CONNECTING THE LUNAR SURFACE AND SUB-SURFACE RADIATION ENVIRONMENTS

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Introduction: One primary goal of the Artemis program is to build the foundation for establishing a long-term and sustainable human presence on the lunar surface. One of the major challenges we face when we begin sending astronauts to work and live on the Moon for prolonged periods of time is radiation. On the lunar surface—outside of Earth's protective magnetosphere and with no atmosphere to provide shielding—crew members will not only be constantly subjected to the full spectrum of cosmic and solar radiation but also to locally produced secondary (albedo) radiation. To keep the adverse effects of radiation exposure at an acceptable level, habitats and any other structures in which the crew will spend a significant portion of their time must provide shielding against both primary and secondary radiation. It has been suggested that regolith, being the most abundant locally available resource, could be used as an effective and cheap shielding material. The Artemis science program should include investigations that aim to determine the suitability of regolith as a shielding material, preferably through in-situ measurements of the correlation between cosmic and solar radiation and the sub-surface density of locally produced neutrons at various depths.

The Radiation Environment: The lunar surface radiation environment has two major components: galactic cosmic rays (GCR) and particles of solar origin. GCR are mainly composed of protons, alpha particles, and other atomic nuclei spanning a broad range of energies [1]. Most GCR originate in our own galaxy, created and accelerated in supernovae and other astrophysical phenomena [2]. The solar wind is a stream of chiefly protons, alpha particles, and electrons that are continuously emitted by the Sun. Its intensity varies with the Sun's eleven-year activity cycle and particle energies are generally much lower than those of GCR [3]. GCR and solar particles create secondary radiation when interacting with the lunar surface. Most importantly, high-energy cosmic rays produce neutrons in spallation reactions while penetrating the upper layers of regolith to depth of several meters. Adams et. al used data from Lunar Prospector to estimate that neutrons can contribute as much as about 18% to the effective radiation dose astronauts will receive on the lunar surface [4]. Inside a habitat shielded by a layer of regolith, the contribution may even be higher.

The radiation environment in lunar orbit has been studied by several missions over the past decades, most recently by the CRaTER instrument aboard the Lunar Reconnaissance Orbiter [5]. The most comprehensive and precise orbital measurements of albedo neutrons were provided by Lunar Prospector [6]. Until early 2019, the only radiation measurements on the lunar surface were taken by instruments operated during the U.S. Apollo (e.g. [7,8]) and Soviet Luna programs. The only measurement of the sub-surface neutron density profile ever to be performed was conducted during Apollo 17 [9].

Regolith as Radiation Shield: Lunar regolith has frequently been suggested as a possible shielding material against radiation. An industry consortium led by the British architecture studio Foster + Partners, working under contract for the European Space Agency, for example proposed to use 3D printing technologies to cover inflatable habitats with about a meter or more of regolith. Calculations (e.g. [10]) and laboratory measurements with regolith simulant (e.g. [11]) seem to indicate that regolith has a shielding effectiveness close to or exceeding that of aluminum. It has, however, the decisive advantage of being abundantly available on the Moon. Using a locally available resource for radiation shielding would significantly lower the cost of establishing a lunar outpost by reducing the amount of material that must be brought from Earth.

Our knowledge of the composition and texture of regolith and the variation of these parameters across distances relevant to manned exploration missions is, however, too limited to accurately determine the required shielding thicknesses and to calculate the radiation dose astronauts would receive inside their habitats. Understanding the interactions of cosmic and solar radiation with regolith is crucial to derive a viable shielding strategy: How much material is required to reduce the effective dose of GCR and solar particles to an acceptable level? How much is required to absorb a sufficient fraction of the neutrons produced locally in the shielding so that the shielding does not cause more harm than good? How much load must the habitat's structure be able to carry?

New (Sub-)Surface Measurements: Determining the suitability of regolith as a radiation shielding material requires a more detailed knowledge of its shielding properties, ideally provided by measurements performed in-situ. The optimum instrumentation for such an investigation is centered around a charged-particle spectrometer that can analyze GCR and solar radiation with sufficient precision and with a suitable sensitivity range in energy. This range must at the very least cover energies above the neutron production threshold. The spectrometer would be placed on the lunar surface. A neutron spectrometer would be placed close to it, such that neutrons diffusing out of the regolith can be measured and the correlation between primary (GCR and solar particles) and secondary radiation (neutrons) can be determined.

To determine the shielding effectiveness against cosmic and solar particles and to investigate the production of neutrons in the regolith, several sensor packs would be distributed at various depths in the ground surrounding the two spectrometers on the surface. Each pack must at least contain a dosimeter sensitive to charged radiation and a neutron detector. The former would record the residual radiation exposure at increasing shielding thickness and the latter the corresponding neutron density. To achieve a more precise result, the packs would also contain a sensor that can record the energy spectrum of charged particles and another one to determine the energy spectrum of neutrons. In the ideal setup, the packs would simply consist of the same spectrometers as placed on the surface.

This setup would be capable of recording the surface radiation environment (GCR, solar particles, and albedo neutrons) and the sub-surface radiation environment (charged particles and neutrons) at various depths at the same location and time, providing and unprecedented data set of very high value for the establishment of a permanent human presence on the Moon. Artemis III is ideally suited to place such an investigation at a suitable location at the lunar South Pole. The Apollo missions and more recent experiences on Mars have shown that deploying sub-surface instrumentation can still best be done by humans who can react to unanticipated events.

None of the current and planned experiments investigating the lunar radiation environment would provide the data the investigation described here could. The only radiation sensor currently operational on the lunar surface is the Lunar Lander Neutron and Dosimetry experiment aboard the Chinese Chang'E 4 lander [12]. NASA is planning to deploy several other sensors on commercial landers, but from the little information that is publicly available it seems they would also not be able to do the job.

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