 2, T is kinetic energy, T_0 is the neutron energy threshold, $\sigma(\text{system1})$ and $\sigma(\text{system2})$ are the total reaction cross sections for systems 1 and 2, A_{tgt1} and A_{proj1} are the target and projectile mass numbers in system 1, A_{tgt2} and A_{proj2} are the target and projectile mass numbers in system 2, and $a(T_0)$ is a parameter from Reference (18). This formalism seems to work well with both neutron cross-section measurements and with thick-target yields in heavy-ion systems. Studies are currently being made to see whether this formalism can be used to reproduce the multiplicities from proton-induced interactions, using the data recently acquired from Meier 7-12.

In April 2000, neutron-production cross-section measurements were made from 290 MeV/nucleon C and 600 MeV/nucleon Ne interactions in prototype of an *in-situ* shielding block developed by NASA Langley Research Center. In addition, neutron cross sections from 400 MeV/nucleon Ne interacting in ISS crew quarter wall materials were also measured. Additional measurements of 290 MeV/nucleon Ne, 400 MeV/nucleon Ar, and 650 MeV/nucleon Ar interactions in *in-situ* materials are planned for late 2000 or early 2001.

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