Developing Materials and Coating Technologies for Mitigation of Lunar Dust Adhesion and Abrasion

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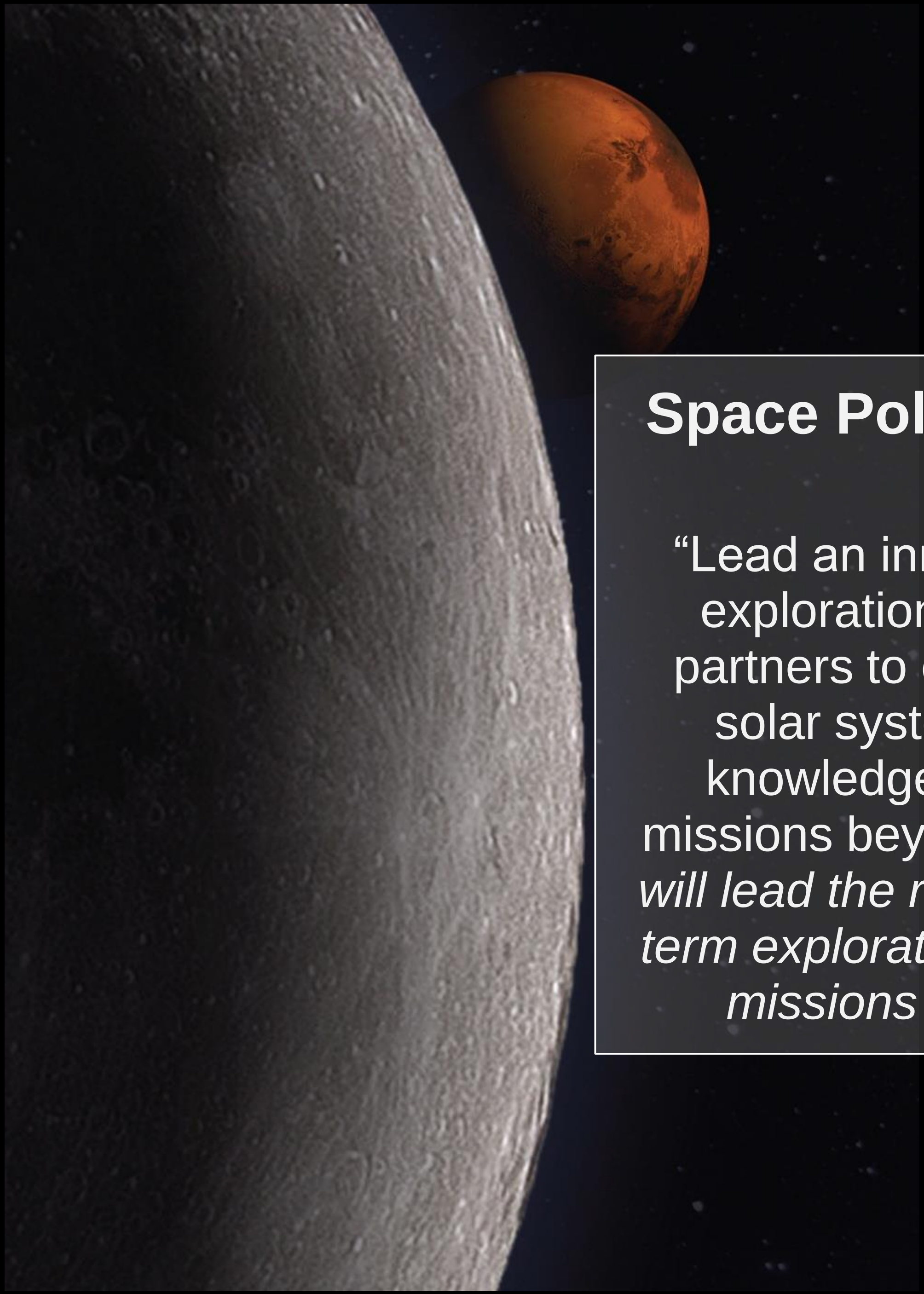
Image credit: NASA

Processing and Manufacturing Opportunities: Materials and Coatings for Lunar Applications

- **Return to the Moon**
  - Sustainable presence on lunar surface through Artemis Program
  - Moon as proving ground to enable future Mars missions
- **Lunar Surface Innovation Initiative (LSII)**
  - Goals and technologies
- **Applications and approaches to mitigate and manage dust**
  - Surface modification to minimize lunar dust adhesion
  - Lunar dust tolerant materials and coatings
- **Ongoing research and development efforts at NASA**
  - Processing and manufacturing of materials and coating technologies
    - Laser ablative patterning of material surfaces
    - Bio-inspired surface design
    - Additive manufacturing of boride-containing ternaries (MAB)
    - Wear-resilient ceramic coatings for lunar lander applications
  - Opportunities for testing and evaluation
    - Developing in-house screening capabilities
    - Patch Plate Materials Compatibility Assessment

NASA artist's depiction of the lunar surface environment. Lunar dust will impact a variety of critical technologies needed to enable a sustainable human lunar presence. [*Image credit*: NASA]

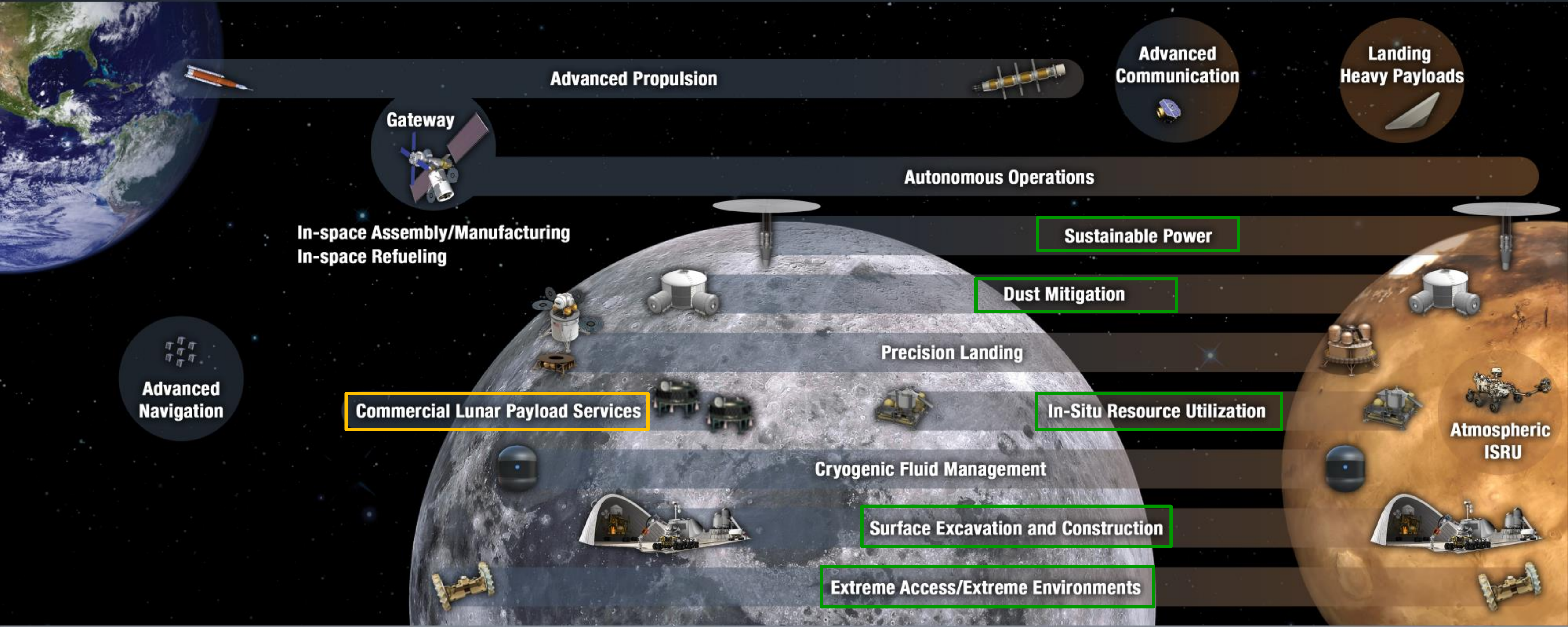


Space Policy Directive 1: To The Moon, Then Mars (2017)

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, *the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations*…"

Forward to the Moon: NASA's Strategic Plan for Human Exploration (2019).

GO	LAND	LIVE	EXPLORE
Rapid, Safe, and Efficient Space Transportation	Expanded Access to Diverse Surface Destinations	Sustainable Living and Working Farther from Earth	Transformative Missions and Discoveries



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Lunar Surface Innovation Initiative (LSII)

Image credit: NASA

Lunar Surface Innovation Initiative (LSII)

In Situ Resource Utilization

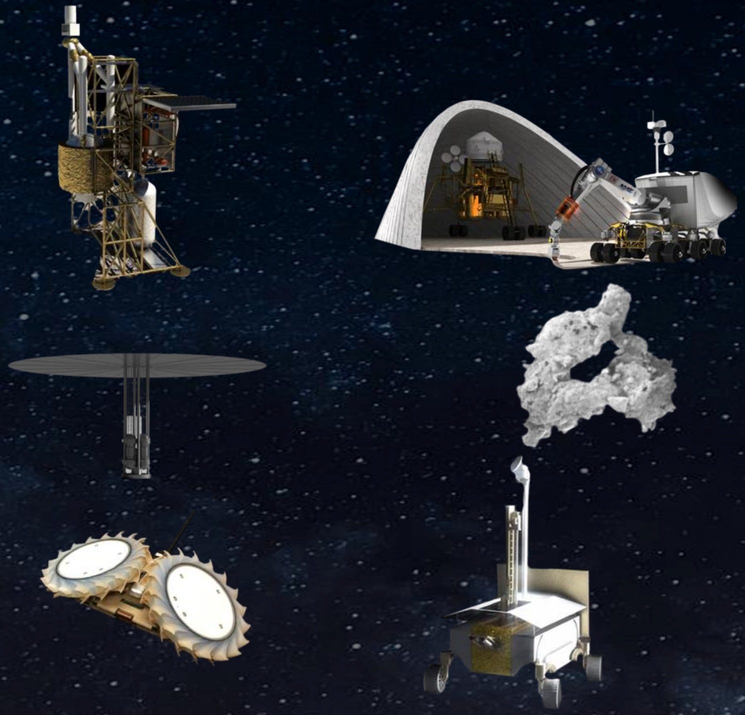
Collection, processing, storing and use of material found or manufactured on other astronomical objects

Sustainable Power

Enable continuous power throughout lunar day and night

Extreme Access

Access, navigate, and explore surface/subsurface areas



Surface Excavation/Construction

Enable affordable, autonomous manufacturing or construction

Lunar Dust Mitigation

Mitigate lunar dust hazards

Extreme Environments

Enable systems to operate through out the full range of lunar surface conditions

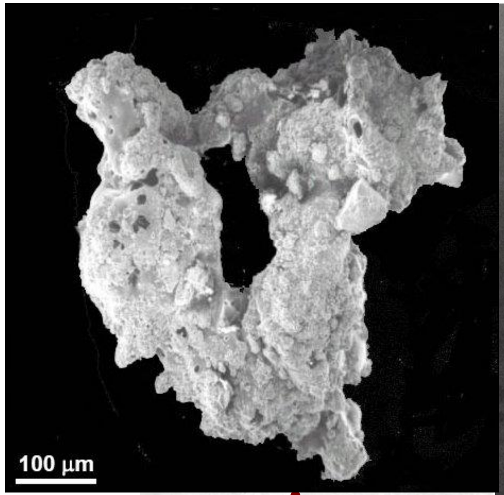
- STMD LSII will develop the technologies required for establishing lunar infrastructure across these six primary capability areas
- LSII will accelerate technology readiness for key components and systems and provide early technology demonstrations which will help to inform relatively early uncrewed commercial missions, as well as development of crewed flight systems

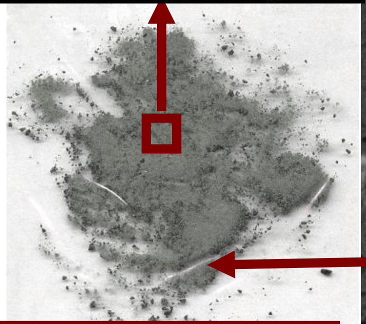
Image credit: NASA

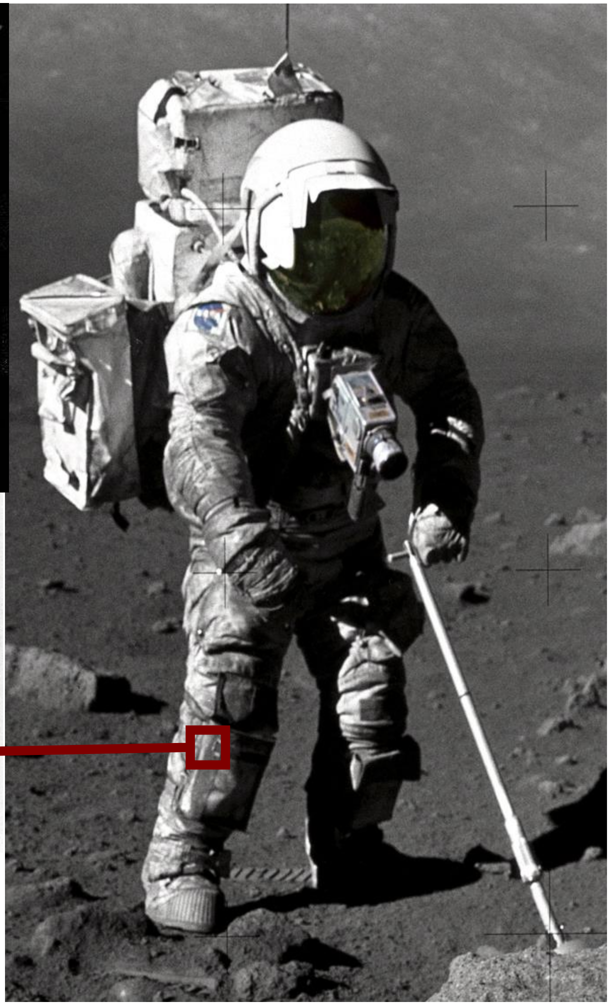
Lunar Dust Composition and Characteristics

Composition: 50wt.% SiO_2, 15wt.% Al_2O_3, 10wt.% CaO, 10wt.% MgO, 5wt.% TiO_2 and 5-15wt.% Fe

- Composition varies depending on location [1]
  - Lesser amounts of sodium, potassium, chromium and zirconium
  - Trace amounts of virtually all elements from ppb to ppm level
  - Mixture of crystalline and amorphous material
- Particle properties [2]
  - Particle size varies from nm to mm; range of primary concern 1-100μm-sized particles
  - Nominal density ~1.5g/cm^3
  - Irregular, jagged morphology
  - Electrically charged





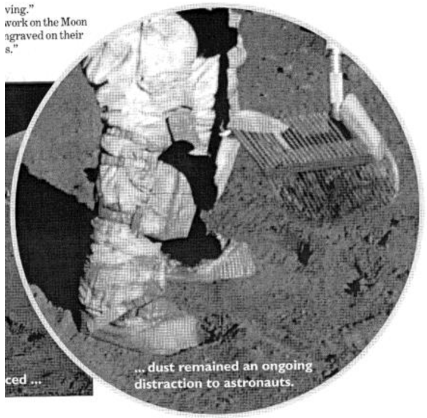


Preventing dust adhesion to spacesuits and equipment will be a critical component of safety and success of future lunar surface exploration missions

Image Credits **Top :** David McKay, NASA/JSC, **Middle:**http://www.bccmeteorites.com/image7L5.JPG, **Bottom:** NASA JSC: AS17-137-20979
[1] D.J. Loftus, et al., “The Chemical Reactivity of Lunar Dust Relevant to Human Exploration of the Moon,” *Planetary Science Division Decadal Survery white paper* (2020).
[2] C. Meyer, NASA Lunar Petrographic Thin Section Set (2003).

Lunar Dust Influence on Apollo Missions

- Lunar dust interfered with several different aspects of the Apollo missions
  - False instrument readings, clogging, thermal control issues, vision impairment, loss of foot traction, inhalation hazards, etc.
- Adhesion due to various forces
  - Mechanical interlocking, chemical bonding, Van der Waals forces, electrostatic and Coulombic interactions, donor-acceptor (acid-base) interactions
- Abrasion and wear caused by disturbing lunar dust layer
  - Walking and vehicle operation
  - Sampling and mining activities
  - Plume-surface interactions during and after lunar landing events



NASA HQ GRIN: GPN-2000-001124

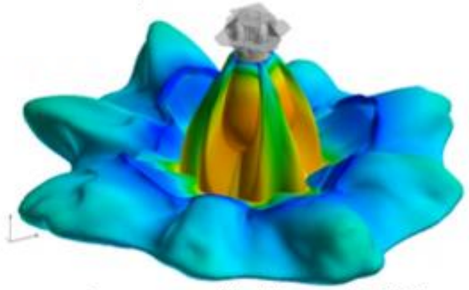
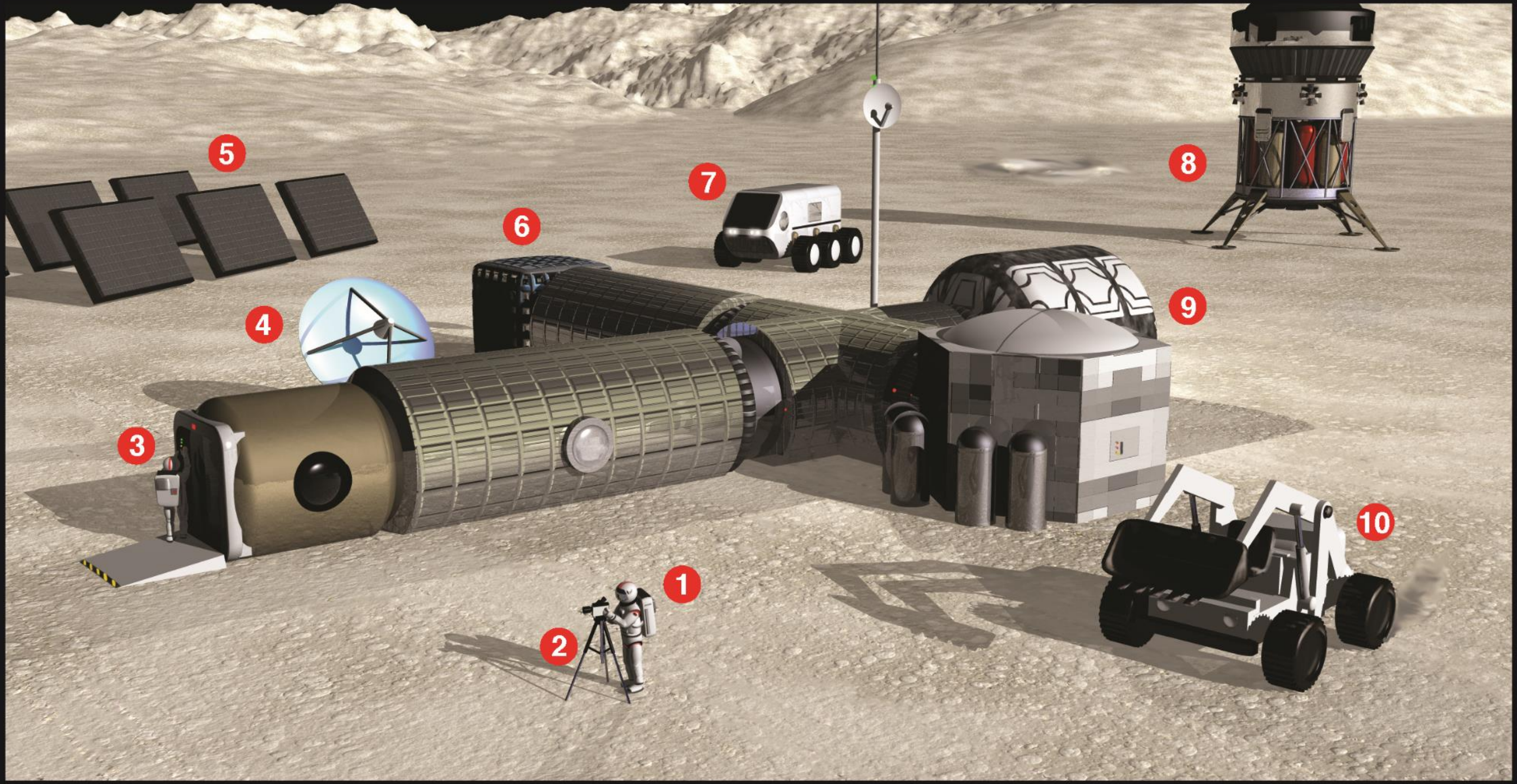


Image credit: Liever (2019)

Bell, T.; Phillips, T., “Don’t Breathe the Moondust,” in *Science@NASA* (2005).
J. Adhesion Sci. Technol. **1995**, *9(8)*, 1103.

Target Applications in Lunar Environment



Lunar Dust Adhesion Mitigation Opportunities and Needs

1. **Environment suits** Visors, joints, controls
2. **Sensing / optical equipment** Lenses, sensors, connectors
3. **Airlocks** Door seals, interior surfaces, controls
4. **Communications equipment** Dish surfaces, sensors
5. **Solar arrays** Panel surfaces
6. **Power distribution equipment** Connectors, radiators
7. **Lunar rovers** Gears, bearings, shafts, screens, radiators, instrumentation
8. **Lander / Landing site** Hatches, instrumentation, fueling equipment
9. **Habitat** Joints / seals / interlocks
10. **Excavating equipment** Bearings, controls, gears

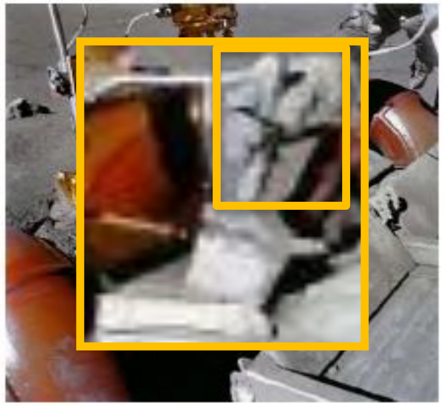
Image credit: NASA

- Enable sustainable human presence by leveraging materials and coating technologies to ***mitigate*** and/or ***manage*** lunar dust
  - **Lunar rover mechanisms:** gears, bearings, shafts
  - **Lander:** lander legs, hatches
  - **Habitat:** joints, interlocks
  - **Excavating equipment:** bearings, gears

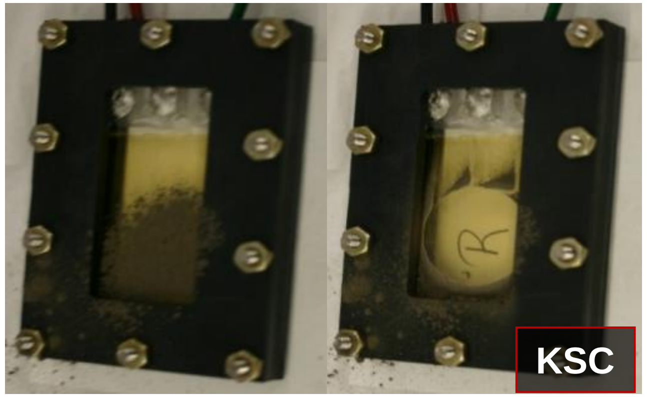
Approaches to Dust Mitigation

- Primary technologies for lunar dust mitigation based on following strategies:
  - **Active**: requires power consumption and/or mechanical actuation
  - **Passive**: surface/topological modification, dust tolerant materials and coatings
  - Combination of active and passive methods

Active Mitigation Strategies

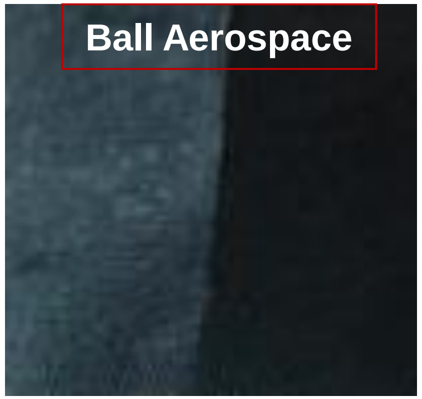


Brushes, Magnetic Wands

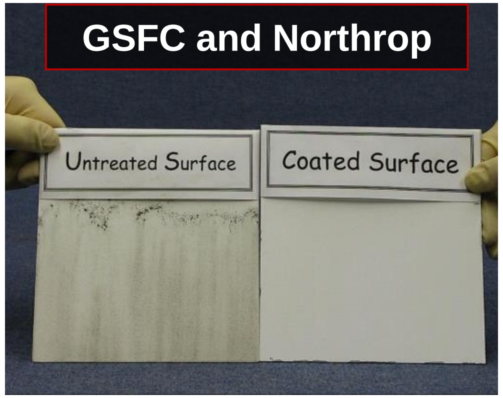


Electrodynamic Dust Screen

Passive Mitigation Strategies



Low Surface Energy Coatings



Lotus Coatings

Image credit clockwise from top left: NASA, KSC, Ball Aerospace, D.V. Margiotta, et al." Society of Photo-optical Instrumentation Engineers (SPIE) Conference Series, vol. 7794(2010)

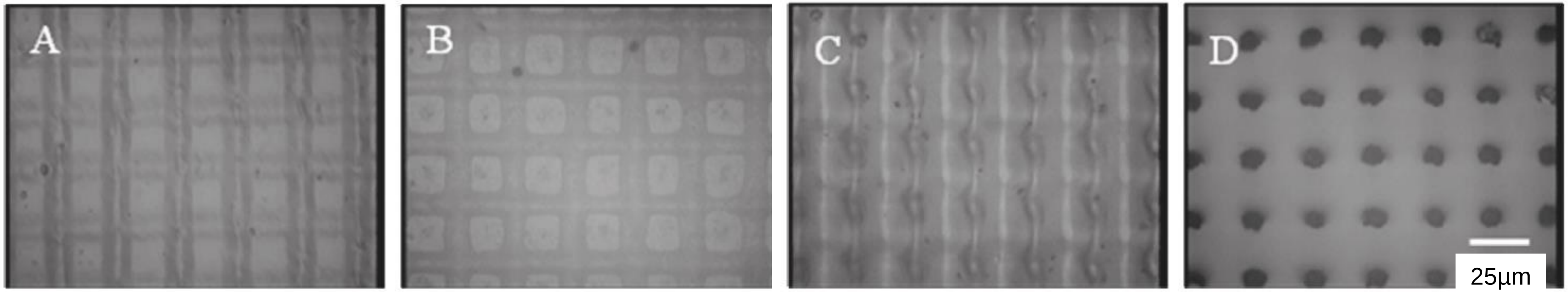
Processing and Manufacturing Opportunities: Materials and Coatings for Lunar Applications

- Lunar dust mitigation by surface modification to minimize lunar dust adhesion
  - Laser ablative patterning of surfaces
  - Bio-inspired surface design
- Lunar dust tolerant materials and coatings
  - Additive manufacturing of boride-containing ternaries (MAB)
  - Wear-resilient ceramic coatings for lunar lander applications
- Evaluating performance of passive mitigation technologies in lunar environment
  - Patch Plate Materials Compatibility Assessment

Left and middle image credit: NASA
Right image credit: http://www.theartblog.org/wp-content/uploaded/sachslunarlandingmodule.jpg

Laser Ablative Patterning

- Pattern material surface using laser to engineer surfaces to minimize lunar dust adhesion
  - **Laser parameters**: wavelength, power, beam diameter, scan speed
  - Tunable to different material substrates
    - Polymers
    - Metals
    - Ceramics
  - Variety of achievable patterns with resolution depending on laser system



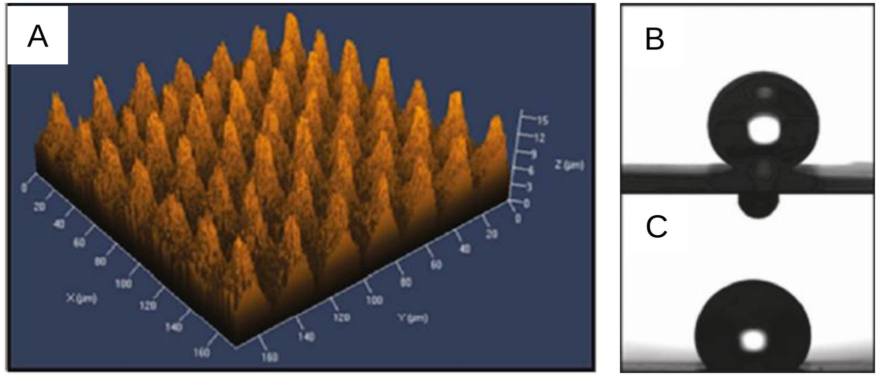
Optical micrographs of laser ablation patterned (LAP) (A), (C) Kapton HN and (B), (D) copoly(imide siloxane)s highlighting some of the achievable LAP patterns depending on laser parameters

Data and image credit: C. Wohl, et al., *Langmuir*, 26(13), 11469-11478 (2010).

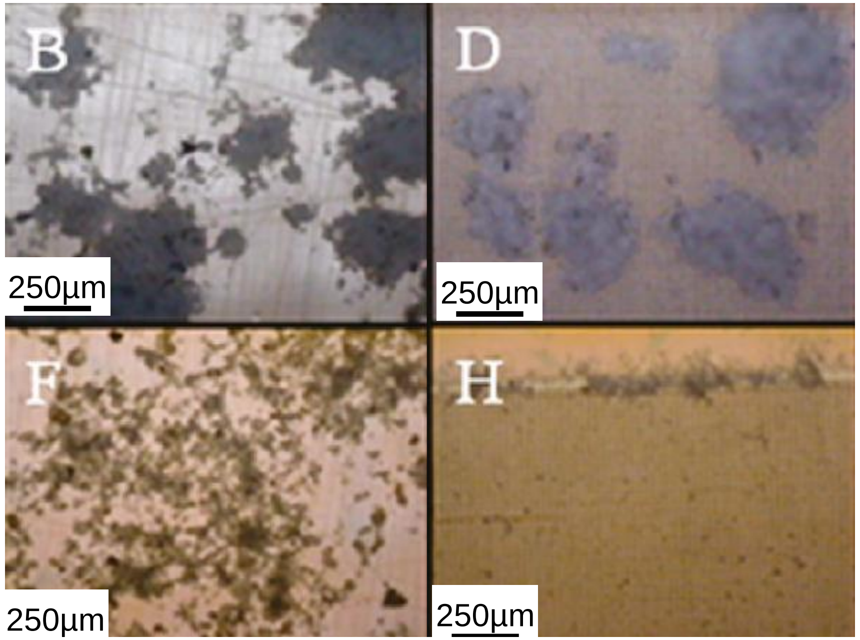
Laser Ablative Patterning: Polymers

- **Copoly(imide siloxane)s**
  - PhotoMachining, Inc. laser ablation system with Coherent Avia frequency-tripled Nd:YAG laser with λ=355nm, average power=7W
    - Laser beam diameter= 25 μm
    - Scan speed=25.4 cm/s
    - Line spacing=25 μm
- ➢ Superhydrophobic pattern
  - Demonstrated reduced lunar dust adhesion after laboratory-based lunar dust simulant adhesion performance experiments

Translating promising results with polymers to metals and ceramics and exploring new patterns



Before lunar dust simulant adhesion performance testing



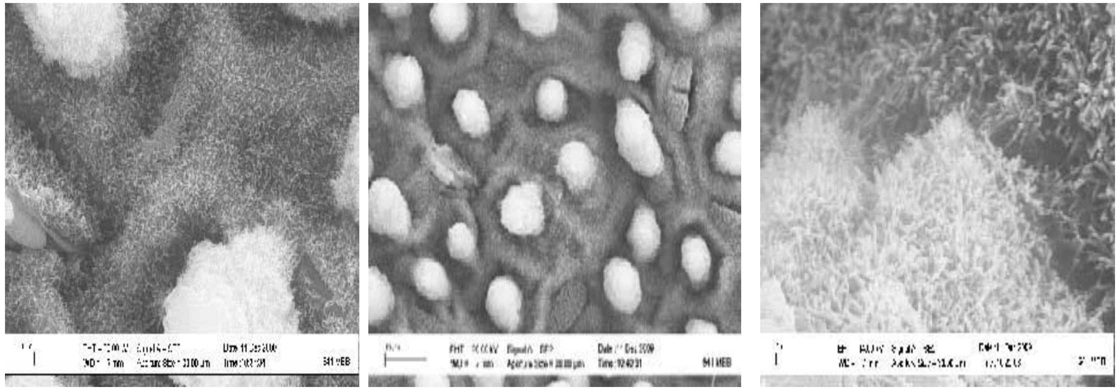
After lunar dust simulant adhesion performance testing

Data and image credit: C. Wohl, et al., *Langmuir*, 26(13), 11469-11478 (2010).

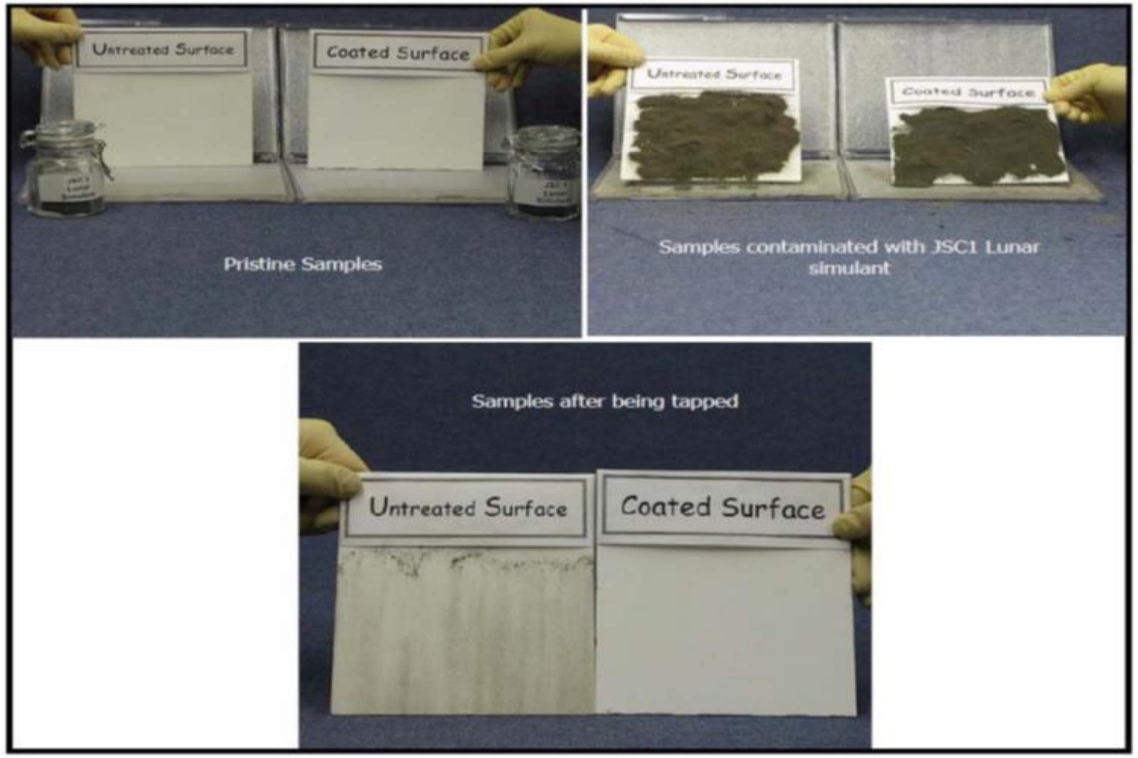
Bio-Inspired Surface Design to Minimize Adhesion

- Biological surfaces could inspire designs to minimize lunar dust adhesion by promoting surface hydrophobicity
  - ➢ Lotus leaf

Lotus leaf surface naturally repels water [Image from[1]]



SEM images of lotus leaf's nanostructures [Image from [2]]



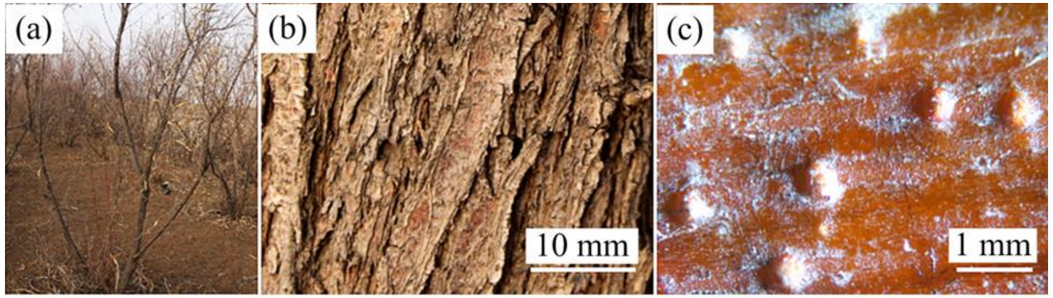
Anti-Contamination/self-cleaning properties assessment of untreated and treated Lotus coated radiator samples [Image from [2]]

[1] www.biomimicrybe.org/portfolio/lotus-leaf-inspired-texiles/

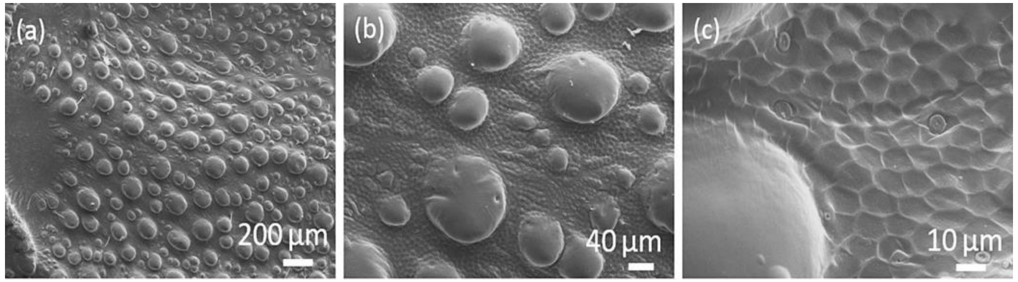
[2]: D.V. Margiotta, W.C. Peters, S.A. Straka, M. Rodriguez, K.R. McKittrick, C.B. Jones, "The Lotus coating for space exploration: a dust mitigation tool," Society of Photo-optical Instrumentation Engineers (SPIE) Conference Series, vol. 7794(2010)

Bio-Inspired Surface Design to Minimize Wear

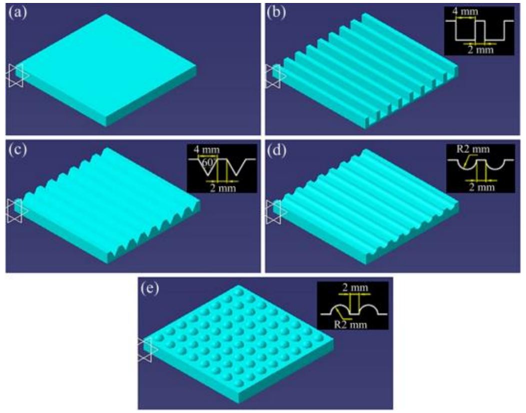
- Biological surfaces could inspire wear- and erosion-resistant design
  - ➢ Tamarisk plant
  - ➢ Desert Scorpion carapace



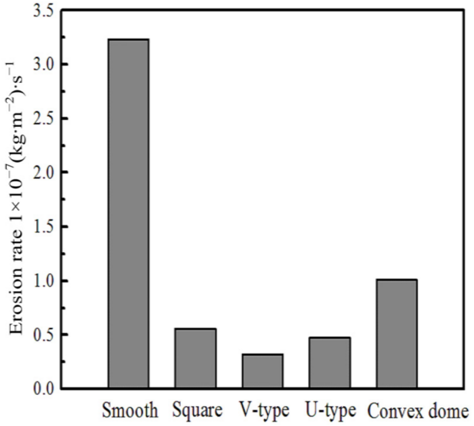
(a) Tamarisk (b) grooves and (c) convex domes on tamarisk trunk surface. [Images in [1]]



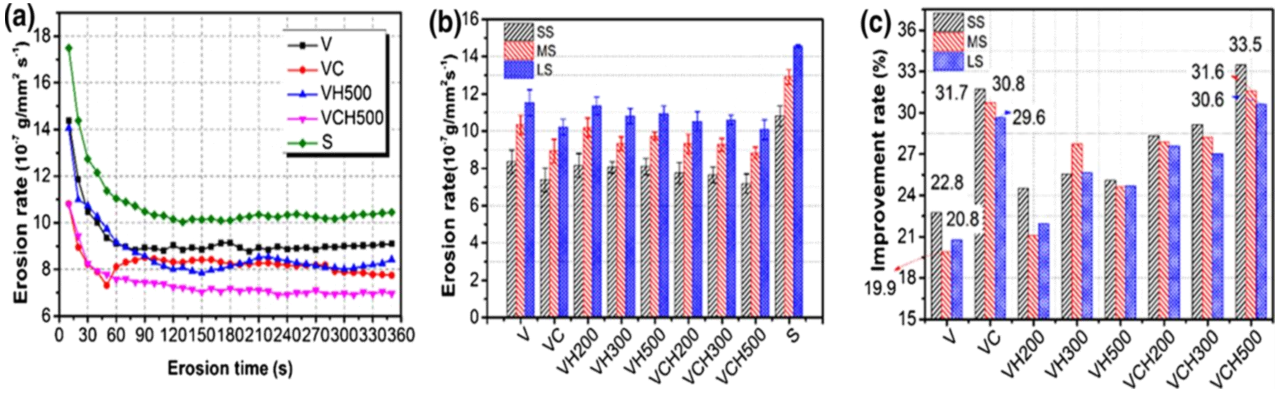
The gradually enlarged microstructures of the back of desert scorpion *Androctonus australis* by SEM. [Micrographs in [2]]



Bionic models according to the tamarisk surface morphology, grooves, and convex domes. [Images in [1]]



Erosion wear rates of the different surface morphologies. [Images in [1]]



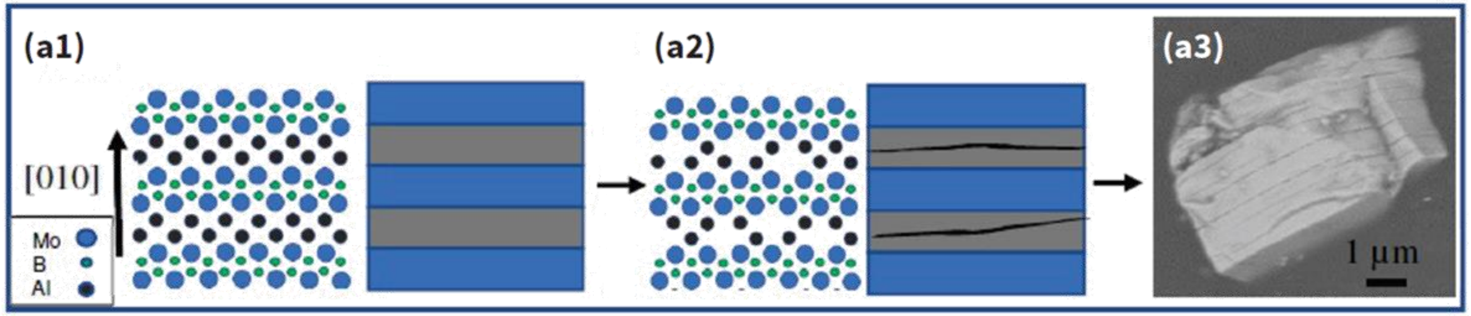
a) The erosion rate of the samples changes with erosion time; b) the erosion rate of the eroded samples under the impact of three kinds of different solid particle sizes; c) the improvement rate of the eroded samples under the impact of three kinds of different solid particle sizes. [Charts in [2]]

[1]: Zhiwu Han, Wei Yin, Junqiu Zhang, Jialian Jiang, Shichao Niu, Luquan Ren, "Erosion-Resistant Surfaces Inspired by Tamarisk", Journal of Bionic Engineering,10(2013)

[2] Junqiu Zhan, Wenna Chen,Mingkang Yang,Siqi Chen, Bin Zhu,Shichao Niu, Zhiwu Han, Huiyuan Wang, "The Ingenious Structure of Scorpion Armor Inspires Sand-Resistant Surfaces", Tribology Letters(2017)

Additive Manufacturing of Boride-Containing Ternaries

- Boride-containing ternaries based on chemical formula $(MB)_2Al_y(MB_2)_x$, referred to as MAB phases:
  - Molybdenum aluminum boride (MoAlB)
    - High toughness and hardness
    - Lower density than metals
    - Thermal shock resistance
  - Fabrication route of MAB particulates by University of North Dakota

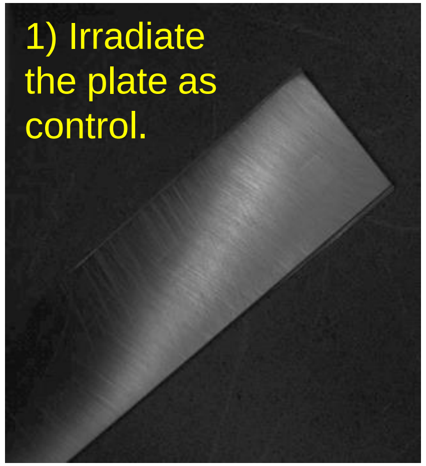


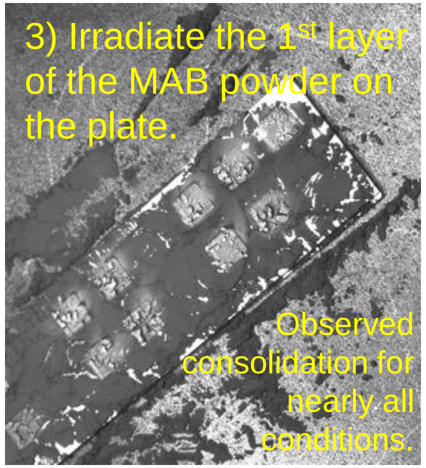
(a1) MA template, (a2) partial etching of MAB and (a3) image of MAB particulate that will be used to additively manufacture parts [from Gupta 2019]

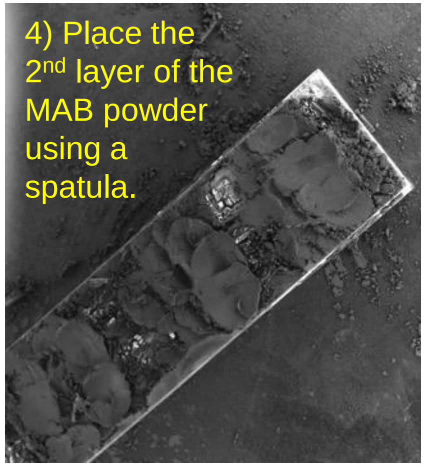
- Laser powder bed deposition (LPBD) using Configurable Architecture Additive Testbed (CAAT) system at NASA Langley Research Center

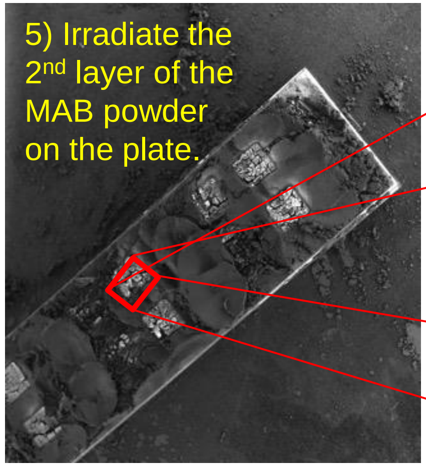
S. Gupta, M. Dey, *Advanced Materials and Processes*, (Feb/March 2019).

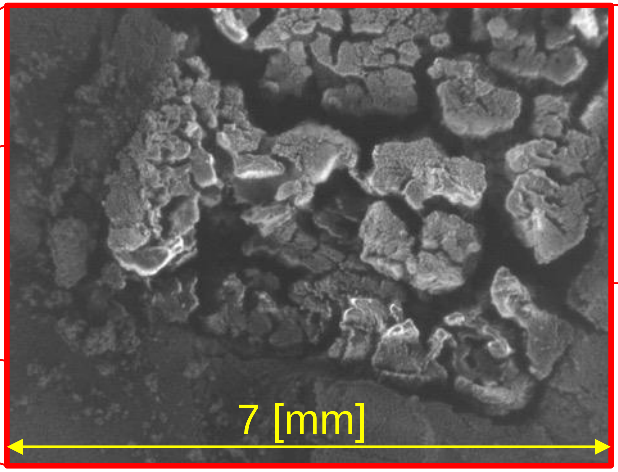
Additive Manufacturing of Boride-Containing Ternaries









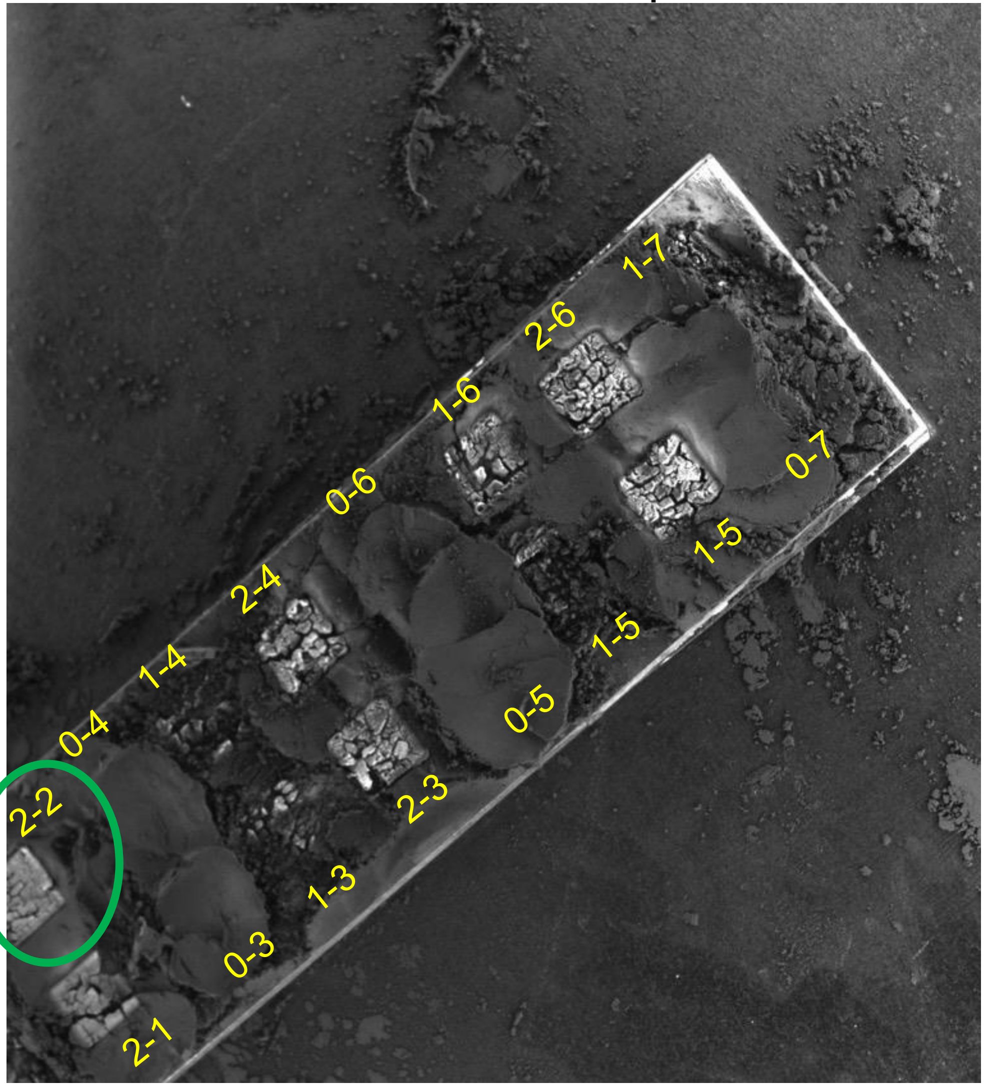


ID# 2-4: Consolidation observed, but high degree of heat cracking.

S. Hocker, unpublished results (2020).

LPBD of MAB Particulates

Post-Process in-situ photo



Process: in-situ video

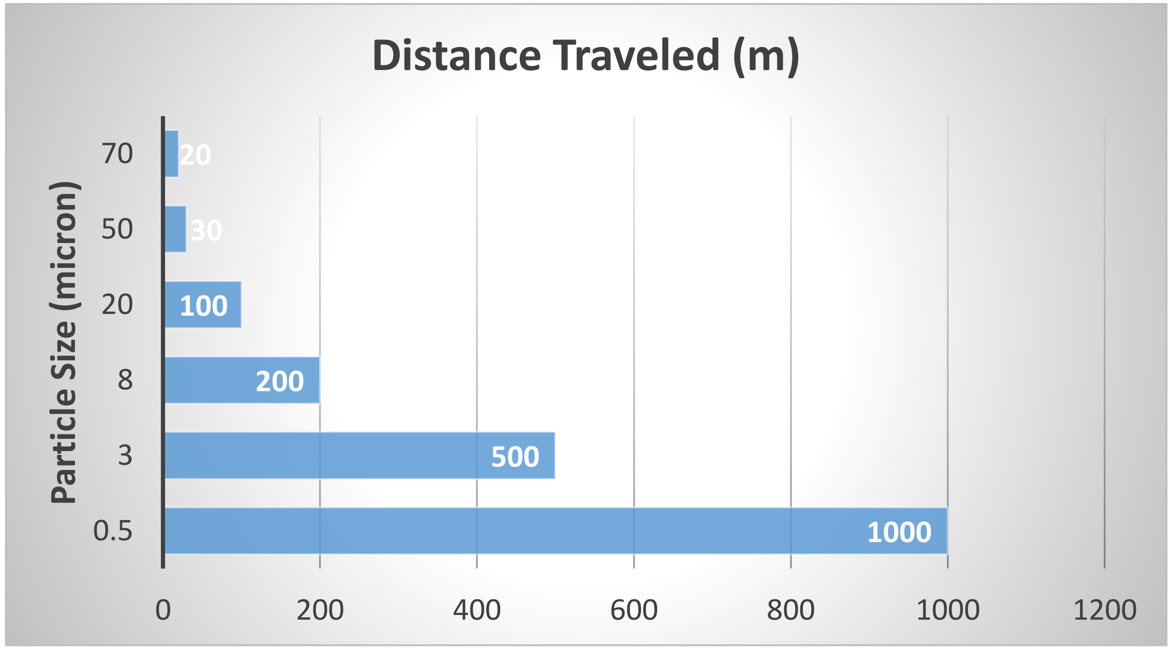
- Evaluating LPBD parameters to enable MAB consolidation on Ti-6Al-4V substrate
  - Power
  - Scan speed
  - Number of layers

➢ Preliminary results of LPBD experiments show promising results for additively manufacturing MAB parts
  - Powder size and morphology of MAB particulates

S. Hocker, unpublished results (2020).

Plume-Surface Interactions during and after Lunar Landing Events

- Limited experimental data on lunar dust particle velocities and angles of impingement
  - Nano- to micro-sized particle sizes
  - Within 50m of landing site, particle velocity estimates 300-2000m/s



Lunar Surface Wear Map: https://plumesurfacewearmap.larc.nasa.gov/ (internal)

Wear-Resilient Coatings for Lunar Lander Legs

- Ceramic-based coatings to protect underlying metallic substrate from lunar dust abrasion/wear
  - Goal: Demonstrate enhanced performance with coating versus pristine metal
- Coatings prepared by plasma spray and chemical vapor deposition (CVD)

- Assessing performance in more representative environments
  - Taber wear
  - Hardness (RT and cryo)
  - Lunar dust adhesion
  - Wear under vacuum
  - Particulate erosion rig

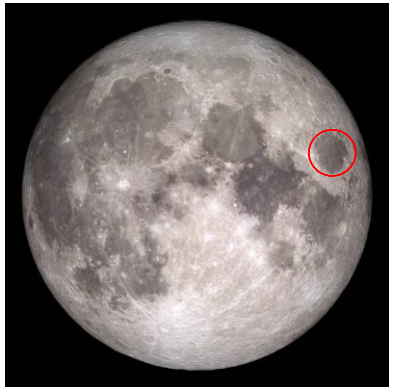
Material	Density (g/cm^3)	YM (Pa)	Vickers Hardness	Fracture Toughness ($Pa.m^{0.5}$)	Thermal Expansion Coefficient (Strain/C)
Substrate Materials					
Ti-6Al-4V	4.43	1.15E+11	366	1.14E+8	9.10E-6
Aluminum 2219	2.87	7.57E+10	121	4.50E+7	2.38E-5
Coating Candidate Materials					
Alumina (95)	3.76	3.20E+11	1850	4.50E+6	8.30E-6
Boron Carbide	2.53	4.72E+11	4200	3.00E+6	9.40E-6
Chromium Oxide	5.22	8.00E+10	1200	-	3.70E-6

Image credit: http://www.theartblog.org/wp-content/uploaded/sachslunarlandingmodule.jpg

Patch Plate Materials Compatibility Assessment

Evaluating performance of passive mitigation materials technologies in lunar environment

- Multicenter task focuses on developing passive methods for reducing lunar dust adherence to surfaces to address the technology gap of efficiently and effectively removing lunar dust from power systems, radiators, space suits, visors, sensor lenses and other critical surfaces
- Passive technologies include low surface energy coatings, work function matching coatings, chemically modified surfaces, patterned surfaces, and ceramic surfaces
- Goal is to further develop these technologies by ground testing in relevant environments culminating in a flight experiment for technology demonstration
- Recent accomplishments
  - Draft science requirements for flight experiment collected and consolidated
  - Dust adhesion sample proposals submitted for additional flight opportunity on Alpha Space RAC platform, going to Mare Crisium on CLPS lander in 2023
- Ongoing activities plans
  - Develop technologies and test in ground-based relevant environments
  - Complete flight experiment design



Mare Crisium as potential CLPS lander site in 2023 [*Image credit*: NASA]

Concept drawing of experiment on leg of CLPS lander [*Image credit*: NASA]

Processing and Manufacturing Opportunities: Materials and Coatings for Lunar Applications

- Exploring variety of processing and manufacturing opportunities for materials and coatings to enable lunar applications
  - Laser ablative patterning of polymeric, metallic and ceramic surfaces
  - Bio-inspired surface design
  - Additive manufacturing of boride-containing ternaries (MAB)
  - Wear-resilient ceramic coatings for lunar lander applications
- Evaluation performance of passive mitigation materials technologies in lunar environment
  - Developing in-house screening capabilities, including vacuum chamber for wear testing and system performance as a result of simulant exposure
  - Patch Plate Materials Compatibility Assessment

Image credit: NASA

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ARTEMIS

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