RADIATION SHIELDING PROPERTIES OF LUNAR REGOLITH AND REGOLITH SIMULANT.
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Introduction: Exposure to space radiation will be a limiting factor in future manned missions to the moon. In contrast to the brief stays by the Apollo astronauts, in the coming decades humans will remain on the lunar surface for weeks and eventually months at a time. Chronic exposure to highly ionizing ions in the galactic cosmic radiation (GCR) and sporadic acute exposures to solar protons are serious hazards that can be mitigated in part by radiation shielding. The spacecraft, spacesuits and rovers will provide only modest shielding, and the expense of transporting material to the moon will allow for little if any artificial supplemental shielding material. An obvious alternative is the essentially unlimited supply of lunar regolith, if ways can be found to effectively use it. We have undertaken a study of the radiation transport and dose reduction properties of lunar regolith, using samples returned by the Apollo missions and several types of synthetic regolith and regolith simulant, with the objectives of evaluating regolith as potential shielding and of man-made regolith as a surrogate for use in ground-based studies. The use of synthetics and simulant is essential, owing to the extreme scarcity of Apollo soil. Fortuitously, particle accelerators originally designed for use in high energy physics and radiation therapy produce beams of protons and heavier charged particles at energies comparable to the most biologically damaging components of the GCR and solar protons.

Measurements: Two sets of measurements have been made thus far at the HIMAC accelerator at the National Institute of Radiological Sciences, Chiba, Japan. A pilot study explored the projectile charge and mass dependence of radiation dose behind regolith for a single beam energy and the variation of shielding effectiveness of lunar mare and highland regolith from several sites, as well as synthetic regolith and simulant. A follow-on study measured the average energy deposition as a function of depth—essentially a depth-dose distribution—for a particular beam passing through one type of simulant.

The methods are similar to those described in detail in Refs. [1] and [2]. The average energy deposited in solid state detectors by charged particles before and after passing through the samples was used to estimate radiation dose reduction as a function of regolith thickness. Sixteen different samples of regolith and simulant at areal densities between 6 and 13 gm/cm^2 were exposed to a beam 400 MeV/u ^{10}B ions. The percent dose reduction per unit areal density varied between 0.7% and 1.0%, comparable to aluminum and approximately half that of polyethylene (Fig. 1). *No significant difference in dose reduction between Apollo samples, synthetic regolith and lunar simulant was observed*. The similarity of regolith to aluminum when normalized to areal density is not surprising: the weighted average charge and atomic weight of typical lunar regolith is similar to that of aluminum. These results indicate that regolith simulant is an adequate substitute for lunar samples for purposes of radiation protection studies.

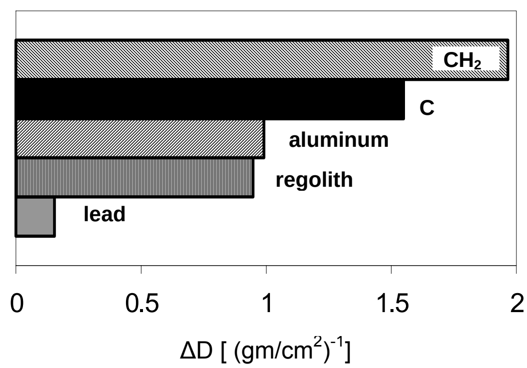

Figure 1. Average percent dose reduction per unit areal density (gm/cm2) for lunar regolith compared to polyethylene, graphite, aluminum and lead.

In the second study, a number of different depths of a lunar highland simulant were exposed to a beam of 290 MeV/nucleon ^{10}B ions. (The different energy was dictated by conditions needed for an unrelated experiment carried out at the same time, but based on other measurements with similar beams, the difference in energy is not expected to be a consideration for purposes of measuring dose reduction.) The dose reduction as a function of depth (Fig. 2) exhibits the characteristic behavior of ionization energy loss by heavy charged particles. When adjusted for density variations due to sample compaction, the data are reproduced well by a model calculation that has been shown to accurately reproduce energy loss by many different heavy ions in a variety of materials [3]. Note that in this case the beam is almost completely attenuated after 25 gm/cm^2 regolith (approximately 15 cm assuming a density of approximately 1.9

gm/cm^3).

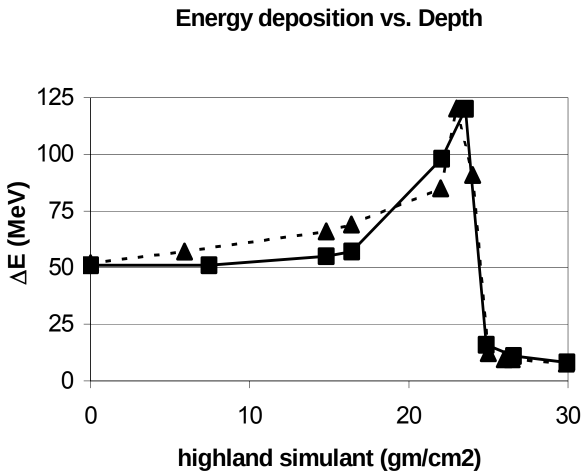

Figure 2. Average energy deposition of 290 MeV/nucleon ^{10}B ions in a 3mm silicon detector after passing through varying depths of lunar regolith simulant. Filled square: data with density correction; filled triangle: model.

Results for solar protons: As opposed to GCR exposures, which are chronic and threaten the long term health of astronauts after their return to Earth, solar particle events (SPE) generate very high intensities of energetic protons, which can produce acute effects that could be disabling or even life-threatening. For example the large SPE of August 1972, which occurred beween Apollo 16 and 17, was one of the largest ever recorded, with integral fluences of greater than 10^{10}protons/cm^2 over its several day duration. Had this event occurred during Earth-Moon transit or during the astronauts' stay in lunar orbit and on the lunar surface, it would have had serious consequences for astronauts on EVA or within the lightly shielded Command Module and LM. Townsend [4] calculated doses from several closely spaced large SPE occurred in September and October 1989 and concluded that, absent substantial shielding, they could have produced serious acute effects. However consideration of the energy spectrum of the October 1989 event (Fig. 3) shows that fairly modest amounts of regolith would stop most of the protons and reduce the dose to manageable levels. (100 MeV protons stop in approximately 5 cm of regolith packed at a density of 1.9 gm/cm^3; for 200 MeV protons, about 18 cm is needed.)

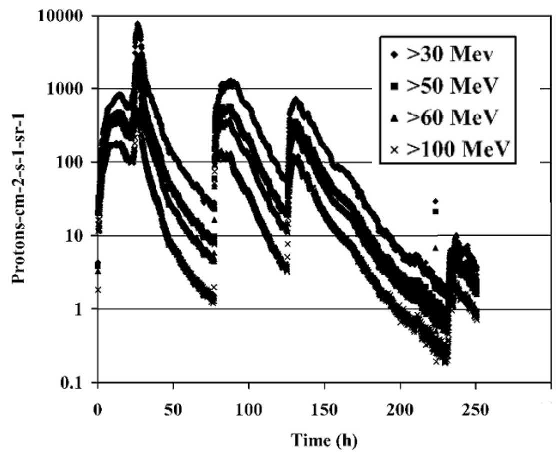

Fig. 3 Time profile of the integral proton flux for the October 1989 SPE. Top curve: ≥30 MeV proton flux; middle curves: ≥50 MeV and ≥60 MeV proton flux; bottom curve: ≥100 MeV proton flux. (From Ref. [4].)

Conclusions: These data indicate that for the ions tested, regolith synthetic and simulant are good surrogates for purposes of radiation protection studies. The results suggest that use of *in situ* resources on the lunar surface holds promise for radiation protection, with modest amounts of lunar soil providing substantial protection against GCR heavy ions. It is important to note that these data were taken with a single heavy ion at two similar energies. The GCR heavy ion flux when weighted by dose has significant components for elements from hydrogen through iron (Z=26, A=56) over several orders of magnitude in energy from 10^2 to at least 10^4 MeV/nucleon. A proper survey would sample several data points over these ranges. Studies of this type will help mission planners determine the efftiveness of lunar regolith as shielding against GCR heavy ions for astronauts on future lunar missions.

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