Energy-Varied Electron-Beam Dust Mitigation (EBDM) Source for Lunar Exploration A. Cabra[1,2,3], X. Wang[1,2,3], B, Farr[3], D. Hansen[3], and M. Horányi[1,2,3]. [1]NASA SSERVI's Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT), University of Colorado, Boulder, CO 80303; [2]Laboratory for Atmospheric and Space Physics (LASP), University of Colorado, Boulder, CO 80303; [3]Space Dust Research & Technologies LLC (SDRT), Louisville, CO 80027 (Email: anna.cabra@colorado.edu)

Introduction: In-Situ Resource Utilization (ISRU) is essential for long-term, sustainable exploration on the lunar surface. However, the lunar environment is covered by electrostatically active dust that becomes charged through direct interactions with the solar wind plasma. These charged particles can strongly adhere to surfaces such as solar panels, optics, excavation systems, astronaut suits, and other hardware. This can cause material degradation materials, human health hazards, and reduced technical performance, presenting a major challenge for efficient ISRU operations. Effective dust mitigation technologies are therefore necessary to maintain reliable surface infrastructure.

The electron-beam dust mitigation (EBDM) technology was developed as an active mechanism to mobilize and remove dust from surfaces through electron charging repulsion [1-3]. EBDM examined removal under fixed beam conditions. Here we present an experimental investigation of a variable electron beam energy approach, which modulates dust charging conditions to further enhance electrostatic dust removal from surfaces.

Methodology: EBDM is supported by the patched charge model (PCM) [4], which describes electrostatic lofting for a pile of regolith particles. In this model, microcavities are formed in between dust grains, where secondary electrons generated by incoming beam electrons can be reabsorbed by surrounding neighboring dust particles (Fig 1). These secondary electrons can accumulate within the cavities, build negative charge, and result in strong coulomb repulsive forces that induce dust lofting.

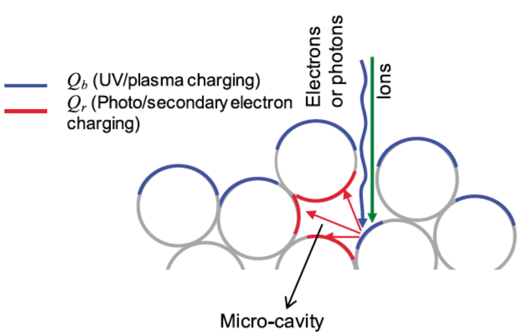

Fig 1. Patched Charge Model. Blue is plasma charging and red is absorbed surrounding secondary electrons, inducing strong repulsive forces.

The efficiency of this process is influenced by the amount of secondary electron emission (SEE) and the resulting plasma sheath potential structure near the surface. Recent experimental studies at University of Colorado Boulder's IMPACT lab have demonstrated that when the beam energy is low (<90 eV), the secondary electron yield (SEY) is <1, which is the ratio of emitted secondary electrons to incident electrons. This produces a classical montonic sheath where the surface potential matches the beam energy. As energy increases (>90 eV), the SEY is >1 and the surface potential becomes more positive than the local plasma potential, inducing a non-monotomic and eventually an inverse sheath. The transition between these sheath profiles corresponds to a crossover region where the effective SEE rate is maximized, helping to promote enhanced electrostatic charging and dust removal based on the PCM.

Experimental Testing: Experiments were conducted in a vacuum chamber using an hot filament source positioned approximately 15 cm above the testing samples. JSC-1A lunar regolith simulant was deposited with a sieve onto four different substrates: glass, Kapton, astronaut suit fabric, and Teflon-silver tape. These samples were mounted at a 45° incline. The electron beam operated at a maximum of 200 eV with a beam current of ~65 mA.

Three tests were carried out: 1) A fixed beam energy followed by oscillating energy; 2) A fixed energy for the entire duration 3) Oscillating energy for the entire duration. The fixed energy was 200 eV, and the oscillating energy was between 0 and 200 eV in a triangle waveform at 1 Hz.

1) Each experiment began with a fixed energy exposure for 5 minutes, followed by an oscillating beam energy on a time scale of approximately 10 minutes.
2) Each experiment was conducted with a fixed electron beam energy for a total of 15 minutes.
3) Each experiment was conducted with an oscillating beam energy for a total of 15 minutes.

Dust removal was recorded by a camera, and the removal rate was analyzed as a function of time to compare improvments of energy-varying beam to fixed beam energy sources.

Results and Discussion:

During fixed energy exposure, dust removal occurs but reaches a decreased removal rate over several minutes [1-3]. Preliminary testing with an oscillating beam showed a large fraction of the dust was removed rapidly, with an increase in removal rate and near complete dust removal occurring on the order of a minute (Fig 2).

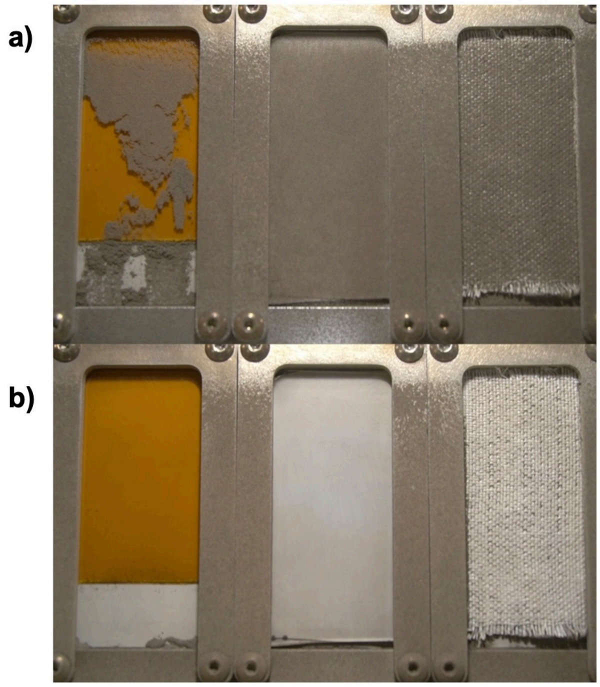

Fig 2. a) JSC-1A lunar regolith simulant deposited on three substrates. From left to right: Kapton, glass, and astronaut suit fabric. B) The same samples following exposure to oscillating electron beam.

This behavior is consistent with the SEE profiles as described in methodology. Oscillating between high and low energy regimes drives the dust particles through a maximum lofting condition. More tests will be conducted with optimized oscillating parameters, including the beam energy range and oscillating frequency.

Summary: We experimentally investigated the EBDM source using an energy-varied electron beam approach with JSC-1A lunar regolith simulant on different samples. It was shown that an oscillating beam energy between 0 and 200 eV significantly improved dust removal efficiency and efficacy, compared to a fixed beam. The enhanced performance is attributed to transitions between SEE regimes and surface charging conditions. These results suggest that variable-energy electron beam systems may provide an effective dust mitigation strategy for maintaining clean surfaces on lunar infrastructure, supporting ISRU and long-duration exploration.

References: [1] Farr et al. (2020), Acta Astronautica, 177, 405-409; [2] Farr et al. (2021), Acta Astronautica, 188, 462-366; [3] Farr et al. (2022), Acta Astronautica, 200, 42-47. [4] Wang et al. (2016), GRL, 43, 6103-6110.