CHARACTERIZING PHYSICAL PROPERTIES AND INDUCED MOTION OF LUNAR DUST AFFECTING SURFACE EXPLORATION MISSIONS. R. L. Kobrick[1] and D. M. Klaus[2], [1]University of Colorado, 429 UCB, Boulder, CO, 80309, Kobrick@colorado.edu, [2]University of Colorado, 429 UCB, Boulder, CO, 80309, Klaus@colorado.edu.

Introduction: Before humankind can return to its nearest celestial outpost for extended stays, many characteristics of the Moon need to be better understood. In particular, improved methods for dealing with lunar dust, which caused a plethora of problems during the six Apollo surface missions, are currently attracting considerable attention. Specific effects of lunar dust on Extravehicular Activity (EVA) Systems during the Apollo era were cataloged by Gaier [1], who additionally noted that the severity of dust problems was consistently underestimated by ground tests. Points of concern for astronauts on lunar EVA included issues such as vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, inhalation and irritation, excessive crew time being used to clean EVA suits and equipment, and electrical conductivity. Potential human health issues arising from exposure to fine-grained particles of lunar dust have also been identified that range from minor nasal issues to severe respiratory reactions [2]. While safety of astronauts is top priority, dust mitigation technologies will also be needed for several other elements of the lunar architecture, including the Lander Lander, EVA Systems and equipment, surface mobility aids (including rovers), and robotic systems.

In order to effectively design against these numerous undesirable effects, it is first necessary to fully characterize the physio-chemical properties of the lunar dust as a function of surface distribution and material interactions. With this information, hardware solutions and/or operational strategies can be developed to mitigate the various dust-related problems. The soil properties and environmental characteristics identified with respect to the lunar location of each mission can also be factored into specific design solutions and assist in mission planning decisions. By synthesizing observed and measured lunar dust attributes, a model can be developed to forecast the primary issues that might be encountered on any given mission.

Lunar Dust Properties: Lunar soil formation is primarily due to innumerable micrometeorite impacts forming sharp, irregular shapes of silicate glass. The dust contains adhering nanoscale (3-30 nm) elemental iron particles (Fe0). Over 95% of the particles are under 1mm, 50% under than 60 μm and 10-20% finer than 20 μm [3]. Lunar regolith has also been shown to exhibit electrostatic properties [4, 5] and magnetic susceptibility [3]. Colwell et al. [6] characterized the Moon as a dusty plasma with gravitational, electrostatic, and photoelectric interactions in addition to the Earth's magnetotail, which creates a plasma sheath on the nightside and a photoelectron sheath on the dayside of the Moon, with a dynamic mix of both at the terminator. The dayside of the Moon is generally characterized as a photon-driven, positively charged environment with solar wind ions and plasma electrons bombarding the surface, which cause photoelectrons and secondary electrons to be ejected from the surface. The nightside is an electron-driven, negatively charged environment that collects solar wind protons and electrons and has a large separation of particles [6, 7]. These interactions, coupled with triboelectric effects such as an astronaut's spacesuit charging the lunar dust during an EVA by walking or from the rover's wheel-surface interaction, need to be further studied and characterized to ensure that the next generation lunar systems are able to function for extended mission compared to the relative short surface stays during Apollo.

The dynamic, electrostatically charging environment and magnetic properties of lunar dust are key characteristics that will define how future hardware is designed and operated on the Moon. Further exploration and observation of the lunar surface will help define the working environment as well as identify potential research opportunities for lunar science. An example of hardware research based on electrostatic properties of fine, coarse particles was conducted by Sims et al. [8] with a self-cleaning active particle removal surface using electromagnetic waves. This research has been further developed by Sims' co-author, Carlos Calle, at NASA's Kennedy Space Center who is investigating an electrodynamic "dust shield" based on Professor Senichi Masuda 1970's device coined 'the electric curtain' (U. of Tokyo) [9] for the future use of removal of dust from solar panels on the Moon.

Lunar Dust Mobility Factors: Traditionally the Moon has been categorized into two distinct regions: the basaltic-rich mare and the anorthositic highlands. By sub-categorizing the Moon to include other environmental parameters as well, specific subregions can be established to help define properties relevant to exploration mission planning. Each subregion can then drive unique requirements for material selection and dust mitigation strategies. Such subregions could include the sunlit, darkside, shadowed regions, and terminator to emphasize the importance of photoelectron emission by ultraviolet light in the dust charging and resultant mobility processes. The targeted lunar exploration zones could be further categorized by geomorphological features such as impact craters and their respective subfeatures, including crater basins, crater rims, slopes, and central peak/rings. An example of how unique terrain and dust properties could impact design choices is that crater rims are thought to consist of less dense regolith (less than 50% of average), which would result in more dust being kicked up from the surface during EVA's as well as greater penetration of objects into the soil [6]. As a consequence, the optimal solution for a rover tire design intended for use in these areas, for example, would have to take into account potential issues like reduced traction or a greater degree of sinking into the surface than a tire that might be used on a mission to the lunar highlands.

Furthermore, accurate predictions of level of dust contamination potential should ideally even include factors such as Solar cycle and the Sun-Earth-Moon relative positions during the mission in order to determine the incident solar flux and resulting photoelectric effects, temperature changes, and the positioning of the Earth's geotail and magnetotail. Each of these variables can influence dust motion.

Defining the entry probability for a grain of dust to come in contact with an astronaut on an EVA and comparing that data to actual field tests can be used as a measure of the success of dust mitigation technologies. The probability can be defined as:

$$P = P_a\,(1 - P_L^{Ext})\,T\,P_L^{Int}$$

Where P_a is the probability of a grain in the near-vicinity of an astronaut adhering to a spacesuit, P_L^{Ext} is the loss probability of a dust grain external to the habitat in regular EVA activity or mitigation process, P_L^{Int} is the probability of grain release from the suit internal to the habitat. The variable T is defined as the transmission coefficient of the internally released dust grain from the airlock to the habitable volume of the habitat (i.e., no airlock T=1) [10].

Conclusion: A model to forecast the expected lunar dust propagation as a function of the physical characteristics in a given region of the Moon, as well as the timing and location of the mission, offers detailed insight into spacecraft and spacesuit dust mitigation hardware requirements, material selection, and mission planning. This information can also be used to develop operational protocols governing habitat ingress and egress procedures, including spacesuit donning and doffing, such that dust penetration into the living quarters is minimized to the extent possible.

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