

**HIGH-FIDELITY LUNAR REGOLITH SIMULANTS: SYNERGIES BETWEEN LUNAR EXPLORATION AND LUNAR SCIENCE.** K. R. Kuhlman<sup>1</sup>, K. Sridharan<sup>2</sup>, D. S. McKay<sup>3</sup> and L. A. Taylor<sup>4</sup>  
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**Introduction:** In returning humans to the Moon, we must address many of the problems faced by the original Apollo astronauts. Major among these is the control of the fine dust (<20  $\mu\text{m}$ ) that makes up a large portion of the lunar surface (~20 wt%). This ubiquitous, clinging, sharp, abrasive, glassy dust [1,2] caused a plethora of problems with seals, abrasion, and coatings, in addition to possible health problems, including ‘lunar dust hay-fever’ and long-term effects with the astronauts [3]. However, an understanding of the toxic properties of lunar dust is critical prior to the return to the Moon because of the hazards it poses to human health.

With the Viking Missions to Mars in the 1970s, it was determined that the martian soil was very chemically reactive, thought by some to be due to the high ultraviolet (UV) activation of the soil. Move Mars closer to the Sun (~1 AU) and take away any vestige of an atmosphere ( $10^{-12}$  torr), and Viola, you have the Moon. The intensity of UV radiation is many times greater on the lunar regolith. What effects will the dust portion have upon humans in the lunar-base habitat?

In addition, individual lunar solar grains are subject to ion implantation from solar wind and flares, ion erosion and sputtering, and coating by both impact-produced vapor and redeposited sputtering products. Each of these processes may create crystal defects and other high-surface-energy effects such as reactive unsatisfied dangling bonds on grains. Consequently, soil grain surfaces may become “activated” compared to simple comminuted grains of the same material.

Unfortunately, all Apollo samples have been compromised by exposure to terrestrial air and physical agitation [3], resulting in materials that may no longer be reactive and may have lost a significant amount of their original volatile content. Thus, lunar dust and soil simulants are required for the studies of both human toxicology and solar-wind particle retentivity. It is not difficult to make a lunar dust simulant with many of the correct physical properties, but the real challenge is in preparing this dust simulant so that it mimics the same chemical reactivity as the dust on the Moon. Here we discuss a technique designed to simulate lunar soil reactivity.

**The Need for “High Fidelity” Simulants:** The surface properties of the lunar regolith will affect

toxicology studies, dust mitigation and the discovery and utilization of lunar resources. The Moon retains a hard vacuum that cannot be readily reproduced on Earth, which means that modification of the surface of sharp and abrasive regolith dust particles by solar-wind implantation and sputtering and UV irradiation will result in particles that are highly reactive and potentially toxic when inhaled [2]. The search for lunar resources and the understanding of the hydrogen deposits found at the lunar poles by Lunar Prospector will require understanding of space weathering and the retention of solar-wind species by lunar regolith simulants.

It is well known that a uniform patina is found on lunar grains that is a result of solar-wind implantation and sputtering, vaporization of lunar regolith by micrometeorite impacts and UV irradiation [4]. This patina can currently be simulated using planar mineral samples using Plasma Source Ion Implantation (PSII) (Figure 1) with resulting annealing release curves approximating those of bulk Apollo samples [5].

**Human Toxicology:** Characterization of mammalian toxicity of dust entering human habitats is extremely important due to the risk it poses to crew health [6]. The properties of lunar dust that will affect its toxicity include size distribution (<10  $\mu\text{m}$ ), surface area, shape, chemical composition, surface properties, and origin and maturation of the dust. Initially, activated mineral coupons will be used as substrates for tissue cultivation. However, high-fidelity simulants that match as many of the properties of lunar dust are needed to perform testing on animal proxies to determine ways of mitigating the effects on humans. Such simulants will enable the characterization of unknown and possibly toxic chemical species that are likely formed at the particle surfaces. These simulants will also enable the study of the bonds broken during UV irradiation and solar wind implantation and sputtering. The quantification of defect lifetimes is an essential component in the development of methods to passivate lunar dust.

**In-situ Resource Utilization (ISRU):** A permanent human presence on the Moon will require the use of indigenous lunar resources, many of which are present as solar wind volatiles in the lunar regolith (e.g. hydrogen and helium-3). High-fidelity lunar simulants will enable the modeling of hydrogen trapping/

implantation at the lunar poles, as well as the reactivity of hydrogen during implantation. The diffusion characteristics of solar-wind volatiles can also be studied while minimizing handling, which is thought to release significant amounts of loosely bound species. High-fidelity simulants are also needed to evaluate different extraction methods for various solar-wind volatiles. Some types of small-scale ISRU demonstrations that may be affected by the surface properties of the material in question, such as oxygen production and solar-cell production, will require validation using simulants with surface properties as similar to those of lunar regolith on the Moon as possible.

**Dust Mitigation:** Dust is expected to be a major hazard on the Moon, not only to humans, but also to spacecraft and equipment. Electrostatic charging of the dust due to UV irradiation and solar-wind implantation must be characterized in order to design methods of mitigating the effects of dust. High-fidelity simulants will allow us to characterize the lifetime of charge and measure the work function of irradiated surfaces. Triboelectric charging must also be characterized. In addition, sputtering is known to dramatically increase the abrasivity of particles due to the low sputtering yield at tips of asperities where the angle of incidence is 90°. The ability to create high-fidelity simulants using implantation and sputtering will allow us to characterize the abrasivity increase due to sputtering.

**Proposed High-Fidelity Lunar Simulant Facility:** Currently, the capability does not exist to generate “high-fidelity” lunar regolith simulants that simulate the surface patina using ion implantation and sputtering, vapor deposition and exposure to UV irradiation. We suggest that such capability is a necessary part of the lunar exploration initiative. This capability will also contribute to our knowledge of lunar space weathering and the search for lunar resources, allowing us to test possible instruments and technologies prior to implementation on the lunar surface.

The technology does exist to implement a dedicated facility to make high-fidelity lunar simulants using PSII, electron vapor deposition and UV irradiation under vacuum. The lunar regolith simulant feedstock of choice can be modified in this facility to develop a surface patina similar to that found on lunar regolith grains. This facility will support a wide variety of technology requirements, such as toxicology and particle mitigation, for the return to the Moon. It will also further our understanding of space weathering and enable the development of systems for in-situ resource utilization (ISRU), such as lunar-volatile

recovery and other uses of the lunar regolith that depend on the surface properties of the particles.

**References:** [1] Park, J.S. (2006) *LPSC XXXVII*, Abstract 2193. [2] Taylor, L.A. and J.T. James (2006) *Space Resources Roundtable VIII*, Abstract #1008. [3] Taylor, L.A., et al., (2005) *AIAA, Proc. 1st Space Explor. Conf.*, Orlando, FL. [4] Keller L.P. and D.S. McKay (1997) *Geochimica et Cosmochimica Acta*, **61**(11) 2331-2341. [5] Harris-Kuhlman, K.R. (1998) *Trapping and Diffusion of Helium in Lunar Minerals*, Ph.D. Thesis, University of Wisconsin-Madison. [6] James, J.T. (2005) *Biological Effects of Lunar Dust Workshop*, Sunnyvale, CA.

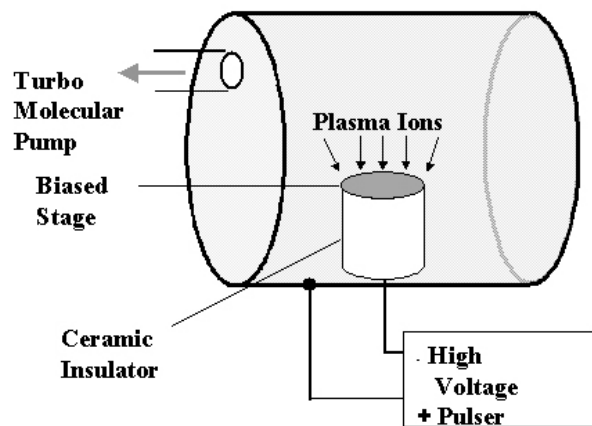


Figure 1. Schematic illustration of the PSII process that can be used for the energetic ion bombardment of mineral and regolith samples.