Strategies Toward Lunar Dust Adhesion Mitigation

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Multi-Purpose Habitation (MPH) Module Lunar Dust Working Group
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The Lunar Environment

Low Gravity
1/6th of Earth's gravity

Lack of Atmosphere
10^{-12} Torr

Elevated Radiation Exposure
~200x more than Earth
~2.6x higher than that of International Space Station (ISS)



Extreme Temperature Variation
127°C to
-173°C

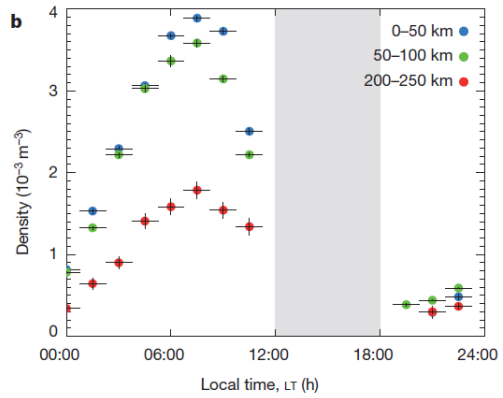
Lunar Regolith
Particle size by weight,
50% < 50 µm
20% < 20 µm
1% < 1 µm

Image credit: NASA

What, Where, and Why of Lunar Dust

Particle Counts

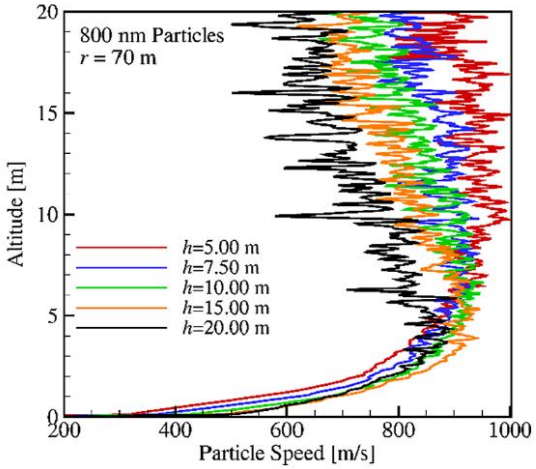
Lunar Dust Experiment (LDEX) Results



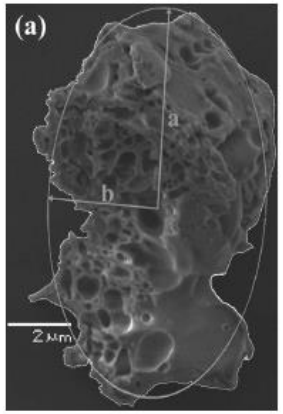
Particle counts as high as 4 x 10^{-3} m^{-3} up to 50 km off the lunar surface. Increased particle counts at terminator.

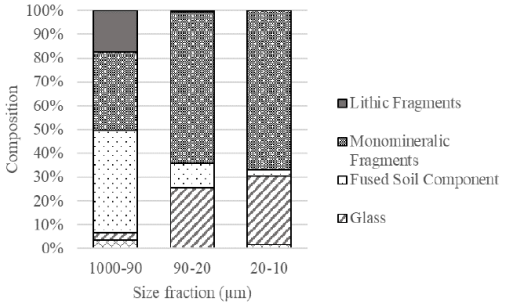
Single engine plume impingement can generate particle velocities > 1000 m/s.

Particle Velocity



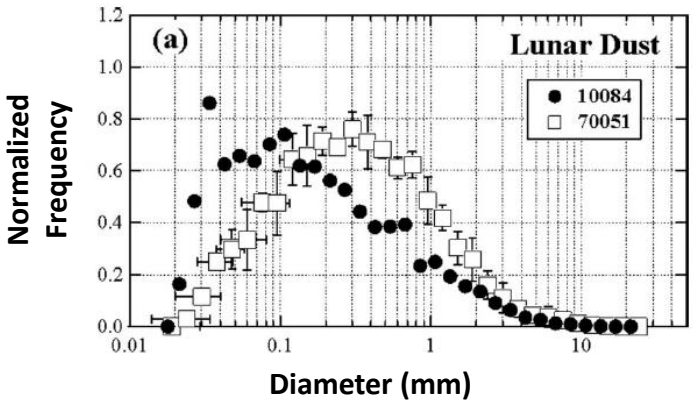
Particle Morphology





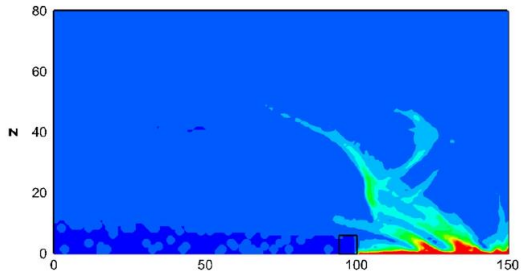
Smooth, glassy spheres <-> High angularity agglutinates

Particle Size



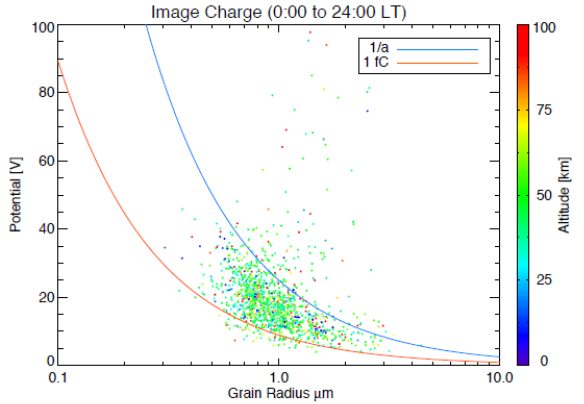
Lunar dust particles range from nm to up to 50 µm in diameter.

Simulated Lofted 10 µm Dust



Electrostatic Environment

LDEX Results



Wohl, Christopher J.; et al., "Lunar Dust Considerations for Vertical Solar Arrays, Volume 1: Lunar Environment and Dust Interactions," NASA Technical Memorandum, 2024, TM-20240003496.

Natural vs Anthropomorphic Lunar Dust Exposure

Dust Accumulation from Natural Phenomena

100 μg/cm^2 annually[1]



Dust Accumulation from Human Activity

<u>Lunar landing:</u>

Apollo 14, 848 μg/cm^2

<u>Lunar rover:</u>

Dust traveling ~ 20 m away from rover

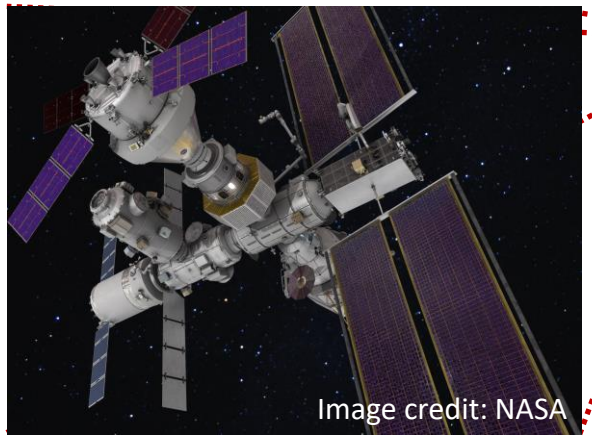
<u>ISRU and construction:</u>

Unknown, likely highly variable

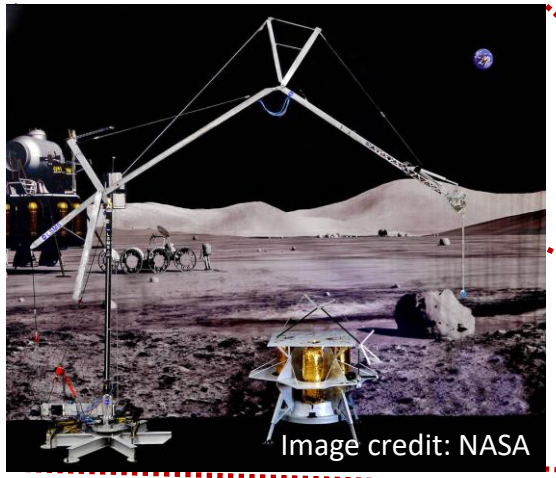
Image generated using Gemini AI

1. Katzan, Cynthia M.; Brinker, David J.; and Kress, Robert: The Effects of Lunar Dust Accumulation on the Performance of Photovoltaic Arrays. Space Photovoltaic Research and Technology Conference, Cleveland, OH, 1991.

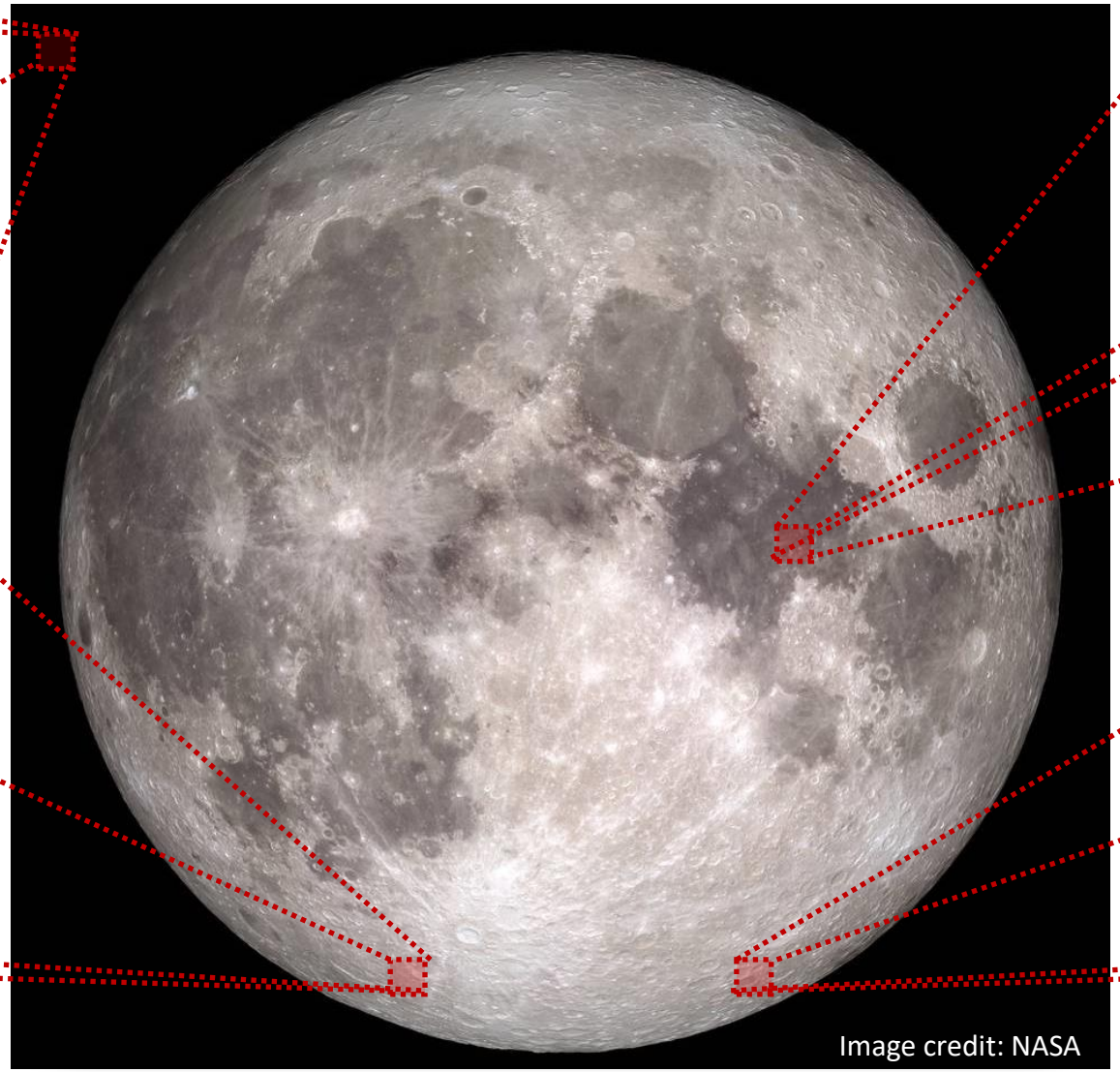
How do we Consider the Influence Lunar Dust has?



Gateway



Infrastructure





Lunar Lander

Image generated using Gemini AI



Vertical Solar Array Technology (VSAT)

How do we Approach Lunar Dust Adhesion Mitigation?

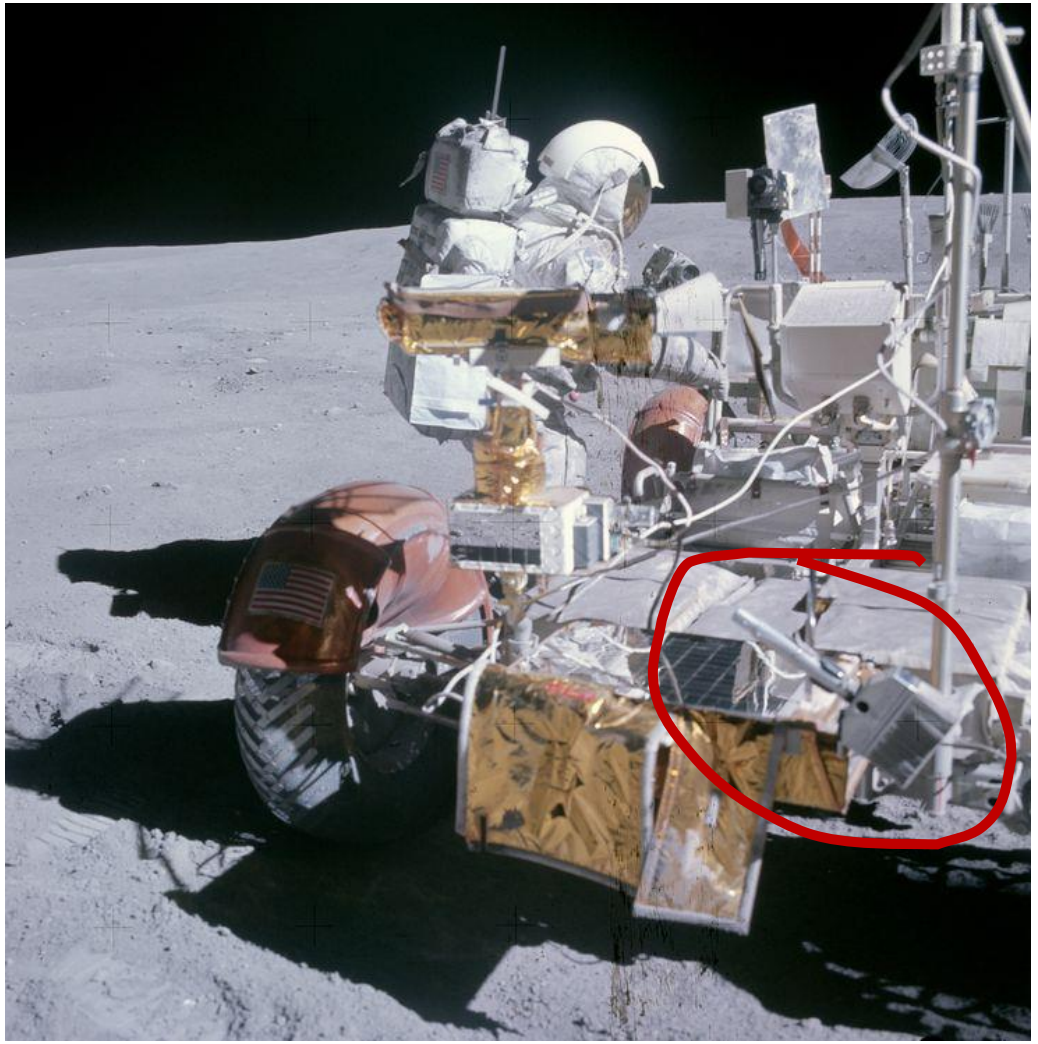
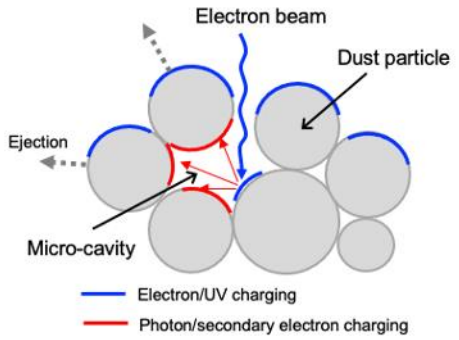
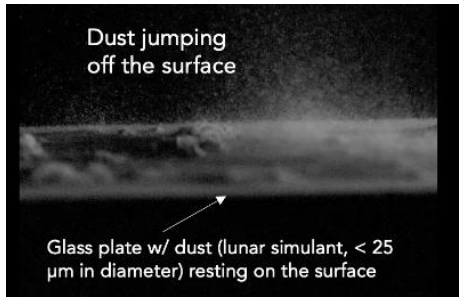


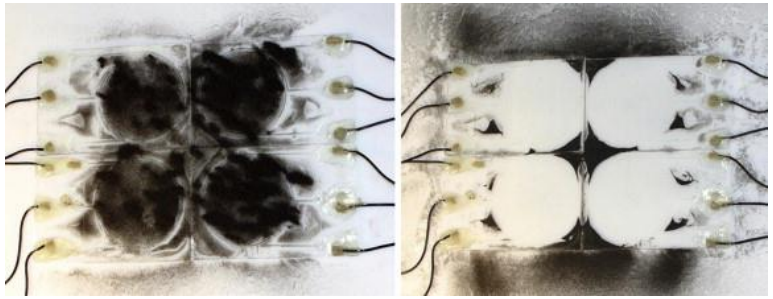
Image credit: NASA

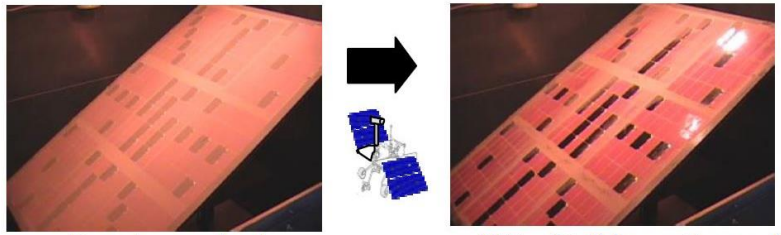
Lunar Dust Adhesion Mitigation Strategies

Active Mitigation Strategies









Dust Accumulated

>90% of Full Power Restored

Passive Mitigation Strategies

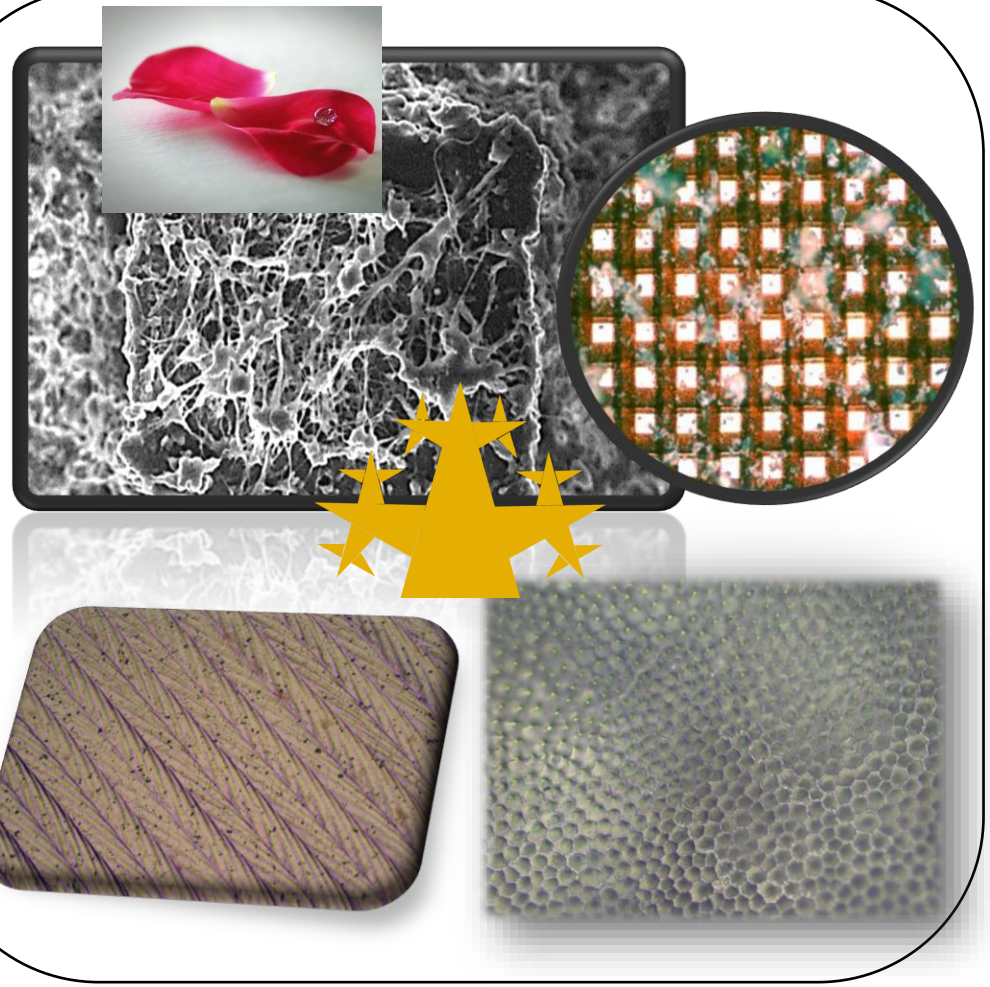
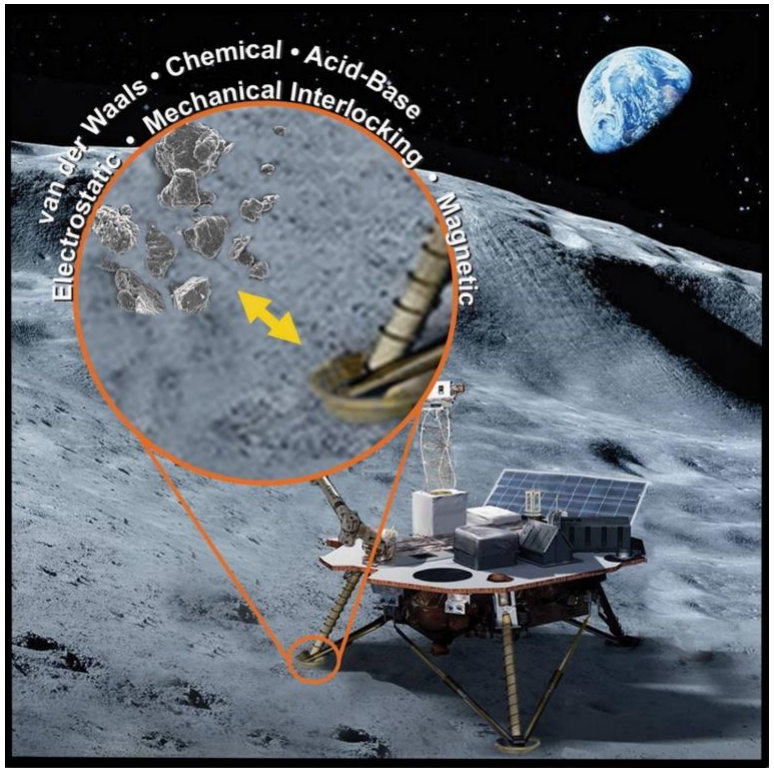


Image credit: NASA

Material Design and Selection for Lunar Applications

Dust Mitigation-
Must Remove





Dust Management-
Must Tolerate



❖Goal: Engage aspects of lunar dust from mitigation to management

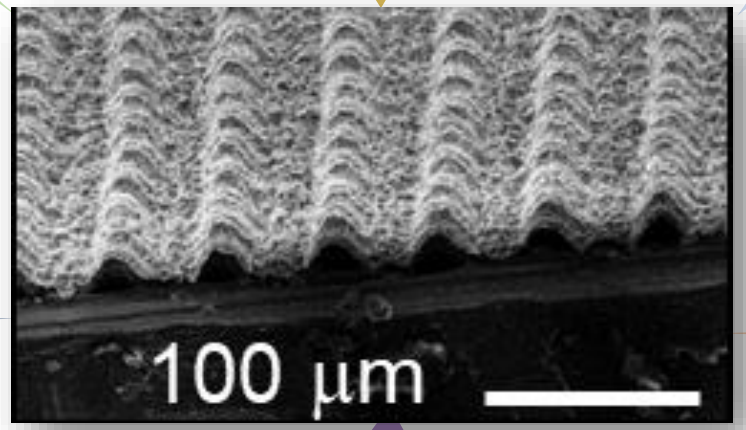
Image credit: NASA

Surface Chemistry

Surface Topography

Surface Conductivity

Surface Mechanical Properties

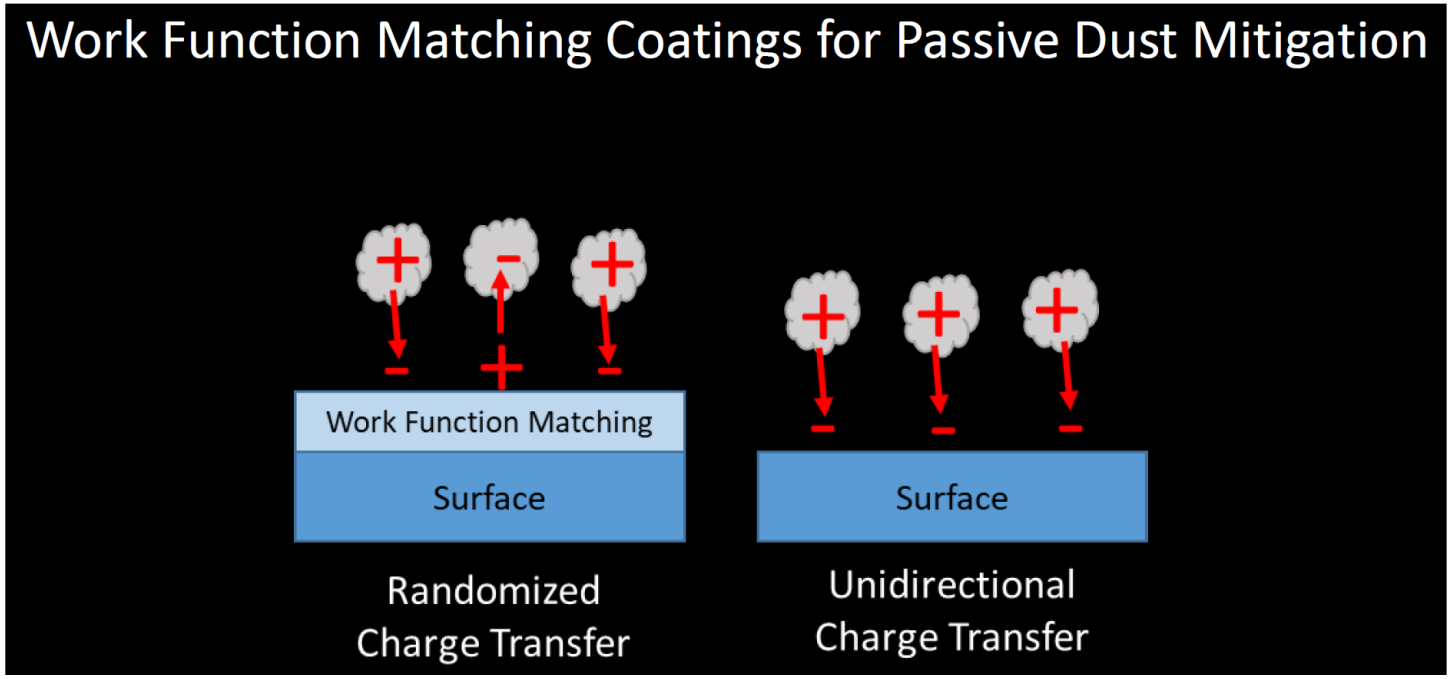


Responsive Surfaces

Surface Hardness

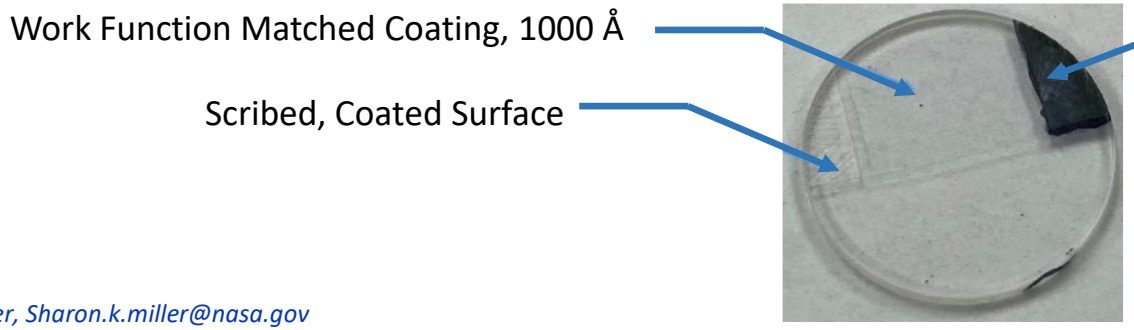
Image credit: NASA

Surface Chemical Modifications
Work Function Matched Surfaces





Coating Generation Facility



GRC

POC: Sharon Miller, NASA Glenn Research Center, Sharon.k.miller@nasa.gov

Image credit: NASA

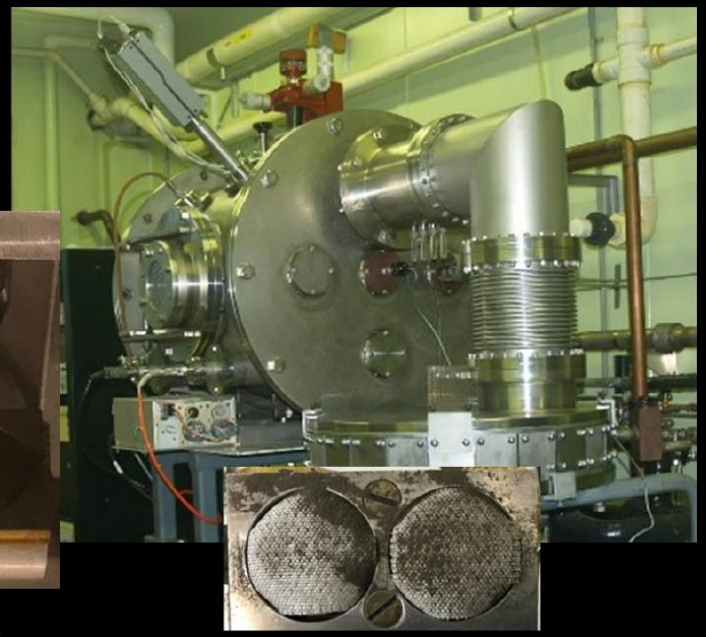
Surface Chemical Modifications
Work Function Matched Surfaces

Ground Testing:

- Simulant (JSC-1AF, LHT-1…) sifted onto surfaces in vacuum (<1e-6 Torr) after bakeout at 200 °C for several hours
- Non-adhering simulant removed by nitrogen jet



Lunar Dust Adhesion Belljar





Sample pair under nitrogen jets after dusting, prior to nitrogen jet

Sample pair after exposure to nitrogen jet

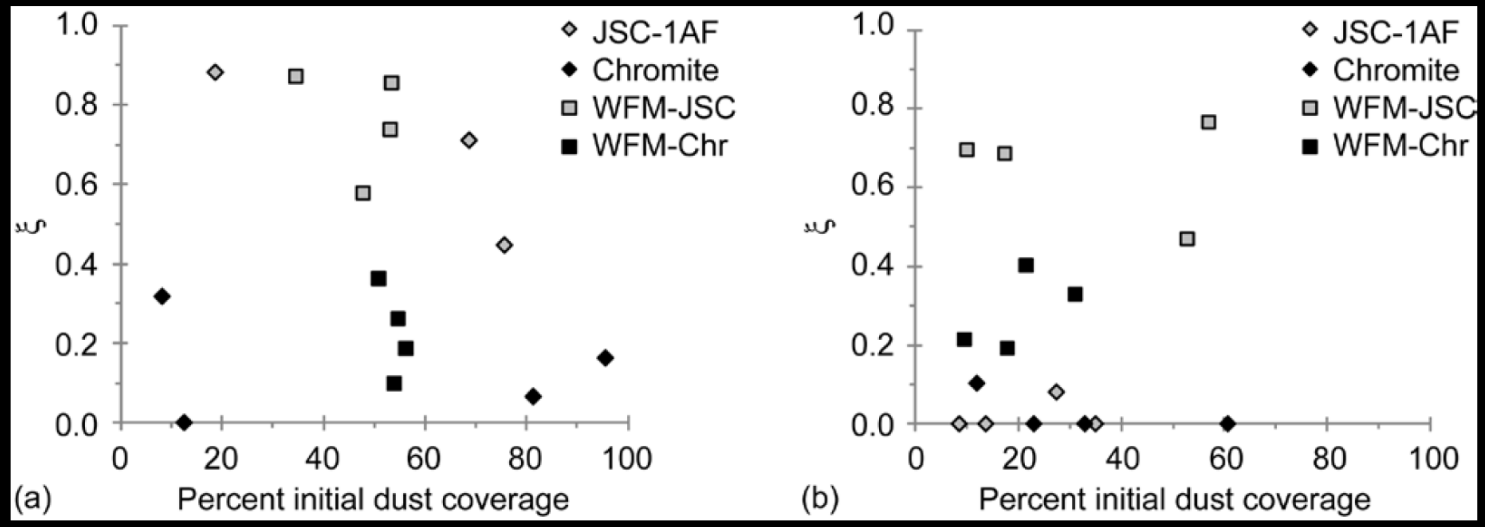
*Simulants: JSC-1AF, fine portion of JSC simulant; LHT-1, lunar highland terrain simulant

GRC

POC: Sharon Miller, NASA Glenn Research Center, Sharon.k.miller@nasa.gov

Surface Chemical Modifications
Work Function Matched Surfaces

Effectiveness of Work Function Matching Coatings in Removal of Lunar Simulant Using a Regulated Puff of Nitrogen Gas



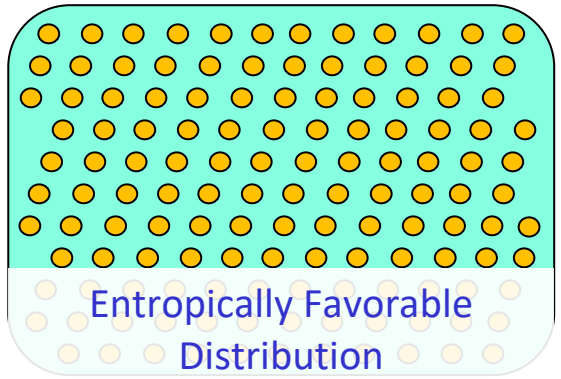
Dust removal efficiency, ξ, calculated for pristine and workfunction matching coated (a) AZ93 and (b) AxFEP using JSC1-AF and Chromite simulants for dusting. (From Gaier, J.R., Waters, D.L., Misconin, R.M., Banks, B.A and Crowder, M. "Evaluation of Surface Modification as a Lunar Dust Mitigation Strategy for Thermal Control Surfaces" NASA/TM—2011-217230.)

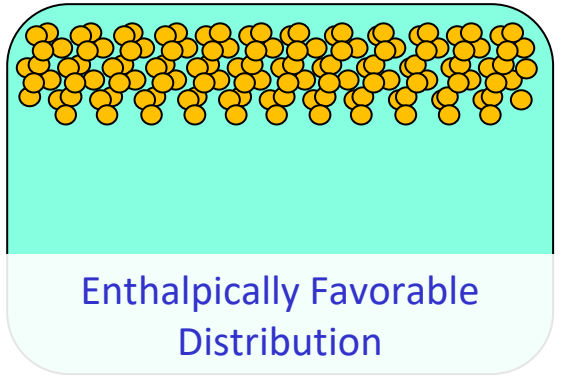
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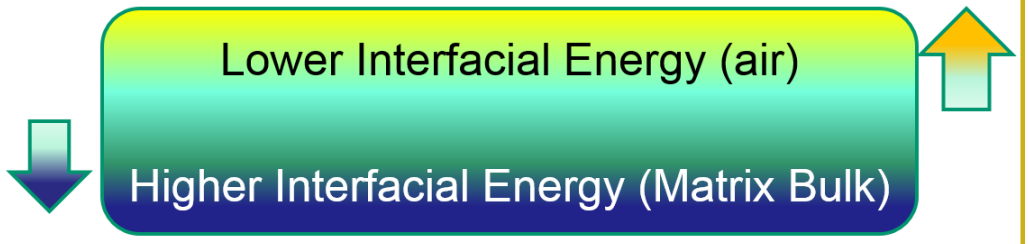
Surface Chemical Modifications

Surface Migration Agents (SMA)

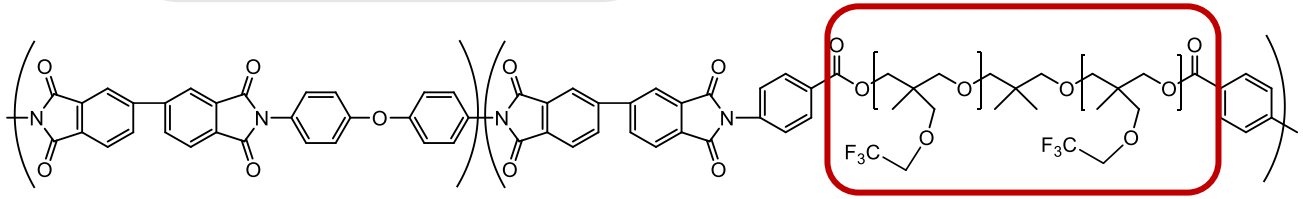


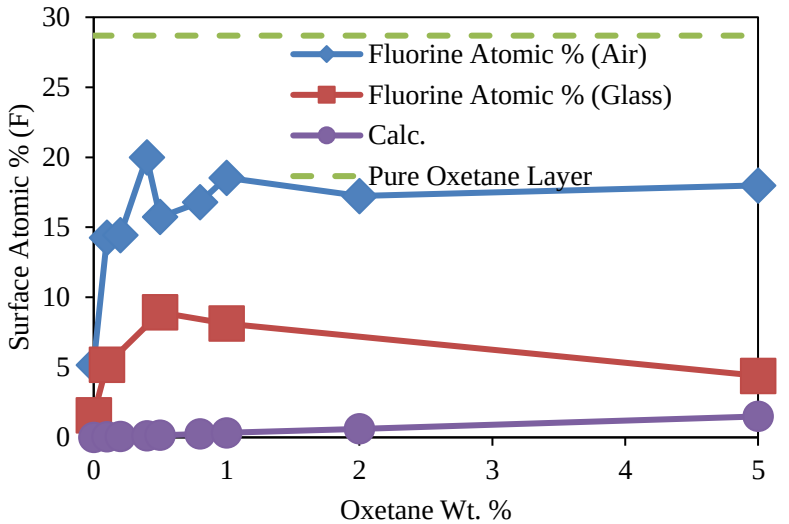


Thermodynamic Response of SMA



Arrows indicate enthalpy-driven migration of **LOW** and **HIGH** surface energy components





LaRC

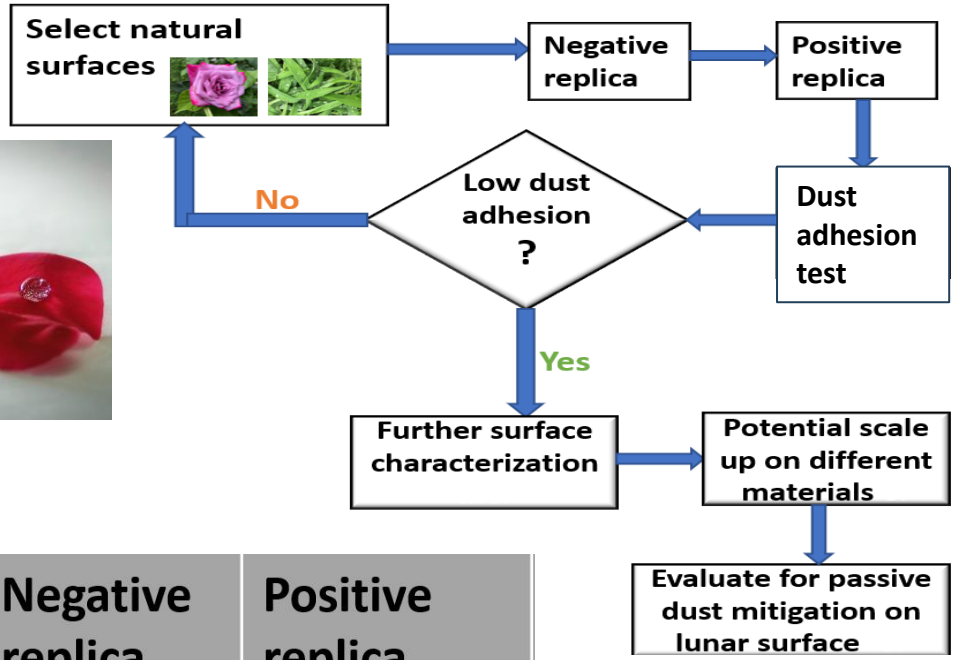
Wohl, Christopher J.; et al., "Lunar Dust Simulant Particle Adhesion on Copolyimide Alkyl Ethers" in The Impact of Lunar Dust on Human Exploration, ed. Joel S. Levine, Cambridge Scholars Publishing, February, 2021.

Surface Topographical Modification
Biomimetic Surfaces

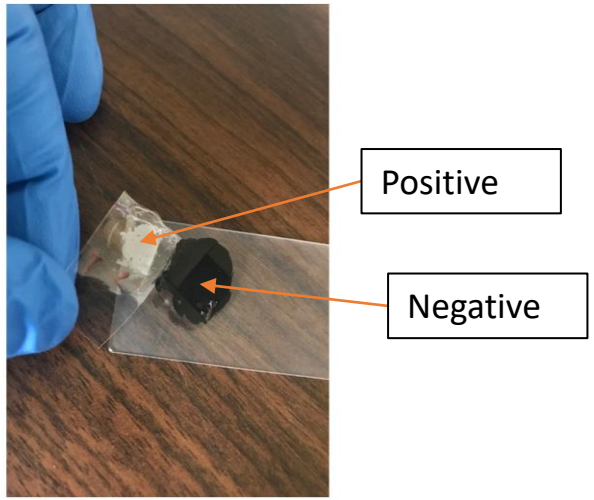
Natural adhesion mitigating surfaces

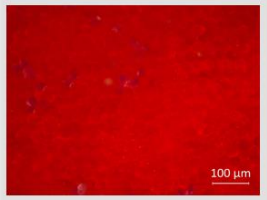
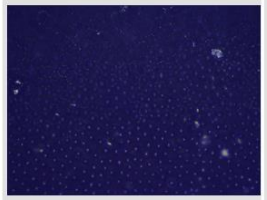
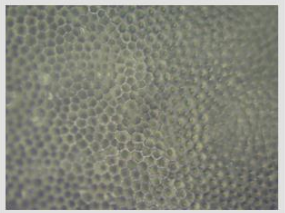




Replication example: rose petal



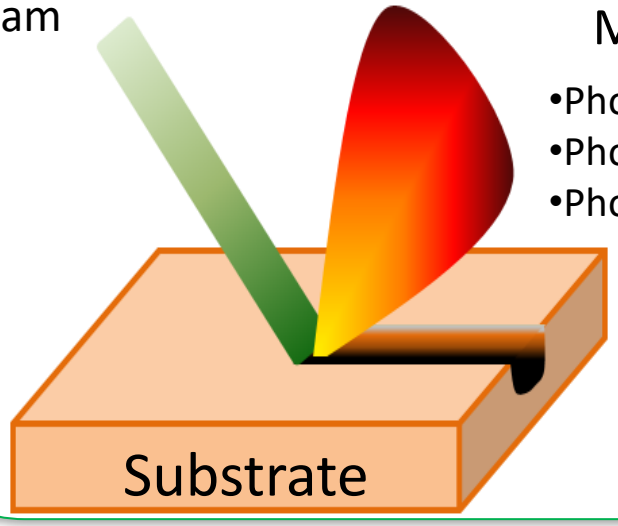
Sample name	Original surface	Negative replica	Positive replica (ctrl)
Rose petal			

LaRC

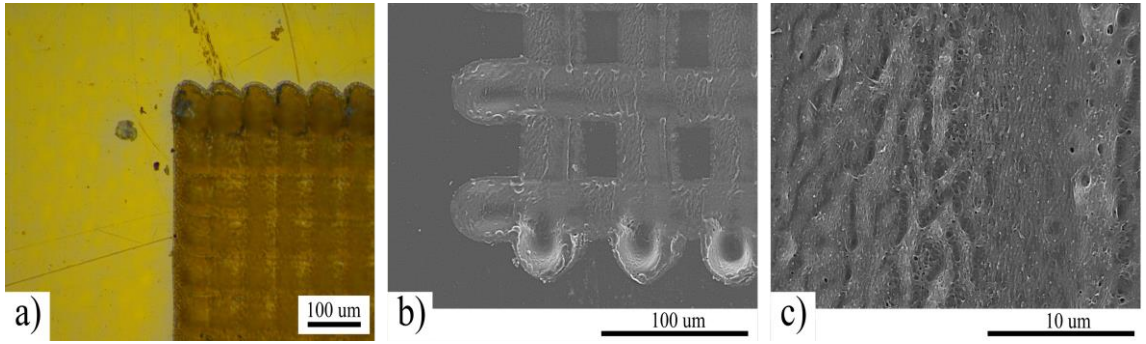
Das, Lopamudra; et al., "Extending Lunar Presence: Dust Adhesion Mitigation Materials and Surfaces to be Evaluated on the Lunar Surface," Acta Astronautica, 2024, 219, 532-541.

Surface Topographical Modification
Laser Ablation

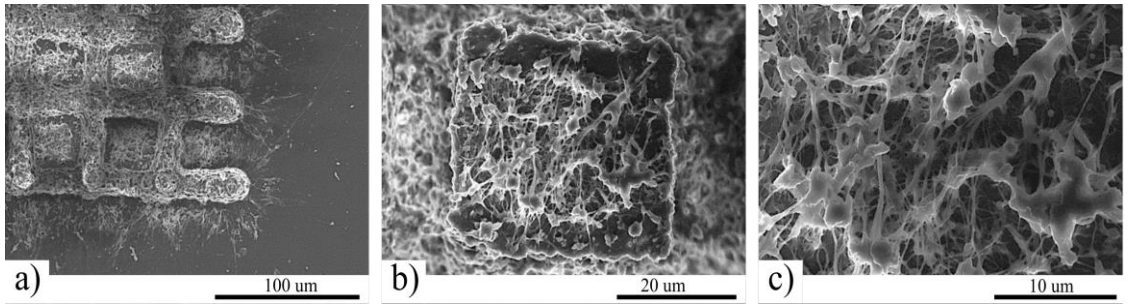
Laser Ablation Patterning



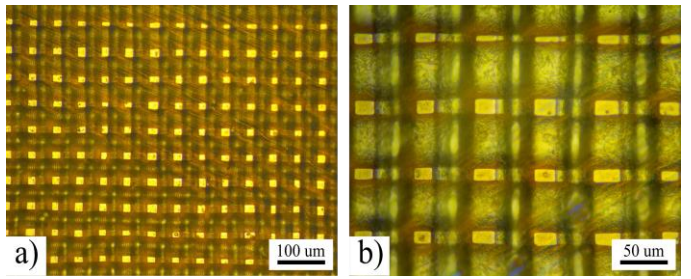
Polyimide



Fluorinated Ethylene Propylene (FEP)



Epoxy

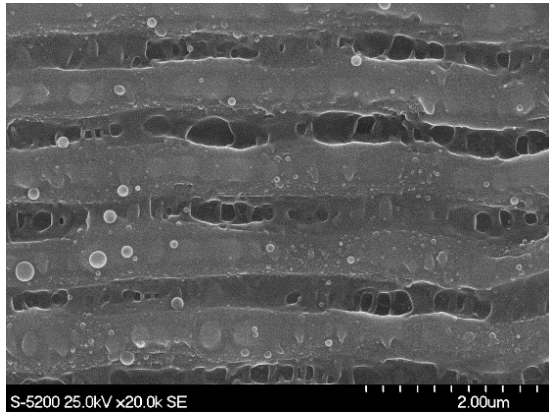


LaRC

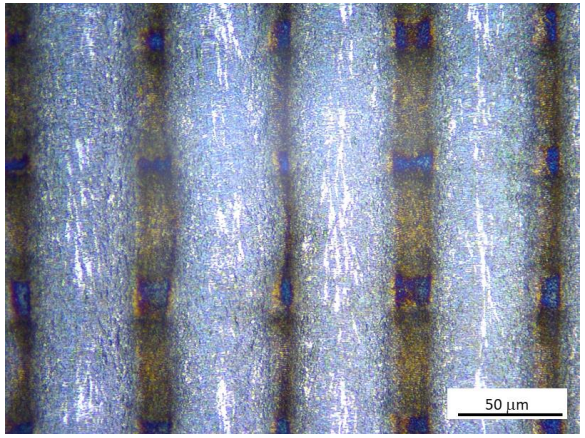
Das, Lopamudra; et al., "Extending Lunar Presence: Dust Adhesion Mitigation Materials and Surfaces to be Evaluated on the Lunar Surface," Acta Astronautica, 2024, 219, 532-541.

Surface Topographical Modification

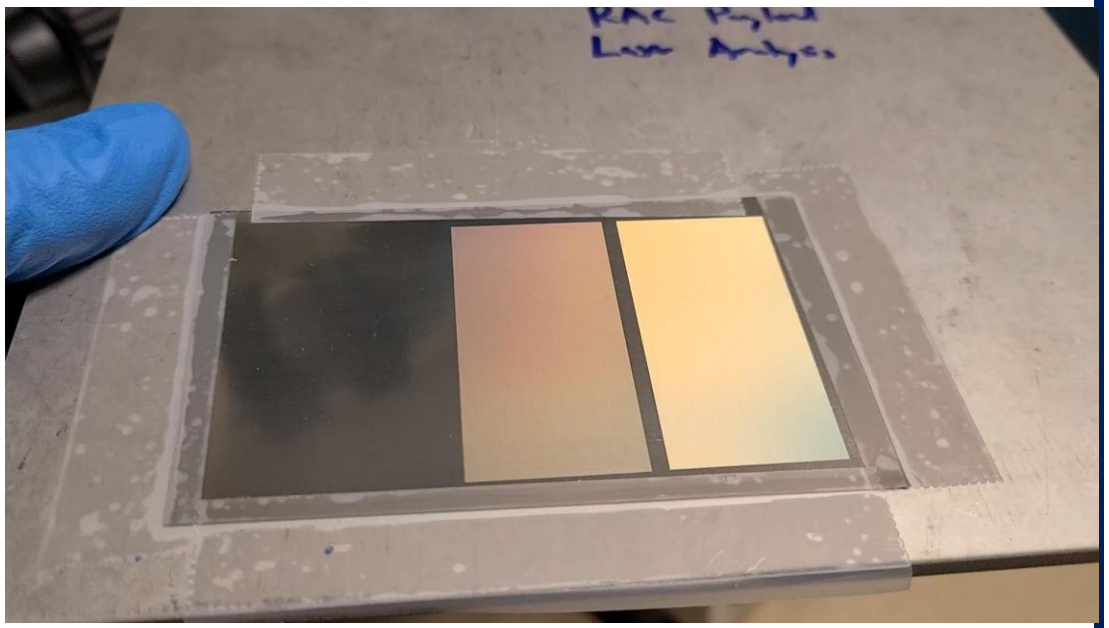
Laser Ablation



Nanometer-scaled Laser-Induced Period Surface Structure (LIPSS)



Micrometer-scaled Direct-write Laser Patterning

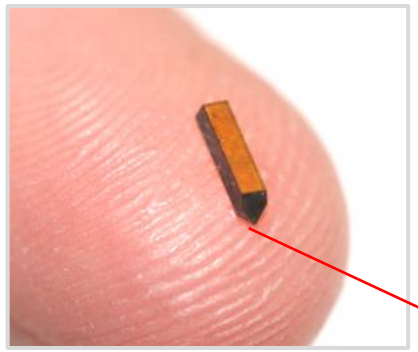


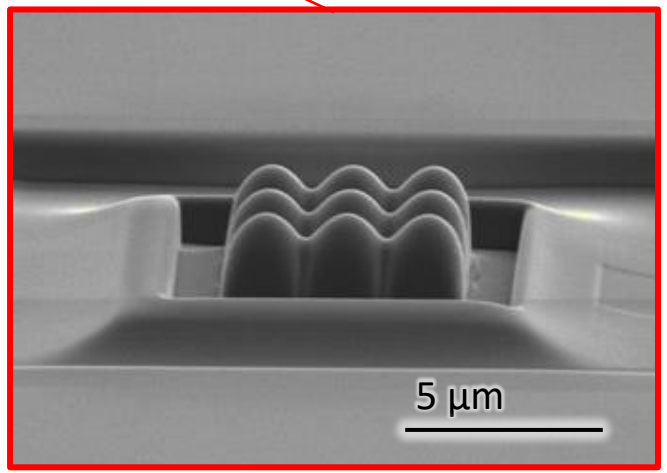
LaRC

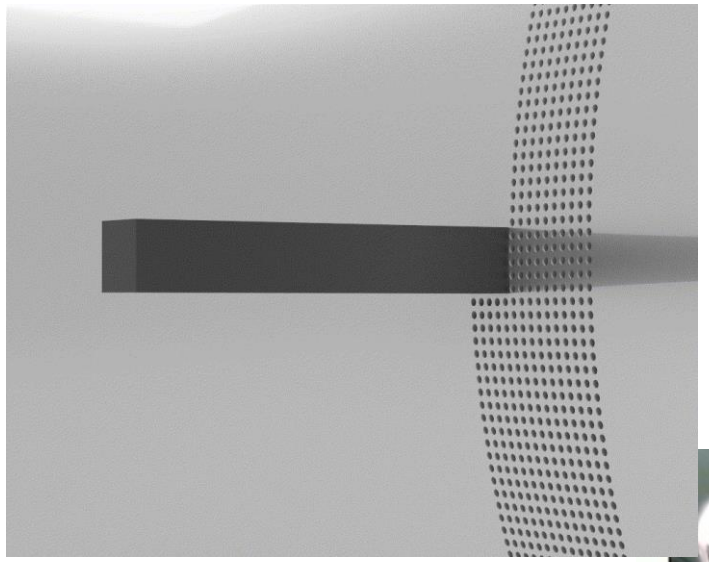
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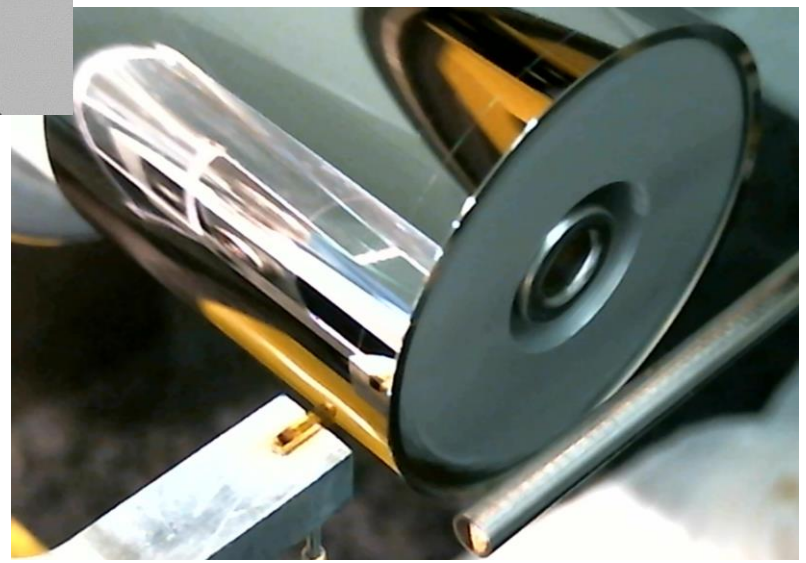
Surface Topographical Modification

Nanocoining







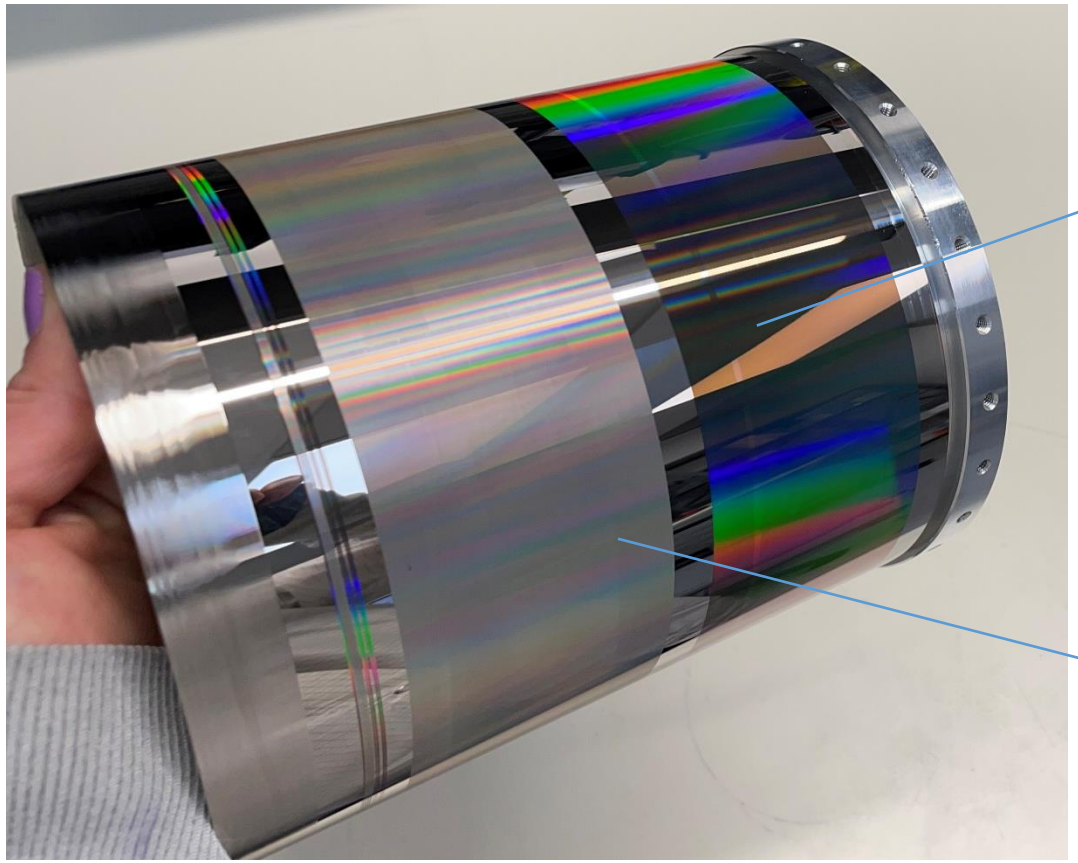


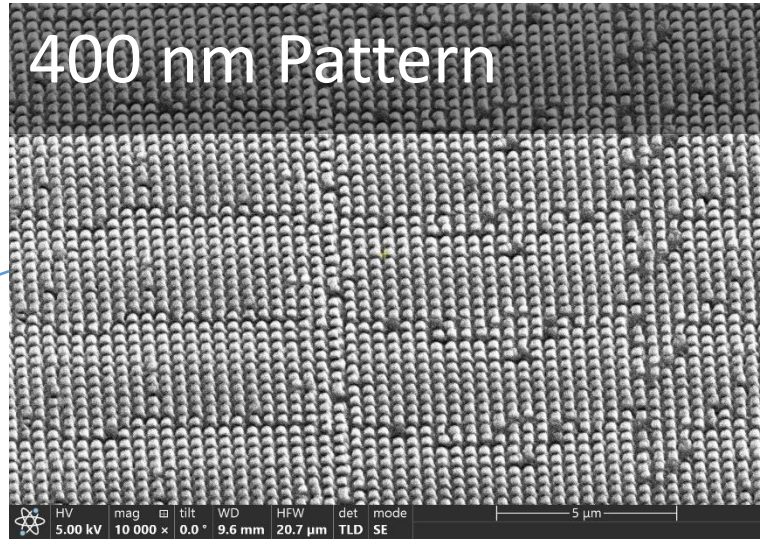
Smart Material Solutions

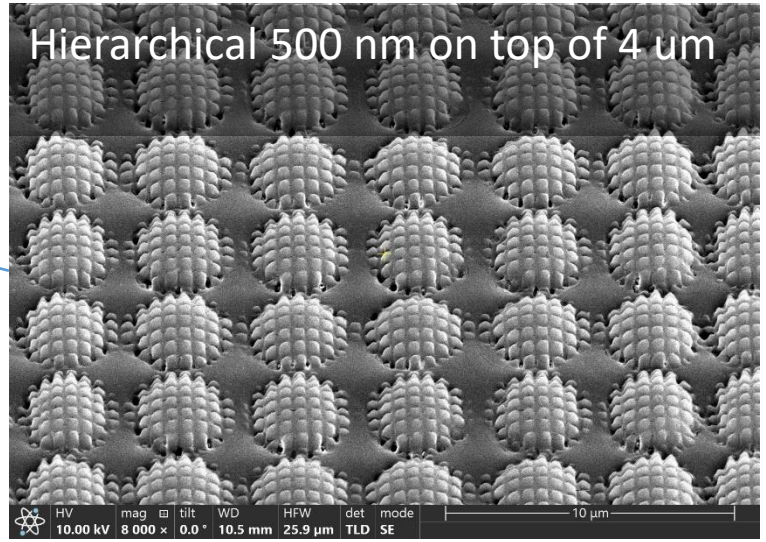
POC: Stephen Furst, Smart Material Solutions, furst@smartmaterialsolution.com; Chih-Hao Chang, University of Texas-Austin, chichang@utexas.edu

Surface Topographical Modification

Nanocoining







Smart Material Solutions

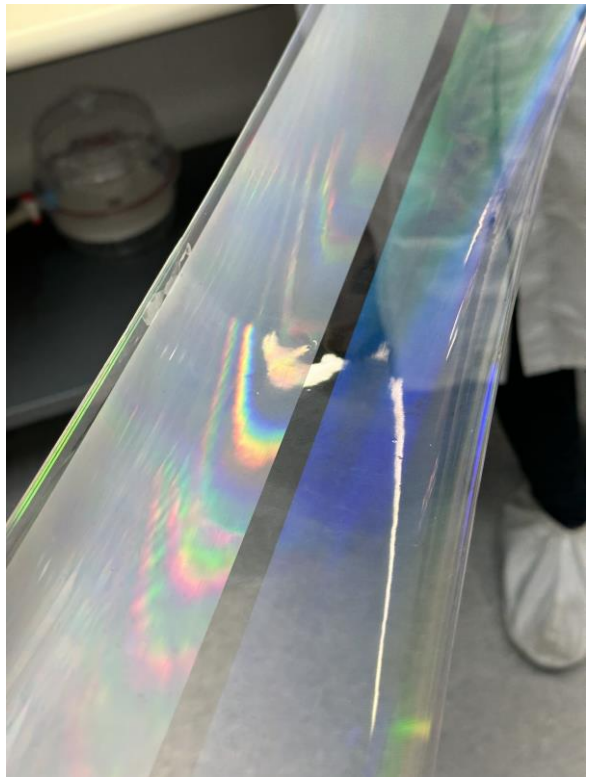
POC: Stephen Furst, Smart Material Solutions, furst@smartmaterialsolution.com; Chih-Hao Chang, University of Texas-Austin, chichang@utexas.edu

Surface Topographical Modification
Nanocoining

More than 150 ft. of imprinted polycarbonate

MicroContinuum



Smart Material Solutions

POC: Stephen Furst, Smart Material Solutions, furst@smartmaterialsolution.com; Chih-Hao Chang, University of Texas-Austin, chichang@utexas.edu

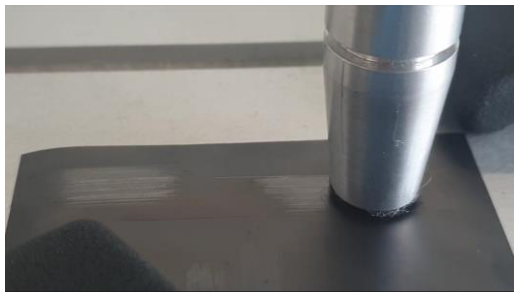
Surface Conductivity Modifications

(a).

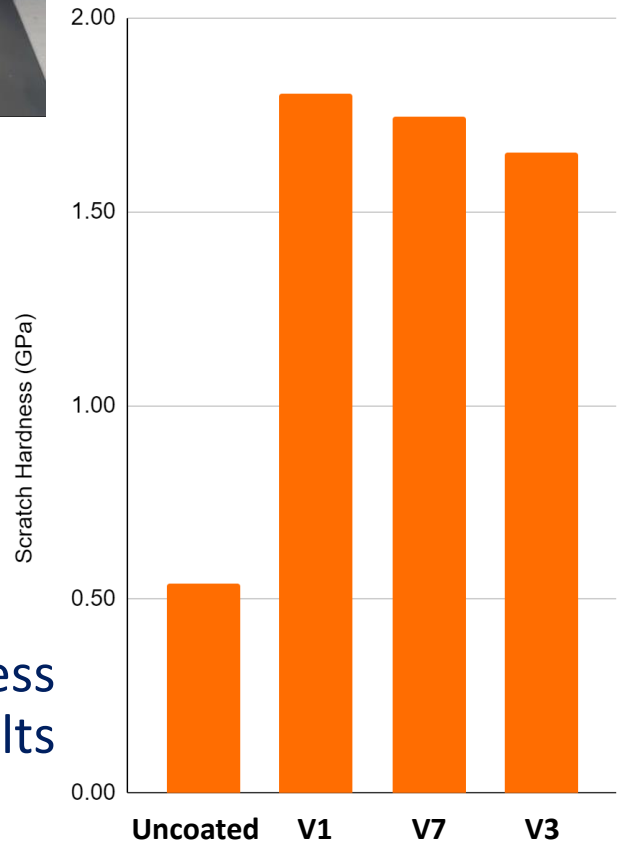
Graphene ink coated Kapton sheets	Surface Resistivity (Ohms/sq)
V1	0
V2	10^3
V3	10^4
V4	10^6
V5	10^8
V6	10^{10}
V7	10^{11}

(b).





Abrasion testing with steel wire mesh



Scratch hardness results

Decreasing sheet resistance



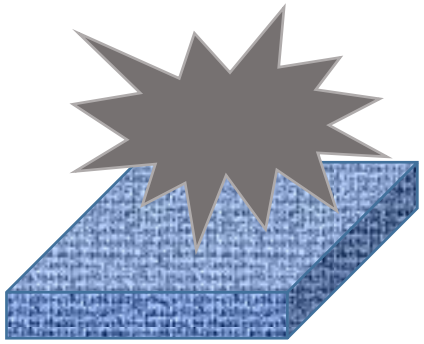
LaRC

Gordon, Keith L.; et al., "Spray-deposition of Graphene/Polymer Thin Coatings on Polyimide Sheets for Lunar Dust Adhesion Mitigation," Acta Astronautica, 2024, 219, 449-458.

Evaluation of Mitigation Efficacy

Generation of a Contaminated Surface

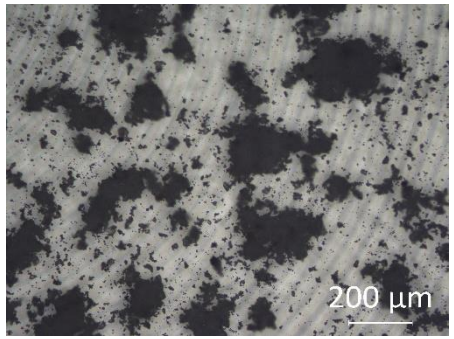
Ideal Case: Isolated Particle



☑ Adhesion forces
- Van der Waals
- Electrostatic
- Magnetic
- Chemical
- Mechanical

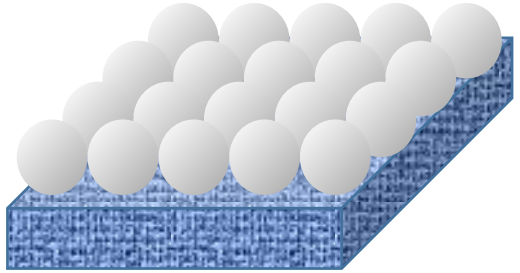
☒ Contributing forces
- Gravitation (Earth)
- Capillary (ambient atmosphere)

Actual Case: Aggregated Particles



☒ Contributing forces
- Cohesion force
- Mechanical interlocking
- Deformation

Hypothetical Case: Particle Monolayer



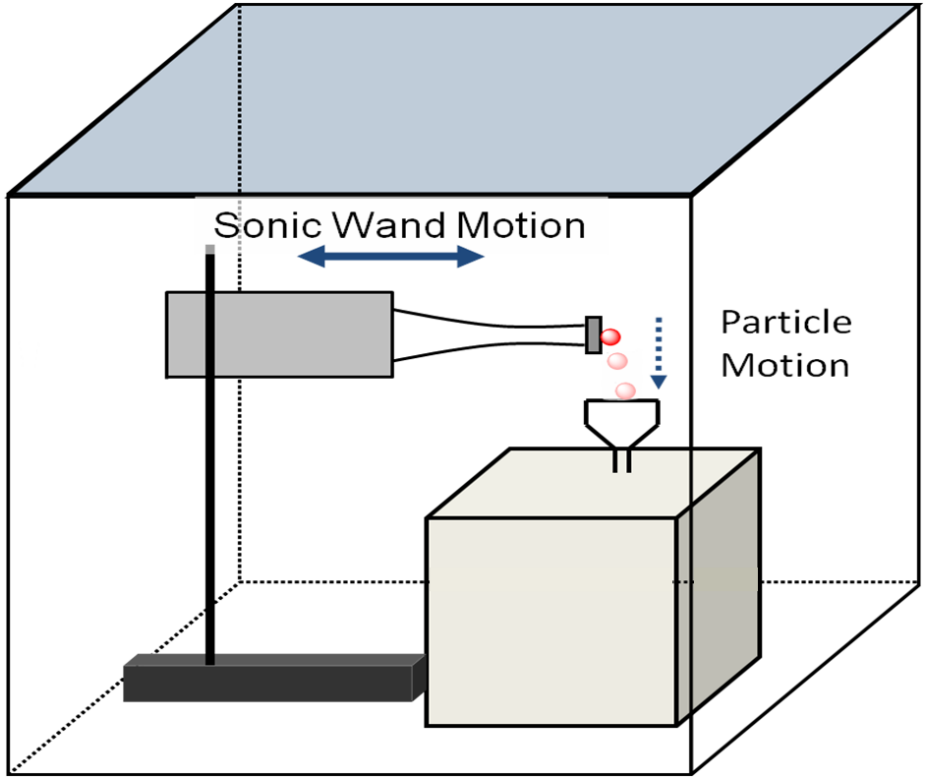
☒ Contributing forces
- Cohesion force
- Mechanical interlocking

Image credit: NASA

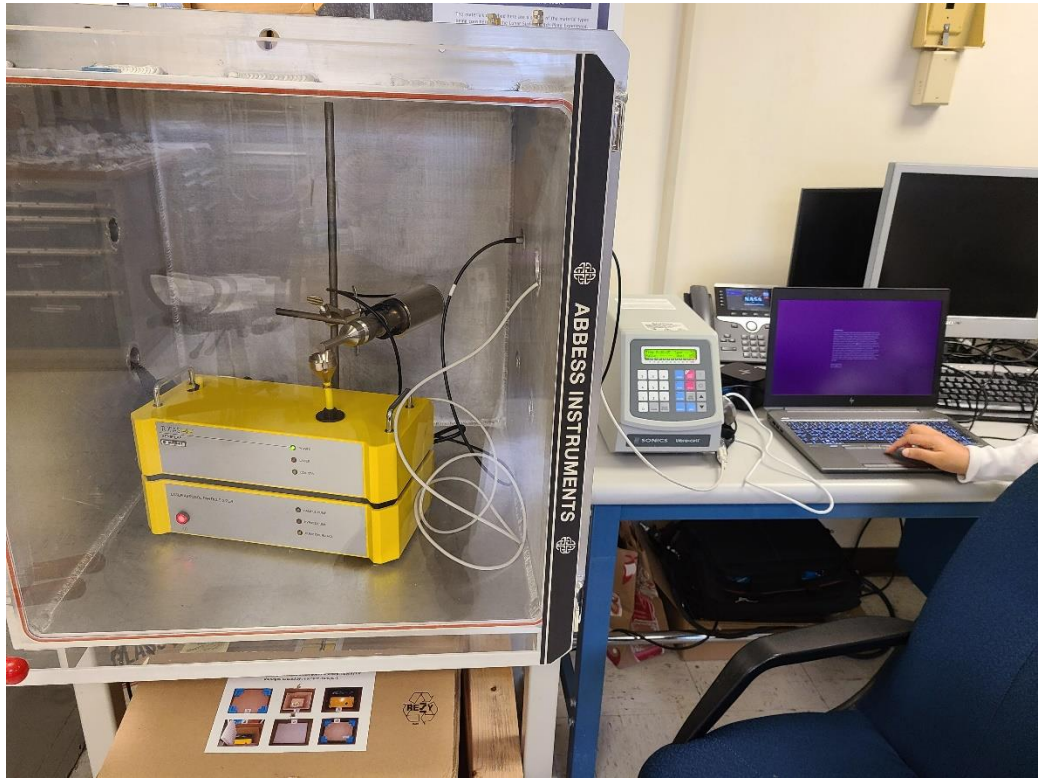
Evaluation of Mitigation Efficacy

Sonication Instrument

Schematic



Actual Instrument



LaRC

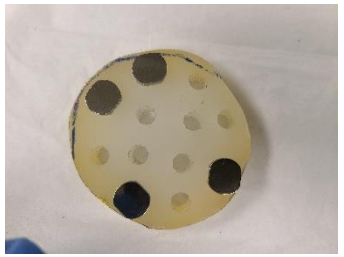
Wohl, C.; Atkins, B.; Connell, J. "Evaluation of Particle Adhesion Properties of Materials Using a Sonication Device: Identifying Materials for Lunar Dust Adhesion Mitigation" NASA Technical Memorandum, 2011, TM-2011-217048.

Image credit: NASA

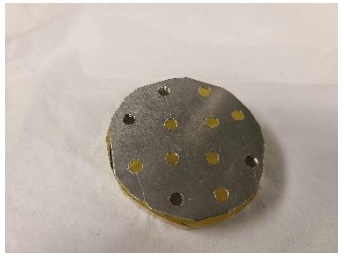
Evaluation of Mitigation Efficacy

Sonication Instrument

Step 1. Prepare Samples

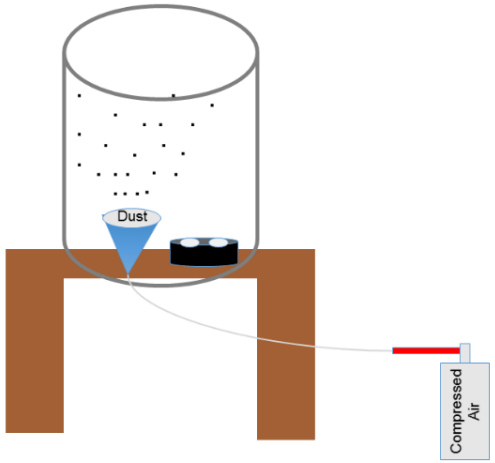


Sonic wand samples on sample holder



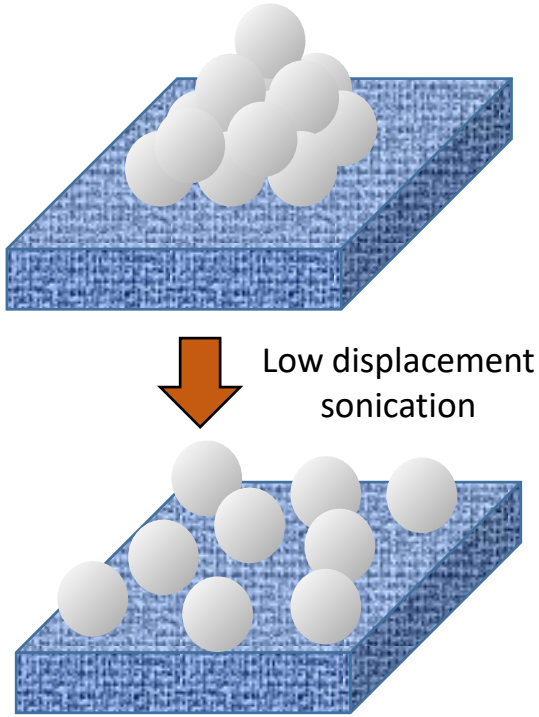
Sample deposition screen

Step 2. Deposit Simulant



Aerosolization technique selected

Step 3. Resolve Cohesion



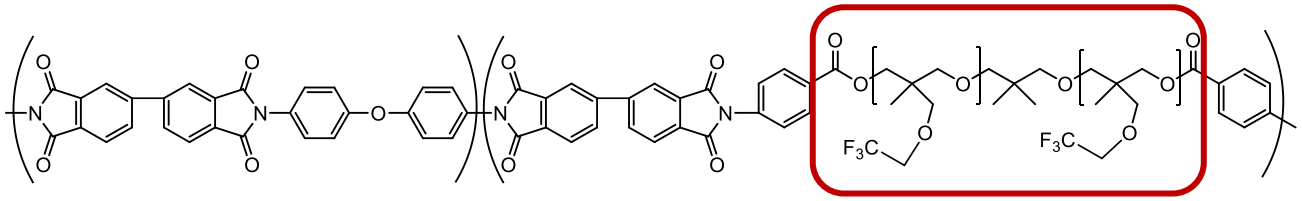
LaRC

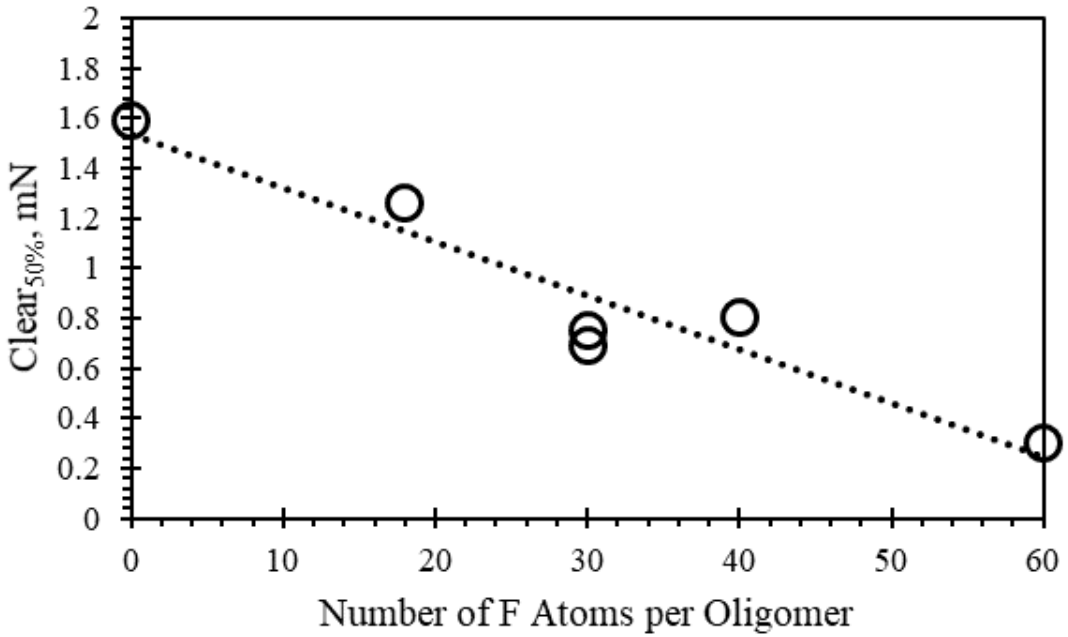
Wohl, C.; Atkins, B.; Connell, J. "Evaluation of Particle Adhesion Properties of Materials Using a Sonication Device: Identifying Materials for Lunar Dust Adhesion Mitigation" NASA Technical Memorandum, 2011, TM-2011-217048.

Image credit: NASA

Evaluation of Mitigation Efficacy

Sonication Instrument-Surface Chemistry



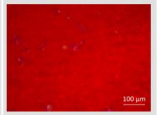
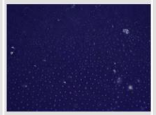
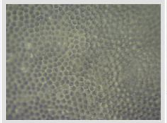
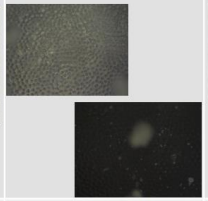
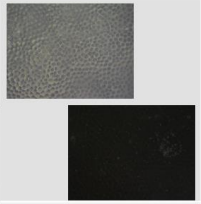
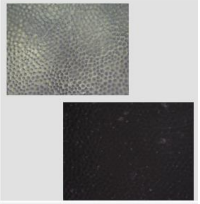
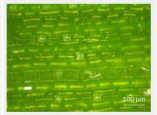
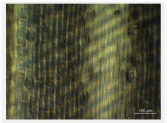
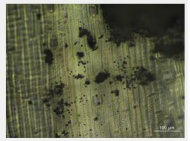
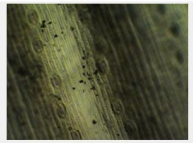
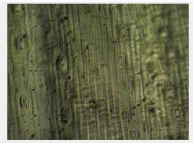
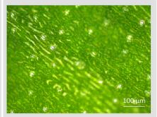
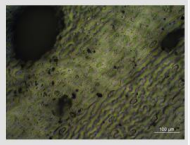
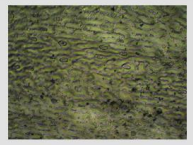
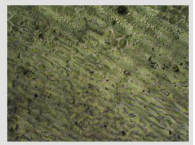


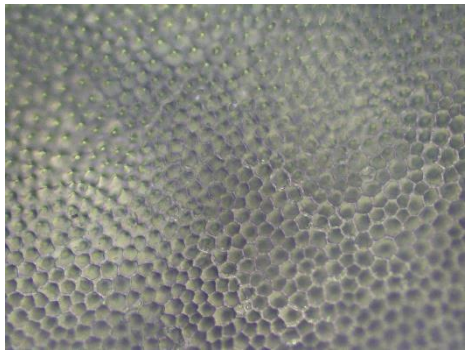
LaRC

Wohl, Christopher J.; et al., "Lunar Dust Simulant Particle Adhesion on Copolyimide Alkyl Ethers" in The Impact of Lunar Dust on Human Exploration, ed. Joel S. Levine, Cambridge Scholars Publishing, February, 2021.

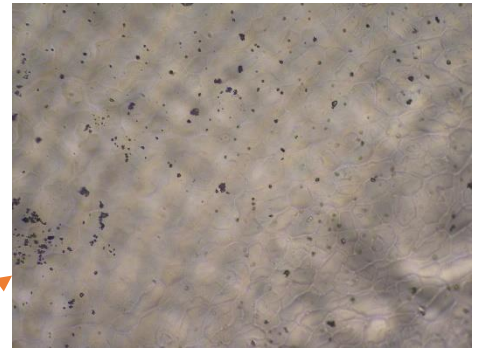
Evaluation of Mitigation Efficacy

Sonication Instrument-Biomimetic Surfaces

Sample no.	Sample name	Original surface	Negative replica	Positive replica (ctrl)	Dust	First run	Full run
1)	Rose petal						
2)	Grass leaf						
3)	Water clover						

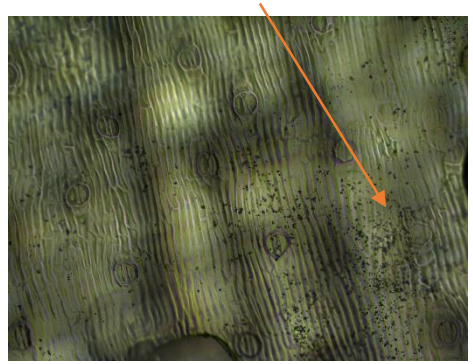


Rose Petal



Cabbage

Clusters of dust particles remain adhered



Banana Leaf

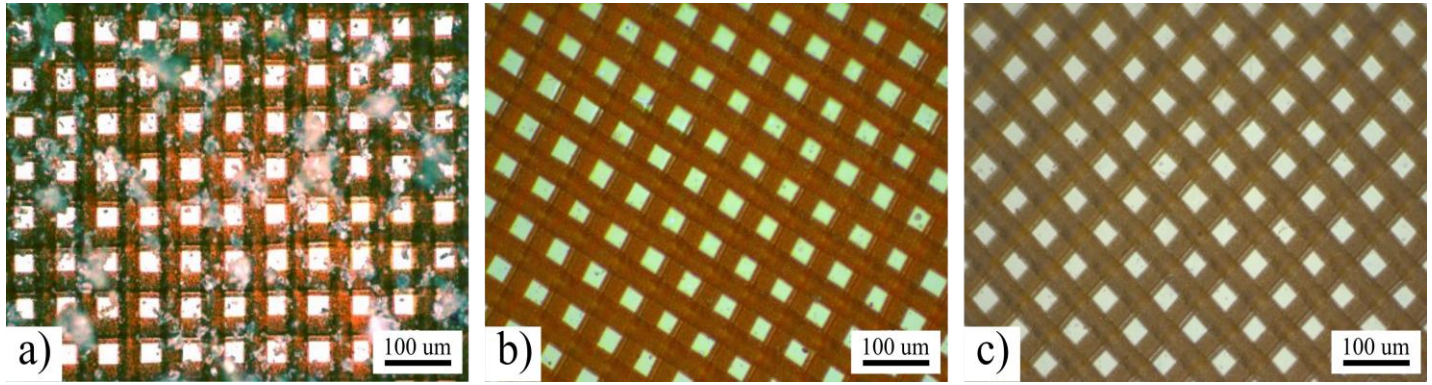
Certain surface topographies exhibited better lunar simulant adhesion mitigation

LaRC

Image credit: NASA

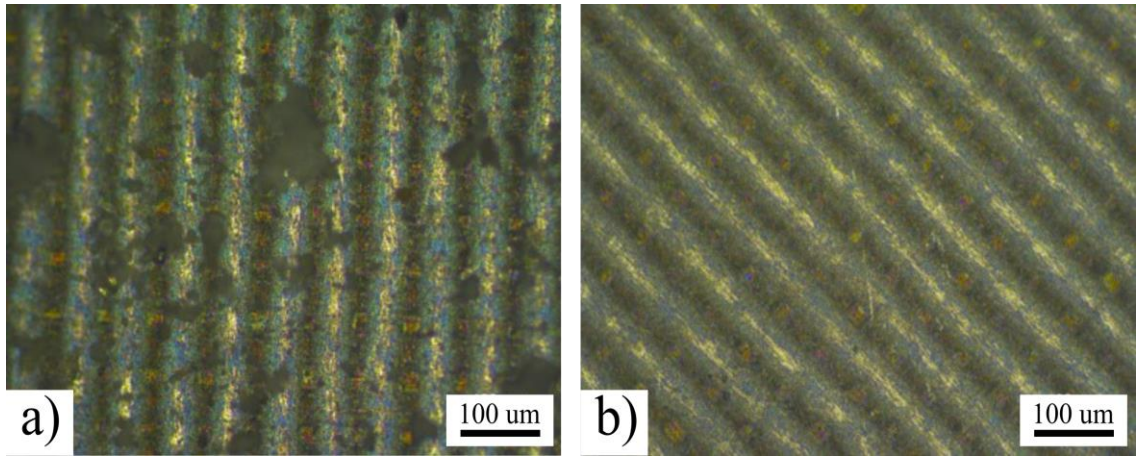
Evaluation of Mitigation Efficacy

Sonication Instrument-Laser Patterning



- **Polymeric Surface**
  - –Left to Right: Contaminated Surface, Cohesion Removal, Full Test

- **Titanium Surface**
  - –Left to Right: Contaminated Surface, Cohesion Removal

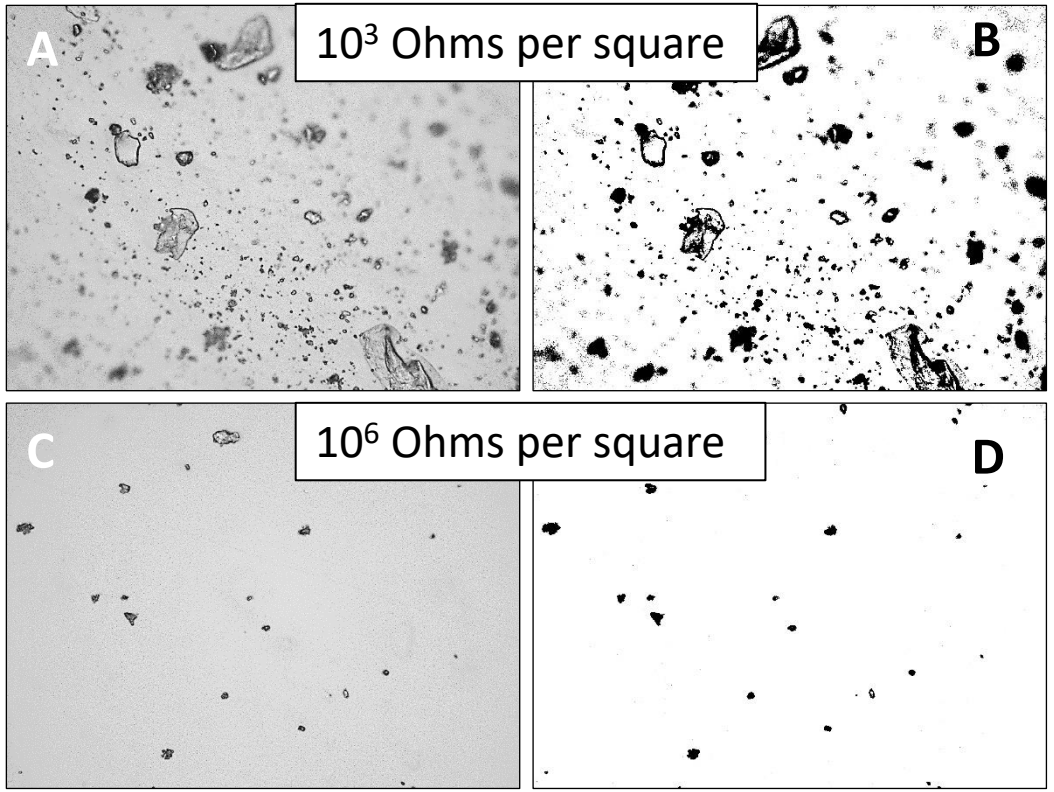


LaRC

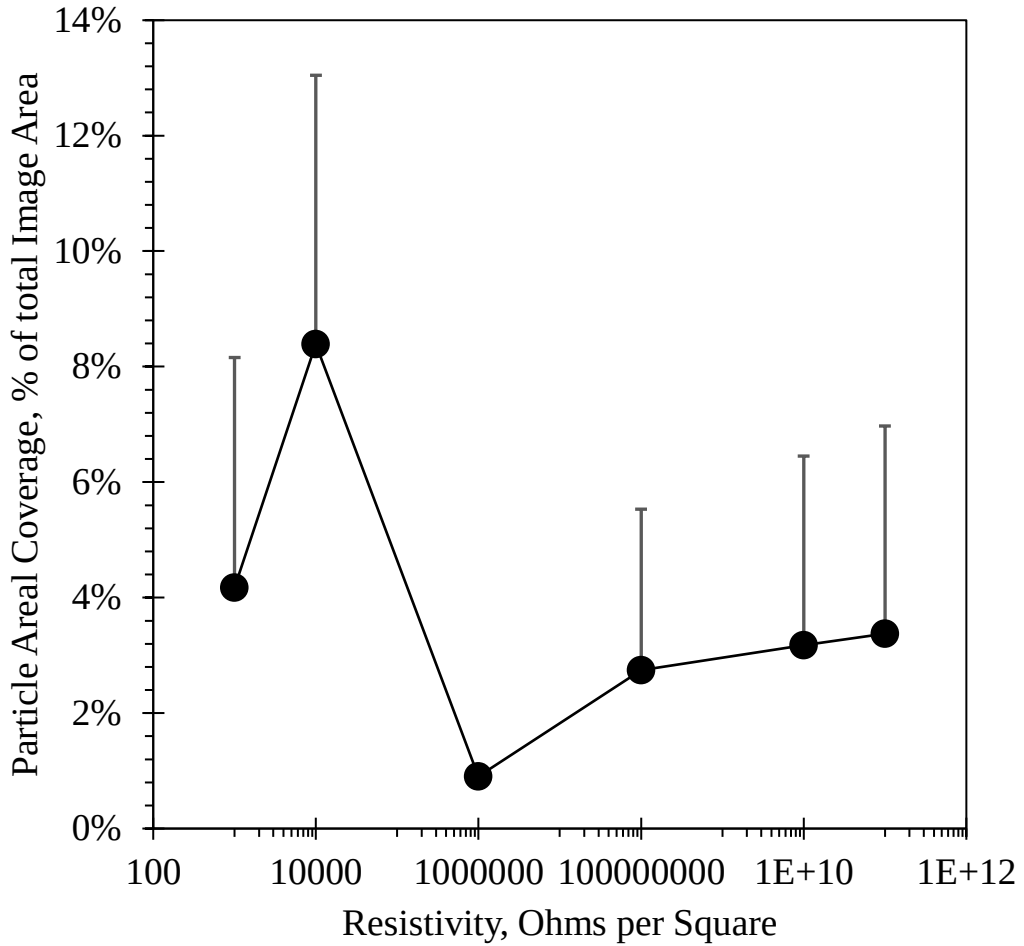
Das, Lopamudra; et al., "Extending Lunar Presence: Dust Adhesion Mitigation Materials and Surfaces to be Evaluated on the Lunar Surface," Acta Astronautica, 2024, 219, 532-541.

Evaluation of Mitigation Efficacy

Sonication Instrument-Surface Conductivity



(A and C) Optical micrographs of simulant particles present on the transfer tape and (B and D) binary image for determination of simulant areal coverage



LaRC

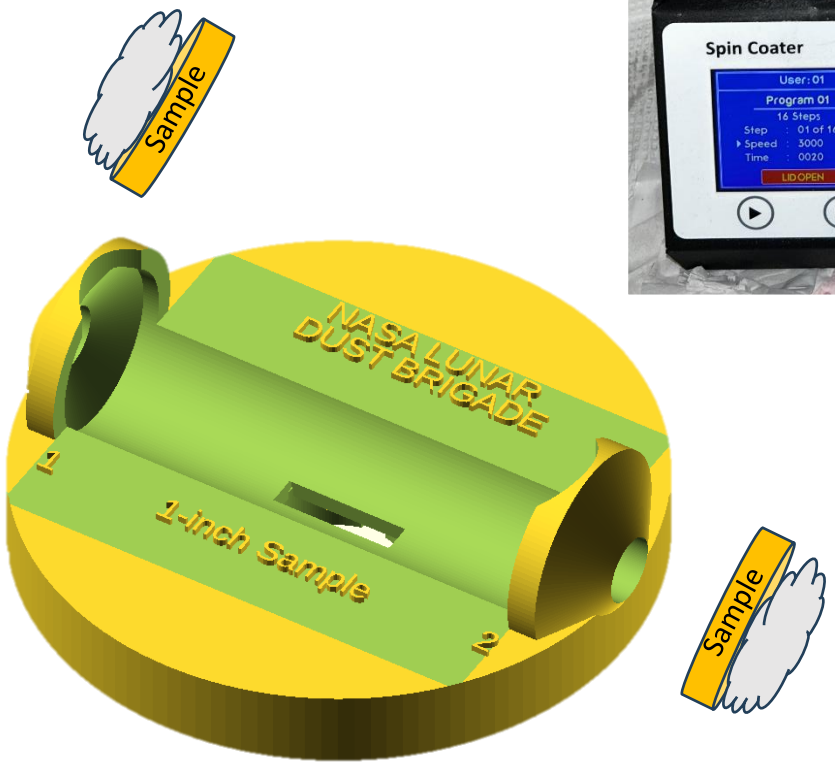
Gordon, Keith L.; et al., "Spray-deposition of Graphene/Polymer Thin Coatings on Polyimide Sheets for Lunar Dust Adhesion Mitigation," Acta Astronautica, 2024, 219, 449-458.

Evaluation of Mitigation Efficacy

Centrifuge Instrument

- Take mass of clean sample
- Deposit simulant and take mass
  - Aerosolize 500 mg of dust in chamber and allow it to fall onto sample
- Run the sample at a given speed (500-4000 RPM) in centrifuge and take mass
  - Custom 3D printed sample holder



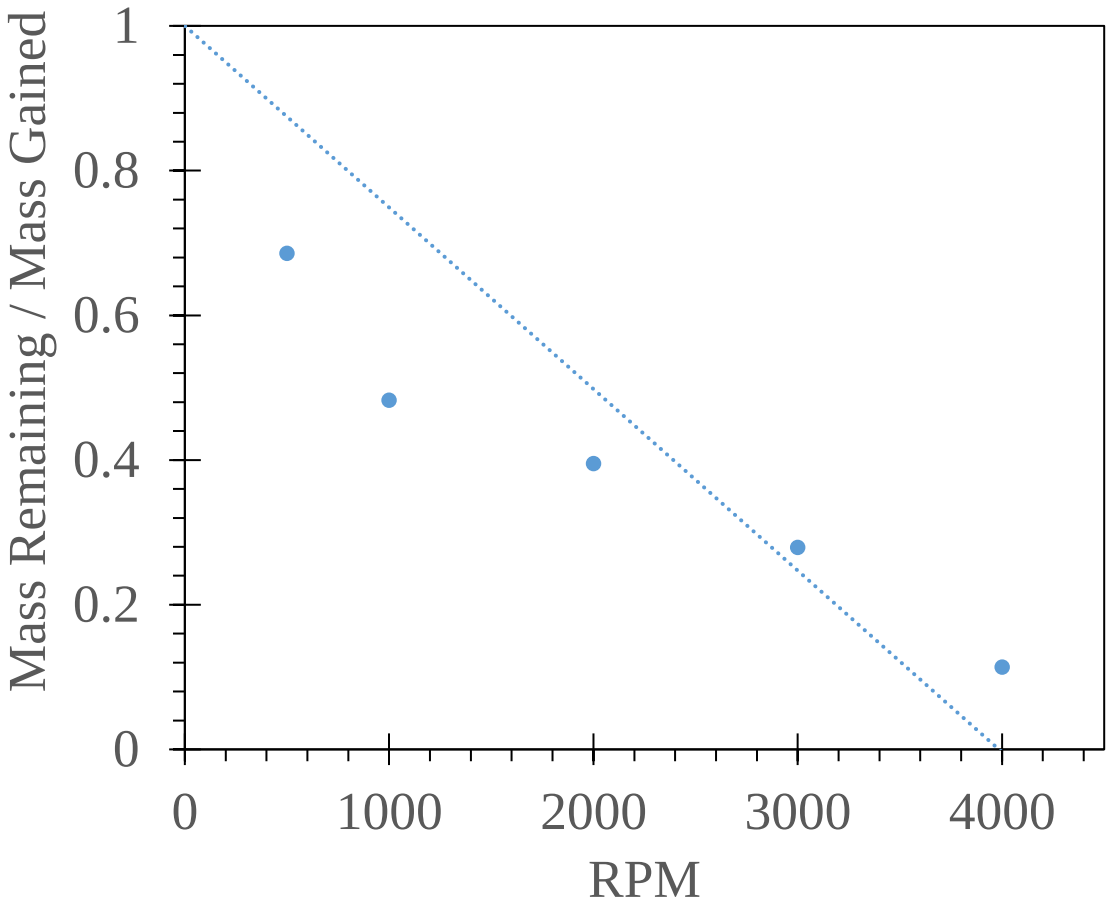


LaRC

Image credit: NASA

Evaluation of Mitigation Efficacy

Centrifuge Instrument-Calculating Clearance Velocity



Hoekstra- Voigt Coefficient

Mass Remaining

$$\frac{m_1}{m_0} = -\mu\omega + 1$$

Mass Gained

Angular Velocity

Zero Mass Remaining at rotations per minute (RPM) of…

$$m_1 = 0$$

$$0 = -\mu\omega + 1$$

$$-1 = -\mu\omega$$

$$\frac{1}{\mu} = \omega$$

Image credit: NASA

Evaluation of Mitigation Efficacy

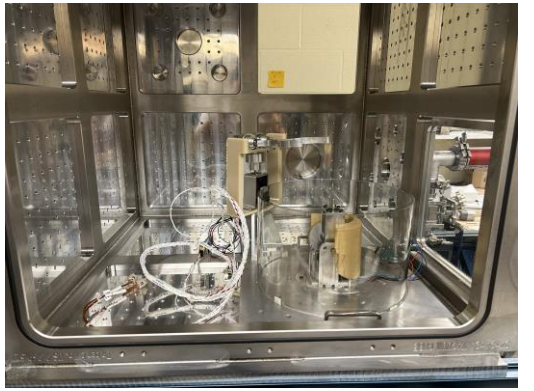
Dust Ejection by Excessive Rotation (DEER)

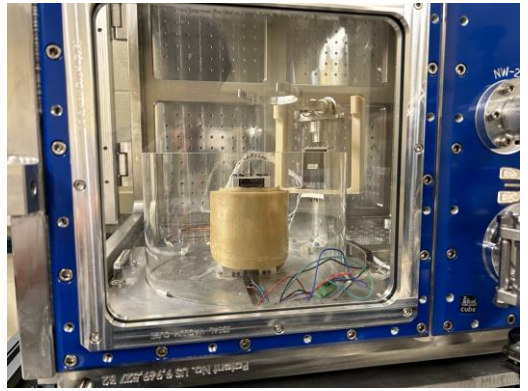
Purpose

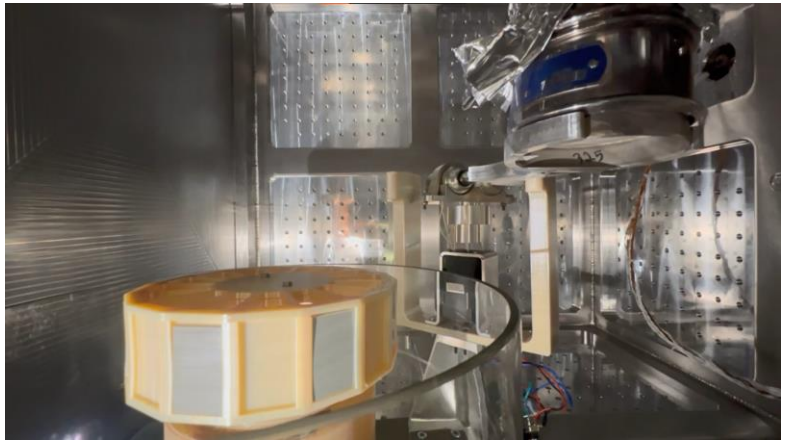
- To determine the adhesive forces of lunar simulant on a variety of materials. These forces are determined by centripetal force calculations after ejection or adhesion on a rapidly spinning sample holder.
  - Tests performed in a vacuum chamber (10^{-6} Torr) with and without UV light exposure.

Objectives

- (Primary) determine the adhesive forces of lunar simulant on a variety of materials
- (Secondary) establish a facility to continue this testing, as needed, for Providers and stakeholders







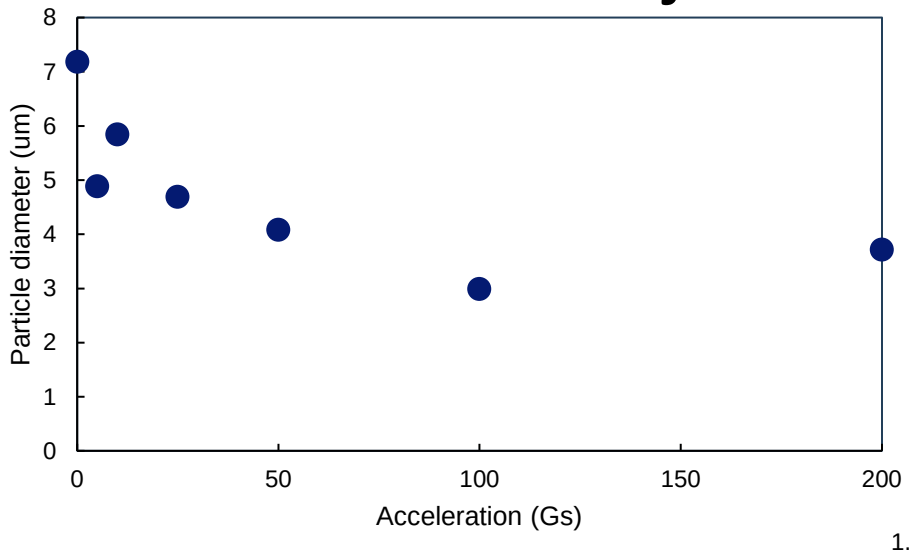
JSC

POC: Josh Litofsky, NASA Johnson Space Center, Joshua.h.Litofsky@nasa.gov

Image credit: NASA

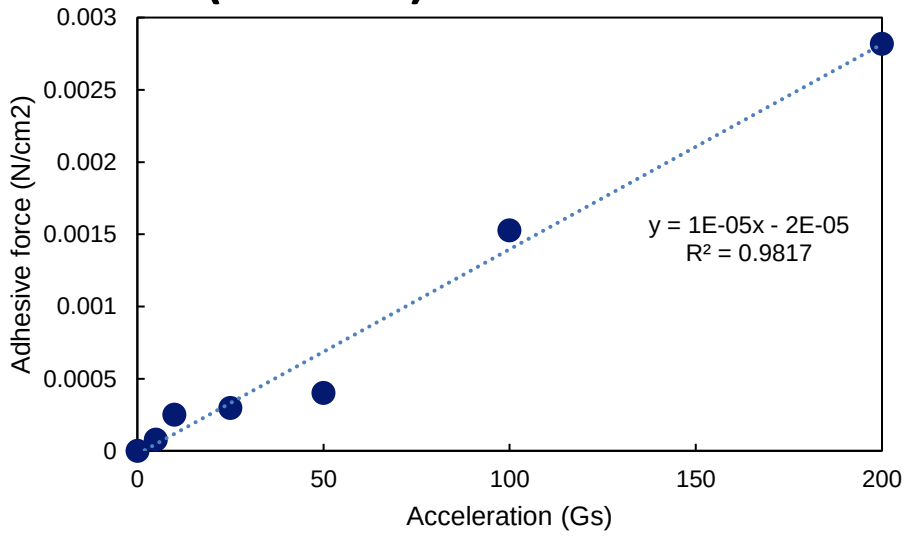
Evaluation of Mitigation Efficacy

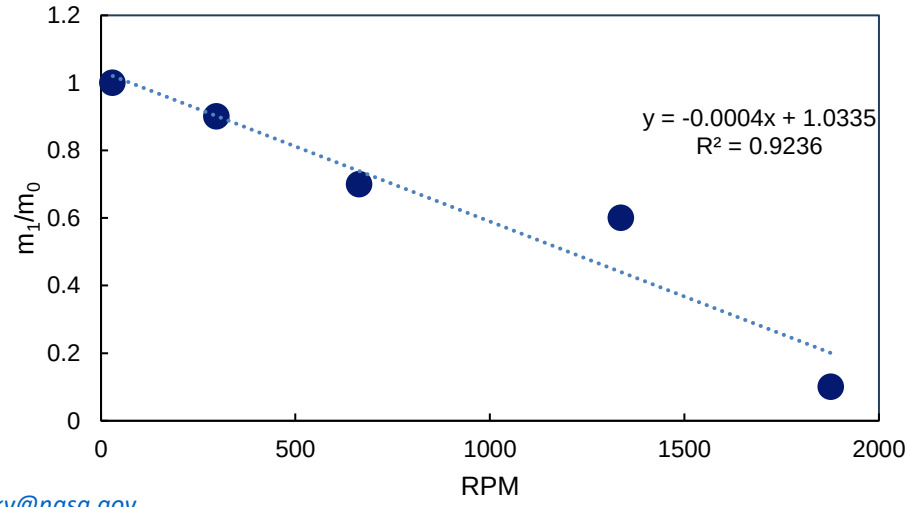
Dust Ejection by Excessive Rotation (DEER)



Average particle diameter decreased with increasing centripetal force.

Adhesion force increased linearly with centripetal force.





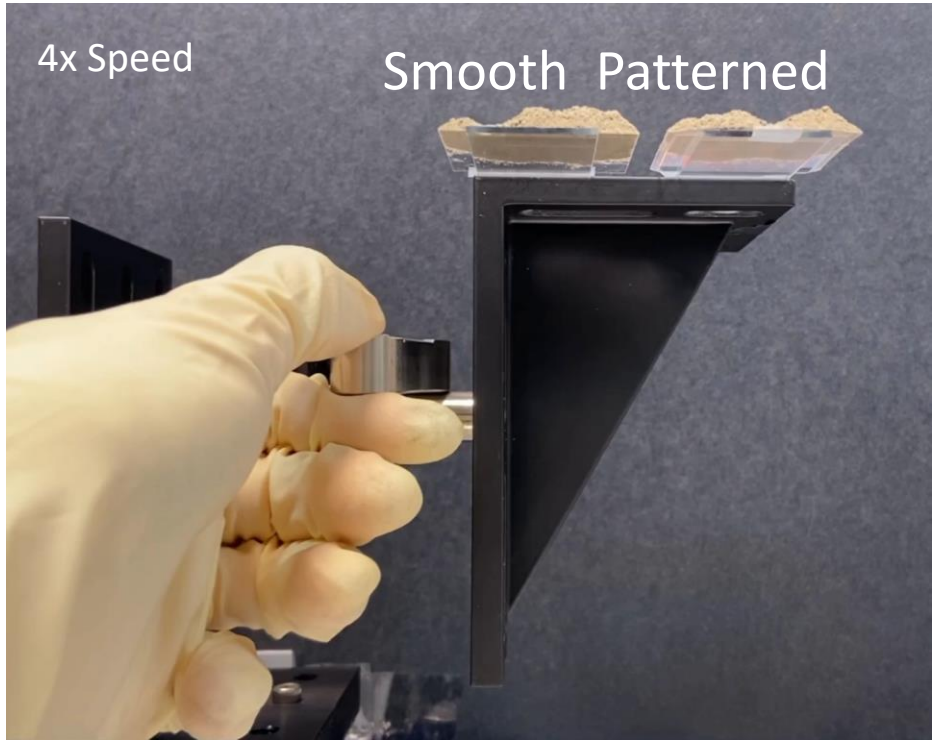
Remaining simulant mass decreased linearly with increasing centripetal force

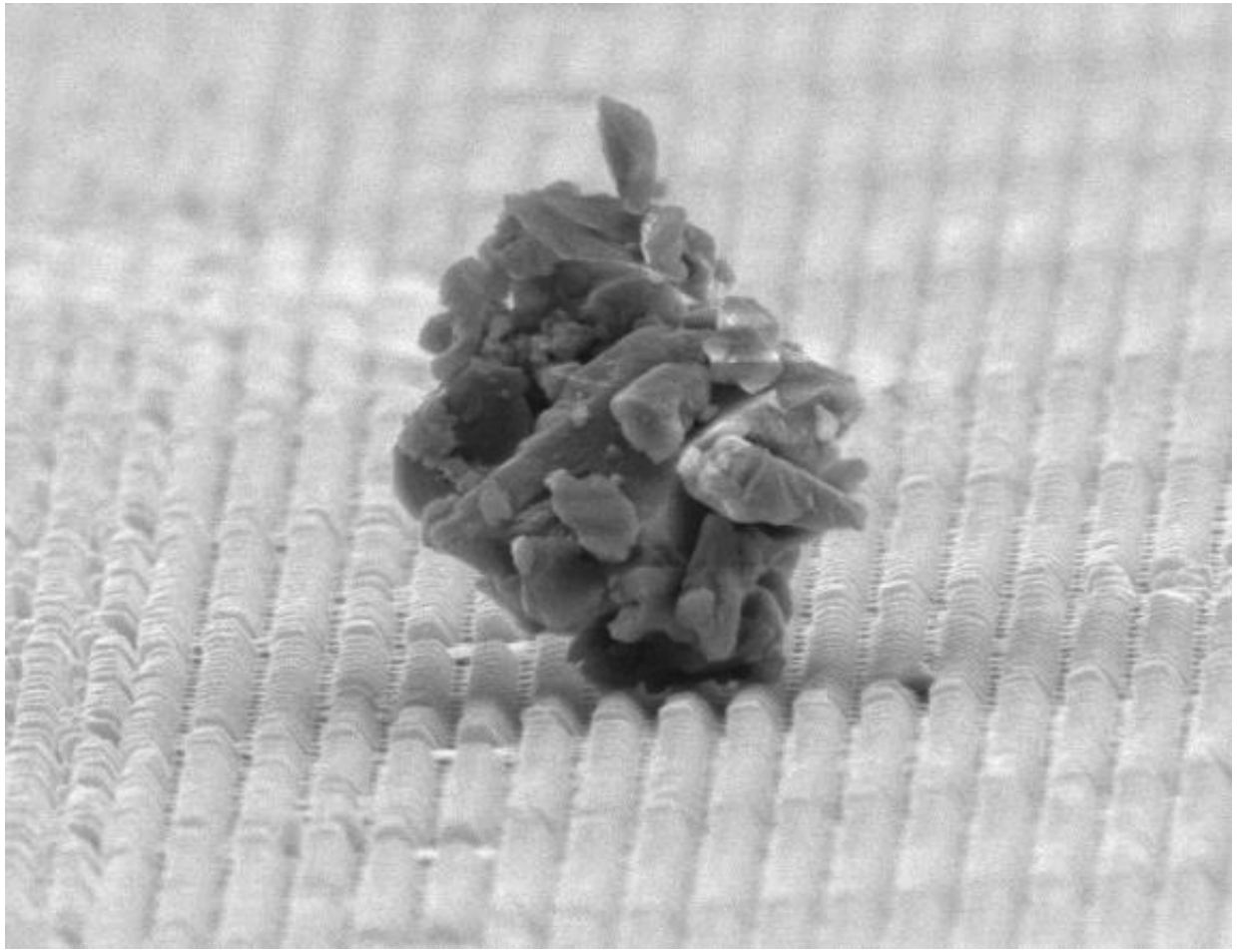
JSC

POC: Josh Litofsky, NASA Johnson Space Center, Joshua.h.Litofsky@nasa.gov

Evaluation of Mitigation Efficacy

Tilt Testing





Smart Material Solutions

UT Austin

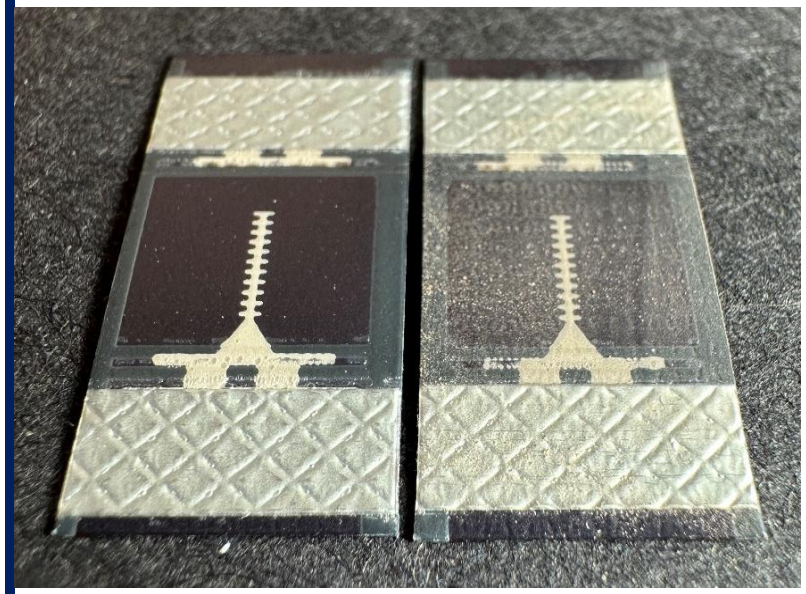
ACS Appl. Mater. and Interfaces. Samuel Lee et. al. 10.1021/acsami.2c19211

Evaluation of Mitigation Efficacy

Tilt Testing- Solar Cells with Nanocoin Topography

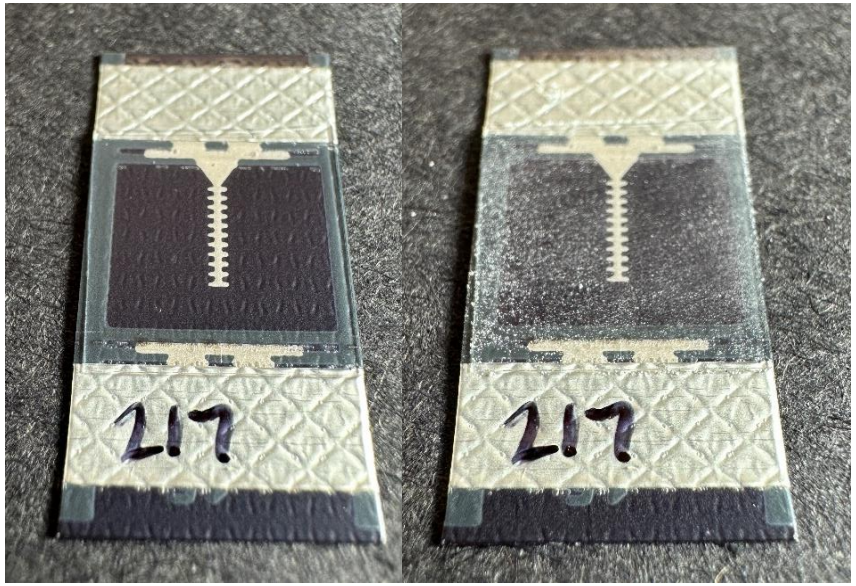
No Coating

Before dusting After dusting



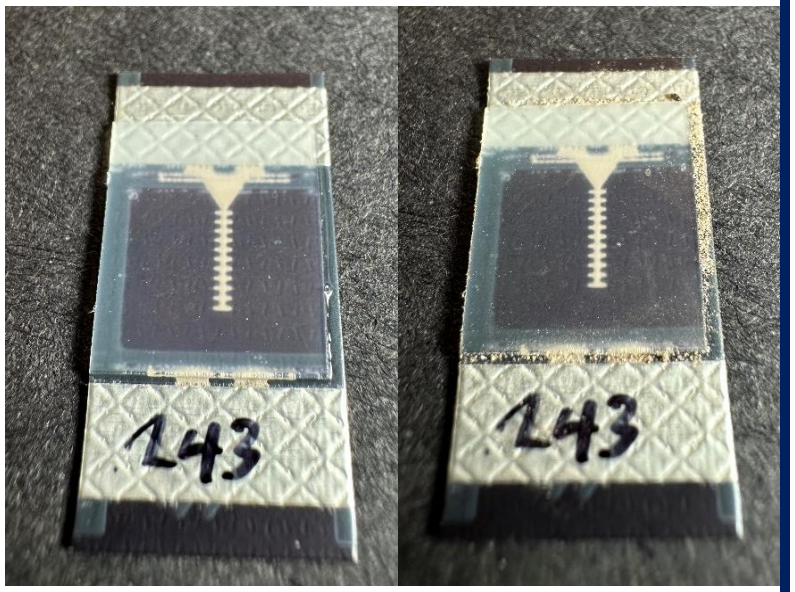
Smooth Coating

Before dusting After dusting



Hierarchical Coating

Before dusting After dusting



Smart Material Solutions

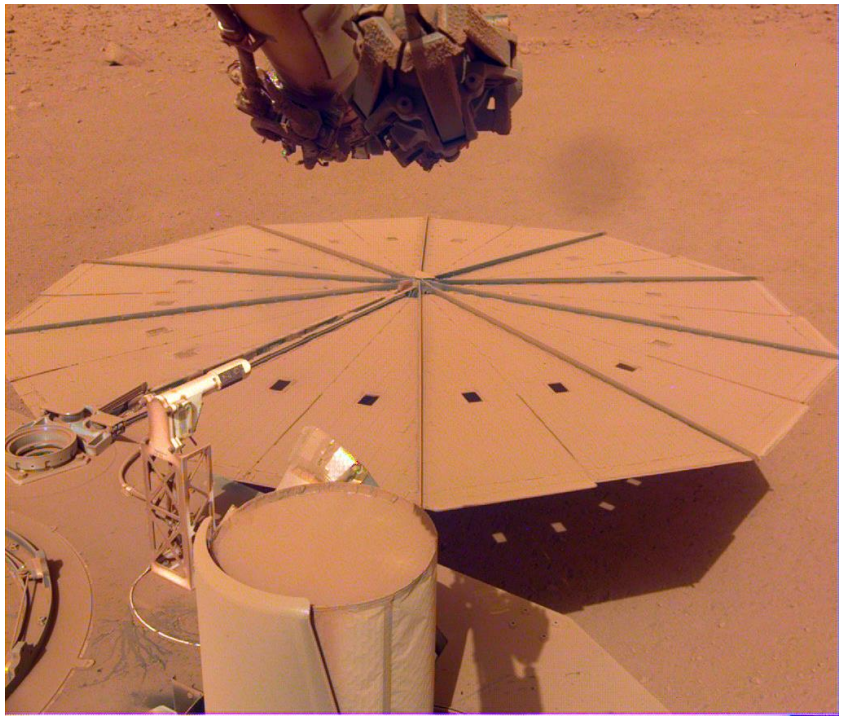
UT Austin

POC: Stephen Furst, Smart Material Solutions, furst@smartmaterialsolution.com; Chih-Hao Chang, University of Texas-Austin, chichang@utexas.edu

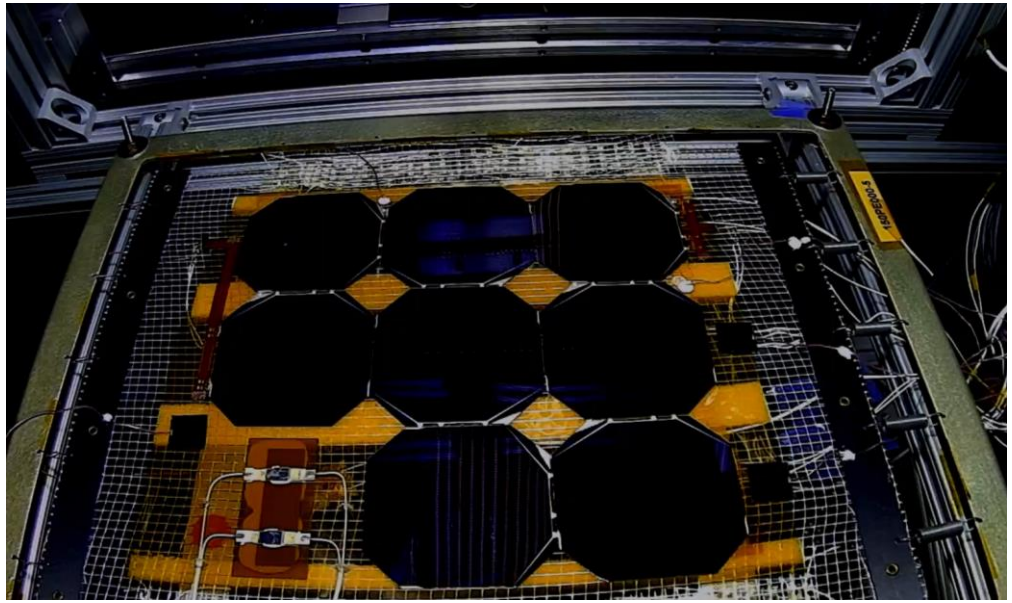
Evaluation of Mitigation Efficacy

Solar Cell Testing- Evaluation of Vibromechanical Dust Removal

Mars Insight Lander



forward bias solar cell → solar cell emits light



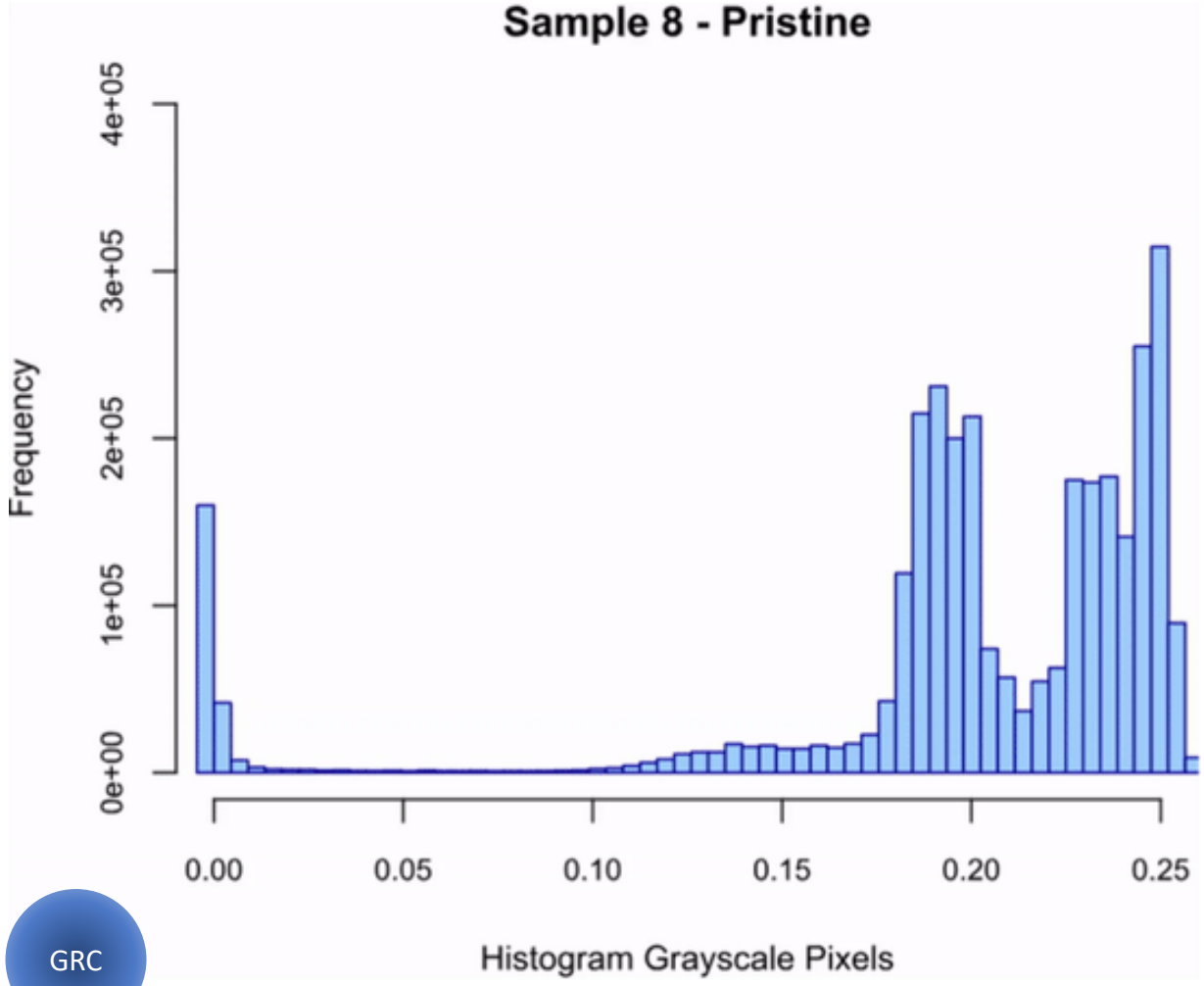
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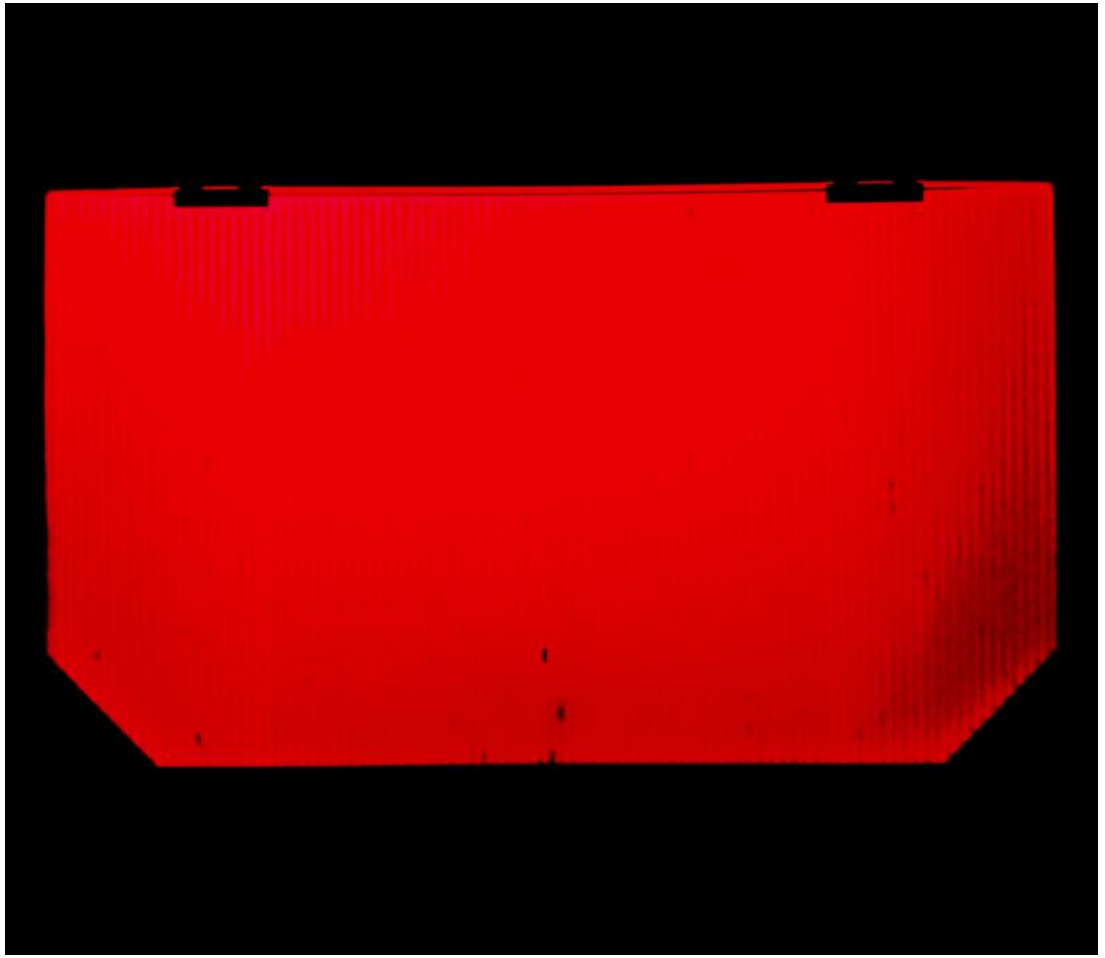
POC: Meghan Bush, NASA Glenn Research Center, Meghan.bush@nasa.gov , DMFlex ACO – 20 – 20 ACO Final – 0020

Image credit: NASA

Evaluation of Mitigation Efficacy

Solar Cell Testing- Evaluation of Vibromechanical Dust Removal





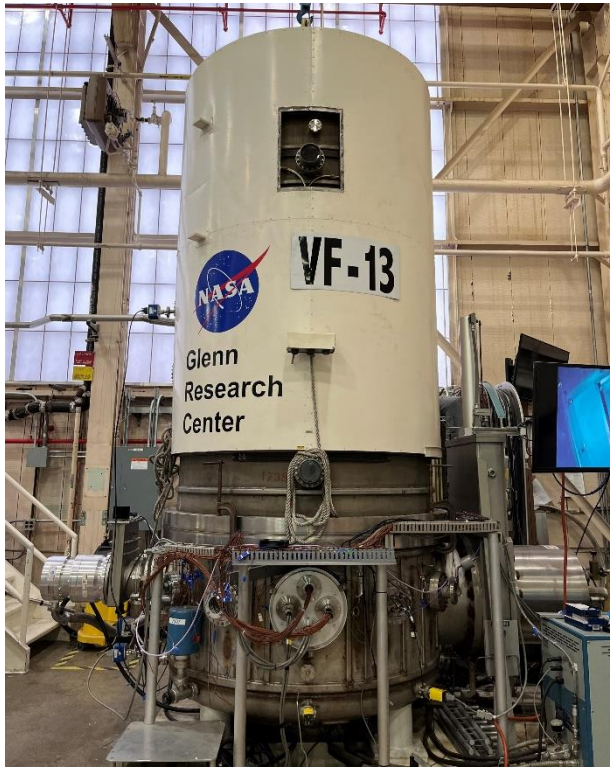
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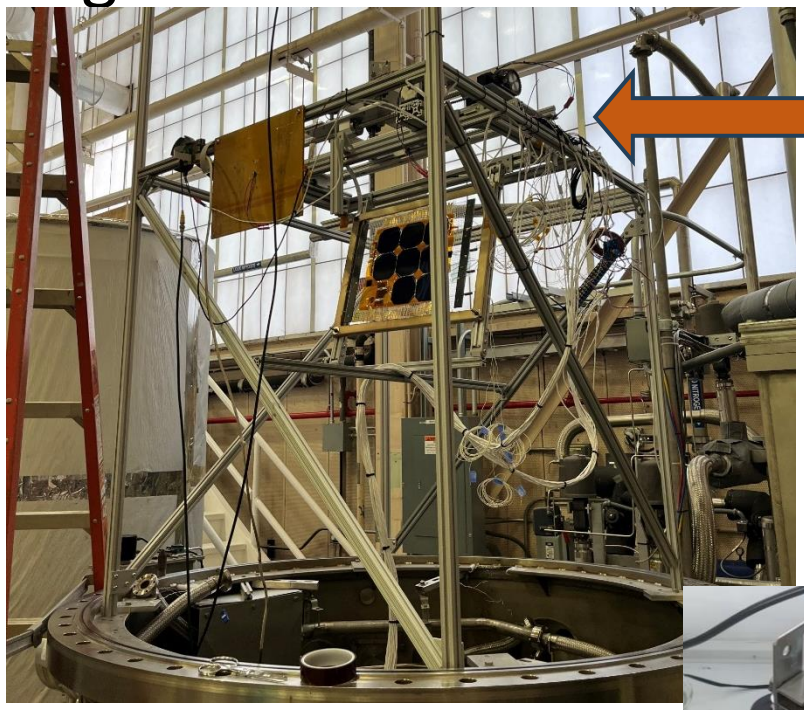
POC: Meghan Bush, NASA Glenn Research Center, Meghan.bush@nasa.gov , DMFlex ACO – 20 – 20 ACO Final – 0020

Image credit: NASA

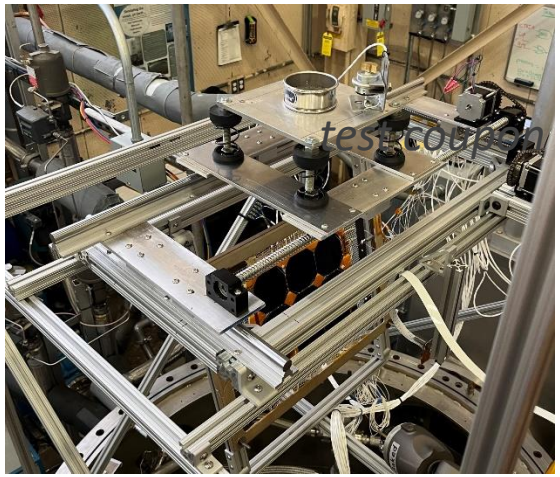
Evaluation of Mitigation Efficacy

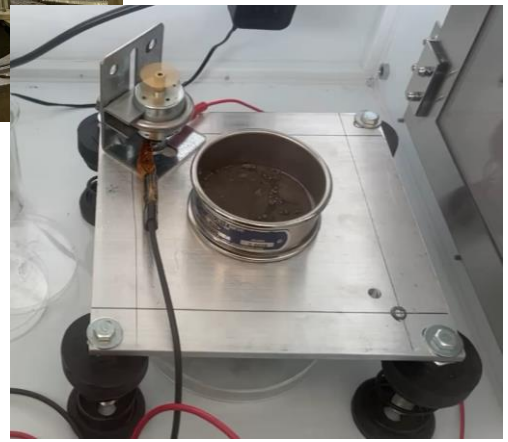
Solar Cell Testing- Evaluation of Vibromechanical Dust Removal





Dust Deposition System







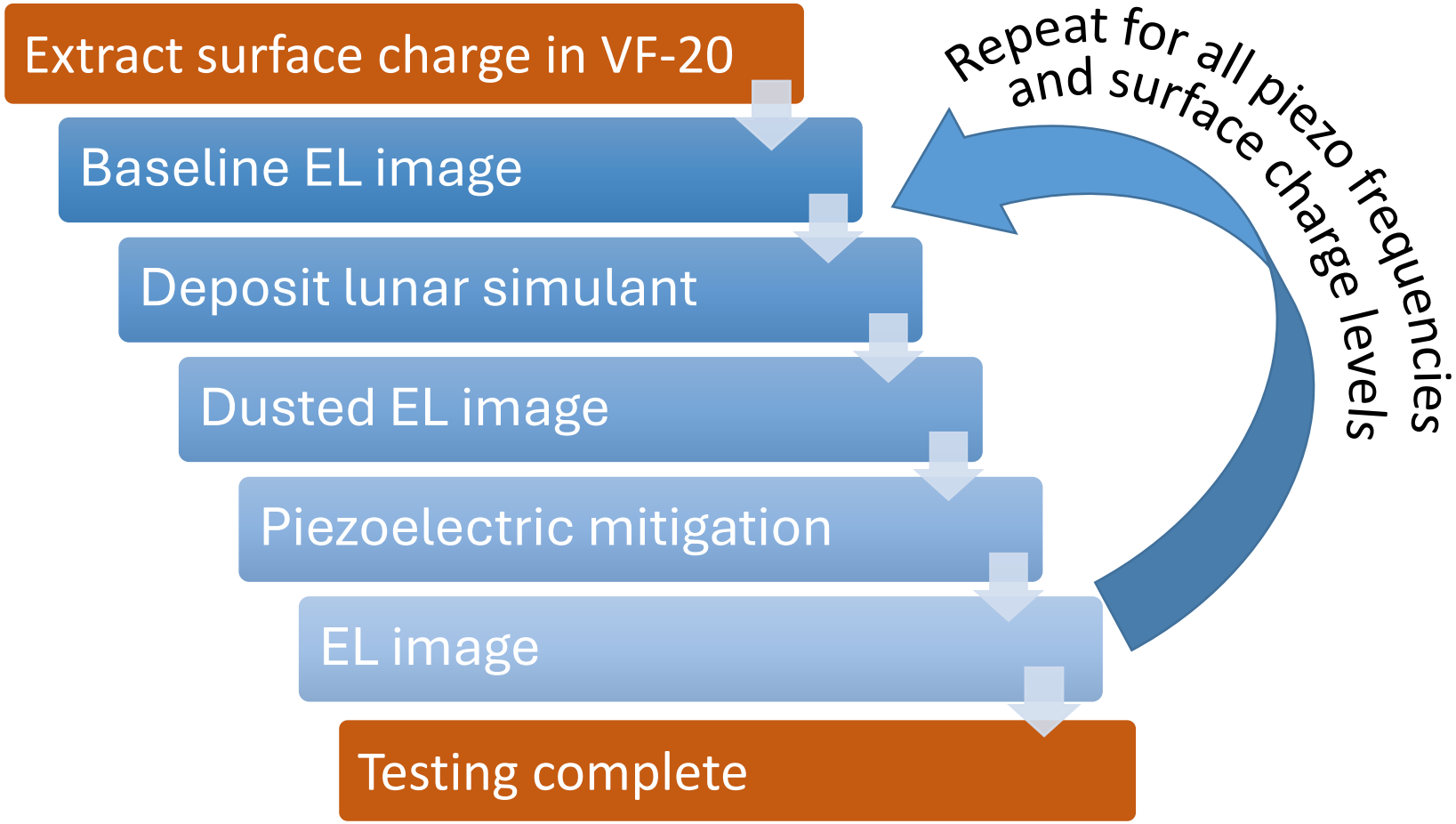
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Image credit: NASA

Evaluation of Mitigation Efficacy

Solar Cell Testing- Evaluation of Vibromechanical Dust Removal



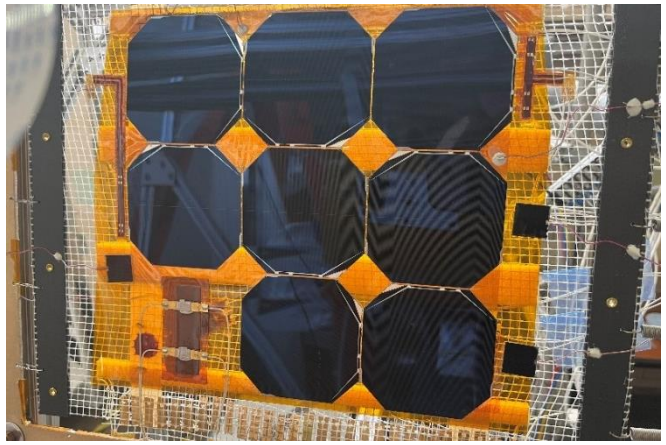
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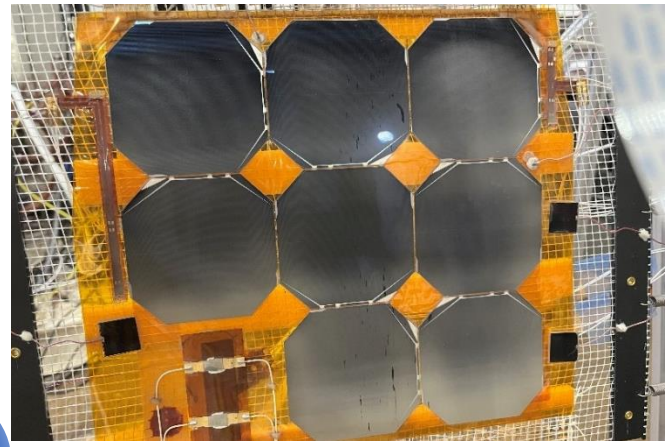
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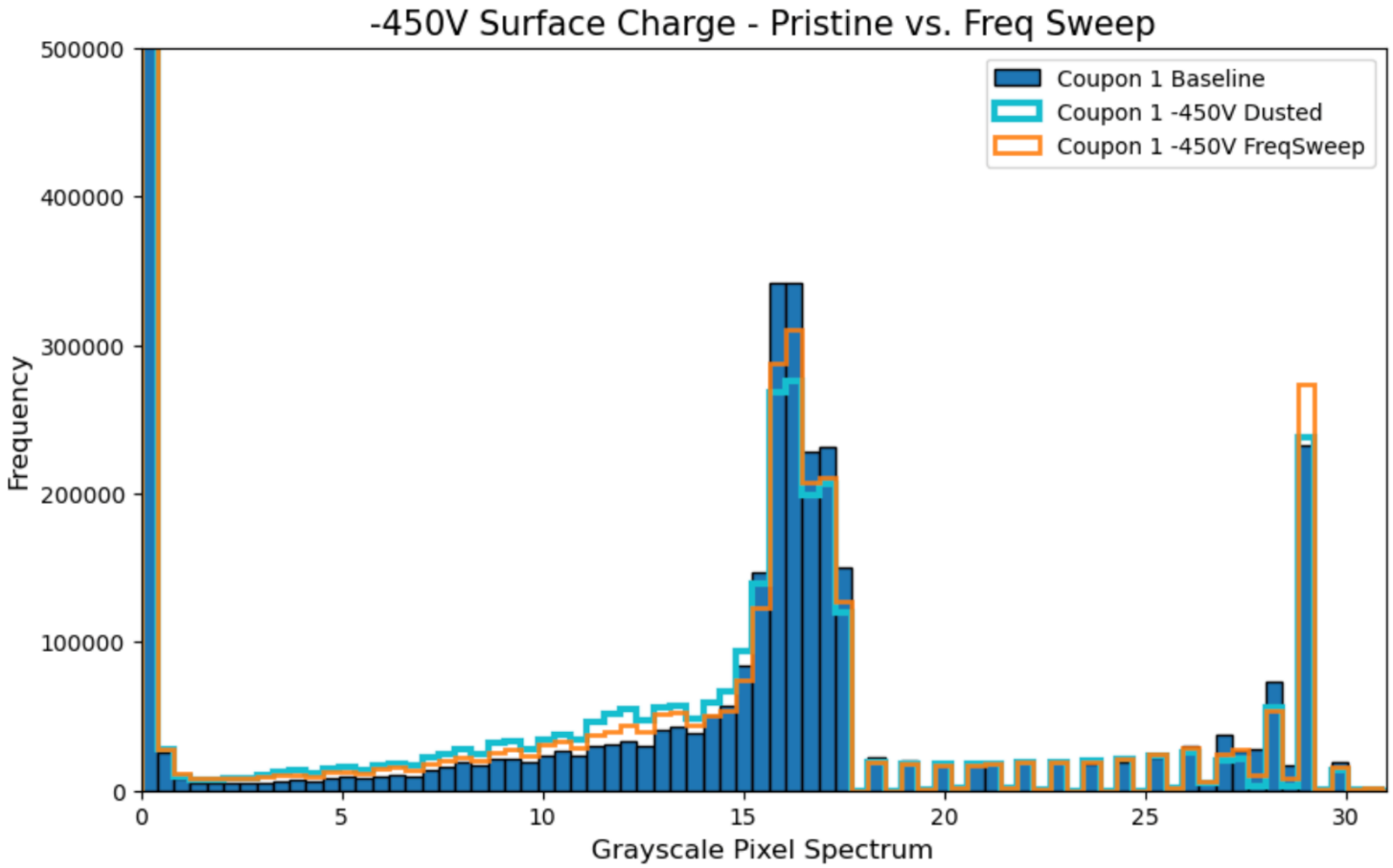
Image credit: NASA

Evaluation of Mitigation Efficacy

Solar Cell Testing- Evaluation of Vibromechanical Dust Removal







GRC

POC: Meghan Bush, NASA Glenn Research Center, Meghan.bush@nasa.gov , DMFlex ACO – 20 – 20 ACO Final – 0020

Image credit: NASA

Evaluation off Planet

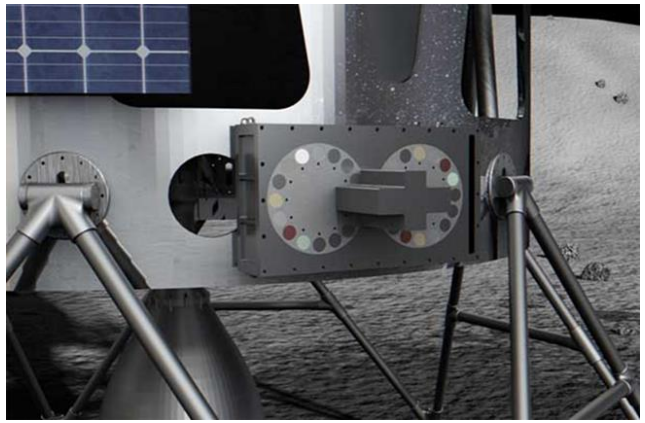
Materials International Space Station Experiment (MISSE) Samples

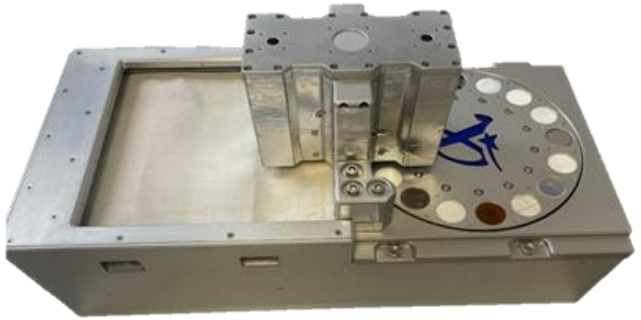
Copper Zirconium	Bulk Metallic Glass	Considered for RAC Payload
Boron Carbide (B4C)	Ceramic	Considered for RAC Payload
Chrome Carbide	Ceramic	LO-DuSST, high wear surface
Chromium Oxide	Ceramic	LO-DuSST, high wear surface
Laser Patterned Kapton	Polymer	On RAC Payload
Laser Patterned FEP	Polymer	On RAC Payload
Laser Patterned Low Creep/Relaxation Polymer	Polymer	Considered for RAC Payload
Laser Patterned Low Creep/Relaxation Composite	Polymer	On RAC Payload (Secondary)

Launched on July 15, 2022 (SpaceX CRS-25)
Returned to Earth on April 15, 2023 (CRS-27)



Regolith Adhesion Characterization (RAC) Payload

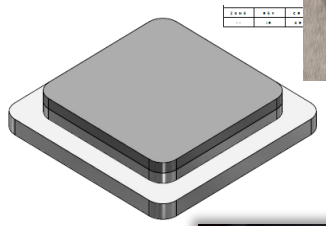


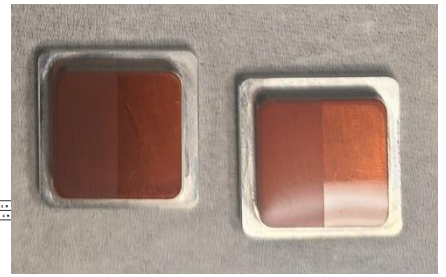


Images credit: Aegis Aerospace

Honeybee Robotics PlanetVac

Coupon Schematic





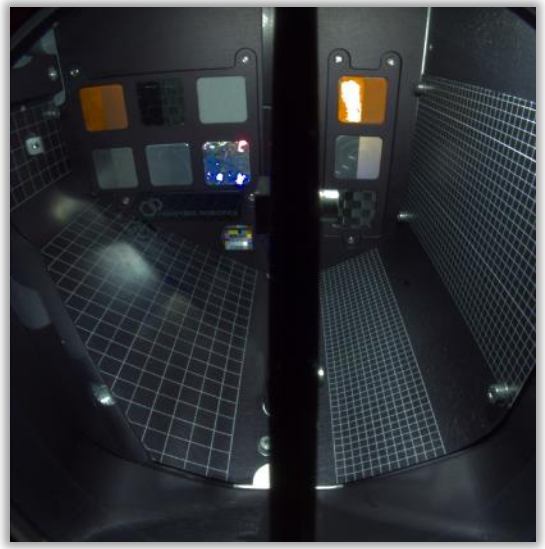
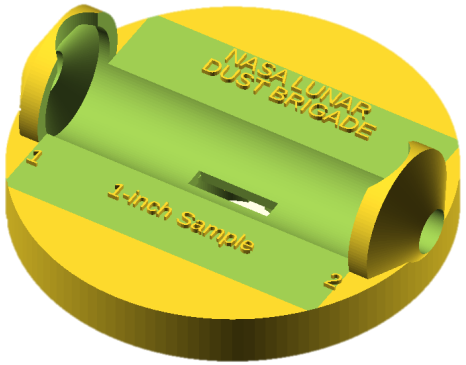


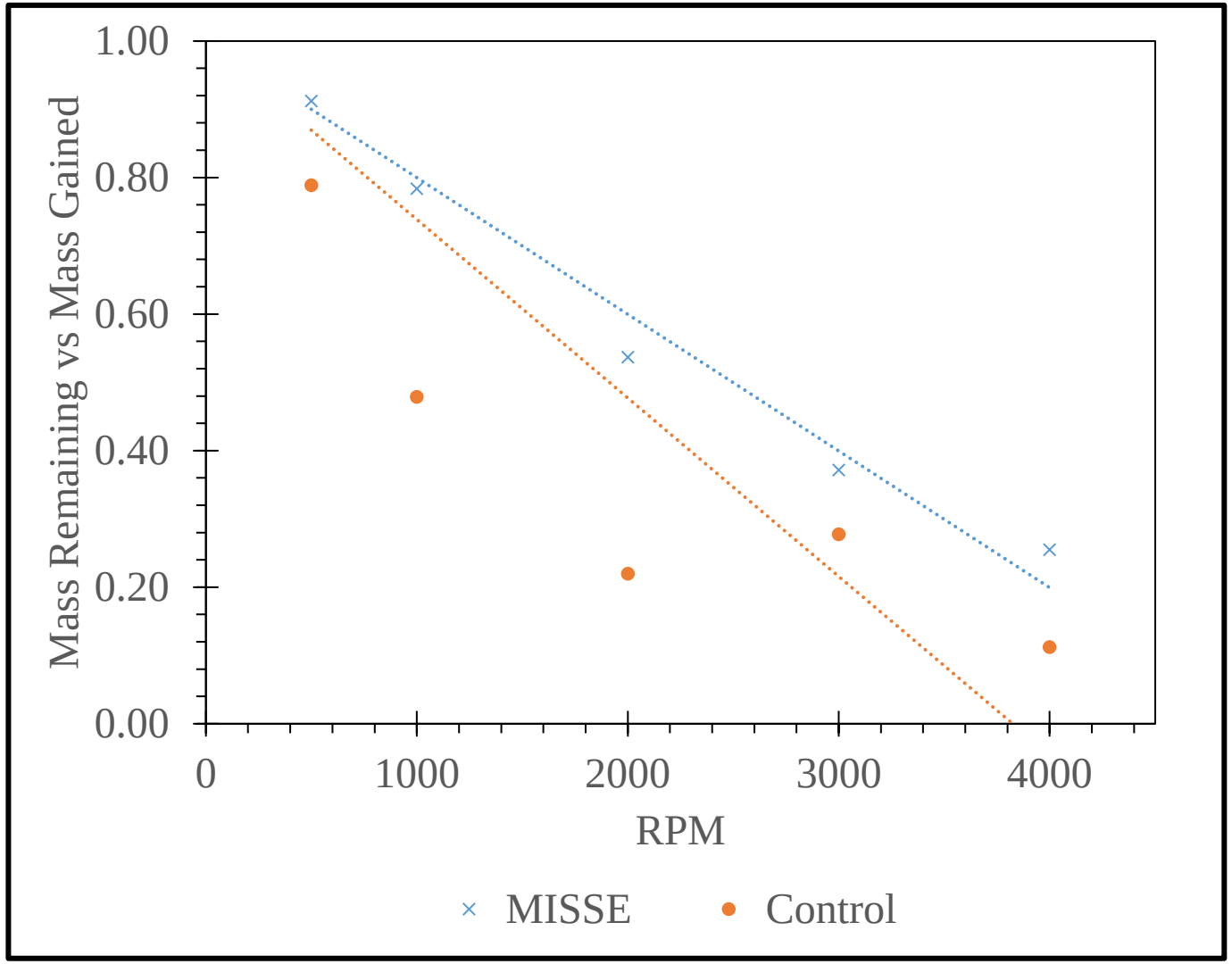
Image credit: NASA

Both experiments scheduled for launch in December, 2024 on Firefly Blue Ghost lander.

LaRC

Results: MISSE-16





Zero Mass Remaining:
3825.26 RPM

Zero Mass Remaining:
4996.25 RPM

LaRC



Conclusions

- Shortfalls Assessment … why does this work need to continue
- There is great work going on across the agency and supported by the agency to make significant inroads to mitigate mission impact as a result of lunar dust contamination
- An array of materials solutions will be required to address the breadth of the need for lunar dust adhesion mitigation
- Evaluation of candidate surfaces is complex and will not be able to completely represent the lunar surface unless it is conducted on the lunar surface



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- **NASA Marshall Space Flight Center**
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