LUNAR DUST-to-SUIT ELECTROSTATIC INTERACTIONS: INSULATING VS. CONDUCTING SPACE SUITS.

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Introduction: The mitigation of lunar dust as a mechanical and biological hazard remains a challenge for exploration: Both are listed as strategic knowledge gaps that need to be filled before long-term lunar occupation [1]. Since the VSE over a decade ago, there is a new understanding of the electrical forces that occur at the scale-size of the grains and suit weave – at the scale of 10's of microns. These electrical effects occur because the grains and suits are immersed in the photon, photoelectron, and solar wind plasma environment – and this environment will have a profound effect on dust grain attraction and attachment.

Wang et al. [2] found, via laboratory experiments, that insulating grains in the regolith bed can become hyper-charged. Specifically, some grain surfaces are partially-exposed to UV and plasma, but emit photoelectrons and secondary electrons onto the surfaces of surrounding unexposed grains. Since the grains are insulators, the charge remains local and there is the development of large inter-grain differential charge/potentials between the exposed and unexposed surfaces. The local micro-E fields between the grains can grow so large as to exceed binding cohesion forces, leading to ejection of small grains from the regolith bed. By analogy, a similar charging situation can occur between the fibers of an insulating space suit.

Zimmerman et al. [3] corroborated the lab results in [2] using a particle-in-cell simulation of the regolith bed that demonstrated that the inter-grain E-fields can exceed 10^5 V/m due to the differential charging between partially-exposed (to UV and plasma) and unexposed insulating grain surfaces. They also demonstrated that if the grains were conductors, this differential charging effect would disappear due to grain charge dissipation. By analogy, an insulating suit weave would develop similar E-fields between the fibers.

Jackson et al. [4] suggested that astronauts roving over the regolith bed should tribocharge due to grain-boot compositional differences, also leading the hyper-charged grains near the charged boot. Due to dayside photoelectrons, the tribocharging would not be severe, but in deep shadow (polar craters, nightside), the tribocharge build-up was shown to become large. They suggested that the space suits be conductive to draw in plasma return currents to dissipate the tribocharge.

The results of these 3 studies suggest that insulating material can develop micro-scale differential charged states, and the local E-fields on the scale size of the grain bed (or a suit weave) can become very large leading to enhanced electrostatic dust capture.

The Trouble with Teflon. Apollo space suit consisted of a T-164 Teflon cloth with the weave spacing at ~ 20 microns [5]. The fabric was found to retain 10^5/cm^2 of grains within the weave, with the grains capable of deteriorating the weave (based on SEM analysis) [5] (see Fig 1.) Teflon is also highly nonconductive ($\ll 10^{-20}$ S/m) and has a very strong affinity for capturing electrons in the tribocharging process – leading to strong differential charging when roving over the regolith.

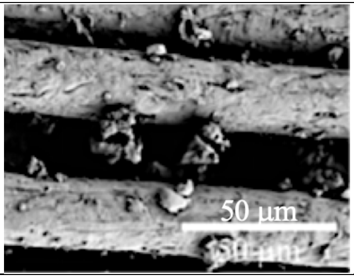

Fig 1. SEM images of the left knee area of the Apollo 12 suit [5]

Fabric Weave Charge Capacity. We perform an analytical analysis similar to that presented in Zimmerman et al. [3] to examine the differential charging between fibers in a suit weave. Figure 2 shows an illustration of the weave. The pink arrows represent with solar UV and/or plasma incident on the weave. By the nature of the weave, the underside of the top layer of fibers will not be exposed to this UV/plasma. However, adjacent regions exposed to sunlight/plasma (region A) will emit photoelectrons and/or secondary electrons onto the unexposed regions (region B). The electron current flux onto surface B is initially $J_o \sim n\,e\,v_o$, where n is the emitted electron density and v_o is the initial speed (about 1 eV or ~ 6 x 10^5 m/s for both photoelectrons and secondary electrons). However, as the surface at B is coated with electrons, an E-field forms that repels the electrons. By conservation of energy, the electron velocity at surface B under influence by this retarding E becomes $v^2 = v_o^2 - 2eEL/m_e$, where L is the average distance between A and B, EL is the potential drop, and m_e is electron mass. One can write the expression for the growth of this E-field as:

$$\varepsilon_o dE/dt = J(E) - \sigma E \qquad (1)$$

where $J(E) = J_o(1 - 2eEL/m_e v_o^2)^{1/2}$ and σE is the conductive/dissipation current that removes surface charge from region B to other regions on the suit.

For a near perfect insulator like Teflon, $\sigma \sim 10^{-22}$ S/m, the electron flow from A to B is limited by the large retarding E-field from surface B. This equilibrium E-field is obtained by setting $J(E) = 0$: $E_{max} = m_e v_o^2/2eL$. For an average distance, L, between weave surface A and B of ~ 3 microns, the equilibrium E field to stop the electron influx onto surface B is $E \sim 3 \times 10^5$ V/m for a 1 eV electrons outflow from surface A. This E-field is comparable to that found by [3] for insulating grains in a regolith bed. Figure 3 shows the equilibrium E-field vs suit conductivity, with $E_{max} \sim m_e v_o^2/2eL$ for suit fiber conductivity $\sigma < 10^{-10}$ S/m.

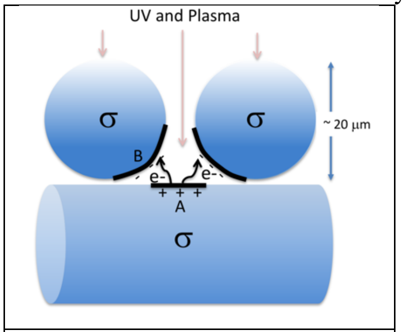

Fig 2. Illustration of differential charging on suit fibers in a weave, analogous to the differential charging with insulating regolith grains examined by [2, 3].

A tribo-charged grain that contacts the weave near surface A and B will feel a 'cling' force toward the surface of opposite polarity. For example, assume a 1 micron grain is tribocharged by passing astronauts to $q_d \sim 1$ fC [6], and this grain is incident with the fibers on the lower leg. For non-conductive fibers, the grain will experience an electrostatic force from the weave that is over 10000 times greater than the force of gravity (see right hand of Fig 3). The grain will electrostatically 'cling' to the fibers.

However, for dissipative or conductive fibers, $\sigma > J_o eL/m_e v_o^2 \sim 10^{-10}$ S/m, the A-B region E-field is limited by the fast dissipation of charge from surface B to other parts of the fiber. In this case, Eq. (1) indicates that $E_{max} \sim J_o/\sigma$. As indicated in Fig 3, for a fiber conductivity of 10^{-6} S/m, the E-field is limited to $E_{max} = 4$ V/m. There is no longer a large electron build-up on the underside/unexposed regions of the fiber and no longer a large E-field between fibers. In this case, $F_{ES}/F_g \sim 0.25$ and and electrostatic forces will not be strong - there will not be an electrostatic cling. In essence, a conductive weave makes the suit an isopotential surface, and effectively 'short's out' the regions of intense micro-E fields in the weave.

Added Benefit to a Conductive Space Suit. Jackson et al. [4] found that an astronaut roving across the regolith bed will charge up due to tribo-electric interactions between the grains and the astronaut boot. In sunlight, photoelectron emission will remove this excess charge, but in shadow the charge can build up on an insulated boot. A way to remediate this charge build-up is to make the suits and boots dissipative or conductive in order to electrically-connect to the surrounding plasma environment. In this regard, the suit is electrically 'grounded' not to the surface but the plasma. The plasma becomes the reservoir of charge that is used for dissipation.

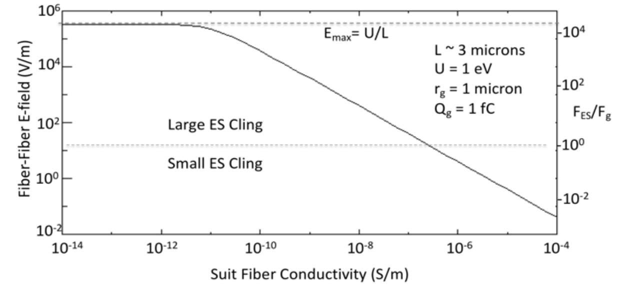

Fig 3. Fiber E-field and ratio of ES force to gravity of a 1 micron/1fC grain as a function of suit conductivity.

For any charge build-up, the dissipating plasma return current will vary directly with conductive area, A. Thus, the entire suit should be dissipative or conductive to maximize this plasma collection area and to ensure the plasma has direct electrical connection to the tribocharging surfaces (boot, gloves).

Recommendations. In order to reduce dust-suit electrostatic 'cling', we make the following recommendations: (A) Make the outer skin electrically dissipative or conductive to reduce the hyper-charging in the weave. (B) Use the conductive suit to get in electrical equilibrium with the surrounding plasma and photoelectron environment – and thus reduce/remove patchy regions on the suit of differential charge. (C) Ensure that surfaces that are in contact with the regolith (boot, etc) are electrically connected to other conductive regions of the suit to garner a path for charge dissipation. (D) Consider the use of a removable/disposable thin metallic cape over the suit – like a foil cape – that has no weave and maximizes the plasma current collection. (E) Avoid the use of Teflon as the outer skin since it is both a super-insulator and strong triboelectric generator. The Apollo suit Teflon weave at 10's of micron made an ideal dust collector [5].

References. [1]https://www.nasa.gov/exploration/library/skg.html. [2] Wang et al. (2016), Geophys. Res. Lett., 43, 6103. [3] Zimmerman et al. (2016), J. Geophys. Res., 121, 2150. [4] Jackson et al. (2011), J. Spacecraft Rockets, 48, 700. [5] Christoffersen et al. (2009), NASA/TP-2009-214786. [6] Melnik and Parrot (1998), J. Geophys. Res., 103, 21107.