Passive Lunar Dust Mitigation Materials Research

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Gateway Dust Mitigation Working Group
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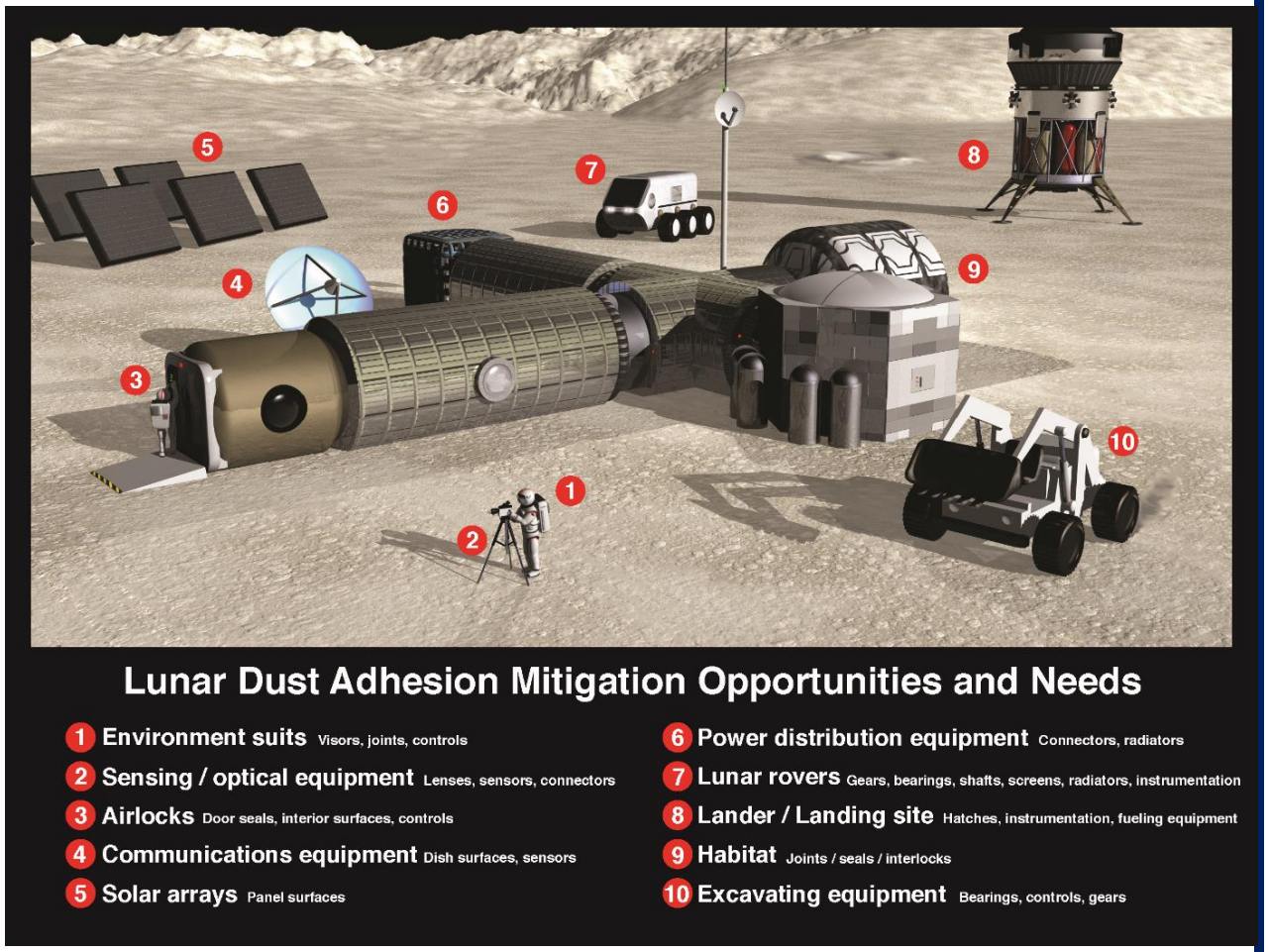
Outline

- Lunar Occupancy Dust Surface Separation Technology (LO-DuSST) Overview
- Materials Research and Characterization at NASA Langley Research Center (LaRC)
  - Surface Engineered Materials
  - Lunar Dust Simulant Adhesion Testing
  - Lunar Dust Simulant Wear Characterization
- Extreme Environment: Low Earth Orbit (LEO) and Lunar Experiments

Lunar Occupancy Dust-Surface Separation Technologies (LO-DuSST) Overview

- Technology Product Capability
  - Technologies for coupled passive and active methods for reducing lunar dust adherence to solar panel arrays, confined systems, drive shafts, and In-Situ Resource Utilization (ISRU) equipment
- Technical Capabilities
  - Reduction in particle retention
  - Retention of power generation in solar arrays
  - Protection of equipment near landing sites
  - Reduce long term wear on surfaces
  - Robust coatings to reduce energy requirements for active dust mitigation technologies
  - Enabling mobile dust removal from various equipment
- Exploration & Science Applicability
  - Applicable to equipment surfaces
    - Solar arrays, power systems, radiators
    - Axels, bearings, drive shafts, rover wheels, rover arms
    - Space suit visors and fabric
    - ISRU: drills, buckets, etc.
  - Potential environments
    - Lunar surface, Lunar Gateway, Mars, Earth



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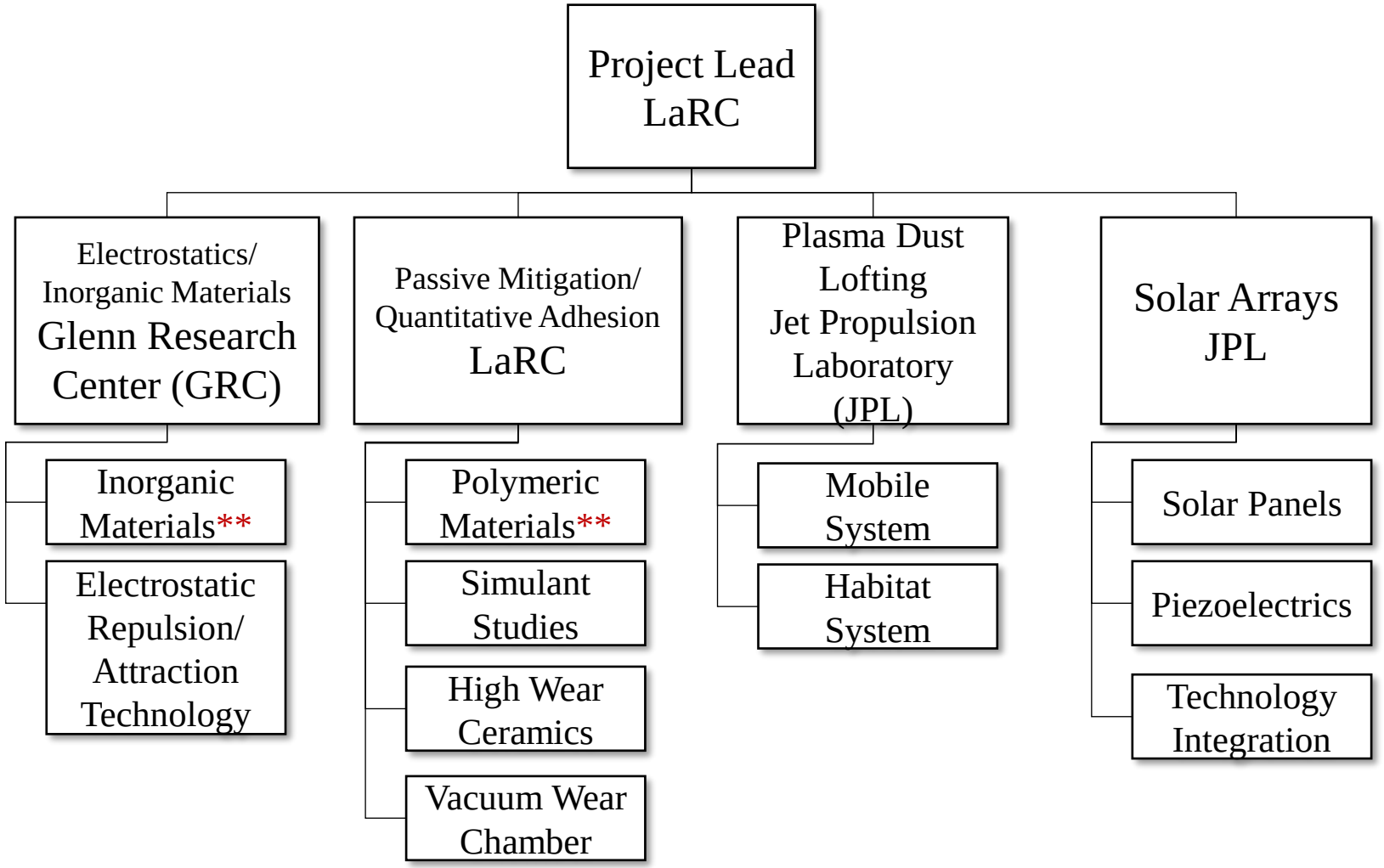
LO-DuSST Team and Focal Areas*



*This project was cancelled in May, 2022.

**These aspects are already being addressed by the Patch Plate Project

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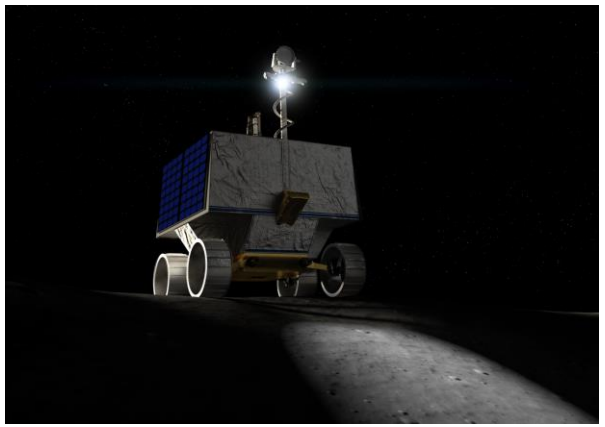
LO-DuSST Team and Focal Areas

- Project Manager: Erica Montbach
- PI: Christopher Wohl, LaRC
  - LaRC
    - Polymeric Materials- Keith Gordon
    - Scaled Topography- Keith Gordon
    - Characterization and Adhesion Testing- Lopamudra Das
    - Wear Resilient Materials- Valerie Wiesner, Lopamudra Das, Glen King, Jonathan Hernandez
  - GRC
    - Electrostatic Repulsion Attraction- Sharon Miller and Bruce Banks (ret.)
    - Scheduling- Adam Marr
  - JPL
    - Dust Lofting- Inseob Hahn and Ulf Israelsson (ret.)
    - Solar Array- Joel Schwarts, Robert Kowalczyk

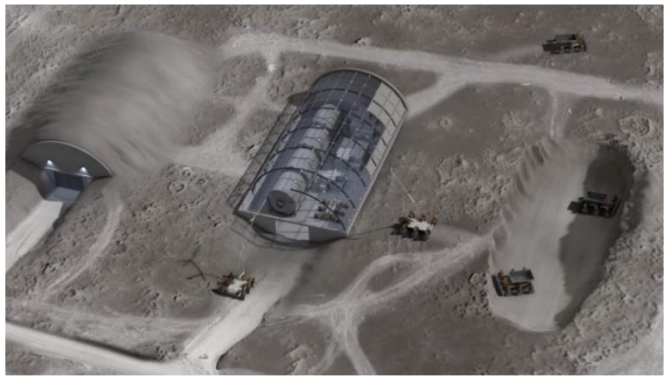
Connectivity to Other Space Technology Mission Directorate (STMD) Activities/Proposals

VIPER*-like Vehicles



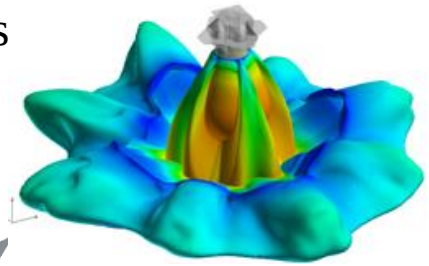
**VIPER: Volatiles Investigating Polar Exploration Rover*

Safe Haven Inflatable Structures



Patch Plate Materials Assessment

Plume-Surface Interactions



LO-DuSST

Lunar Surface Manipulation Systems

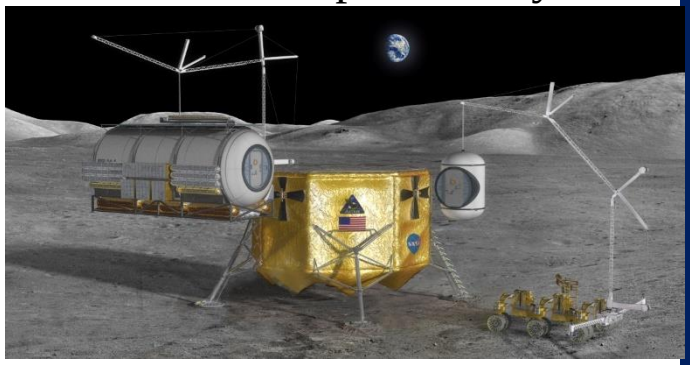


Image credit: Peter Liever/NASA MSFC/2019

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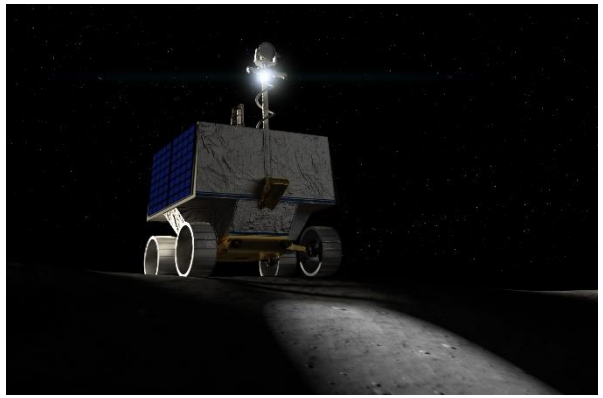
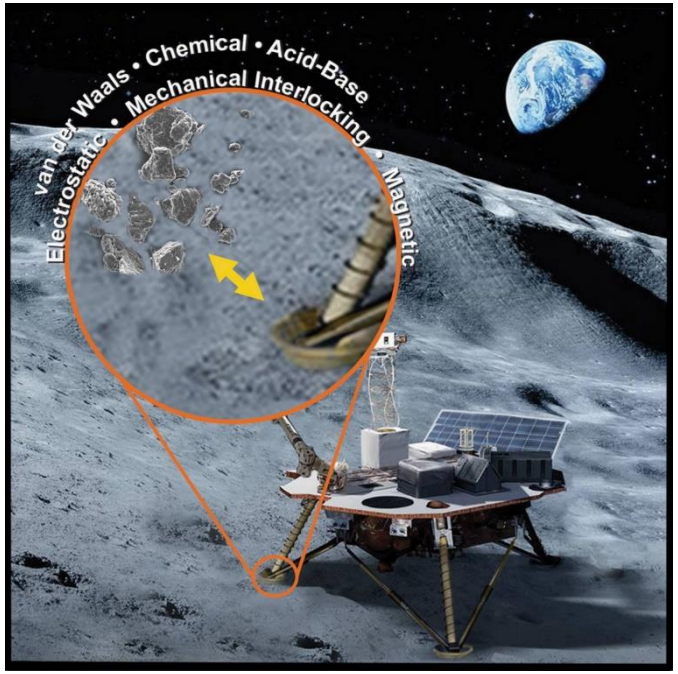
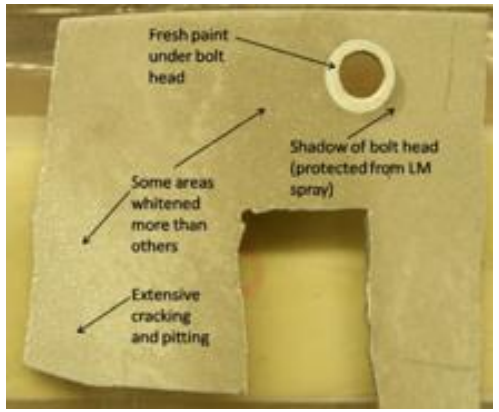
Adhesion Mitigation Materials

Dust Mitigation-
Must Remove





Dust Management-
Must Tolerate



Engaging aspects of lunar dust from mitigation to management

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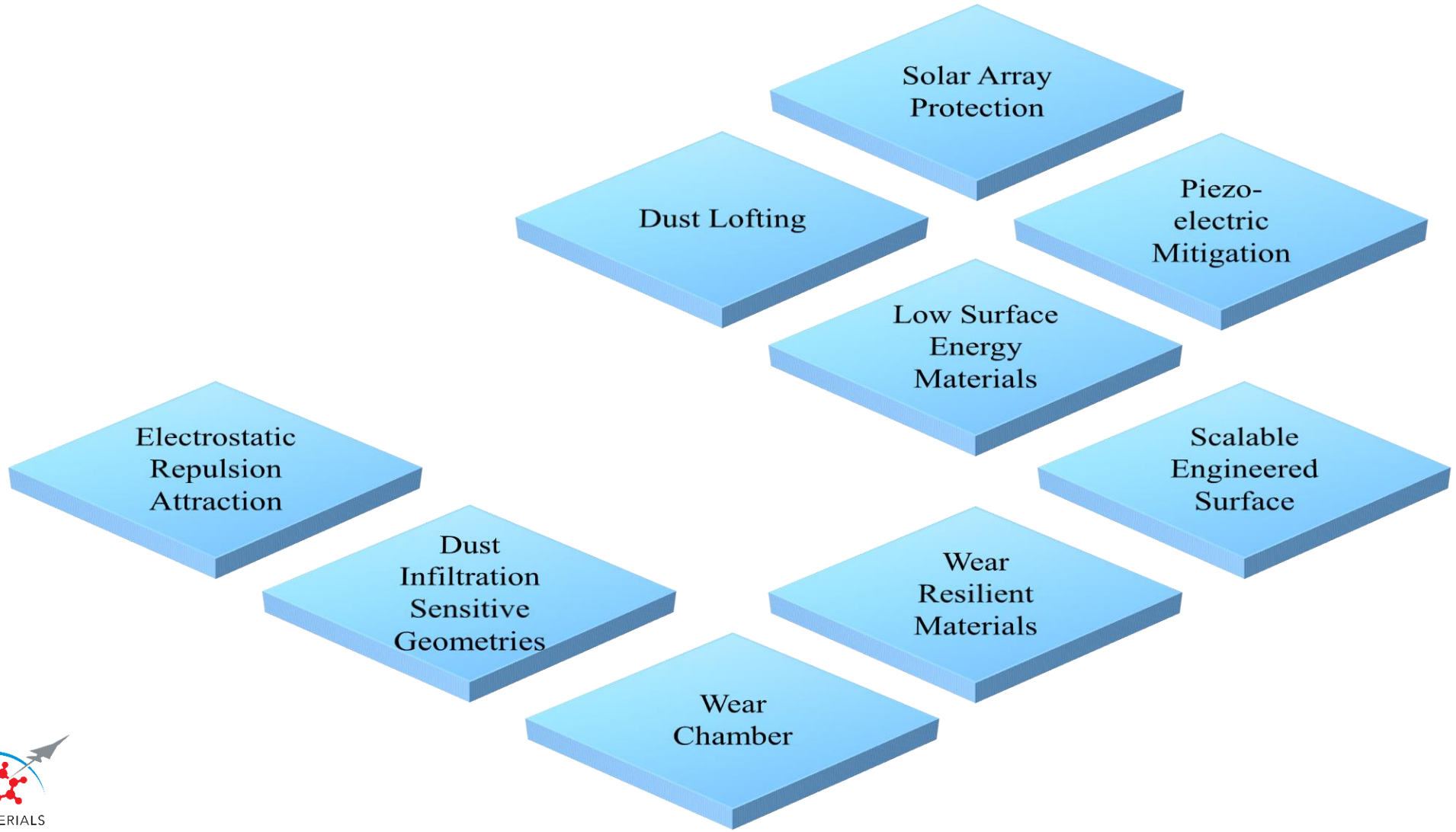
LO-DuSST Technology Goals

LO-DuSST Technology Goals	
Overarching Goal	Develop and demonstrate coupled active-passive lunar dust mitigation technologies that are currently at technology readiness level (TRL) 2-3 to TRL 5. Those technologies are:
Sub-Goal #1	Piezoelectric agitation technology for solar array dust mitigation. Solar Arrays (SA)
Sub-Goal #2	Electrostatic repulsion/attraction technology for dust exclusion in sensitive locations, i.e., bearings, shafts, thermal protection systems, etc. Electrostatic repulsion/attraction (ERA)
Sub-Goal #3	Plasma and electron beam dust lofting technology for mobile dust removal from exposed lunar infrastructure material surfaces and components. Dust Lofting (DL)
Sub-Goal #4	Ceramic coatings for abatement of wear on lunar components, such as lunar lander legs, caused by plume-surface interactions. Coatings (C)

LO-DuSST Connectivity



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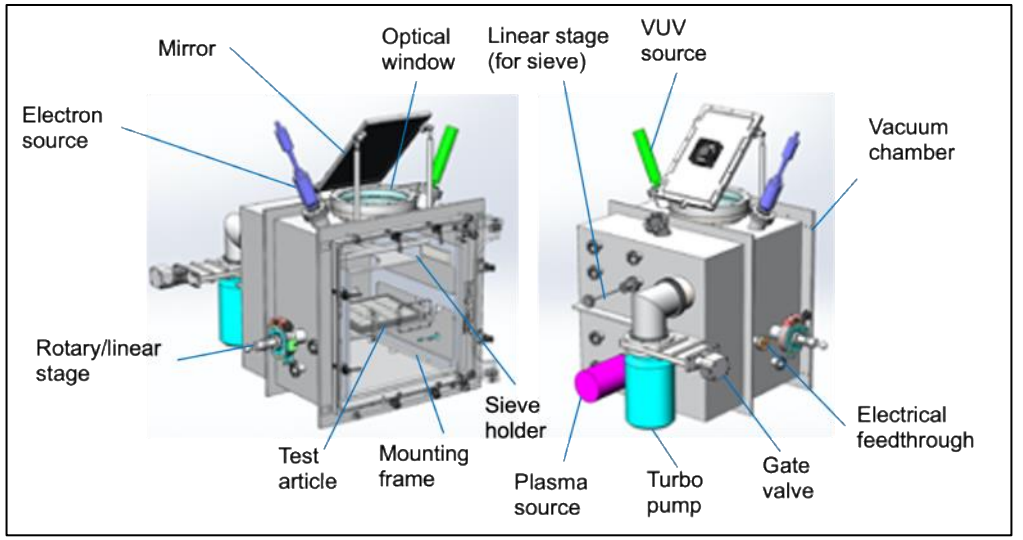
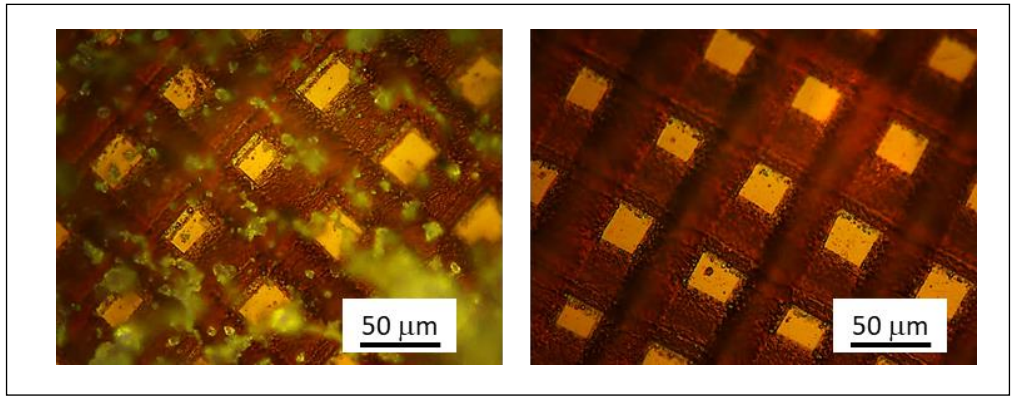
LO-DuSST Project Summary

- Key accomplishments
  - Passive Materials Technologies
    - Milestone K2 completed: Dust Deposition Chamber to enable reproducible contamination of surfaces for adhesion characterization
    - Developed and implemented dust adhesion test and semi-automated image analysis software
    - Prepared materials for inclusion on the Alpha Space Regolith Adherence Characterization (RAC) payload
  - Solar Array
    - Completed design and procurement of solar array vacuum chamber
    - Finalized cart design, selected controllers for heaters to bake out simulant, and designed frame to hold test article
    - Released request for proposals (RFP)s for solar array test coupons, solar cells and solar cell laydown
    - Generated systems requirements document for dust mitigation equipment on the lunar surface regarding protection of solar arrays
    - Generated test plan for dust mitigation experiments



Solar array test chamber



Laser patterned Kapton HN before (left) and after (right) simulant adhesion testing

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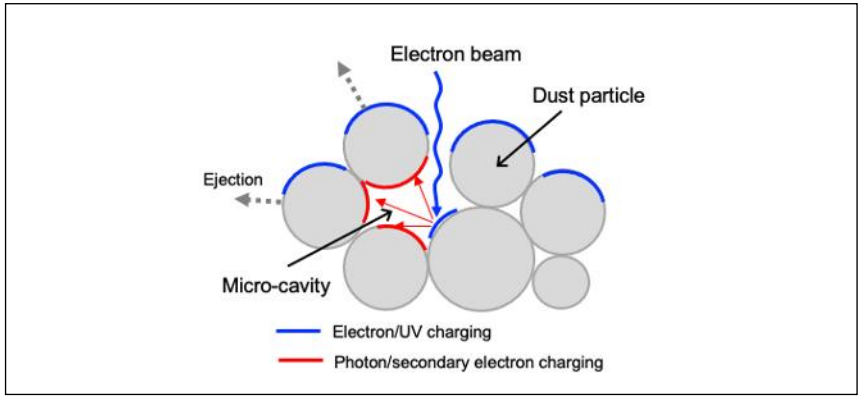
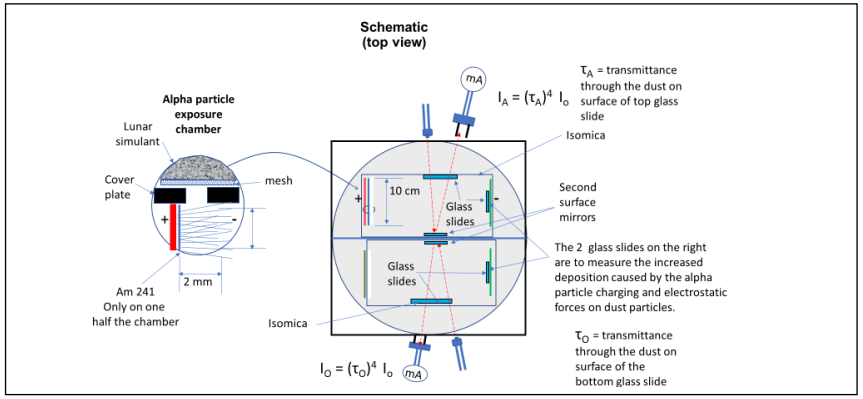
LO-DuSST Project Summary

- Key accomplishments
  - Dust Lofting
    - Completed Electron Beam Dust Lofting Proof of Concept (TRL 3)
    - Released Science Definition Team (SDT) report titled “Payload Recommendations for a Multi-User Facility to Investigate Dust-Plasma Interactions and Dust Remediation Technologies on the Moon”
    - Completed testing of electron beam dust lofting efficiency from prototype solar panel coupon
    - Installed electron beam source and sample rotation stage fixture in the JPL test chamber
  - Electrostatic Repulsion/Attraction
    - Milestone K1 completed: Design for demonstration of electrostatic repulsion/attraction unit
    - Safety permit request and hazard analysis for the use of a Polonium (Po-210) source were submitted to the area safety committee chair for review
  - Wear Resilient Materials
    - Completed test planning for candidate wear resilient commercial off-the-shelf (COTS) materials and design of sample configuration for coupon generation
    - Generated initial design of pin-joint associated with Lightweight Surface Manipulation System (LSMS, POC: Tom Jones, LaRC) to evaluate wear in vacuum environment
    - Identified facility for conducting in-house wear evaluation, SLIDE: Surveying Lunar dust Influence on Device Efficacy



Mechanistic understanding of dust lofting



Design of electrostatic repulsion attraction (ERA) demonstration unit

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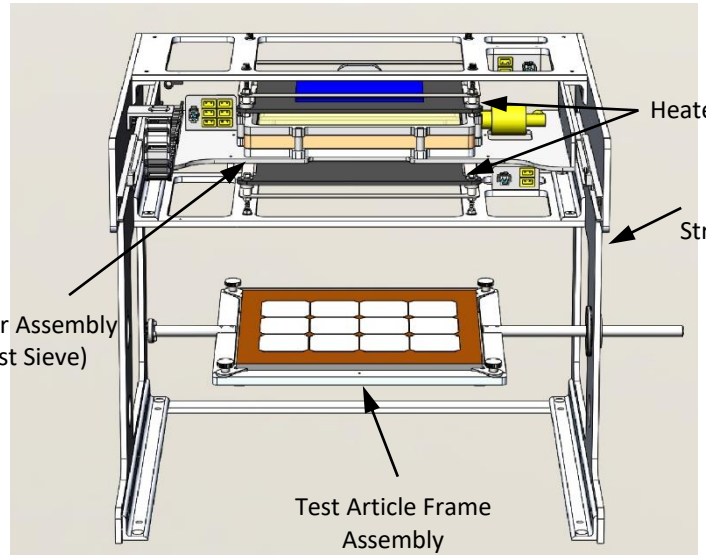
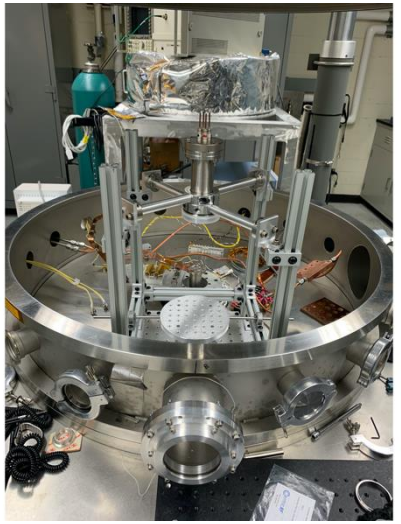
LO-DuSST Next Steps

- Next steps for FY22
  - Obtain quotes for vacuum chamber and solar array test articles (completed)
  - Design interior fixtures for solar array test chamber
  - Model the ionization of lunar dust particles and estimate the expected charge vs dust particle size (completed)
  - Bring vacuum wear chamber at (LaRC) online
  - Down-select wear resilient materials for lander leg demonstration experiment
  - Evaluate solar array and dust lofting topcoat materials at LaRC
  - Bring dust lofting vacuum test chamber at JPL online (completed)
  - Design, fabricate, and demonstrate scalable engineered surface element



Internal frame design for solar array test chamber



JPL dust lofting cryogenic vacuum test chamber with e-beam source and sample rotation stage installed

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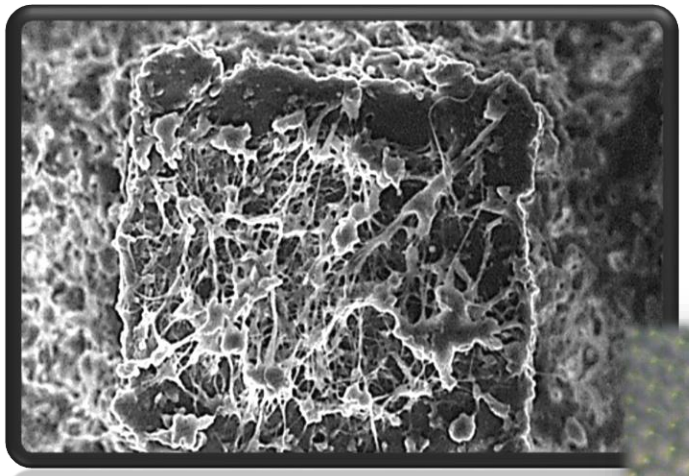
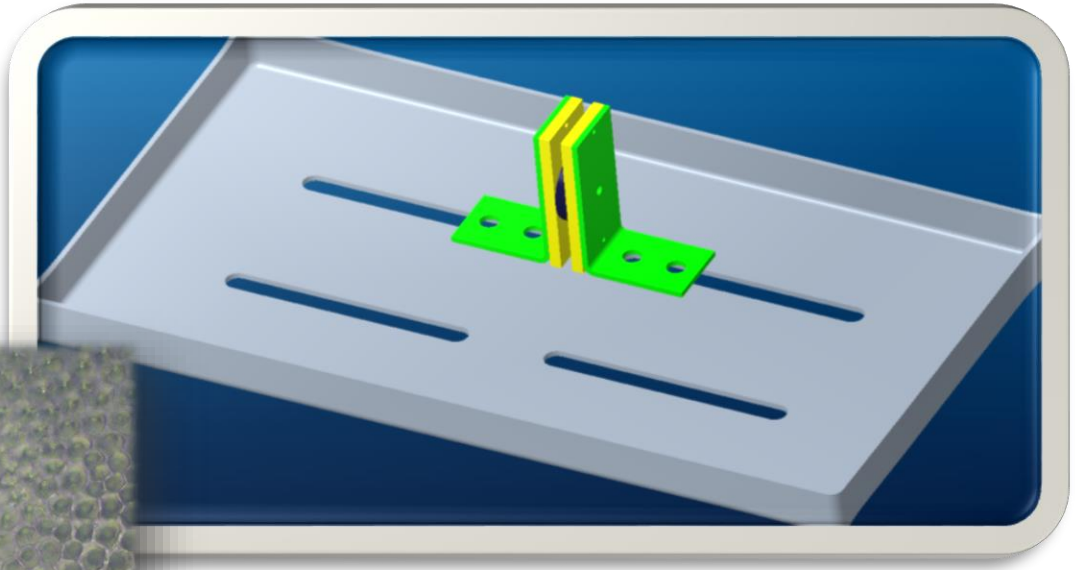
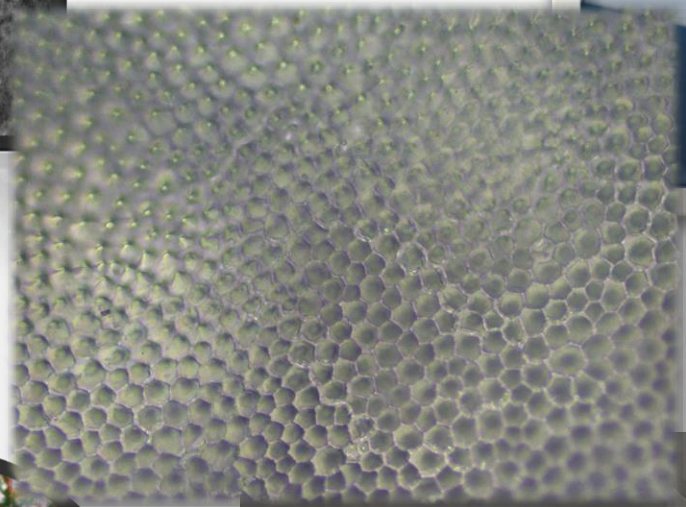
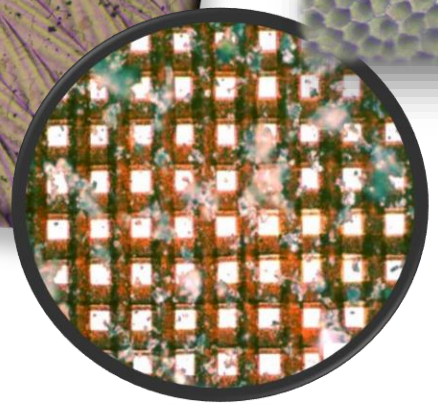
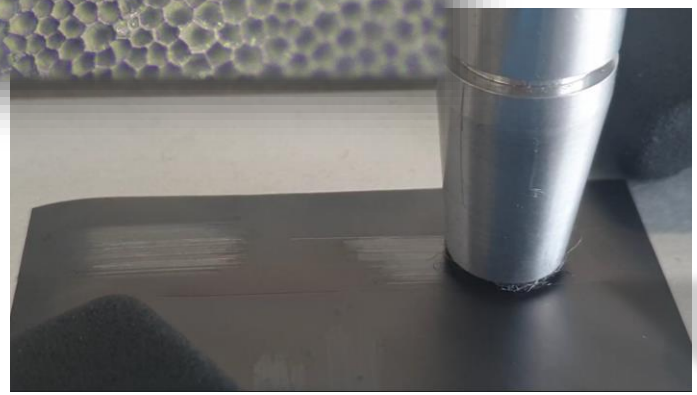
Materials Research and Characterization at LaRC

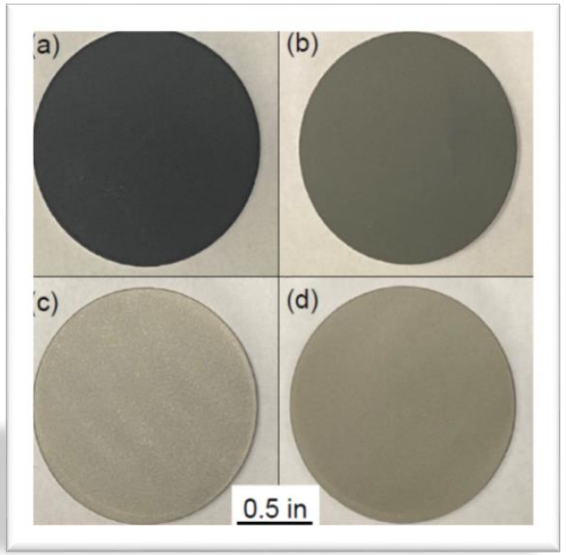












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Charge Dissipative Surfaces

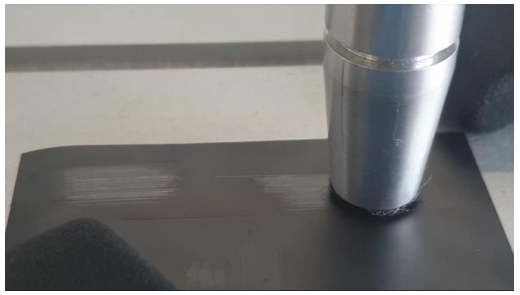
Graphene Ink/Polymer Coated Polyimides

(a).

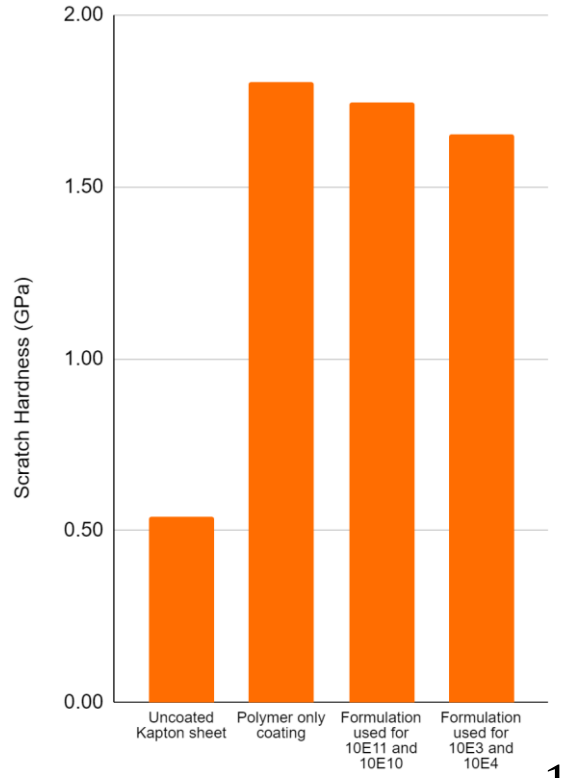
Graphene ink coated Kapton sheets	Surface Resistivity (Ohms/sq)
V1	0
V2	10^3
V3	10^4
V4	10^6
V5	10^8
V6	10^{10}
V7	10^{11}

(b).

Decreasing sheet resistance



Abrasion testing with steel wire mesh



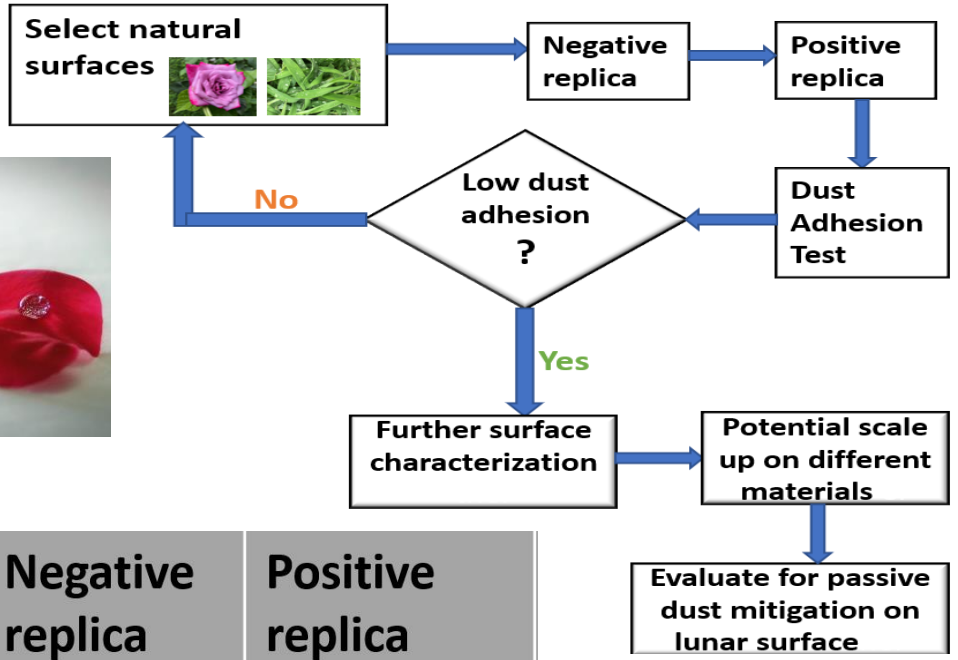
Scratch hardness results

Surface Engineered Polymeric Materials

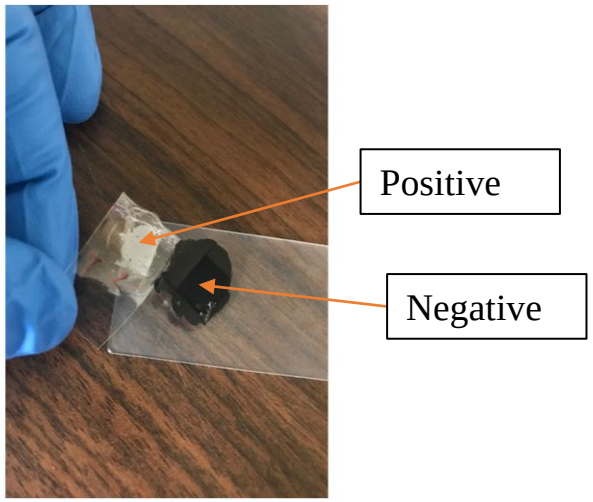
Biomimetic Surface

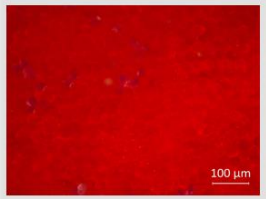
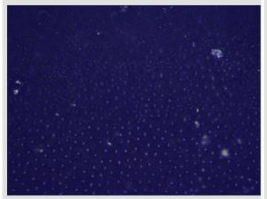
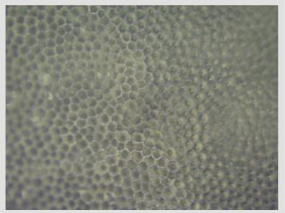
Natural adhesion mitigating surfaces



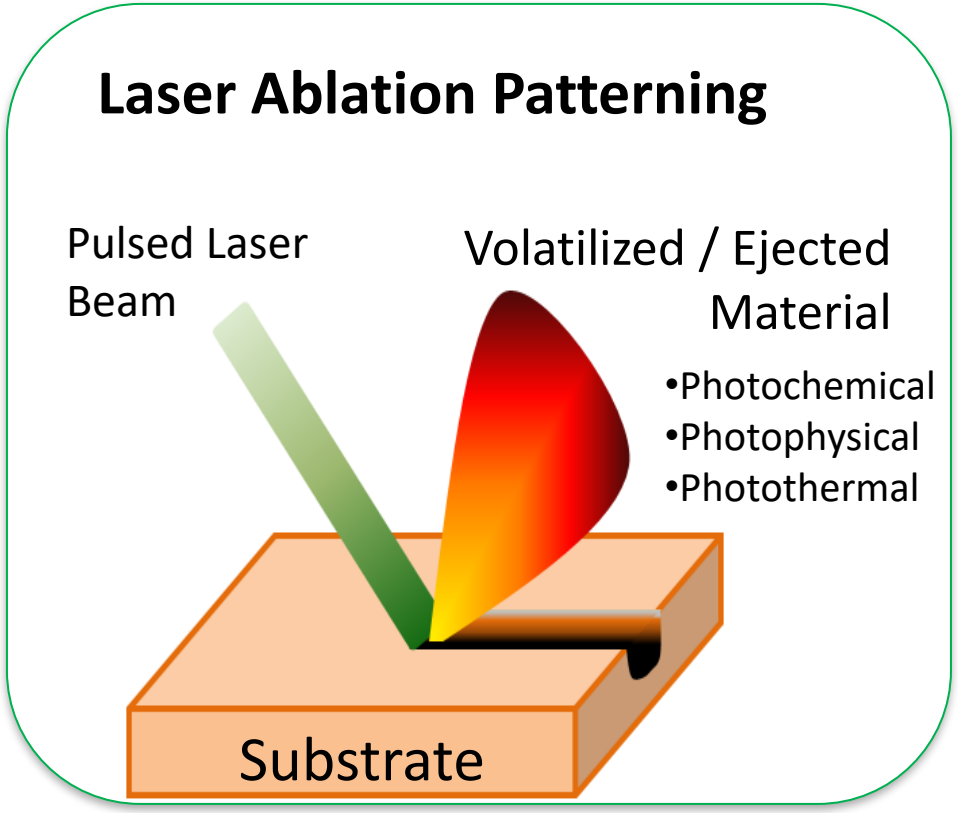
Replication example: rose petal



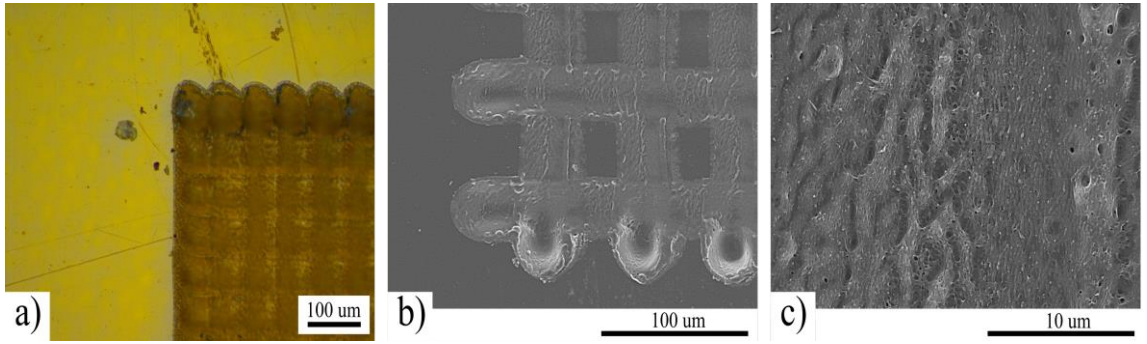
Sample name	Original surface	Negative replica	Positive replica (ctrl)
Rose petal			

Surface Engineered Polymeric Materials

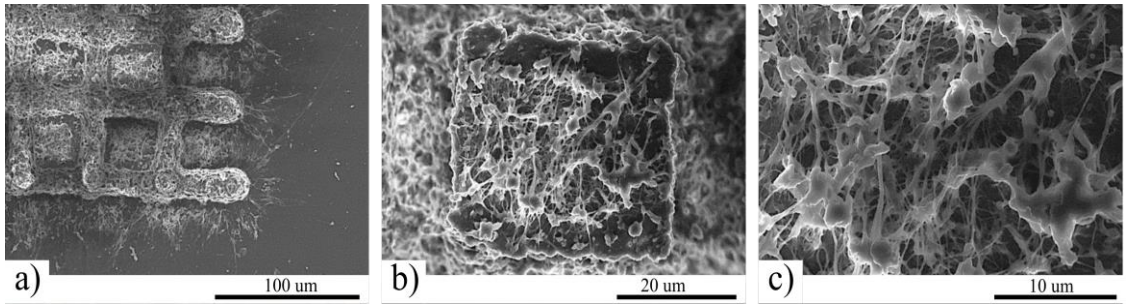
Laser Ablation



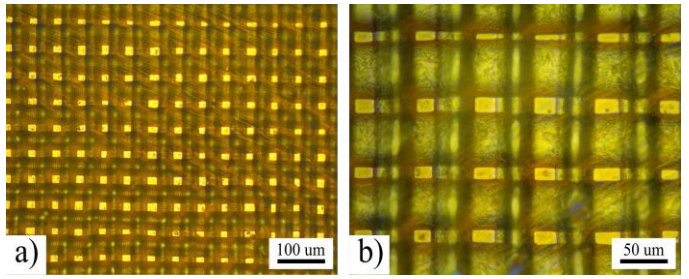
Polyimide



Fluorinated Ethylene Propylene



Composite



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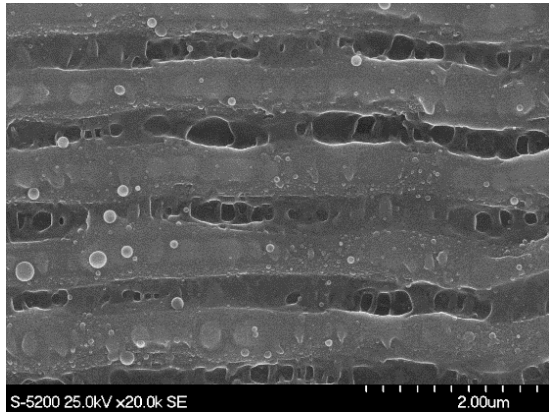
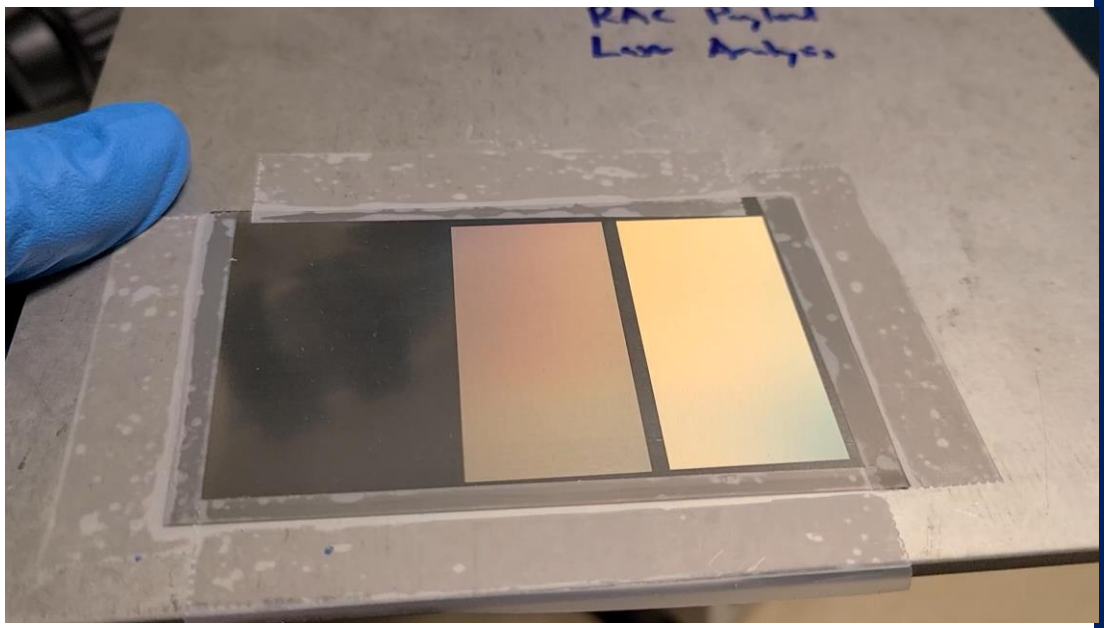
Hierarchical Topography in Metallic Substrates

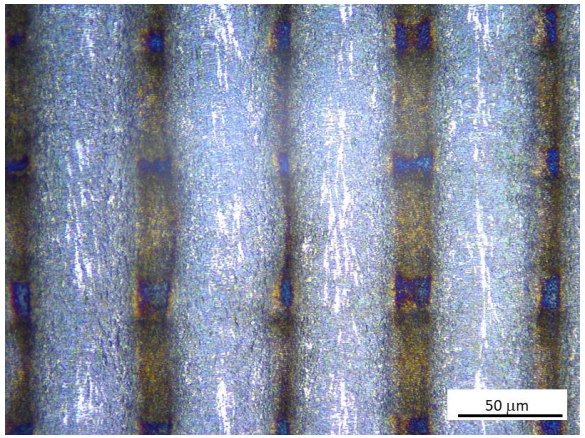
Laser Ablation



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



Micrometer-scaled Direct-write Laser Patterning



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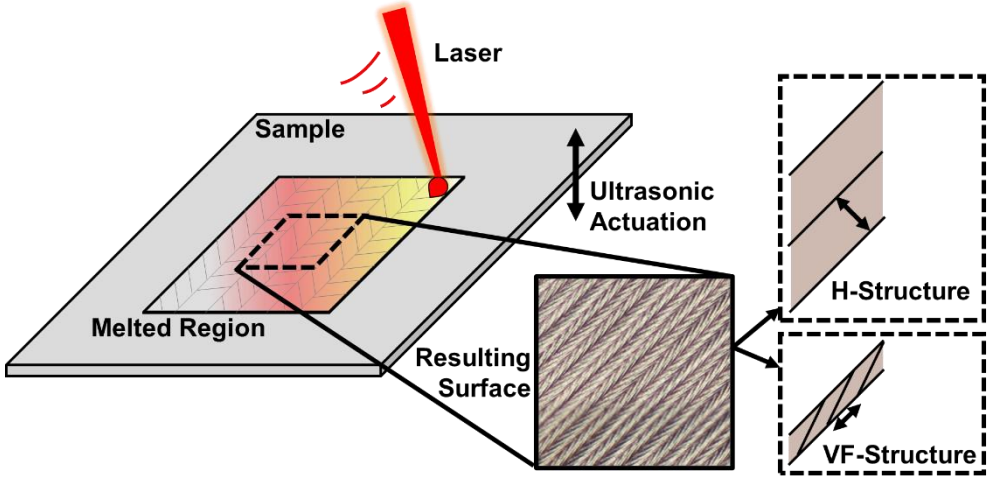
Hierarchical Topography in Metallic Substrates

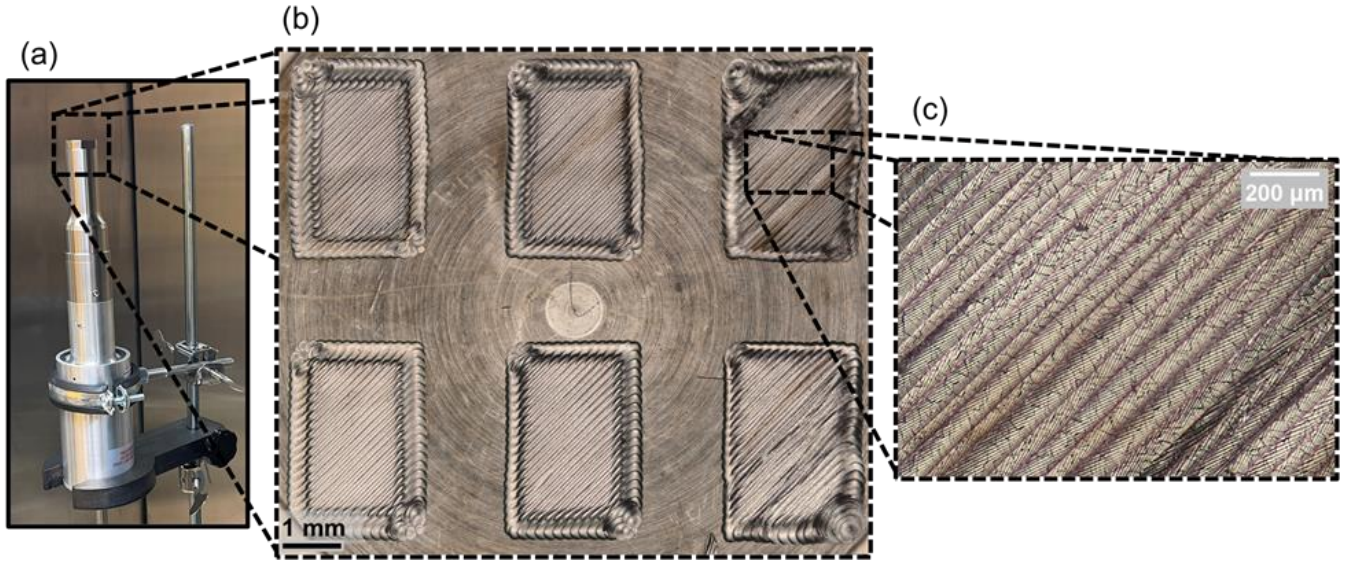
Laser Irradiation with Sonication - CAMMU

CAMMU Sample Preparation Schematic



Interaction between the ultrasonic actuation and laser remelting lead to the micro-hierarchical surface structures

Photo of CAMMU Sample Prep



CAMMU: Controlling Additive Manufacturing using Ultrasonics

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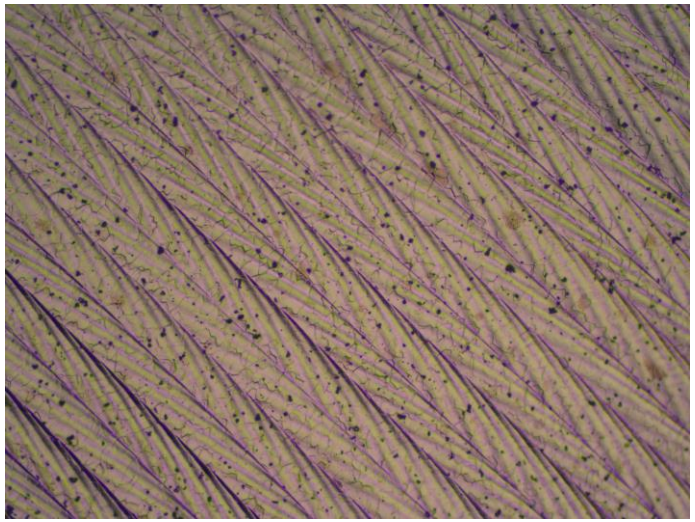
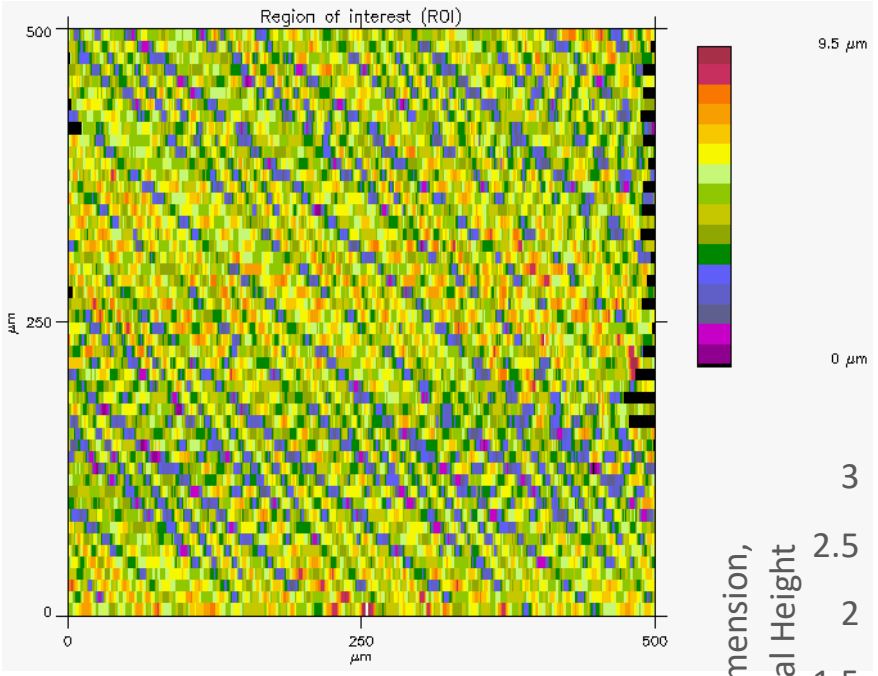
Hierarchical Topography in Metallic Substrates

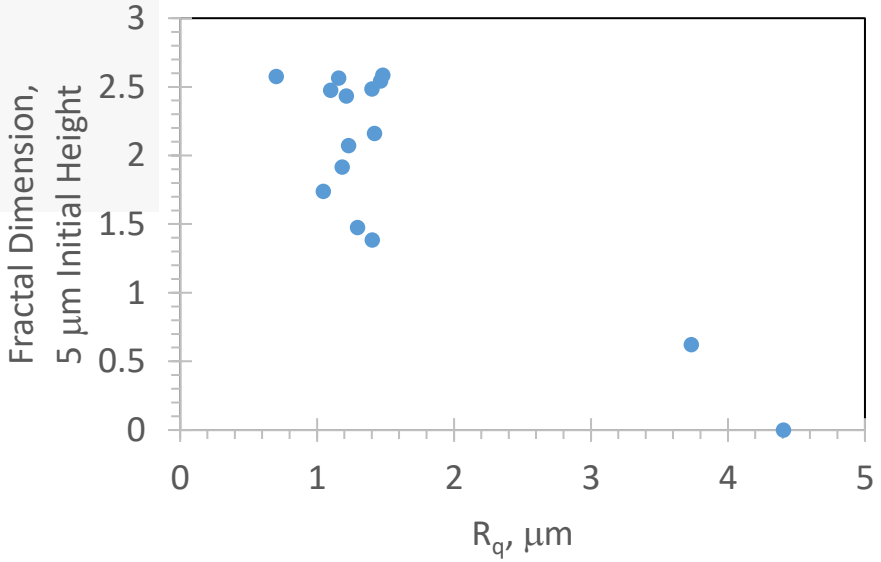
Laser Irradiation with Sonication - CAMMU



Sample preparation parameters:
100% Sonication
Laser speed: 1200 mm/s



Surface topography image collected using optical profilometry



Fractal analysis results:
Indicative of the presence of hierarchical topographies

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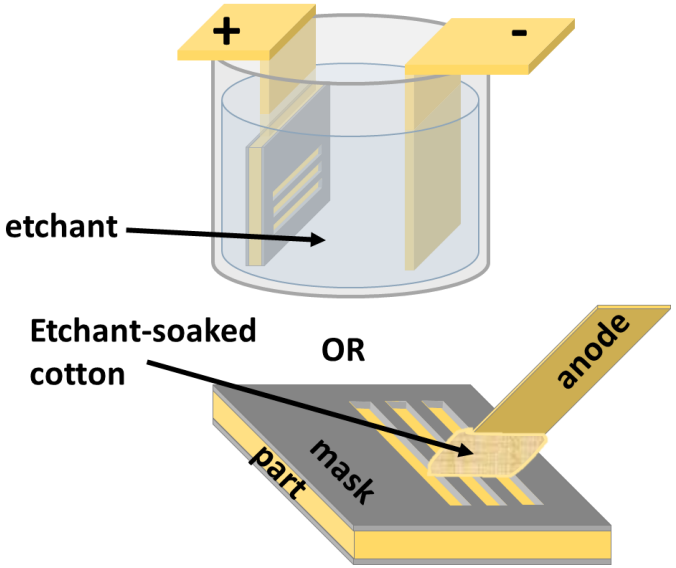
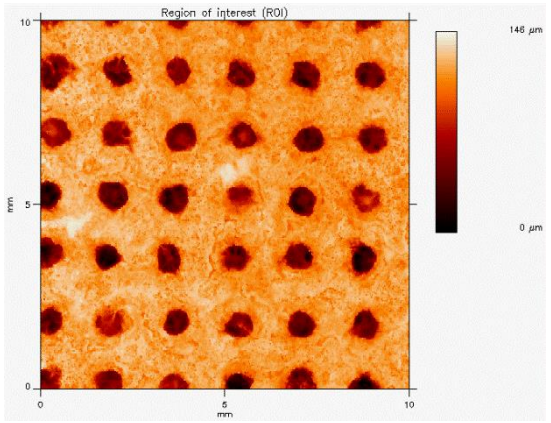
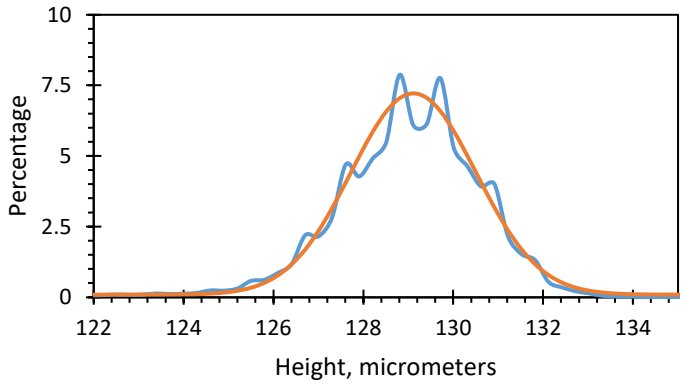
Scalable Engineered Surface Technology Development

Generation of Topography Transfer Die

Electroetching







Roll-to-Roll Imprint Lithography

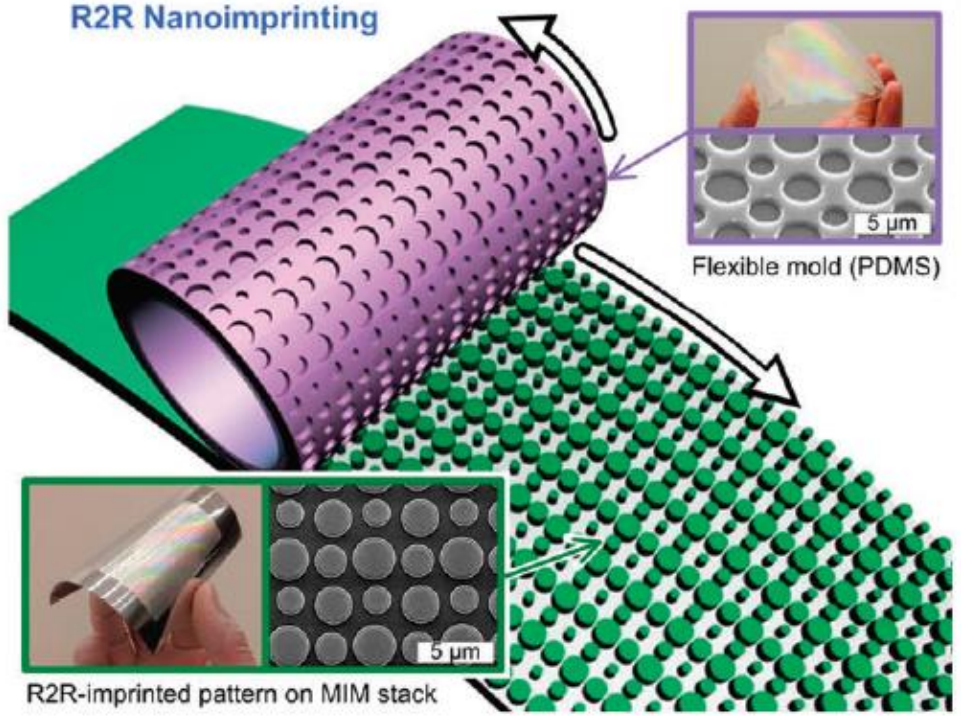


Image credit: J. Mater. Chem. C, 2016, 4, 5133.

Scalable topographical modification is critical to realize future mission applications

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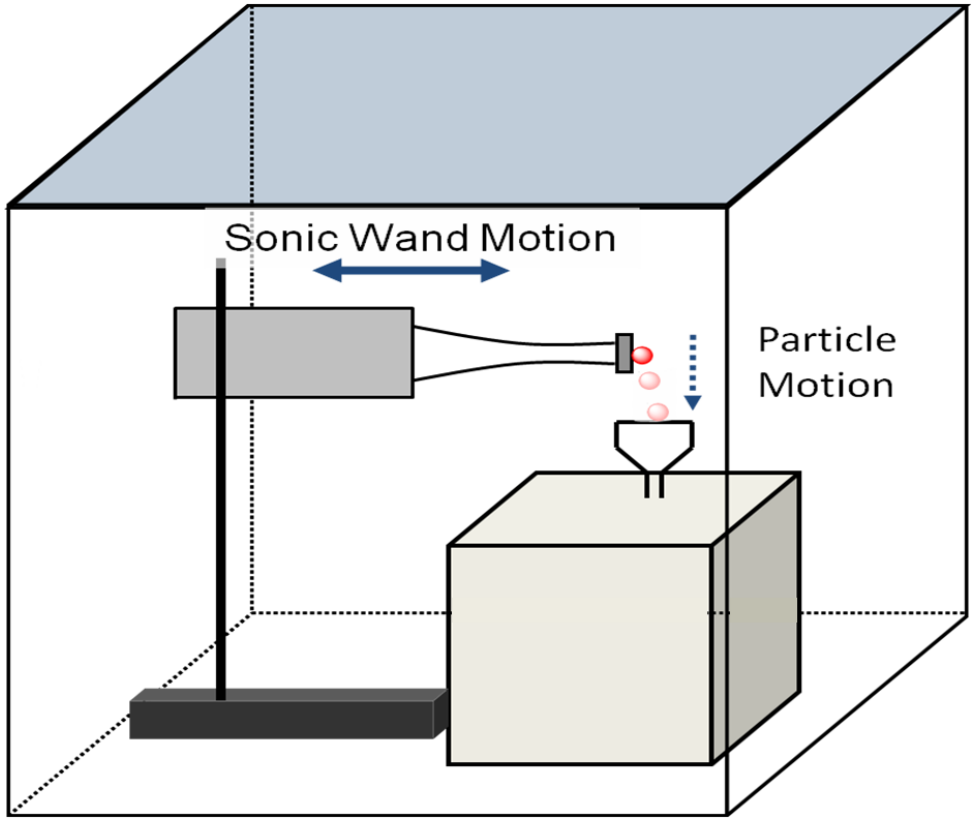
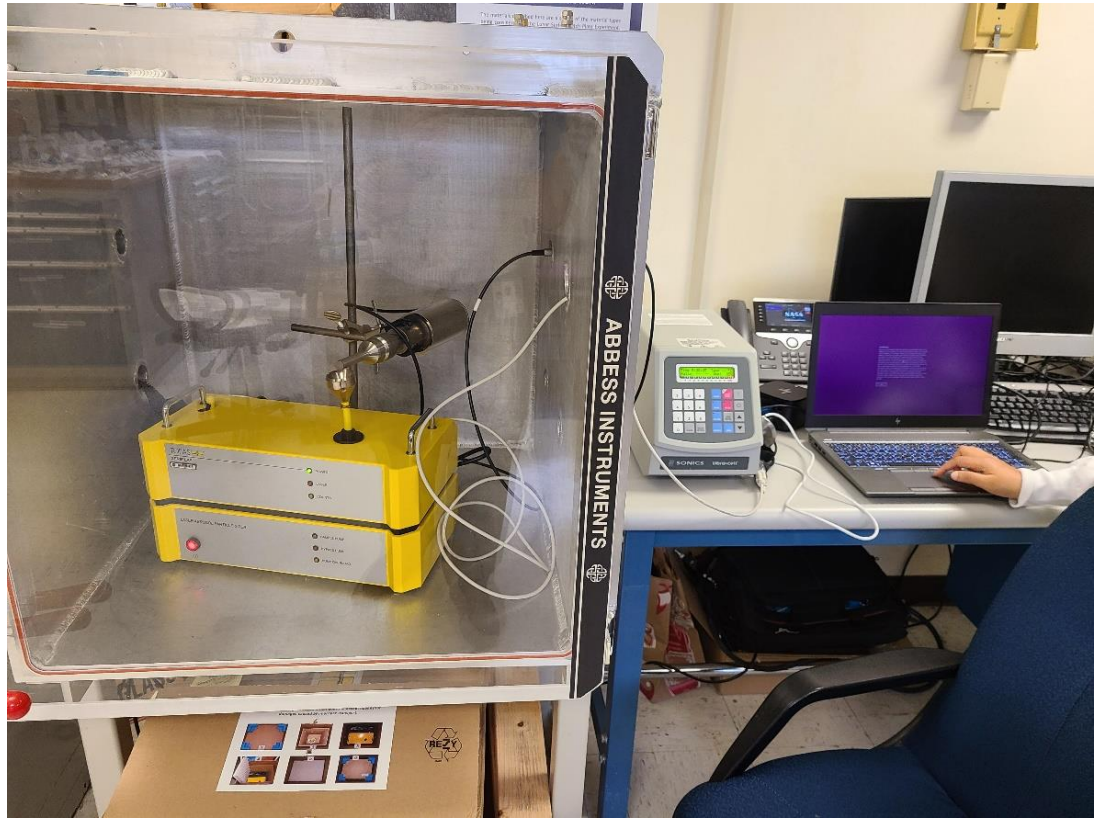
Ultrasonic Dust Adhesion Instrument

- **Schematic**



- **Actual Instrument**



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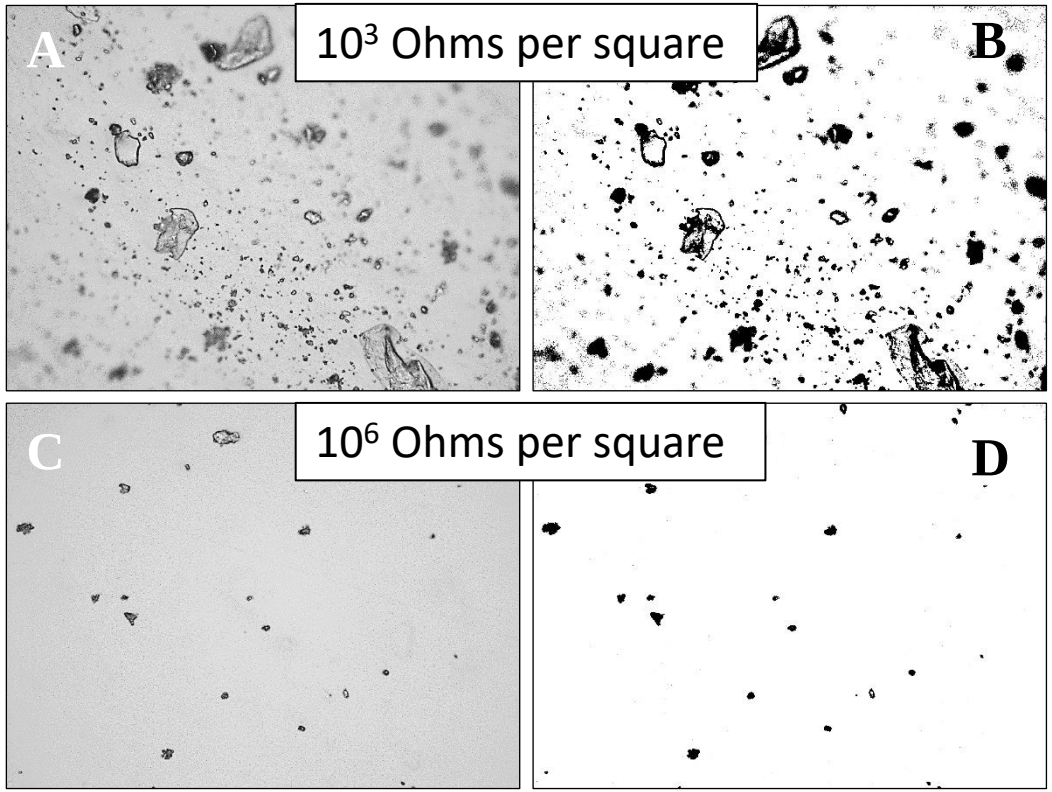
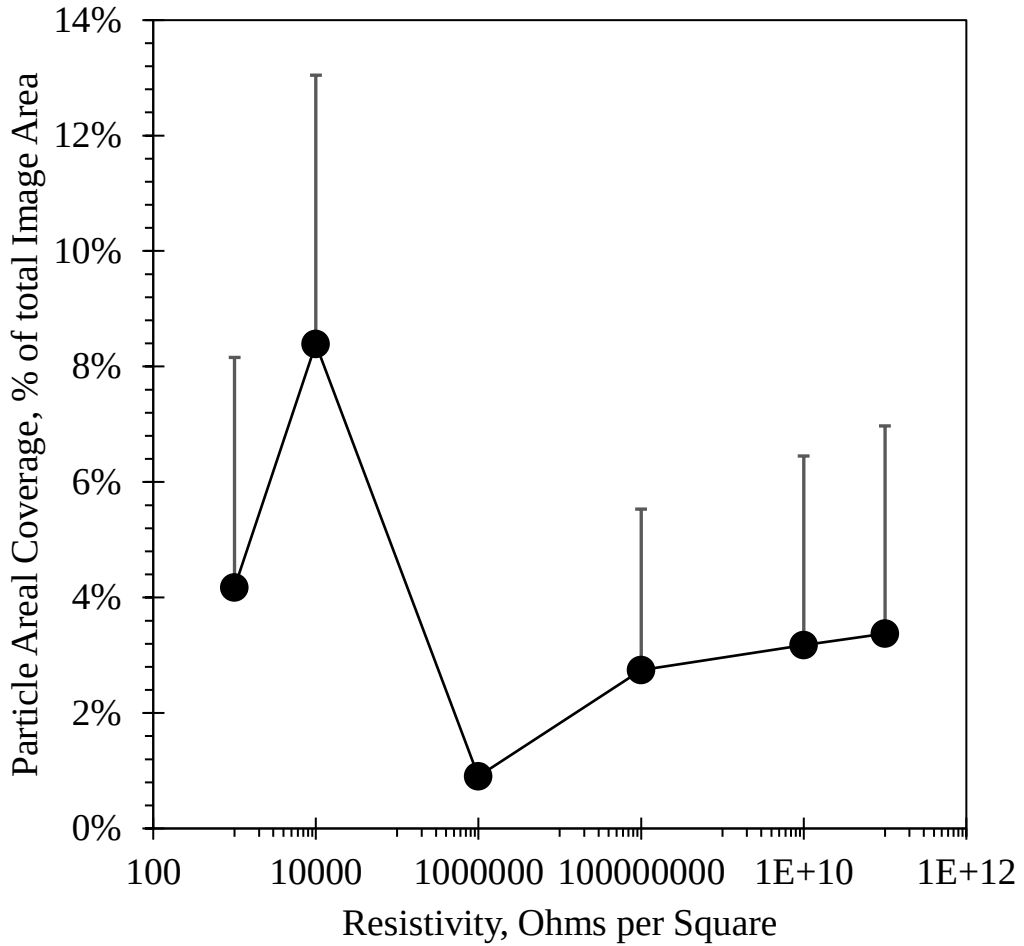
Ultrasonic Dust Adhesion Instrument

Charge Dissipative Surfaces



(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



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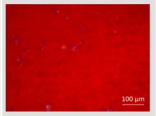
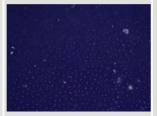
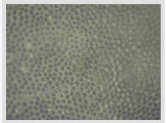
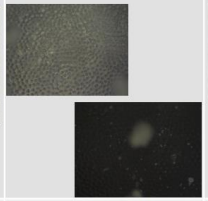
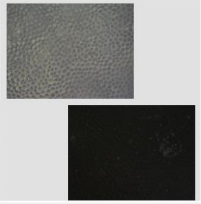
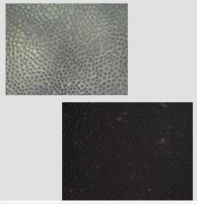
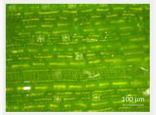
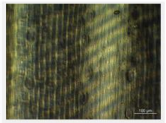
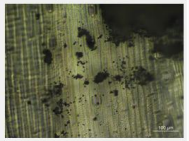
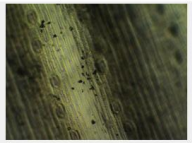
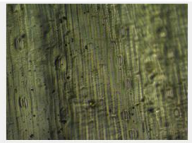
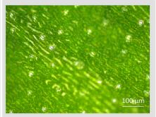
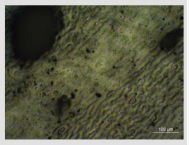
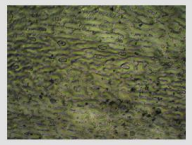
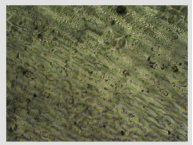
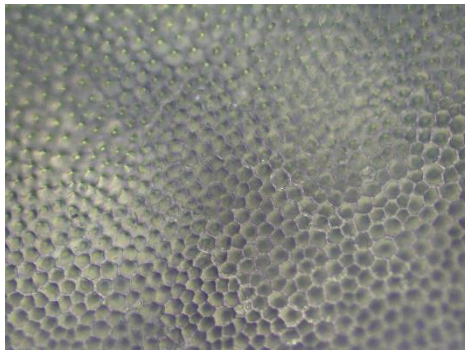
Ultrasonic Dust Adhesion Instrument

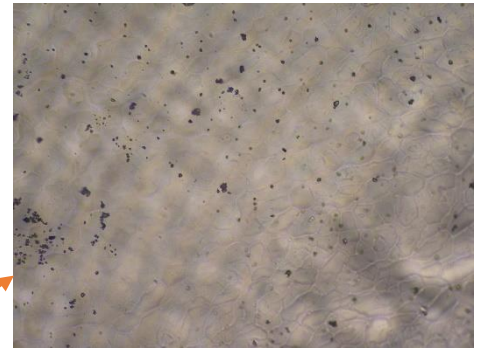
Biomimetic Samples

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						

Replica surfaces after lunar simulant adhesion testing

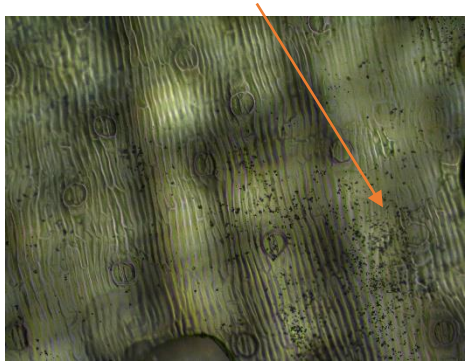


Rose Petal



Cabbage

Clusters of dust particles remain adhered



Banana Leaf

Certain surface topographies exhibited better lunar simulant adhesion mitigation

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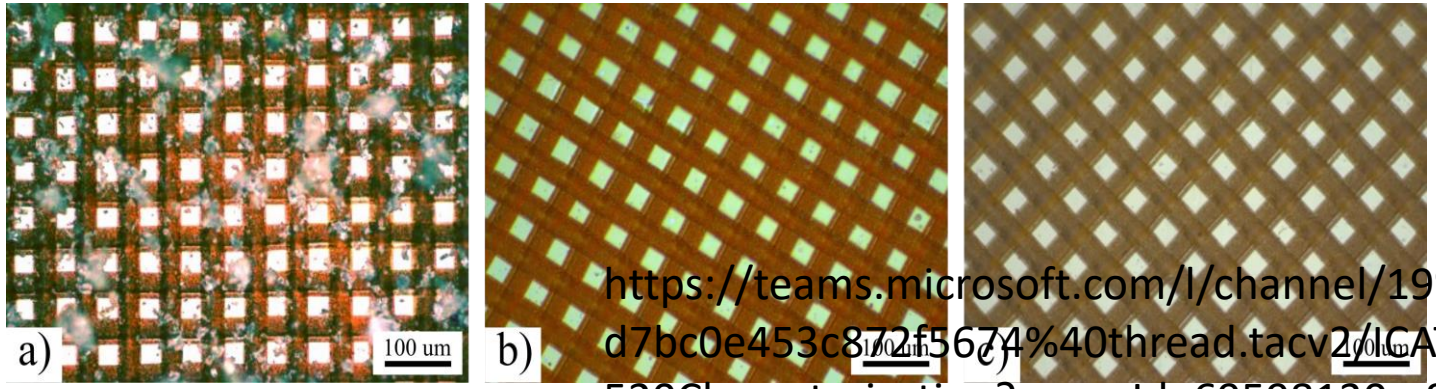
Ultrasonic Dust Adhesion Instrument

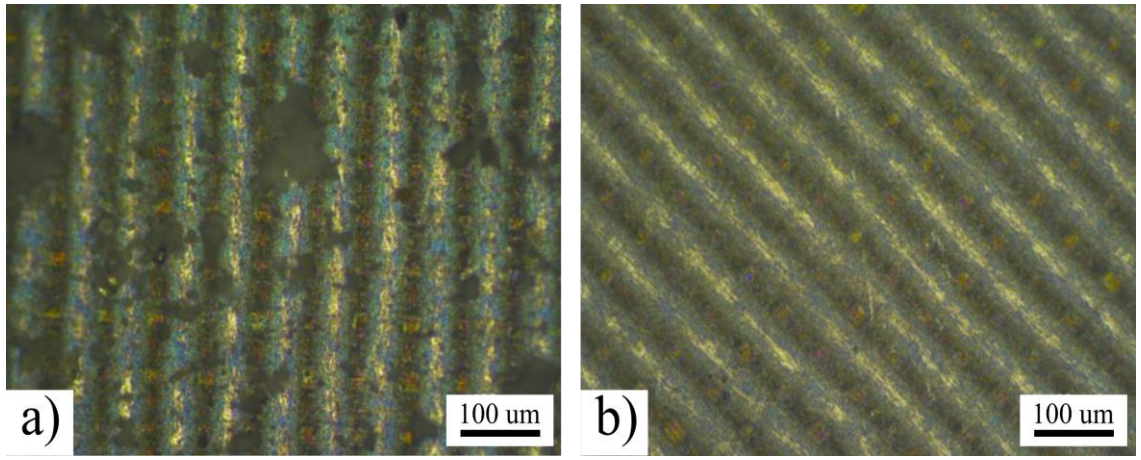
Laser Patterned Surfaces



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

https://teams.microsoft.com/l/channel/19%3aafb9c06cb1c949d7bc0e453c872f5674%40thread.tacv2/ICAT%2520Materials%2520Characterization?groupId=69598130-a840-473e-beb7-969267e90693&tenantId=7005d458-45be-48ae-8140-d43da96dd17b

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



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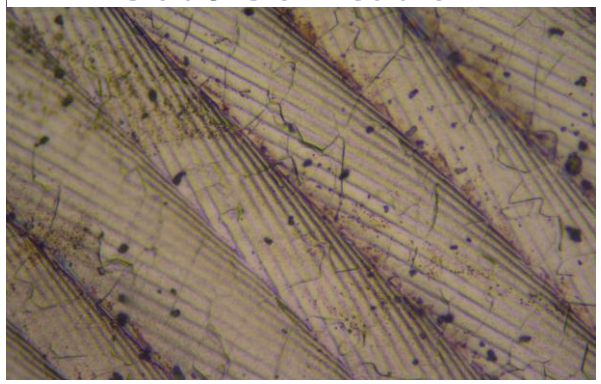
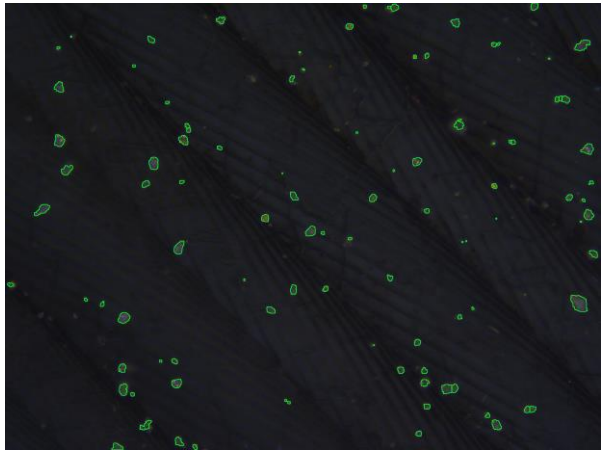
Ultrasonic Dust Adhesion Instrument

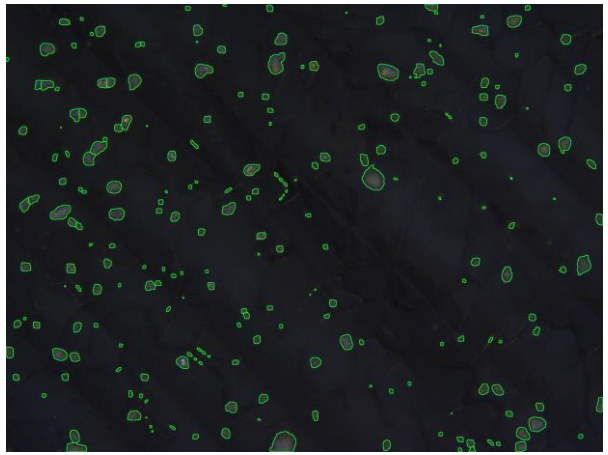
CAMMU Samples

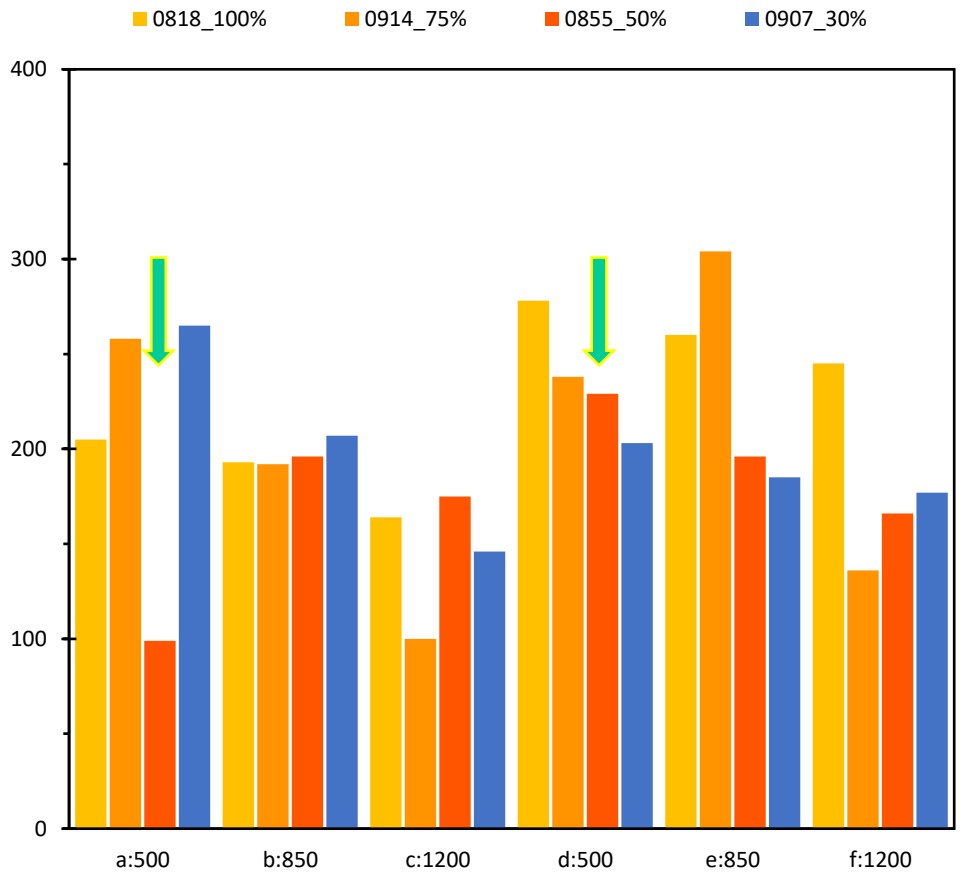
50% Sonication





No Sonication





Sample preparation parameters:
Laser speed: 500 mm/s

Particle count summary

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Centrifuge Dust Adhesion Instrument

- **Force Diagram and Sample Configuration**

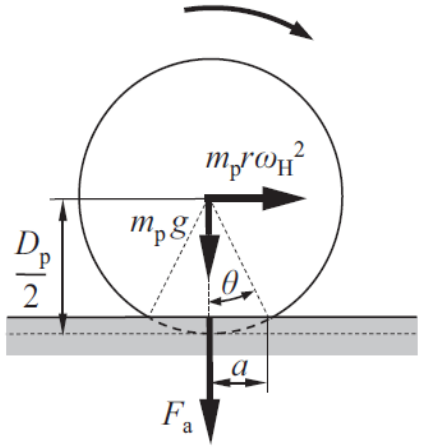
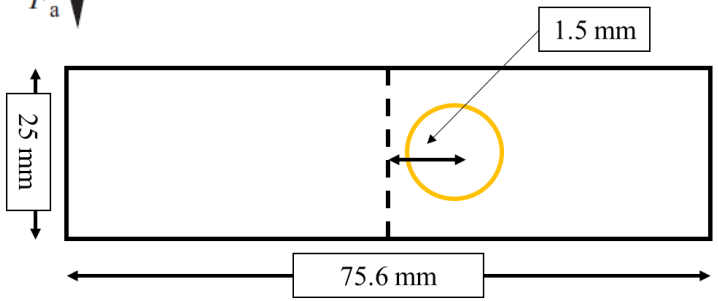
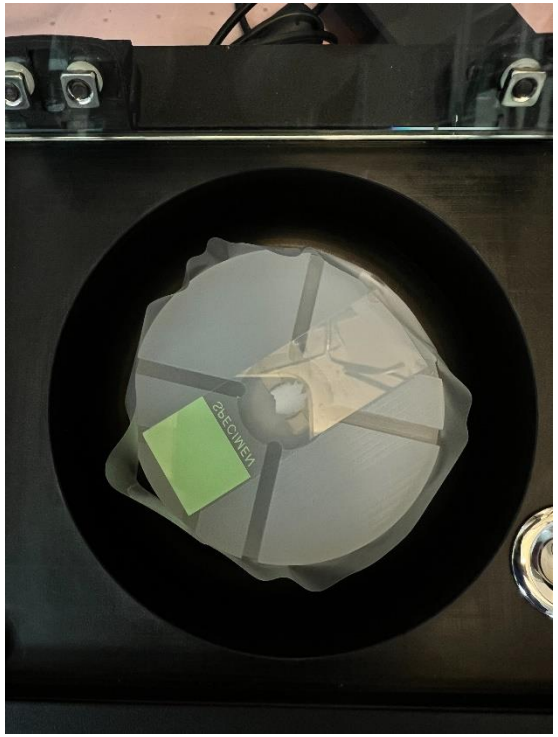


Image credit: Powder Technol., 2022, 397, 117103.



Glass slide with particle deposit location referenced to center of rotation indicated.

- **Instrument Images**



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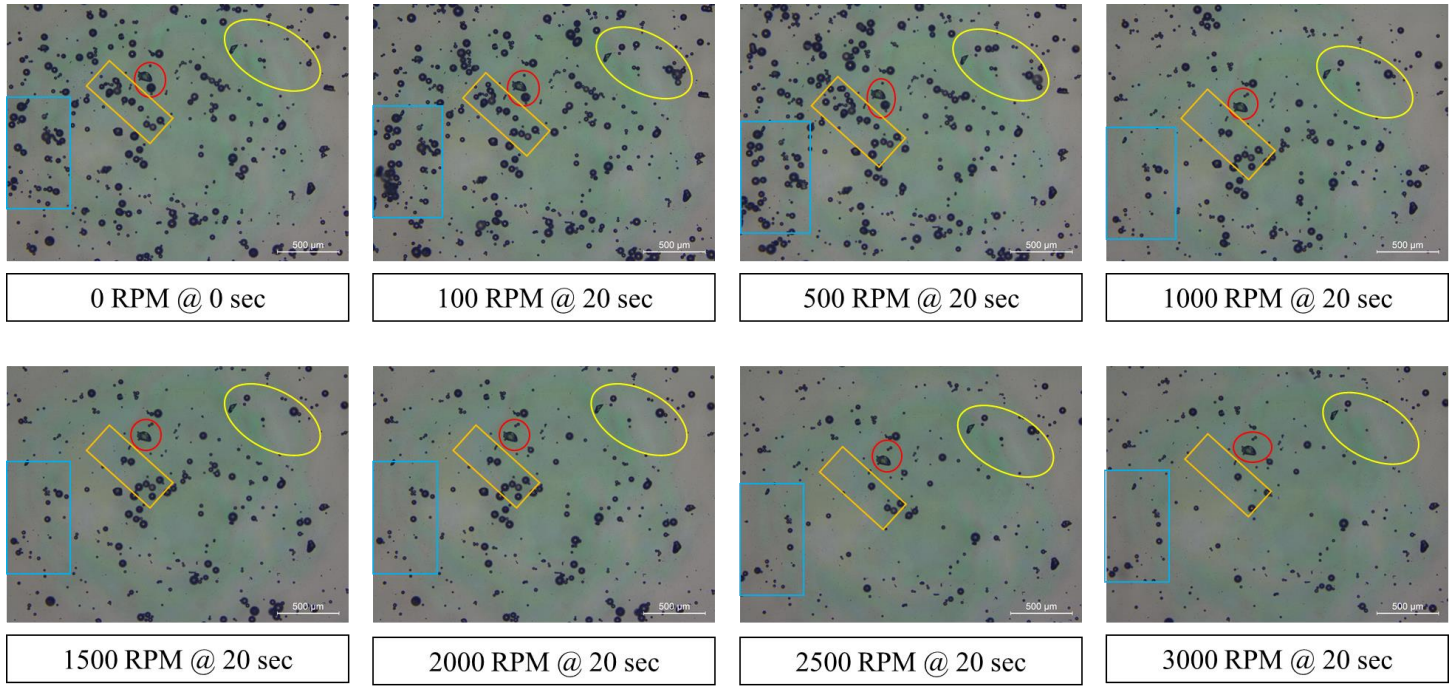
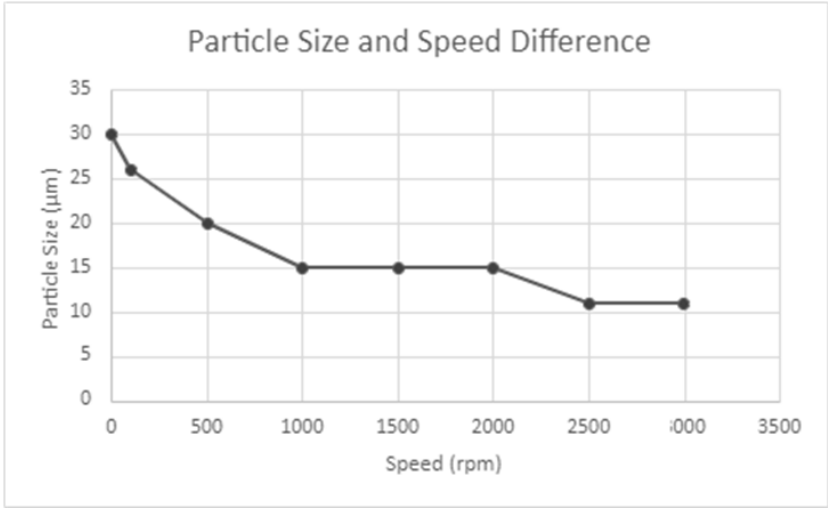
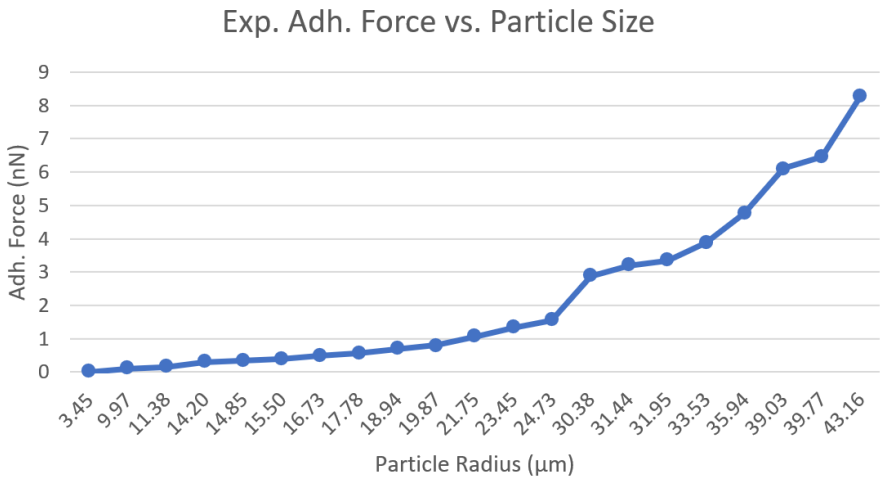
Centrifuge Dust Adhesion Instrument

- **Initial experimental results**



Glass slide with 70 mm glass spheres after indicated rotational speed experimental steps





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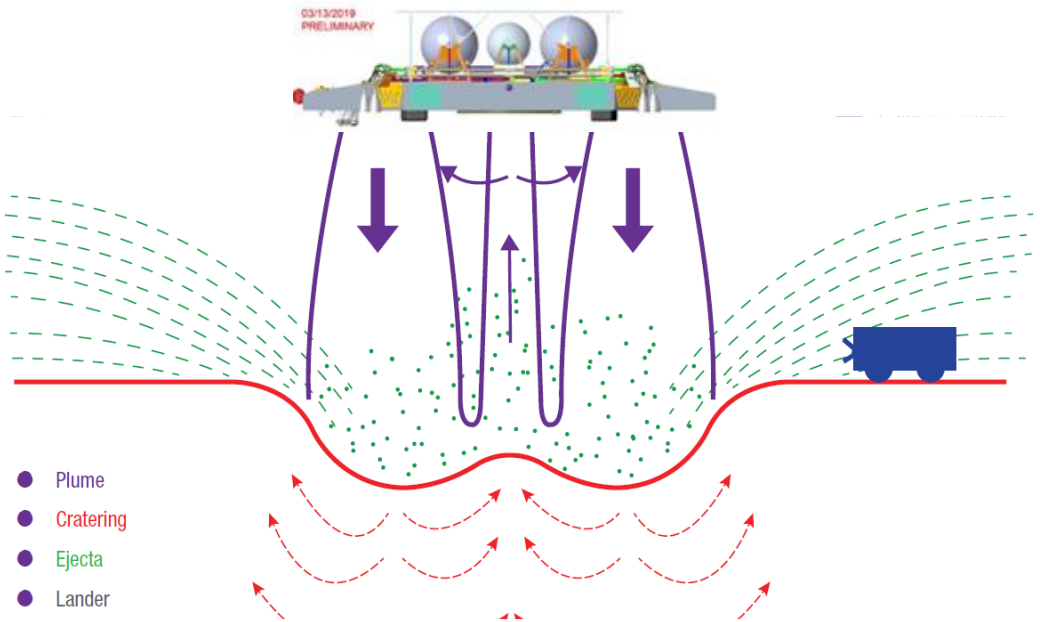
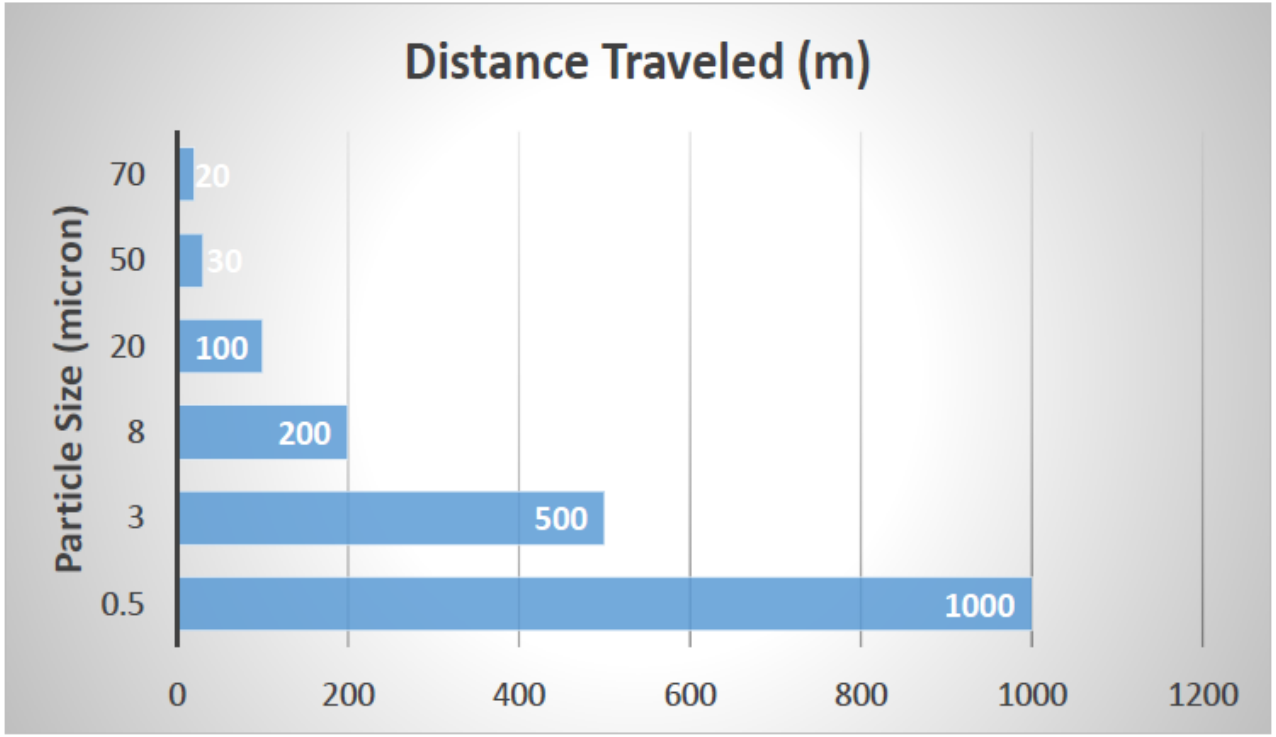
Wear Resistant Materials

- **Plume Surface Interactions**



Within 50 m of landing site, particle velocity estimates range from 300 m/s – 2000 m/s



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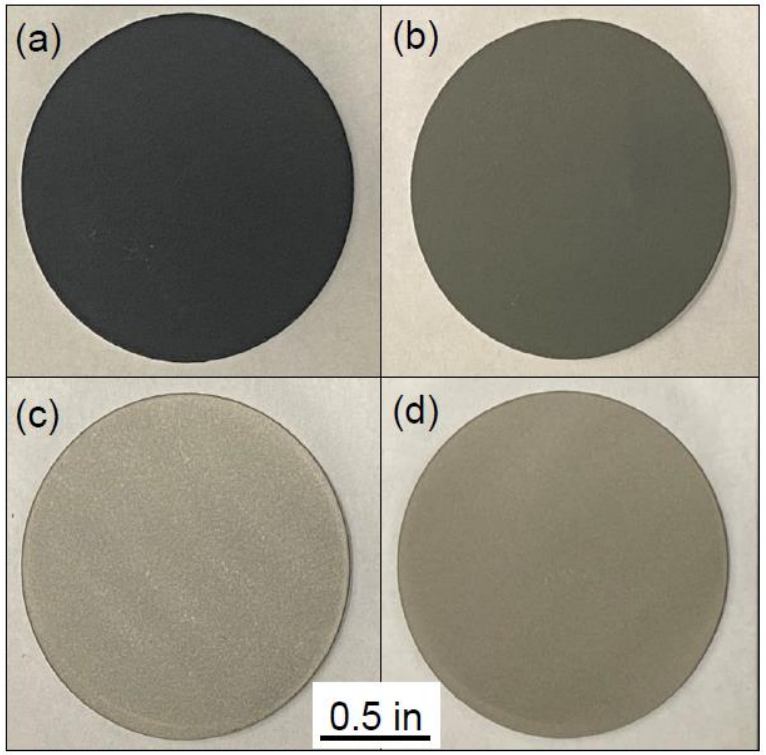
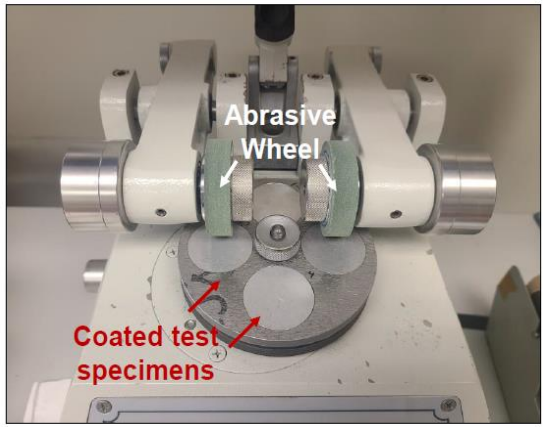
Wear Resistant Materials

- **Ceramic Coatings**

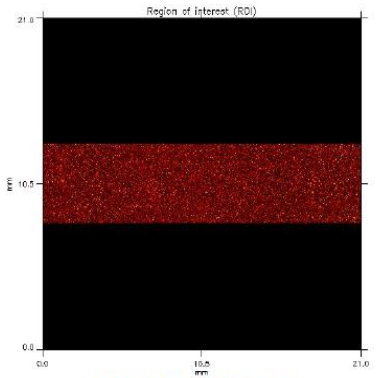


Al 6061 substrates coated with (a) alumina-titania (Al_2O_3-TiO2), (b) chromium oxide (CrO_2), (c) Tribaloy T-800 and (d) chromium carbide-nickel chrome (CrC-NiCr)

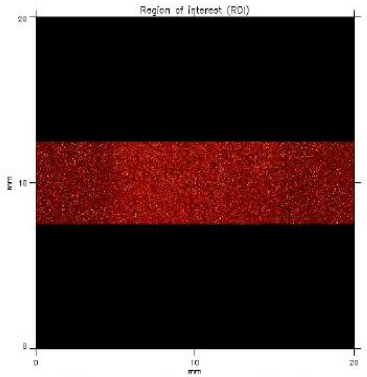
- **Taber Abrasion Testing**



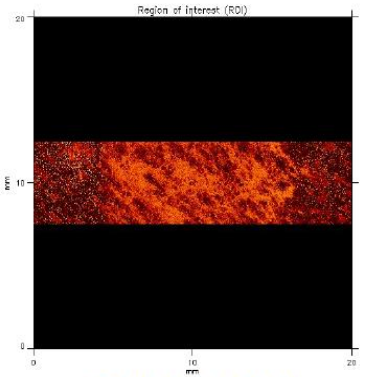
Coating Material	Initial Thickness (µm)	Thickness after 1200 cycles (µm)	Coating Loss (µm)
Al_2O_3-TiO_2	258.0 ± 6.3	250.5 ± 7.4	7.55 ± 1.3
Cr_2O_3	284.1 ± 7.9	280.9 ± 5.7	3.2 ± 6.6



Alumina-titania



Chromium carbide



Stainless Steel

No appreciable wear after 5000 cycles, although there was a change in surface roughness

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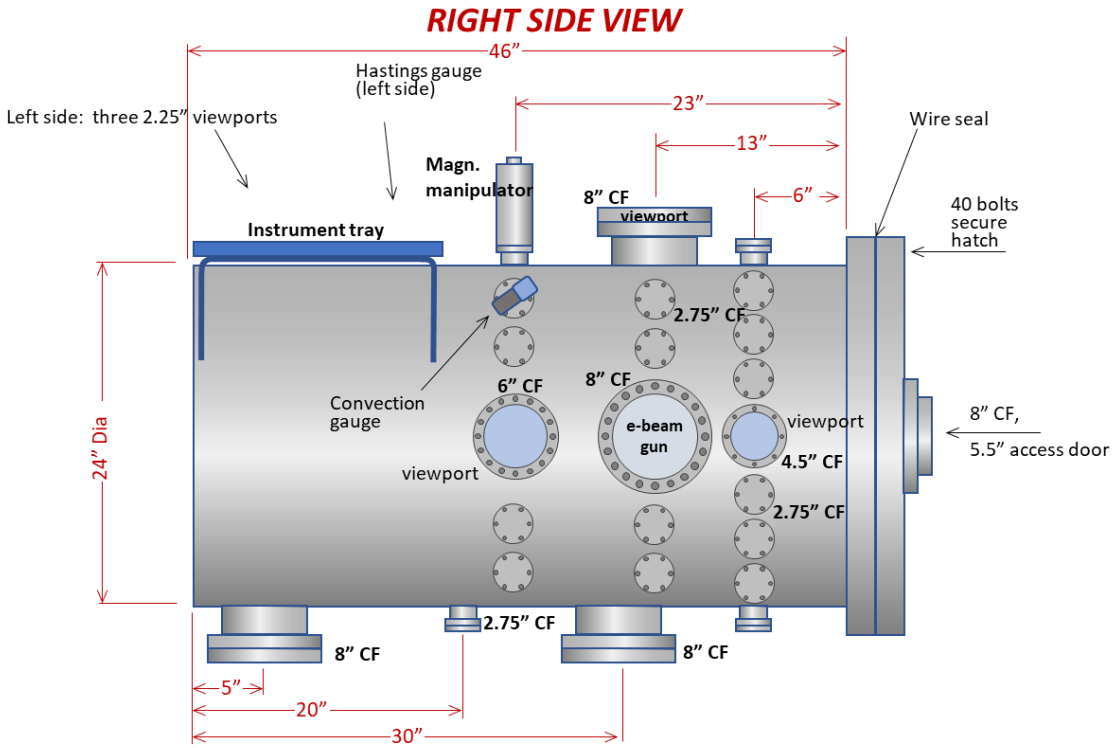
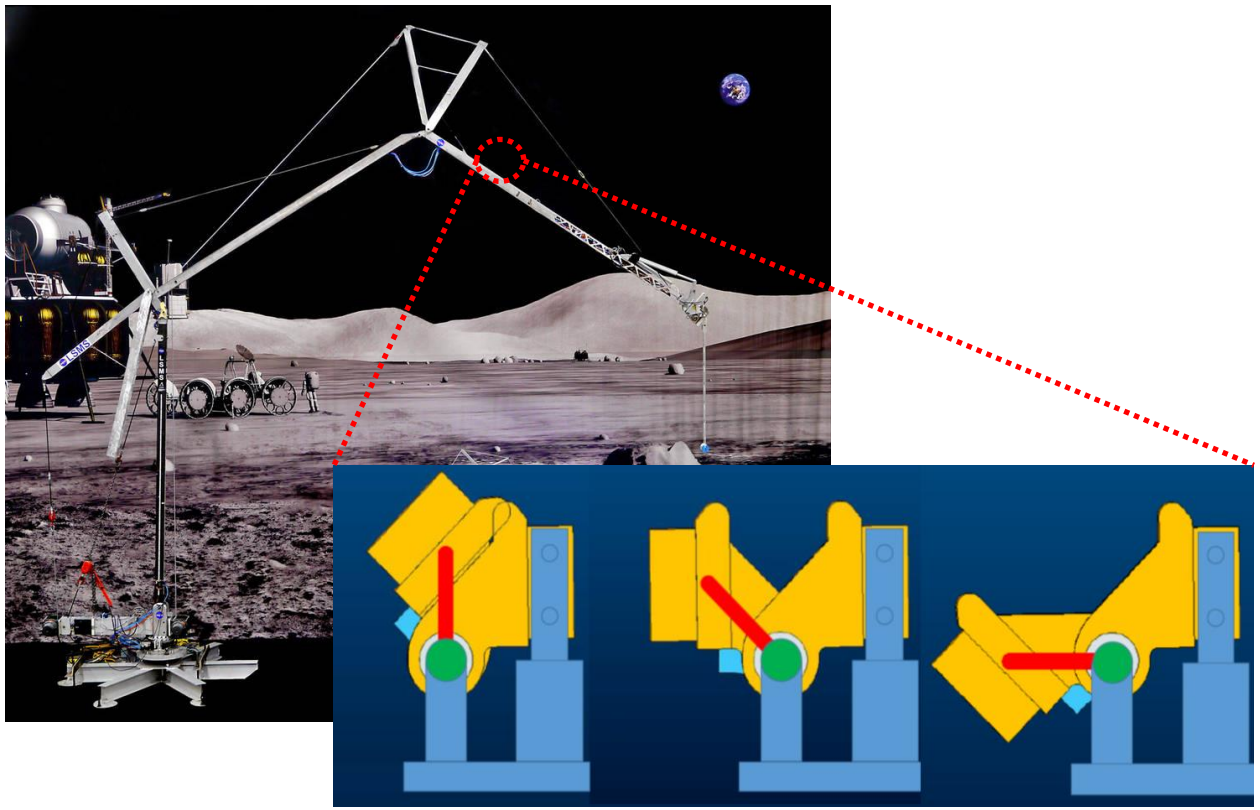
SLIDE Vacuum Chamber for Wear Assessment

- **"Dirty" Vacuum Chamber for Wear Assessment**
- **Evaluation of Relevant Mechanisms**



Vacuum chamber from previous work



SLIDE: Surveying Lunar dust Influence on Device Efficacy

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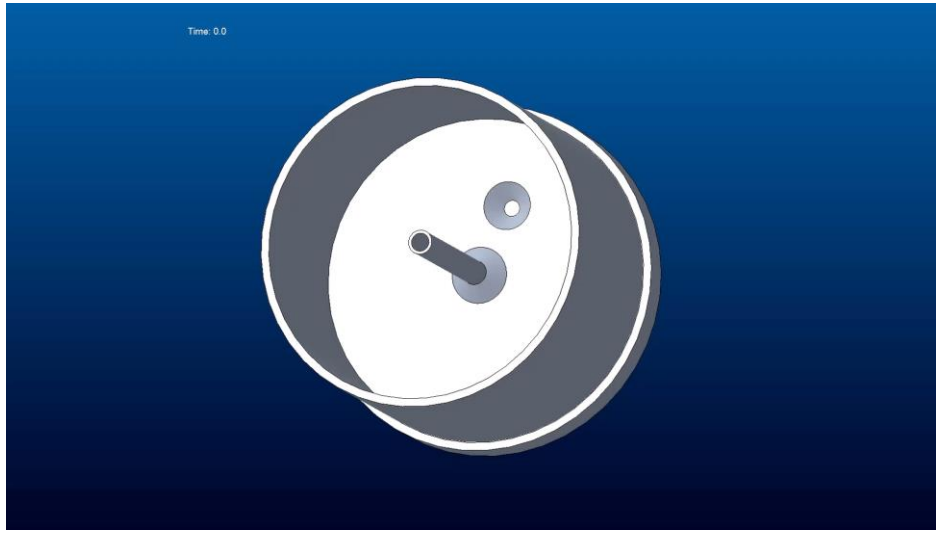
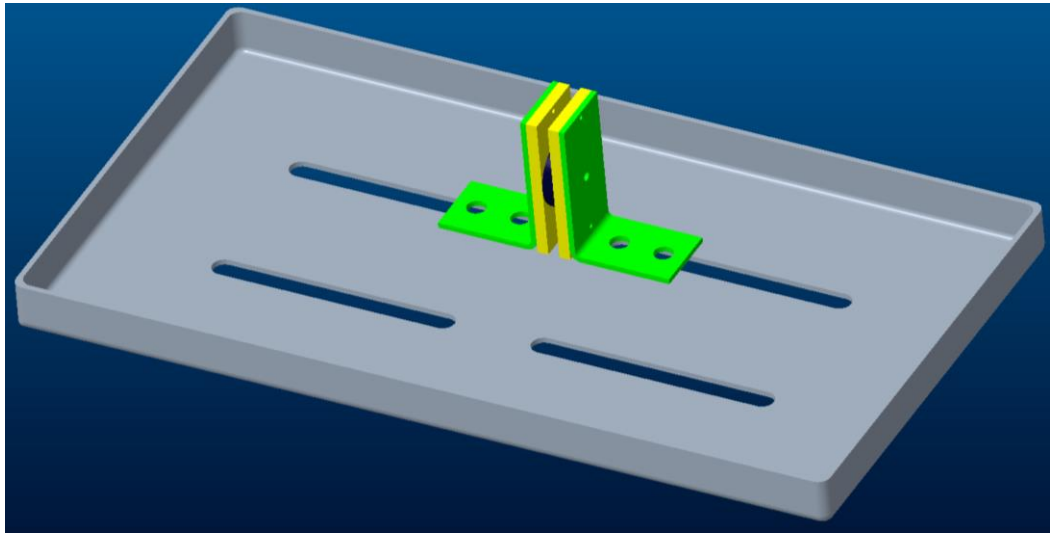
SLIDE Components

- **Dust Deposition Mechanism**



Designed to controllably apply simulant to area of interest

- **Rotational Wear Testing Schematic**



Central disc (dark blue) will rotate and sample surfaces (yellow) will be evaluated for wear. Changes in friction (torque) will be evaluated as well.

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Extreme Environments (LEO and Lunar) Experiments

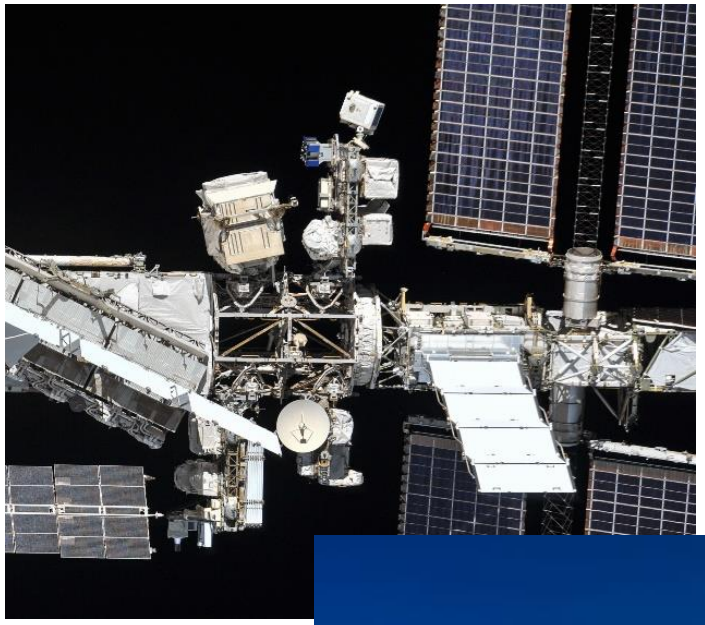
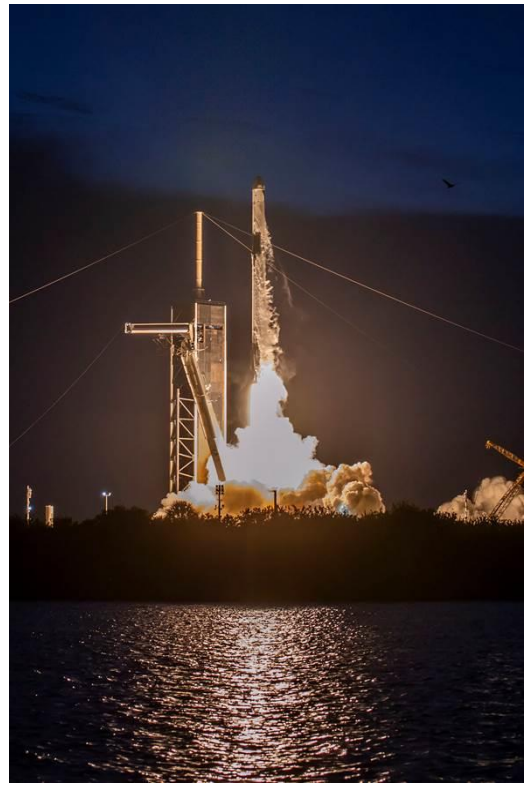


Image credit: Aegis Aerospace



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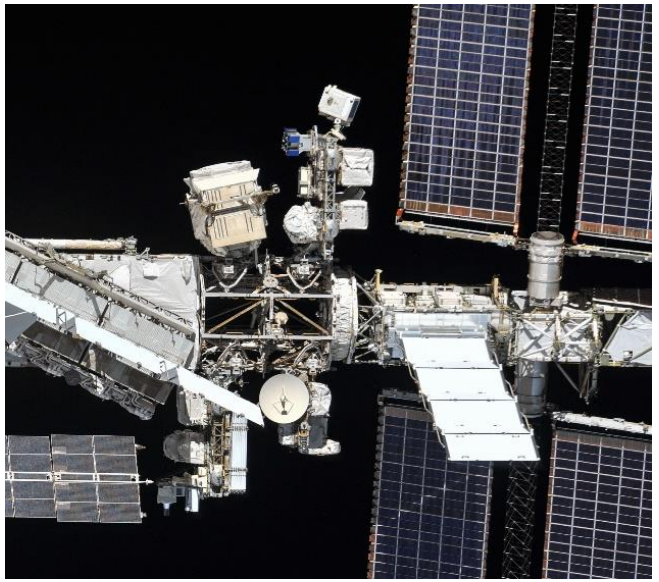
MISSE-16

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

MISSE-16 Location



Zenith 2 Install on MISSE-FF

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RAC Payload Samples Generated

RAC Payload Samples

RAC Payload Concept

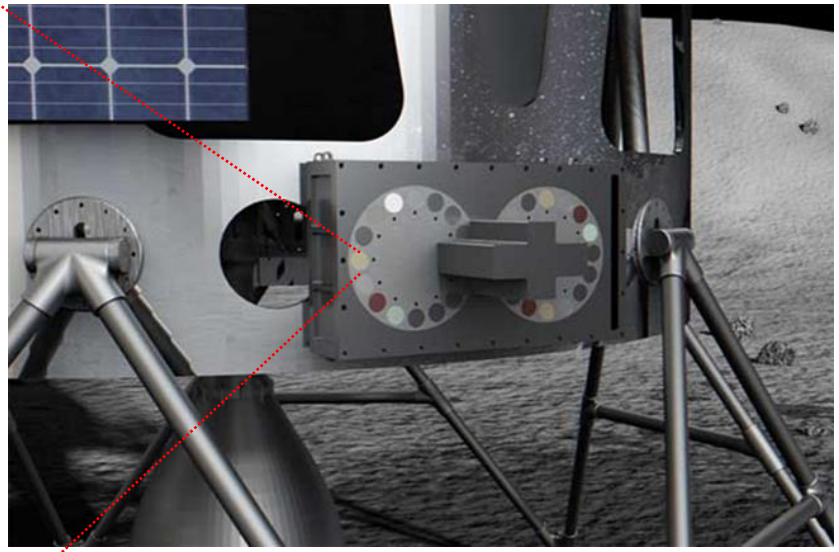
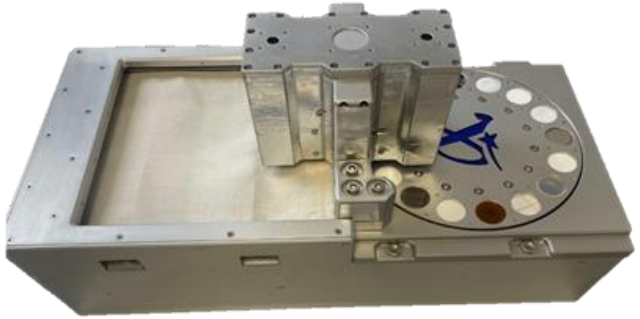


Image credit: Aegis Aerospace

RAC Payload Flight Article



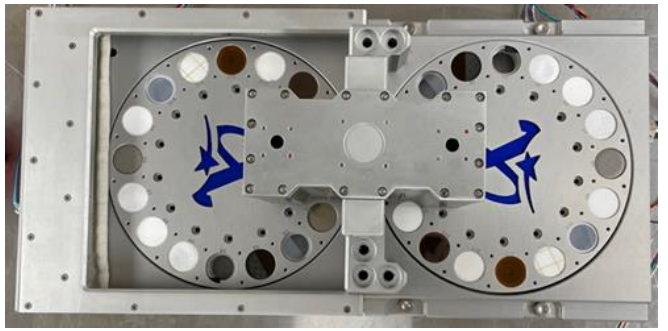


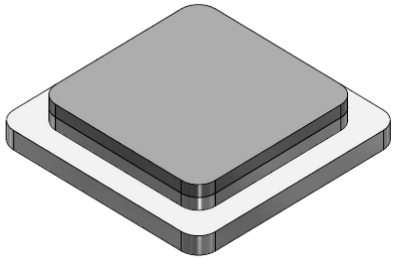
Image credit: Aegis Aerospace

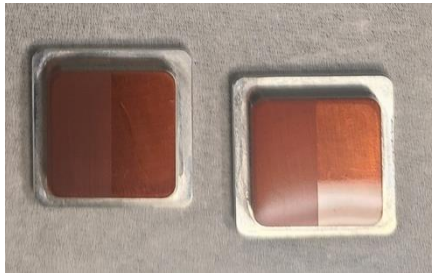
Honeybee Robotics PlanetVac Instrument

PlanetVac Samples

Dash Number	Coupon Material	Coating
-100	AMS 4117 or Equivalent	No Coating - Default Part
-101	Al 6061, T6	Kapton HN
-102	Ti-6Al-4V	No Coating
-103	Al 6061, T6	LCLR Resin
-104	Al 6061, T6	FLEXcon #510 Material
-105	Al 6061, T6	PTI Material, Ceramic coating
-106	Al 6061, T6	Sharon Miller, Work Function Matched Coating
-107	Al 6061, T6	Kapton HN
-108	Ti-6Al-4V	No Coating
-109	Al 6061, T6	LCLR Resin

Coupon Schematic





Kapton Samples

Full Sample Set

PlanetVac on Masten Lander

Image credit:
https://flightopportunities.ndc.nasa.gov/technologies/179/

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