Engineering the Interface: Advanced Surface Technologies for Lunar Dust Management and Equipment Longevity

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Artificial Intelligence (AI) Usage Disclosure
This document was created with assistance from Google Gemini for specified image generate. The content has been reviewed and edited by Chris Wohl. More information on the extent and nature of the AI usage is included in the Acknowledgements section of this presentation.

Image credit NASA unless otherwise indicated

Where will Lunar Dust Pose a Challenge?

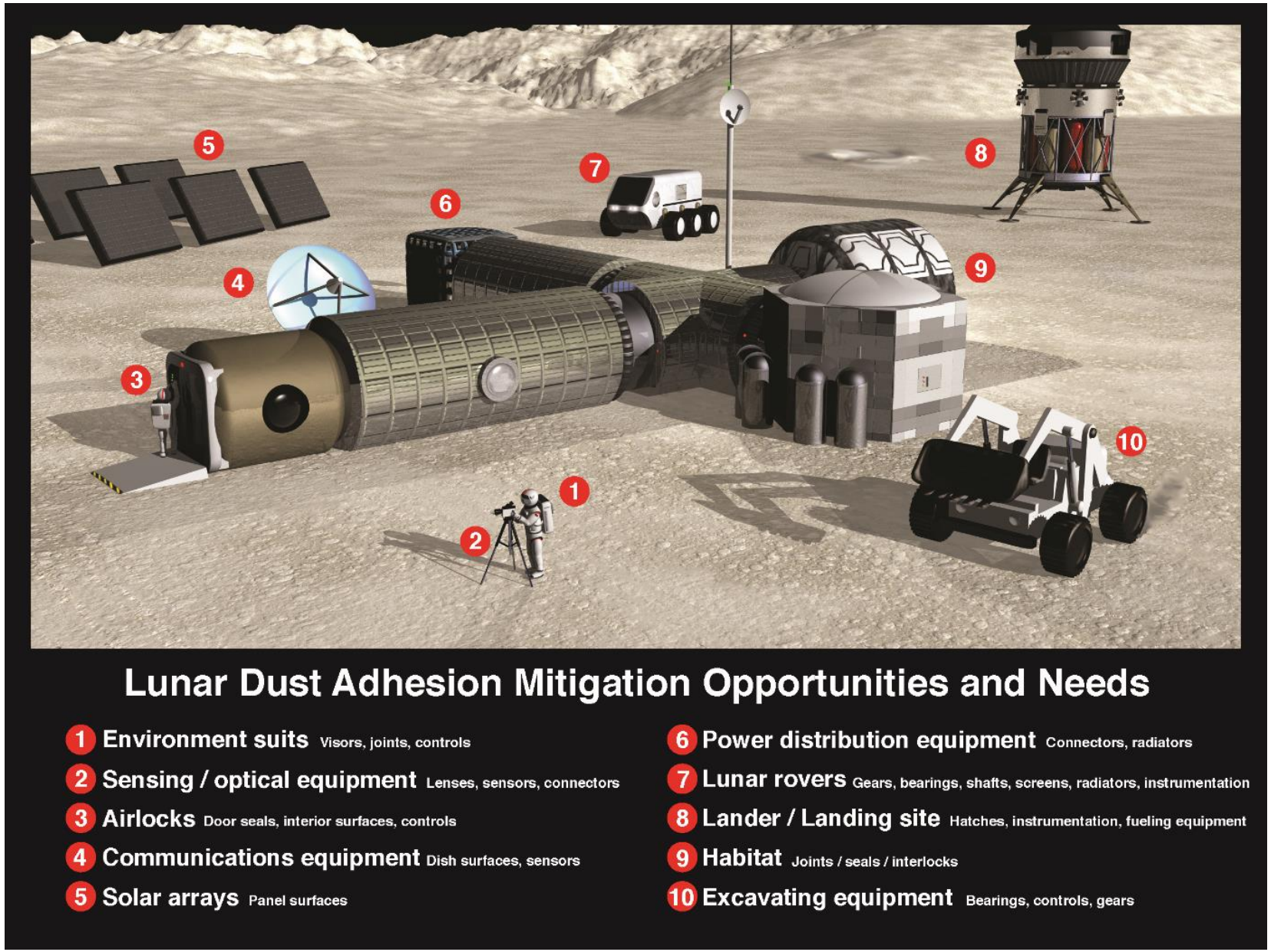
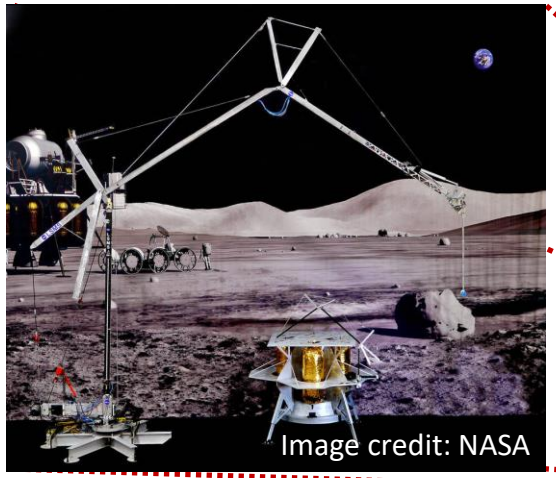


Image credit: NASA

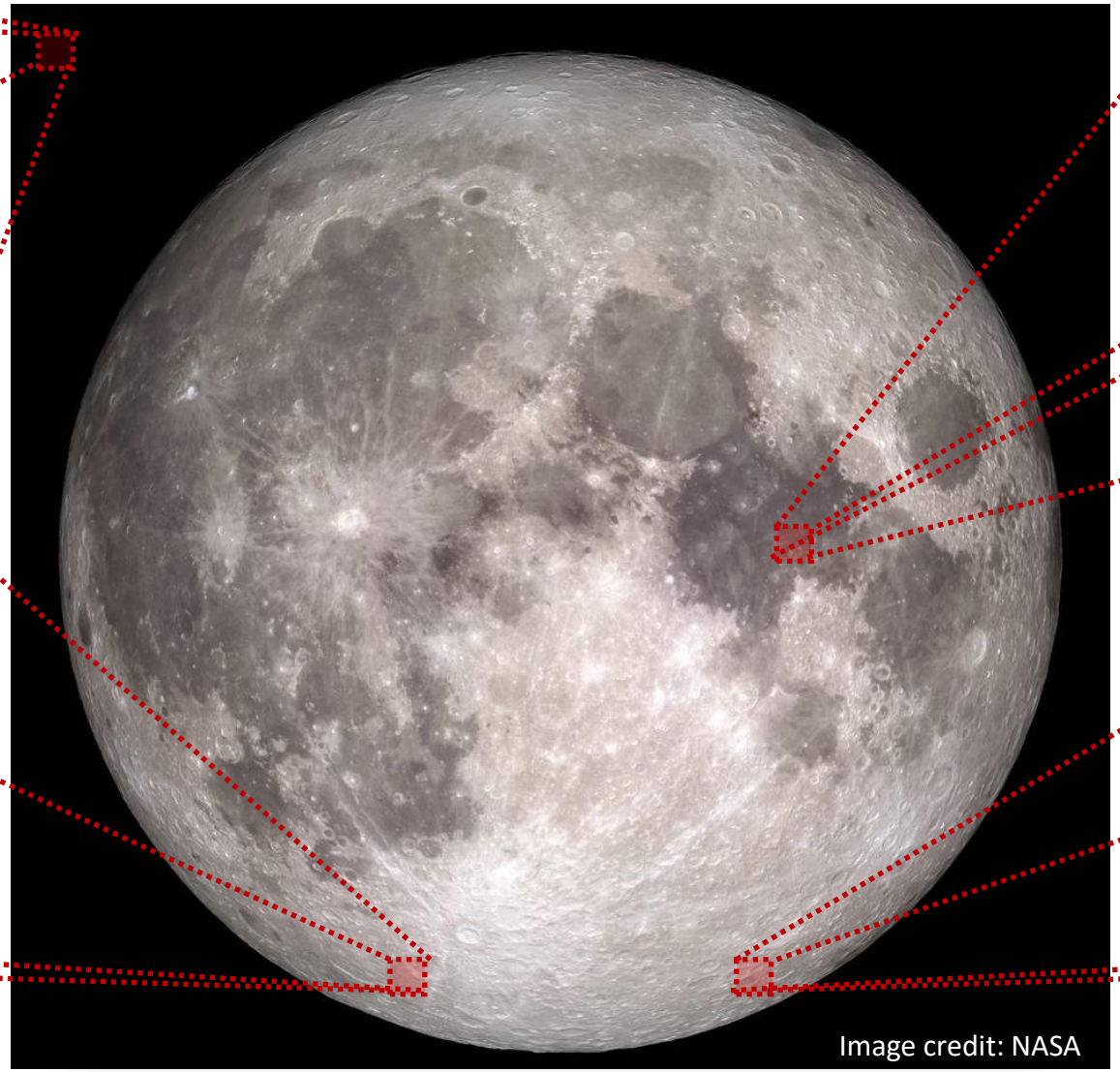
The A.R.T. of Lunar Dust: Avoid, Remove, Tolerate


Image credit: NASA

Gateway

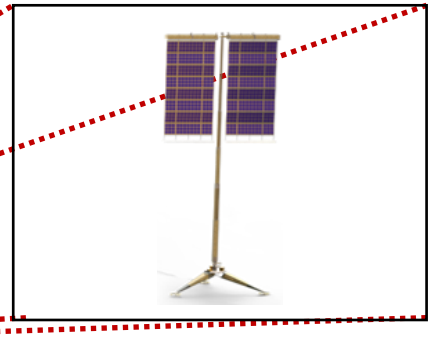

Image credit: NASA

Infrastructure


Image credit: NASA



Lunar Lander



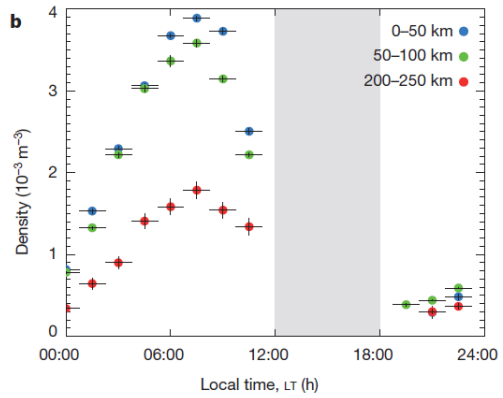
Vertical Solar Array Technology (VSAT)

Image credit: NASA

What, Where, and Why of Lunar Dust

Particle Counts

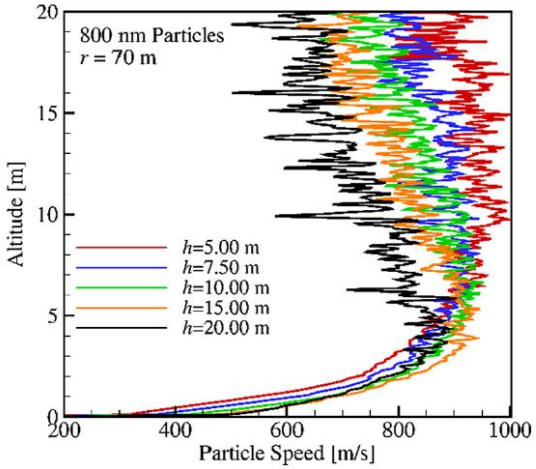
Lunar Dust Experiment (LDEX) Results



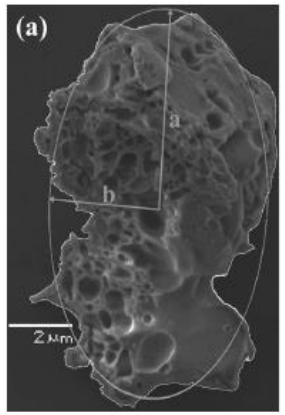
Particle counts as high as 4 x 10^{-3} m^{-3} up to 50 km off the lunar surface. Increased particle counts at terminator.

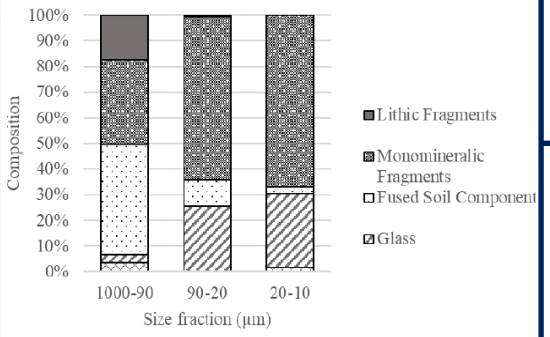
Single engine plume impingement can generate particle velocities > 1000 m/s.

Particle Velocity



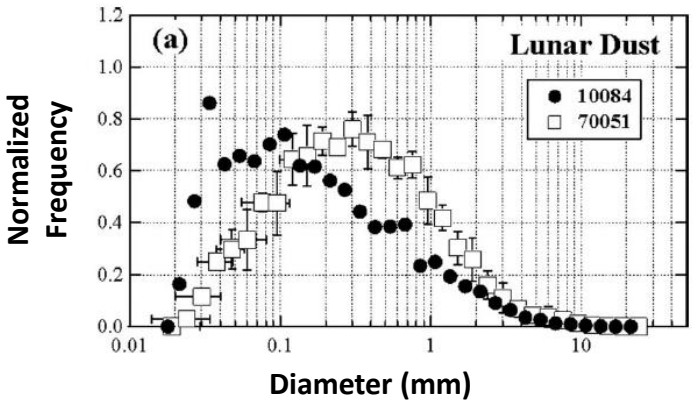
Particle Morphology





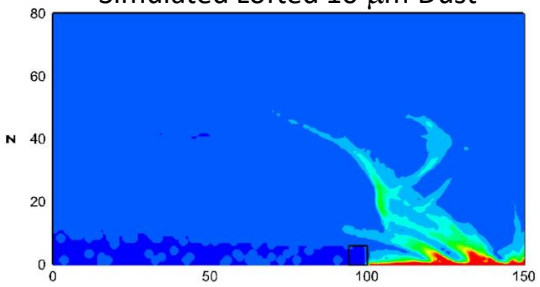
Smooth, glassy spheres <-> High angularity agglutinates

Particle Size



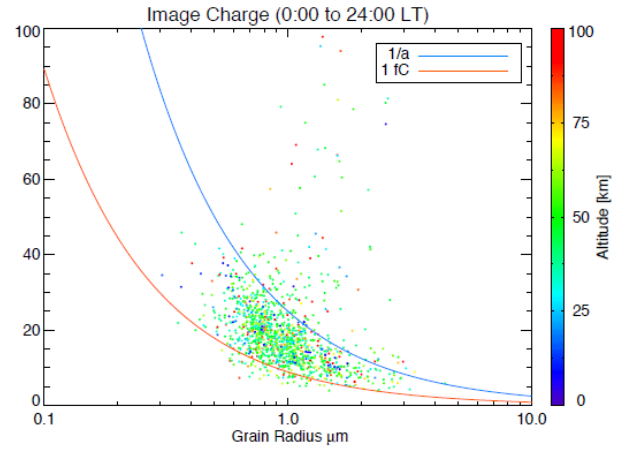
Lunar dust particles range from nm to up to 50 µm in diameter.

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.

Lunar Surface Electrostatic Environment

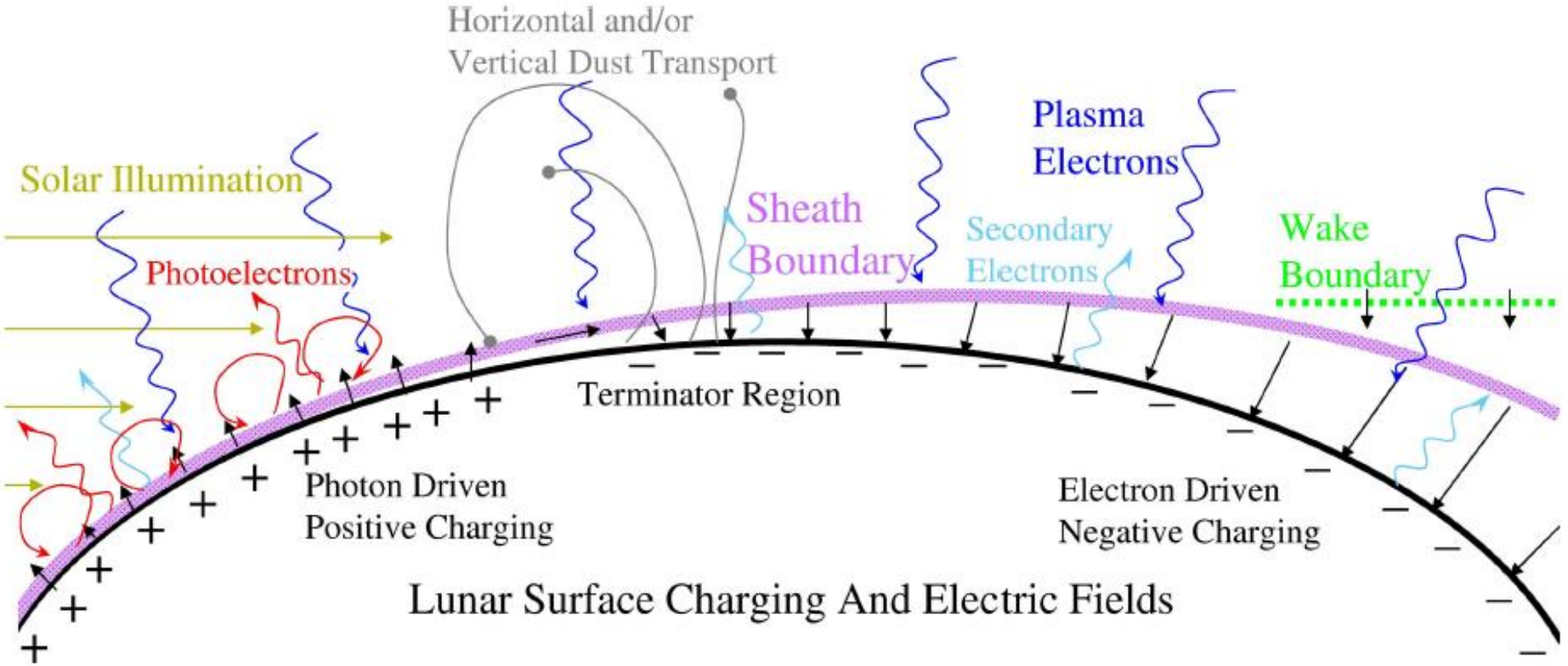


Image Credits: Stubbs, T. J.; Halekas, J. S.; Farrell, W. M.; Vondrak, R. R. Lunar Surface Charging: A Global Perspective using Lunar Prospector Data. Workshop of Dust In Planetary Systems, Lunar and Planetary Institute, Kauai, Hawaii, United States of America, September 26-30, 2005. (used with author permission)

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

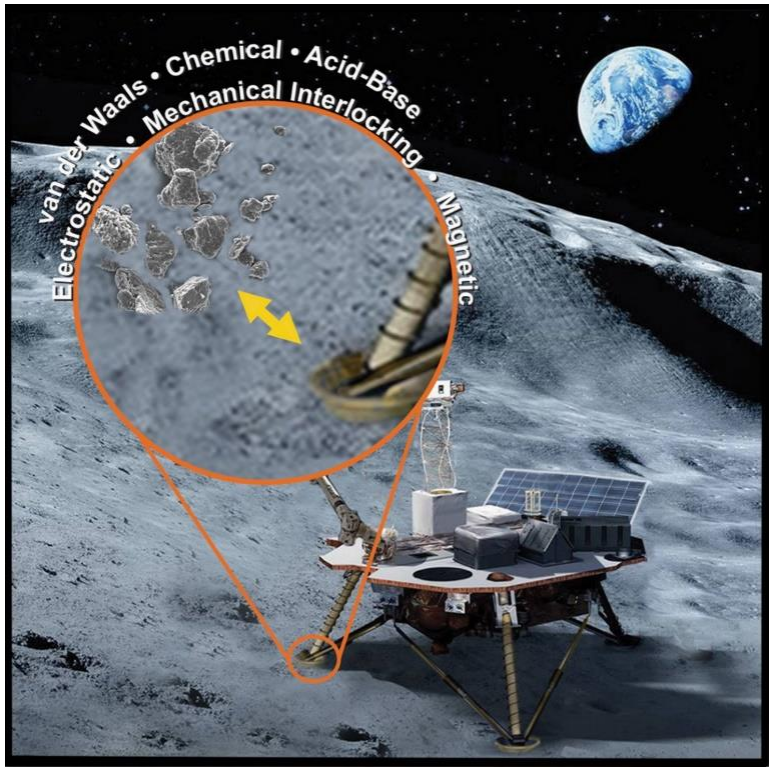
<u>ISRU and construction:</u>
Unknown, likely highly variable

1. 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.

Material Design and Selection for Lunar Applications

Dust Mitigation-
Must Remove





Dust Management-
Must Tolerate



Different aspects of lunar exploration will have different materials requirements

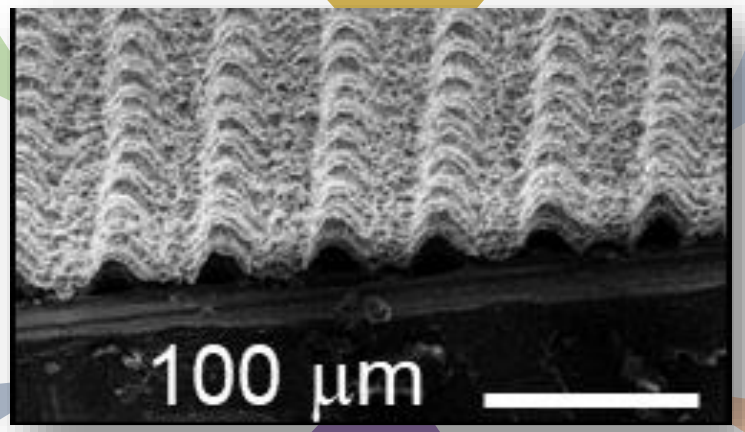
Image credit: NASA

Lunar Dust Passive Adhesion Mitigation

Surface Chemistry

Surface Topography

Surface Conductivity



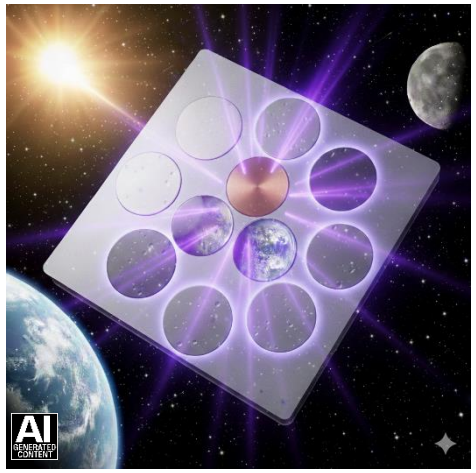
Surface Mechanical Properties

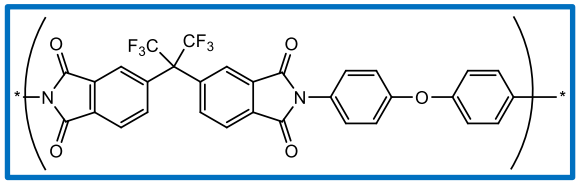
Responsive Surfaces

Surface Hardness

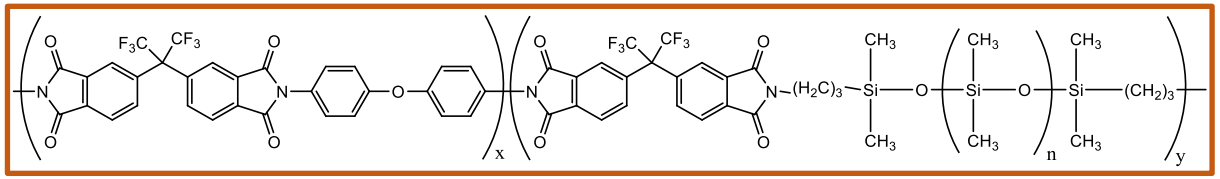
Image credit: NASA

Passive Adhesion Mitigation at NASA Langley





Polyimide



Copolyimide siloxane (PIS)

UV Exposure

Chain Scission Degradation

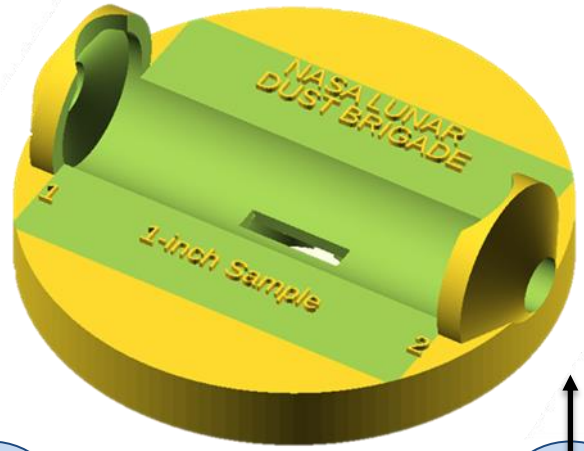
Silica-like Surface Passivation Layer

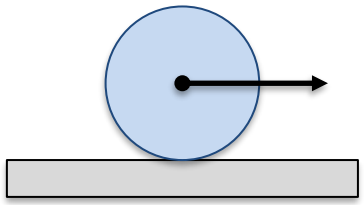
Exposure on International Space Station



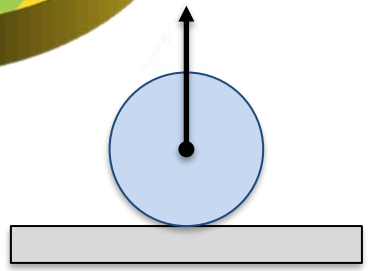
Image credit: NASA

Dust Simulant Adhesion Test



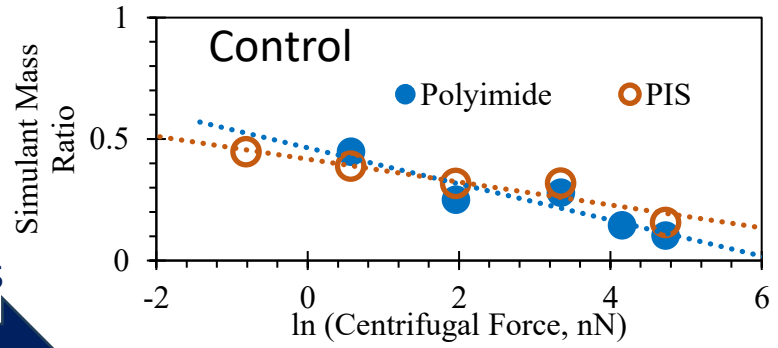


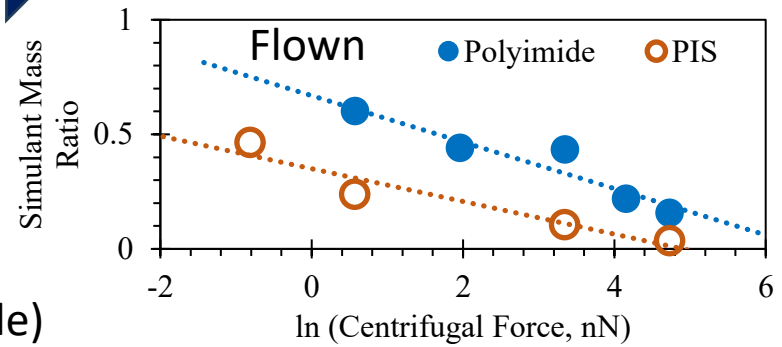
Rolling/Sliding



Pull-off Force (Tensile)

Results



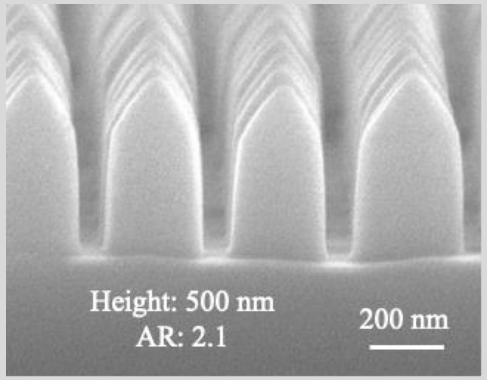


Early Stage Innovation:

Passive Lunar Dust Control through Advanced Materials and Surface Engineering

UT Austin- Dr. Chih-Hao Chang

- Sapphire nanostructures with anti-glare, anti-dust, and anti-scratch properties
- Modulus and hardness are 182 GPa and 3.7 GPa, comparable with bulk glass and tungsten

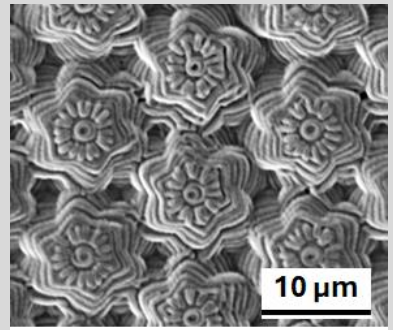


(K.-C. Chien, M. Kepenekci *et. al.*, *Materials Horizon*, **12**, 6, 1796-1807, 2025)

University of Nebraska- Dr. Min Zou

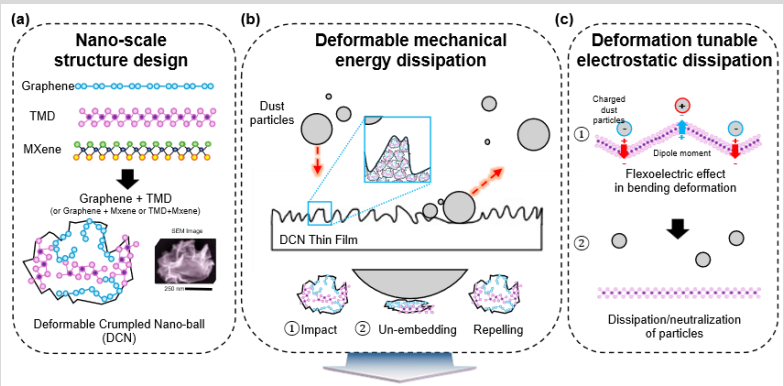
Programmable 3D Interface Engineering for High-Performance Lunar Dust Mitigation

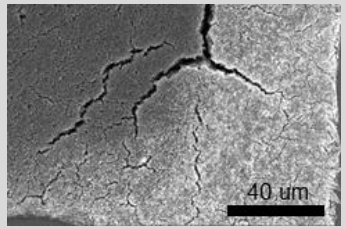
- Demonstrated <1% lunar simulant retention under standardized testing
- Programmable 3D surface architectures with submicron-scale control
- Independent tuning of geometry and thin-film surface chemistry
- Controlled dust localization and adhesion behavior
- Passive surface-based mitigation strategy

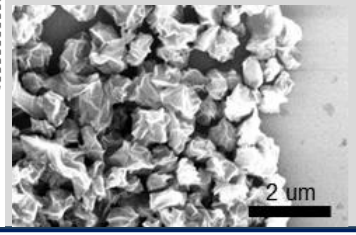


Engineered 3D surface topography with submicron-scale control. Demonstrated passive reduction of lunar dust retention.

UC Irvine- Dr. SungWoo Nam

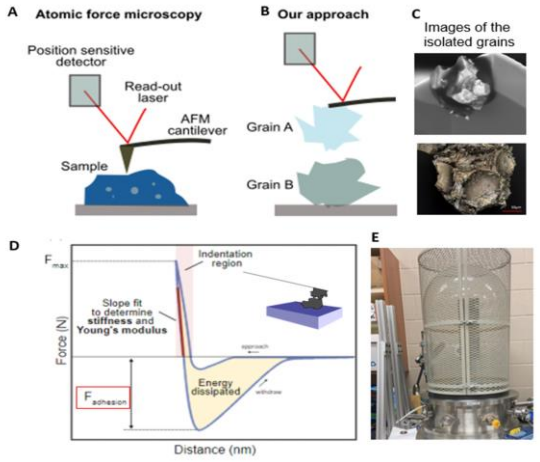






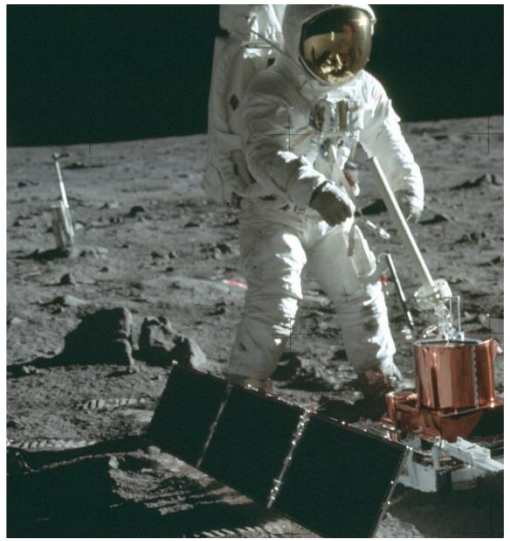
Developing coatings of mixed 2D nanostructures responsive to the lunar dust environment

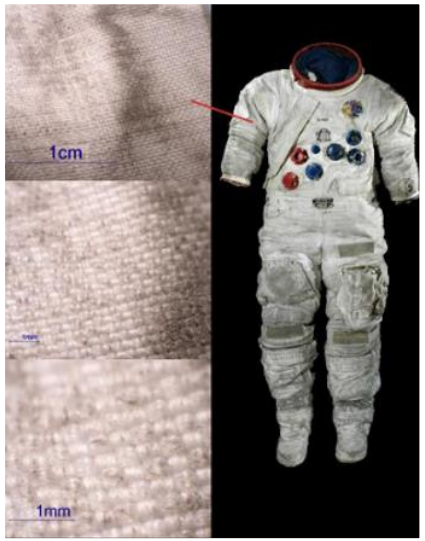
University of Central Floria- Dr. Lei Zhai



- Thermoplastic polyurethane coatings with controlled texture, conductivity, and hardness is fabricated to study dust–surface interactions and passive dust mitigation.
- AFM measures regolith interactions in vacuum to validate simulations using screened Coulomb and contact-based charge-transfer models.
- Centrifugation tests in a simulated lunar environment will evaluate dust mitigation performance.

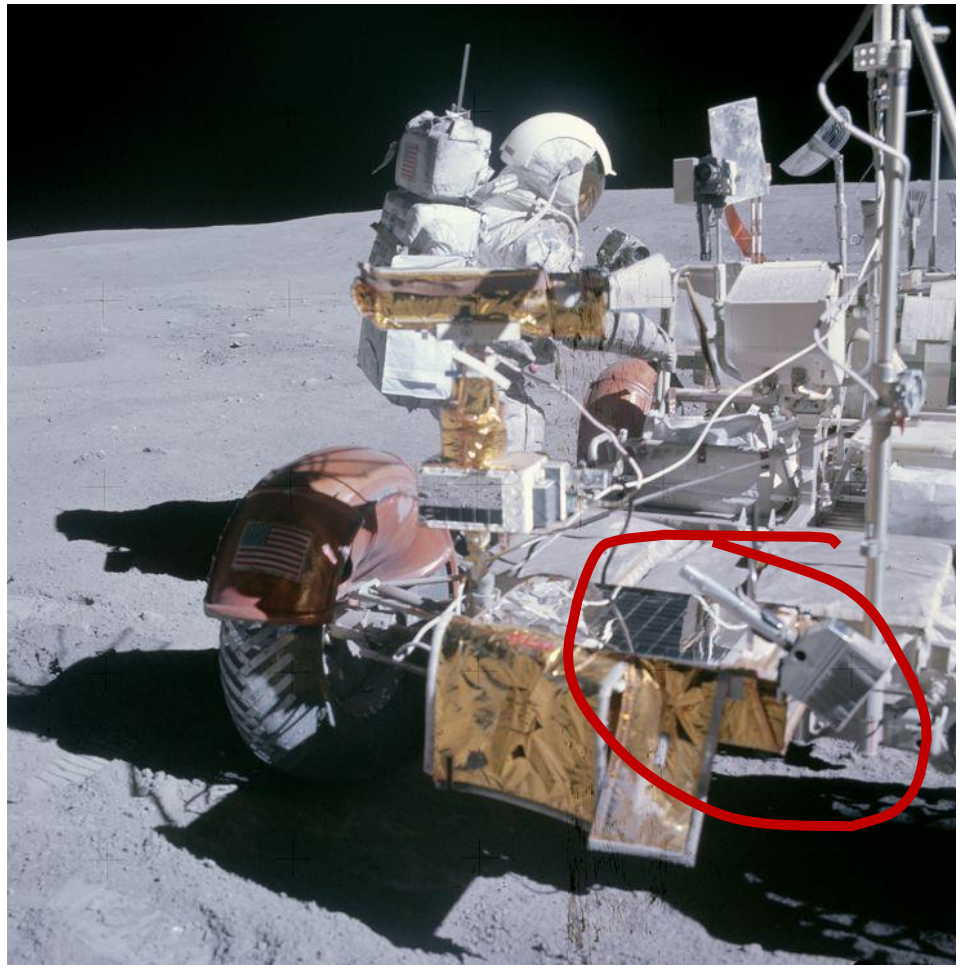
Abrasive Wear from Surface Operations

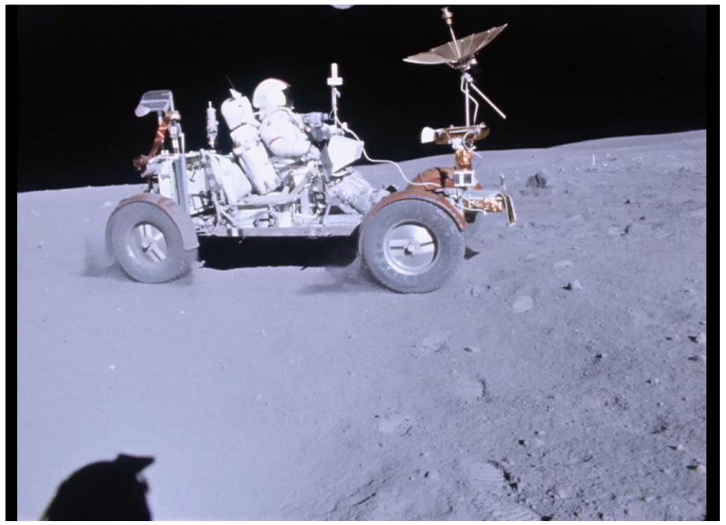


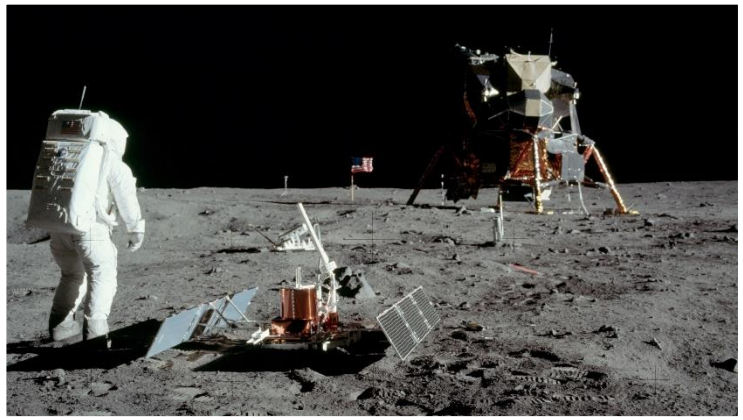




"Dust is probably one of our greatest inhibitors to a nominal operation on the Moon."
Apollo 17 Commander Gene Cernan



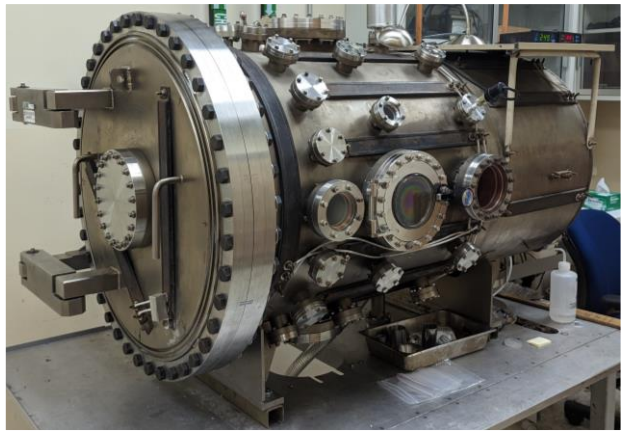


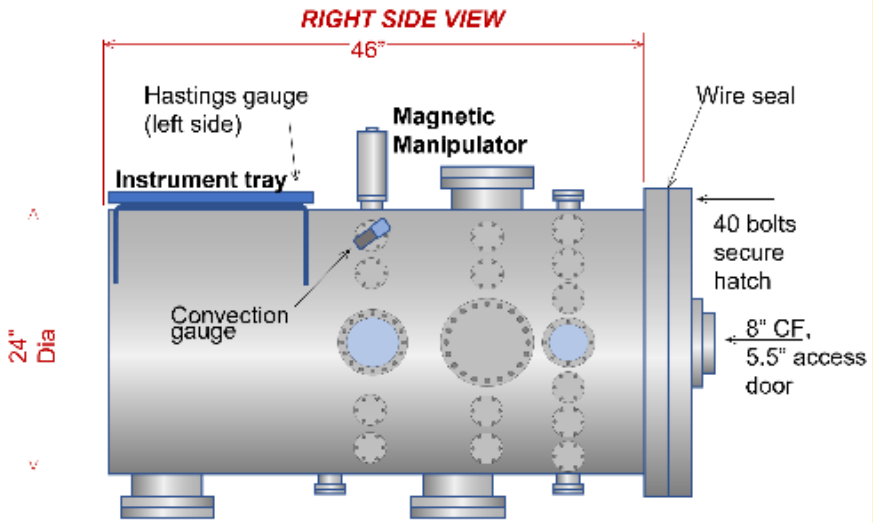


Nearly every surface activity can result in abrasive damage

Image credit: NASA

Dust, Ultraviolet Radiation, and Space Thermal Environment (DUSTE) Chamber

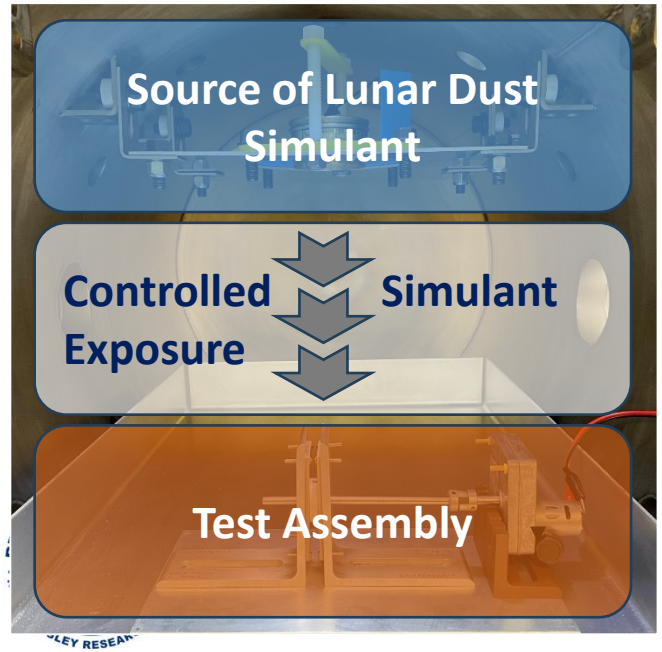


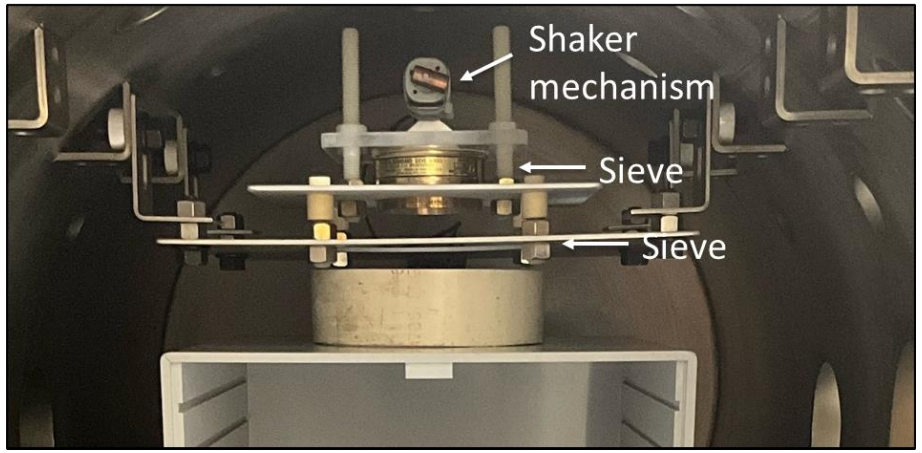


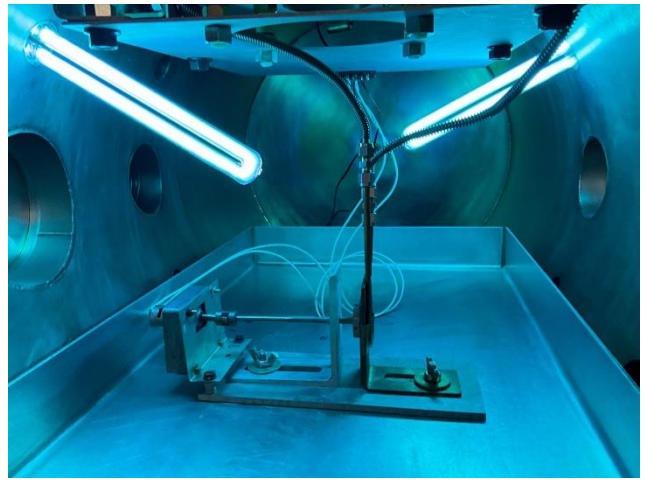
Subject materials and mechanisms to:

- Wear caused by dust (e.g., lunar, Martian, etc.)
- High vacuum (>10^{-6} Torr)
- Temperature fluctuations (ambient to ~ -150°C)
- Ultraviolet (UV) radiation

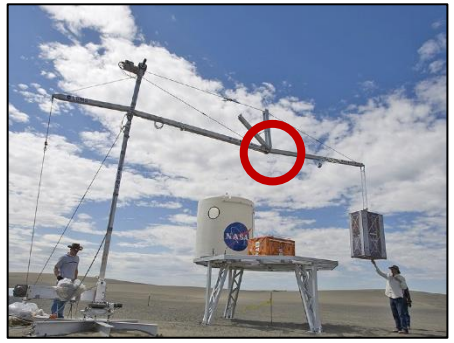
Configurable to accommodate variety of materials, mechanisms and abrasives relevant to applications



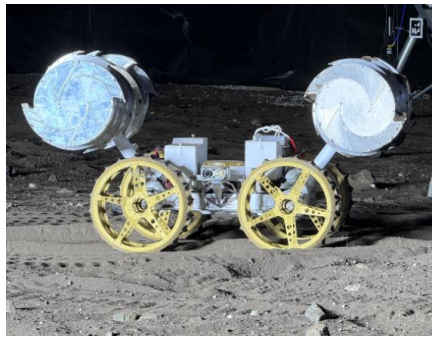




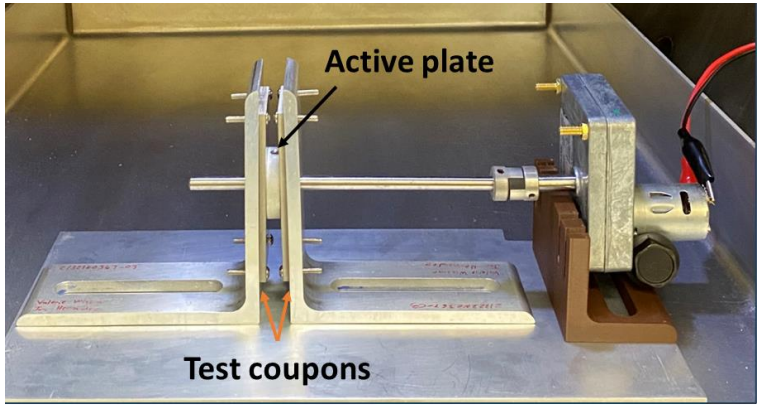
Evaluating Metals and Ceramics in DUSTE



LSMS

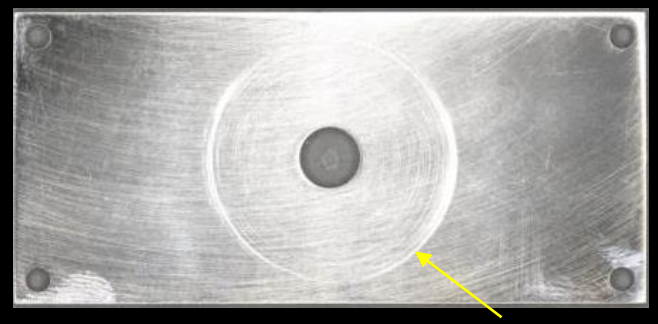


IPEx

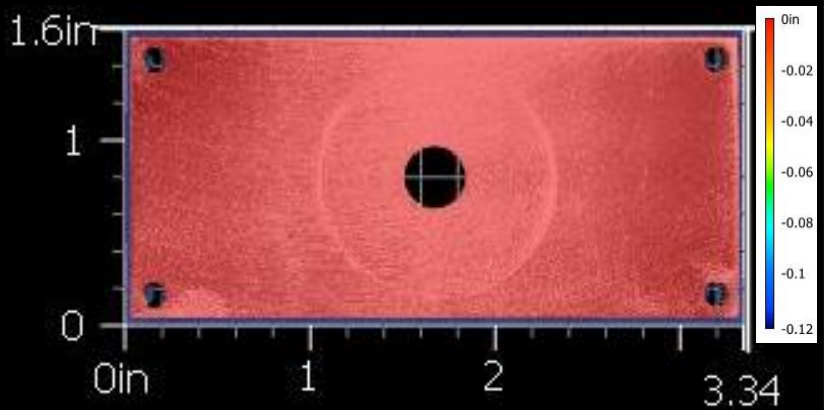


Introduction of lunar dust simulant resulted in a higher degree of wear of the Ti-6Al-4V surface than in wear tests without lunar dust simulant

Ti-6Al-4V test coupon after DUSTE testing ***with*** dust and Al-6061 active plate

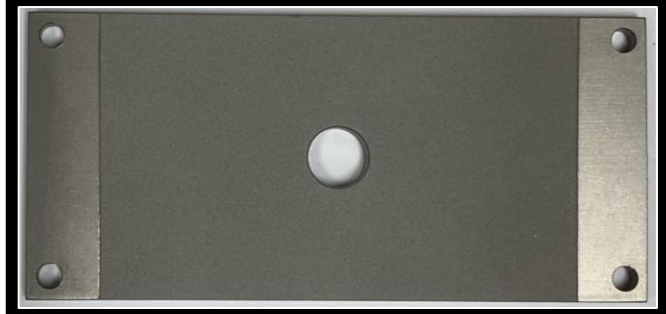


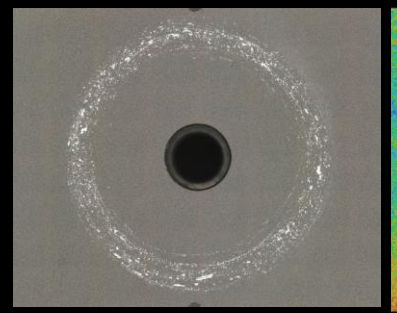
Optical image



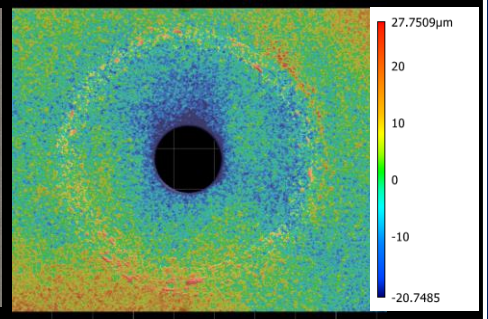
Profilometry image

CrC-NiCr coating test before and after DUSTE testing ***with*** dust and Al-6061 active plate





Optical image



Profilometry image

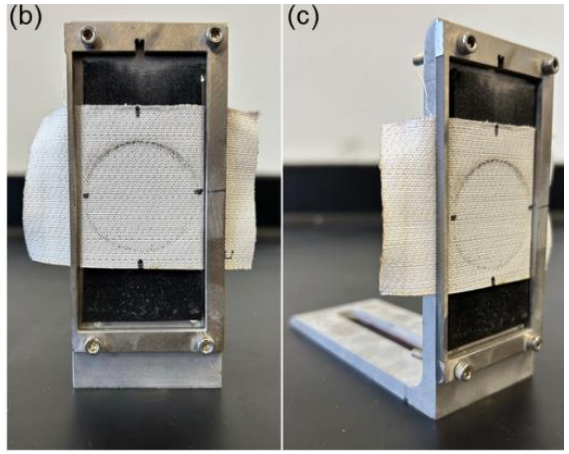
LSMS: Lightweight Surface Manipulation System
IPEx: In-situ Resource Utilization Pilot Excavator

Image credit: NASA

Evaluating Softgoods in DUSTE

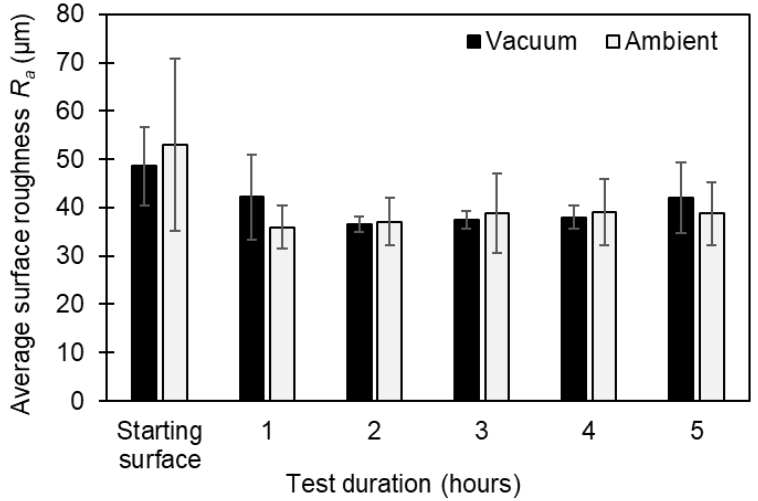


Suit worn by Alan Bean on Apollo 12



Orthofabric swatch in test fixture post DUSTE exposure





Polished Fiber Surfaces

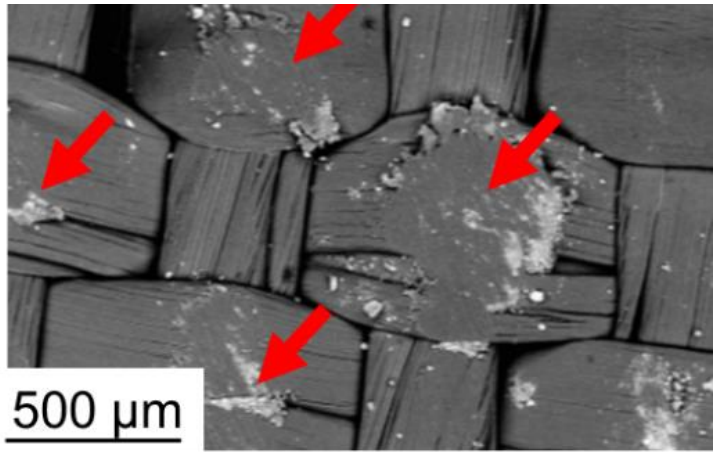
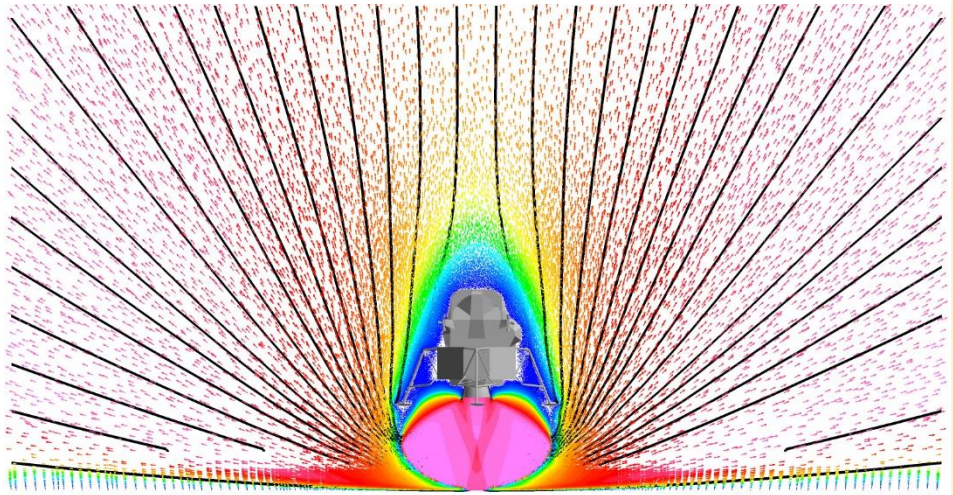


Image credit: NASA

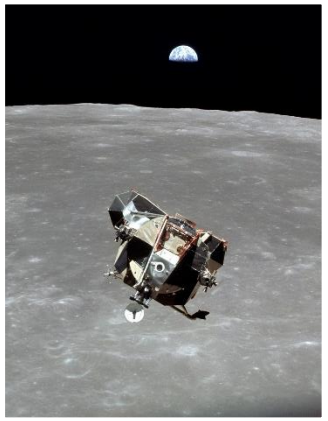
Designing controlled, targeted motion (e.g., elbow folding) test configuration is underway

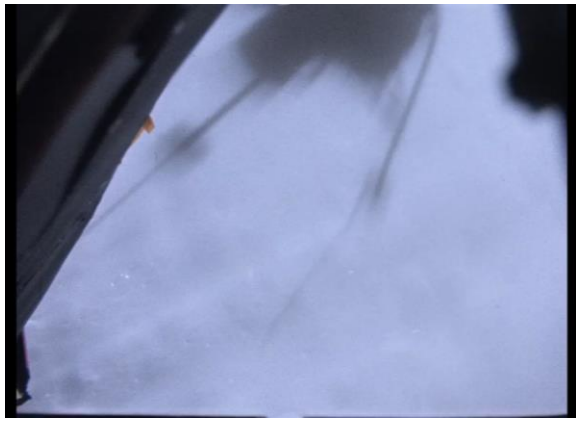
Abrasive Wear Plume-Surface Interactions (PSI)



https://www.nasa.gov/directorates/stmd/plume-surface-interaction-psi/

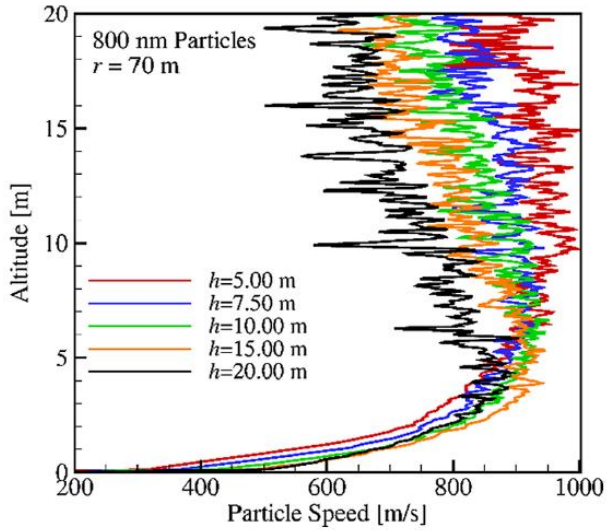
Apollo Lunar Module plume impingement at a distance of 5 m above the landing surface. Plume gas velocity vectors colored by velocity magnitude (blue = low, magenta = high)



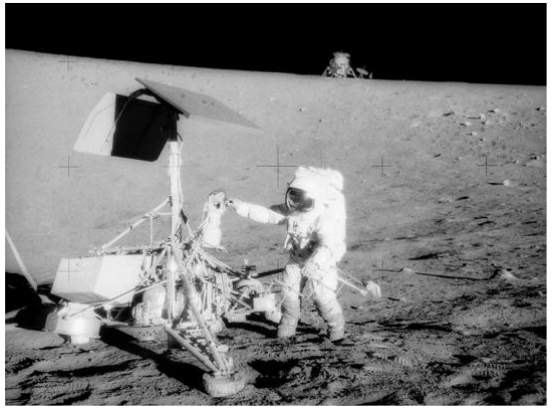


Regolith ejecta from Apollo 12 landing resulted in ***scouring, pitting*** *and* ***cracking*** of nearby Surveyor III's aluminum spacecraft structure

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



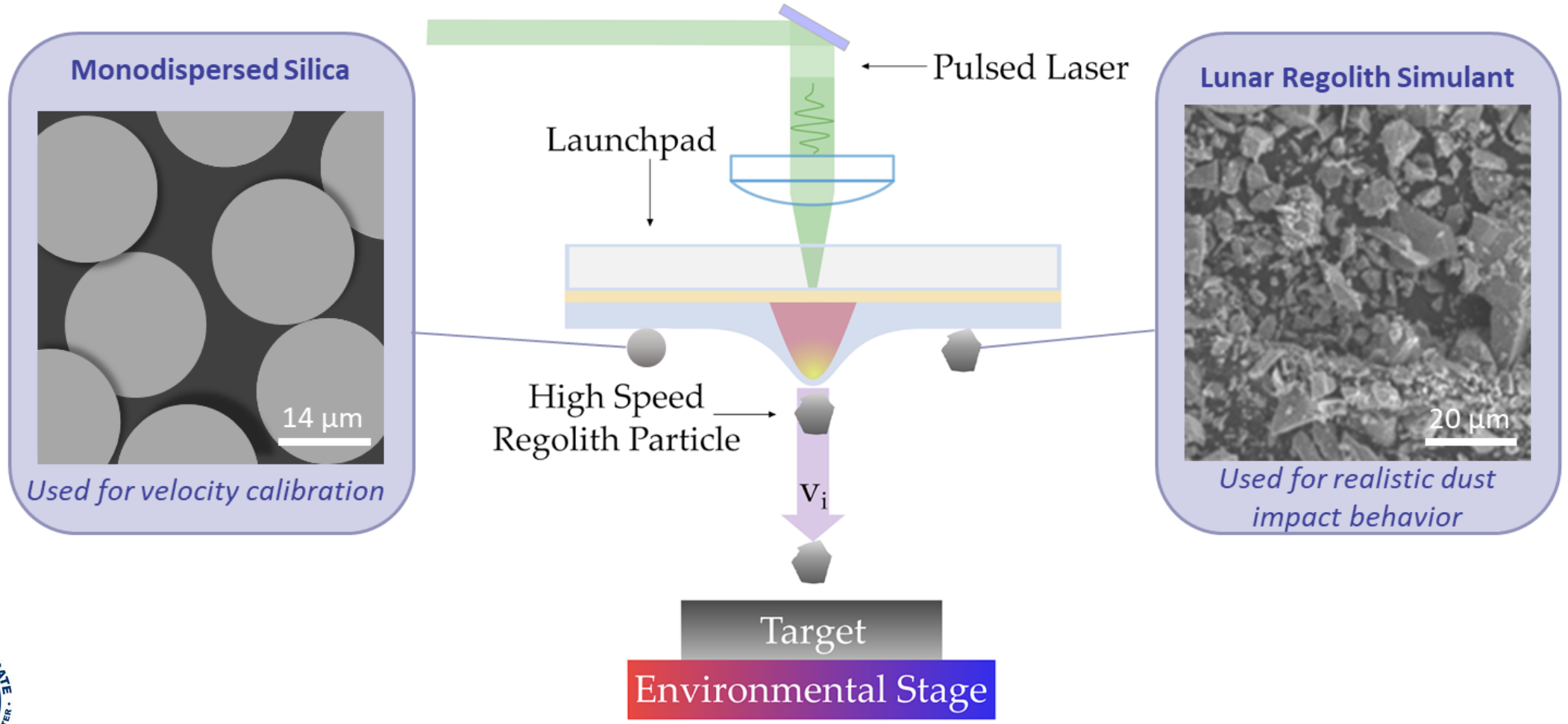
Wohl, Christopher J.; et al., "Lunar Dust Considerations for Vertical Solar Arrays, Volume 1: Lunar Environment and Dust Interactions," NASA Technical Memorandum, 2024, TM-20240003496.



Apollo 12 extravehicular activity (EVA) showing Apollo 12 Lunar Module and Surveyor 3 spacecraft

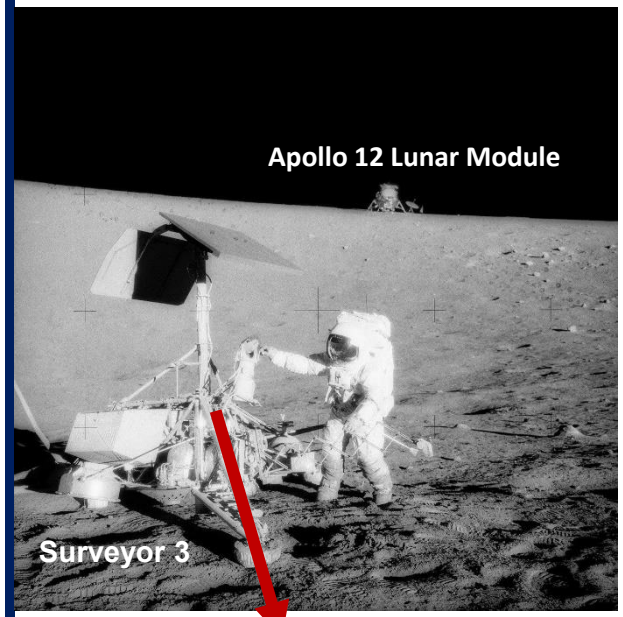
Image credit: NASA

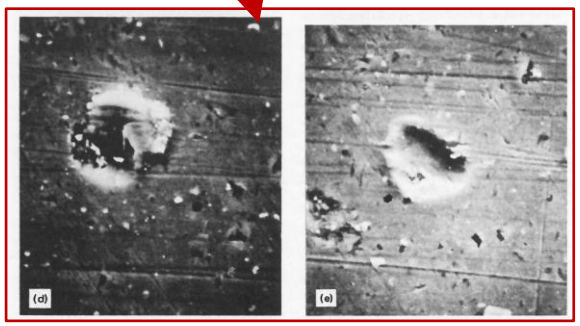
PSI Laser-Induced Projectile Impact Testing (LIPIT)



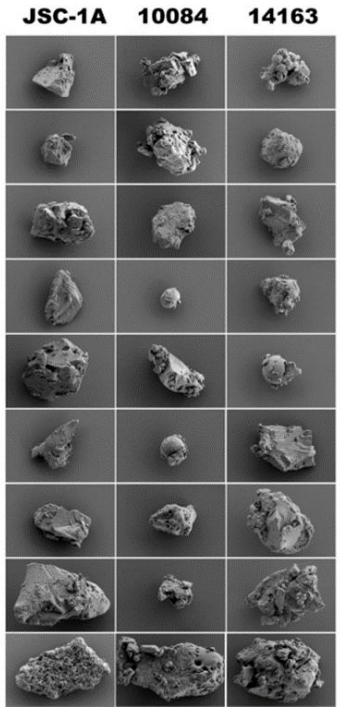
Predictive Modeling of Material Degradation from PSI Studied Via Regolith Particle Impact

Apollo 12 landing ~600 ft caused damage to Surveyor 3 spacecraft





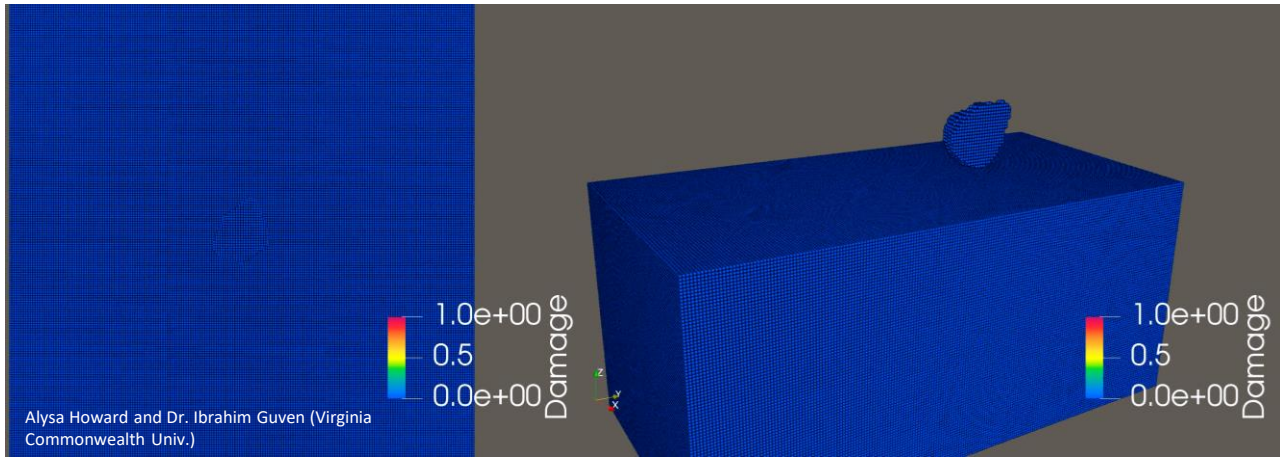
Craters were filled with lunar soil, indicating low-velocity impacts (hundreds of m/s), not micrometeoroids (km/s)

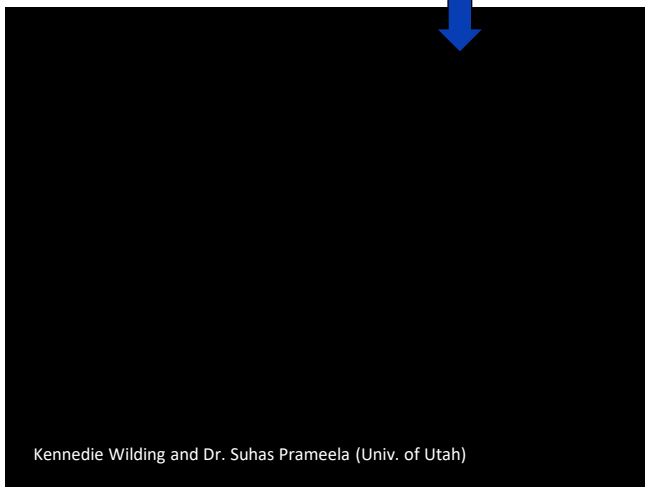




Example of an STL of Apollo 11 lunar regolith particle

Peridynamic simulation of an irregular lunar regolith particle (~15 µm) impacting AlSi10Mg at 686 m/s





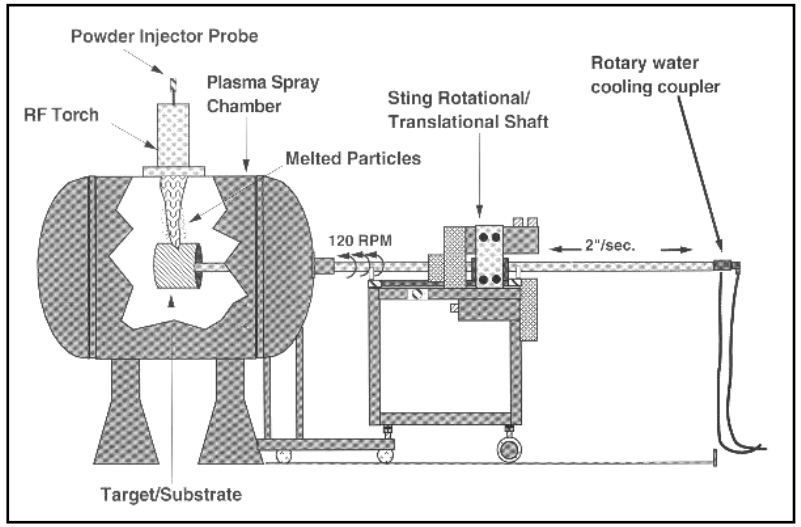
Linking impact velocity and particle geometry to crater formation, damage evolution, and fragmentation

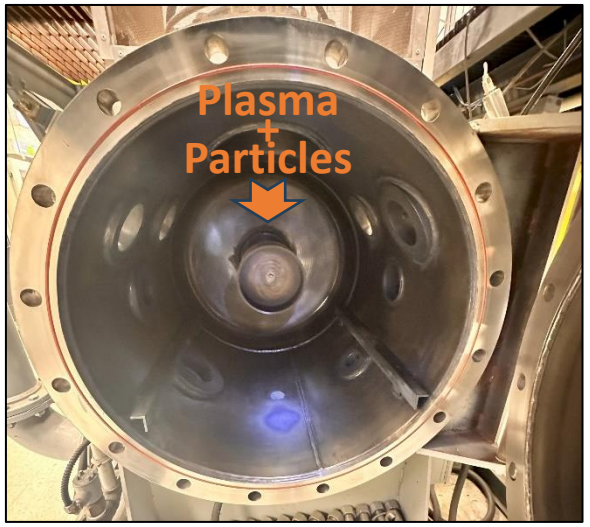
LIPIT (laser-induced projectile impact testing) experiment of a ~12 µm simulant particle impacting AlSi10Mg @ 686 m/s

Image credit: NASA

Integrated Material-PSI Assessment and Component Testing (IMPACT) Rig

Schematic of Langley Vacuum Plasma Spray System





Black Point (BP)-1 simulant flow in plasma stream
BP-1 particle size: 106 µm to 180 µm
Particle velocities: ~ 150 m/s (standard)
> 250 m/s (supersonic)
Vacuum: 10-20 mTorr | 10 Torr with plasma

Langley vacuum plasma spray (VPS) facility as testbed for material erosion under simulated lunar and Martian PSI

- Particle size range: 300 nm to ~500 µm
- Particle speed target: > 340 m/s
- Particle temperature: ambient to ~3000°C
- Vacuum level: > 10 mTorr

Ti-6Al-4V



BP-1 + standard

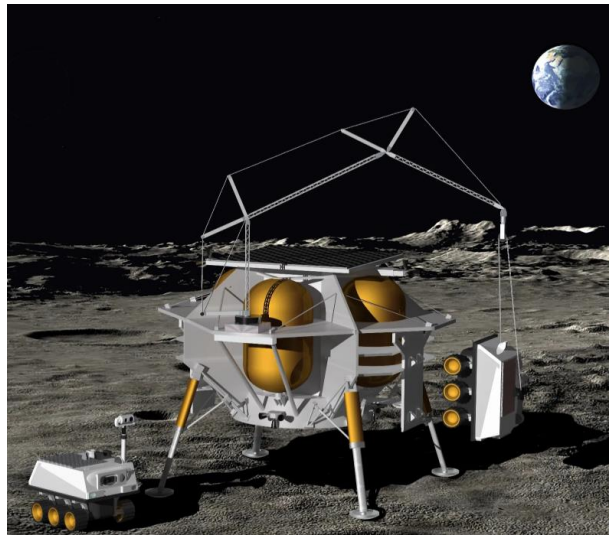


BP-1 + supersonic



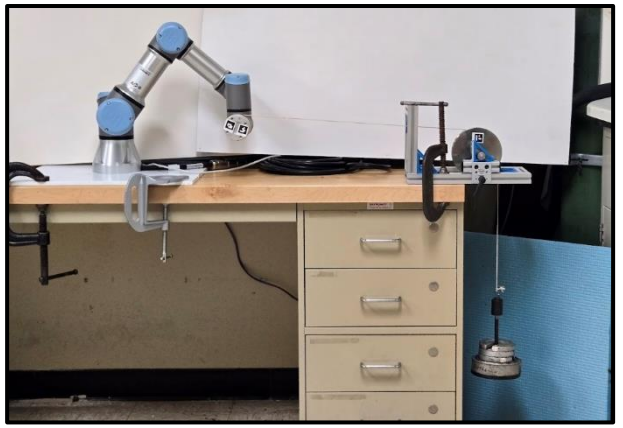
Image credit: NASA

Dust-Exposed Cables and Pulley Testing

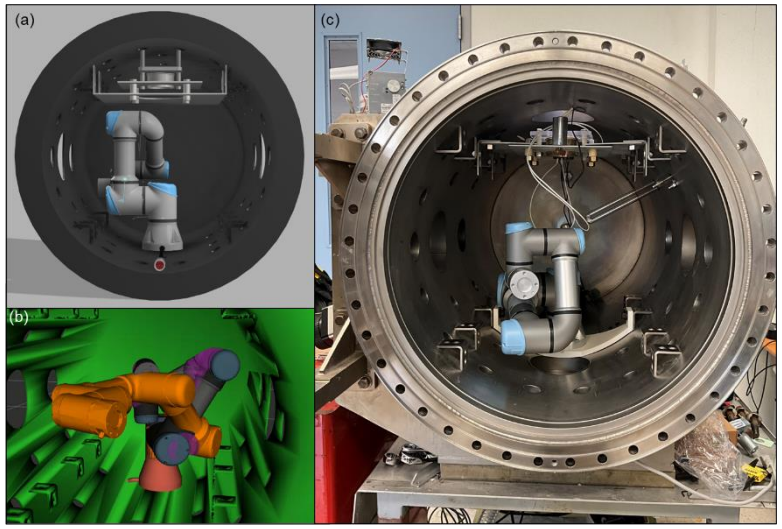


Need

Desktop

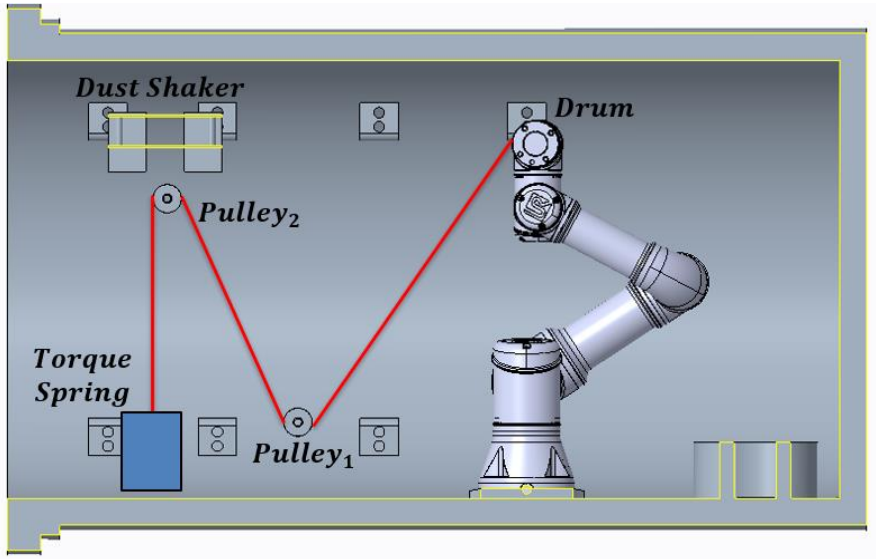


Lunar surface logistics will require cables and pulleys for offloading supplies and positioning assets

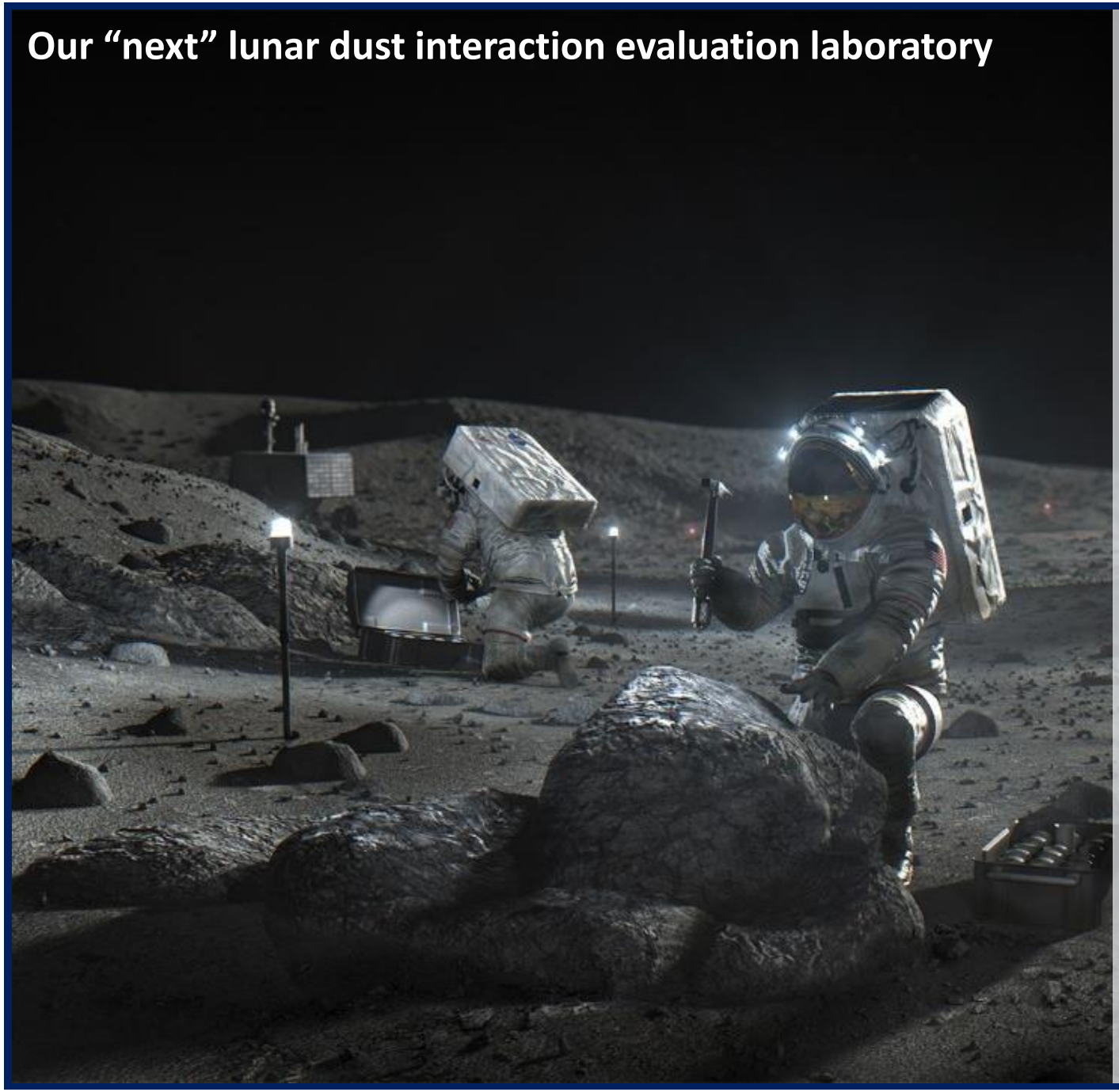


Test

Design



Our “next” lunar dust interaction evaluation laboratory



Conclusions

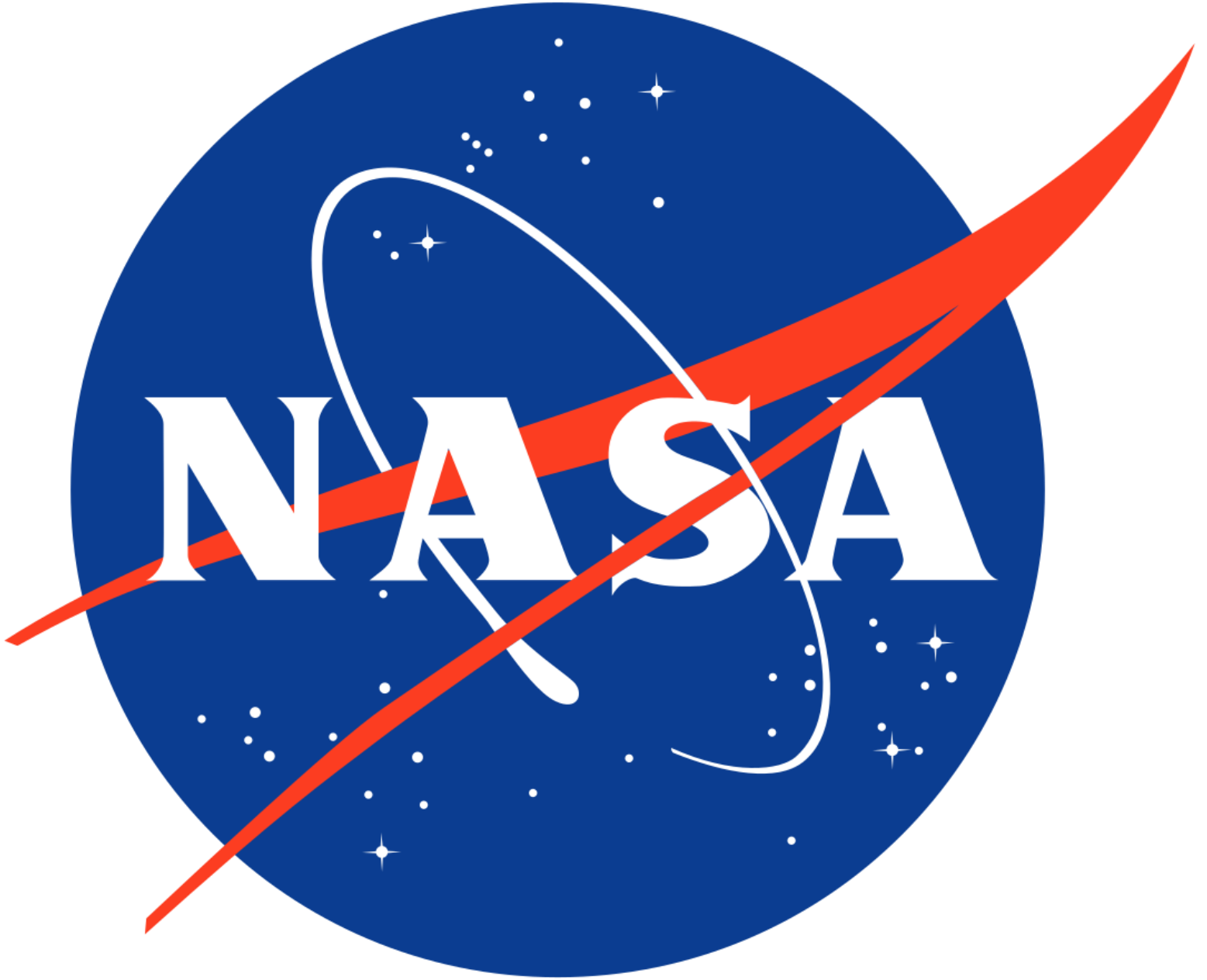
- Consideration of lunar dust influence will be necessary for nearly every aspect of activity on or near the lunar surface
- With few opportunities to evaluate materials in a lunar environment, determination of which materials are the best candidates and how to evaluate them is critical
- An array of materials and technologies will be required to address the breadth of the need for minimizing risk associated with lunar dust interactions



Acknowledgements

- Drs. Chih-Hao Chang and Arun Kota
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  - Jackson Hoekstra, OSTEM Intern, 2023
  - Eric Voigt, OSTEM Intern, 2024
- DUSTE Chamber Operators
- LIPIT Facility Operators
- IMPACT Facility Operators

Several images were created using Google Gemini


NASA