Protective Coatings for Mitigating Lunar Dust Abrasion and Adhesion

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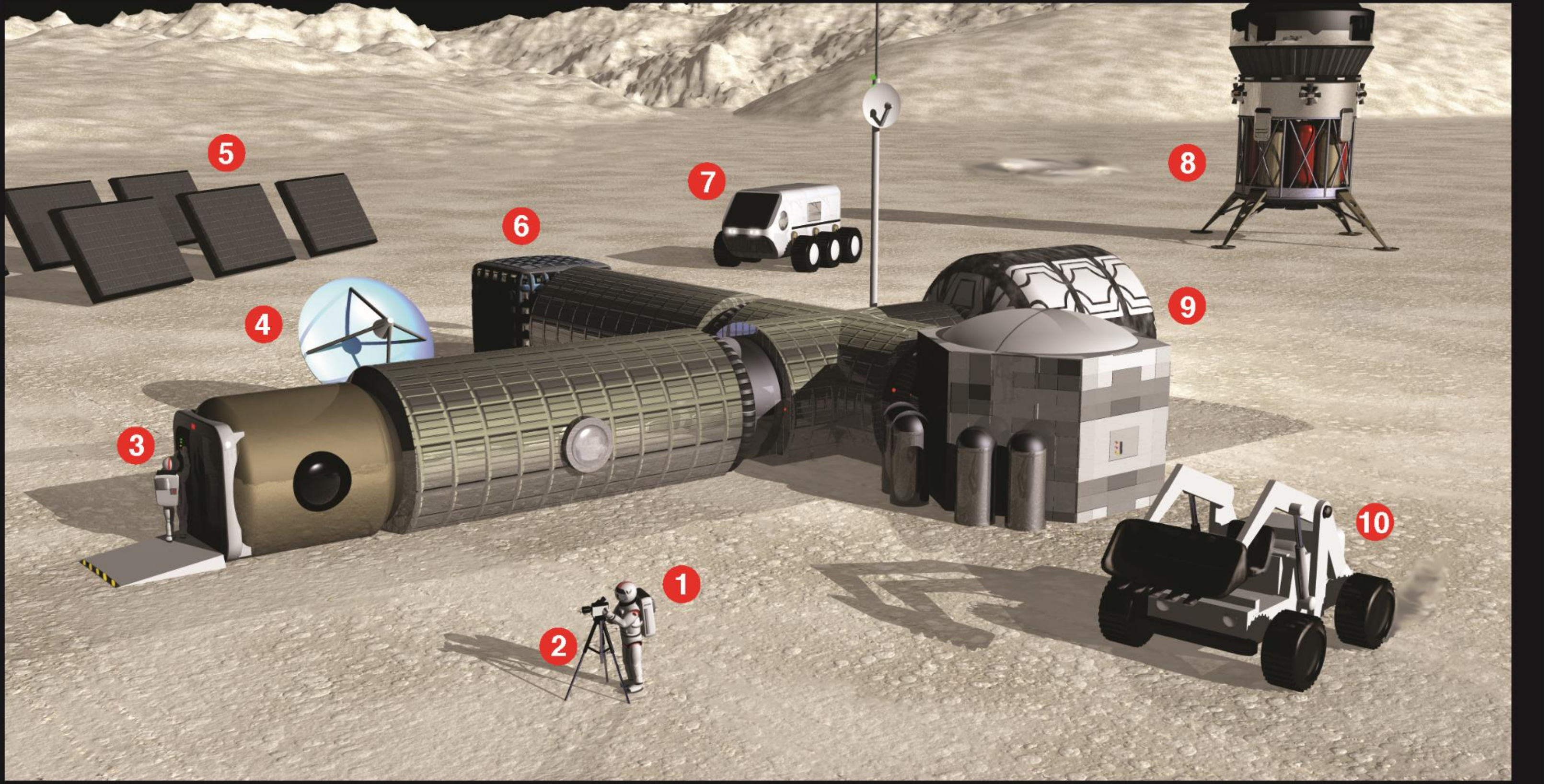
Image credit: NASA

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

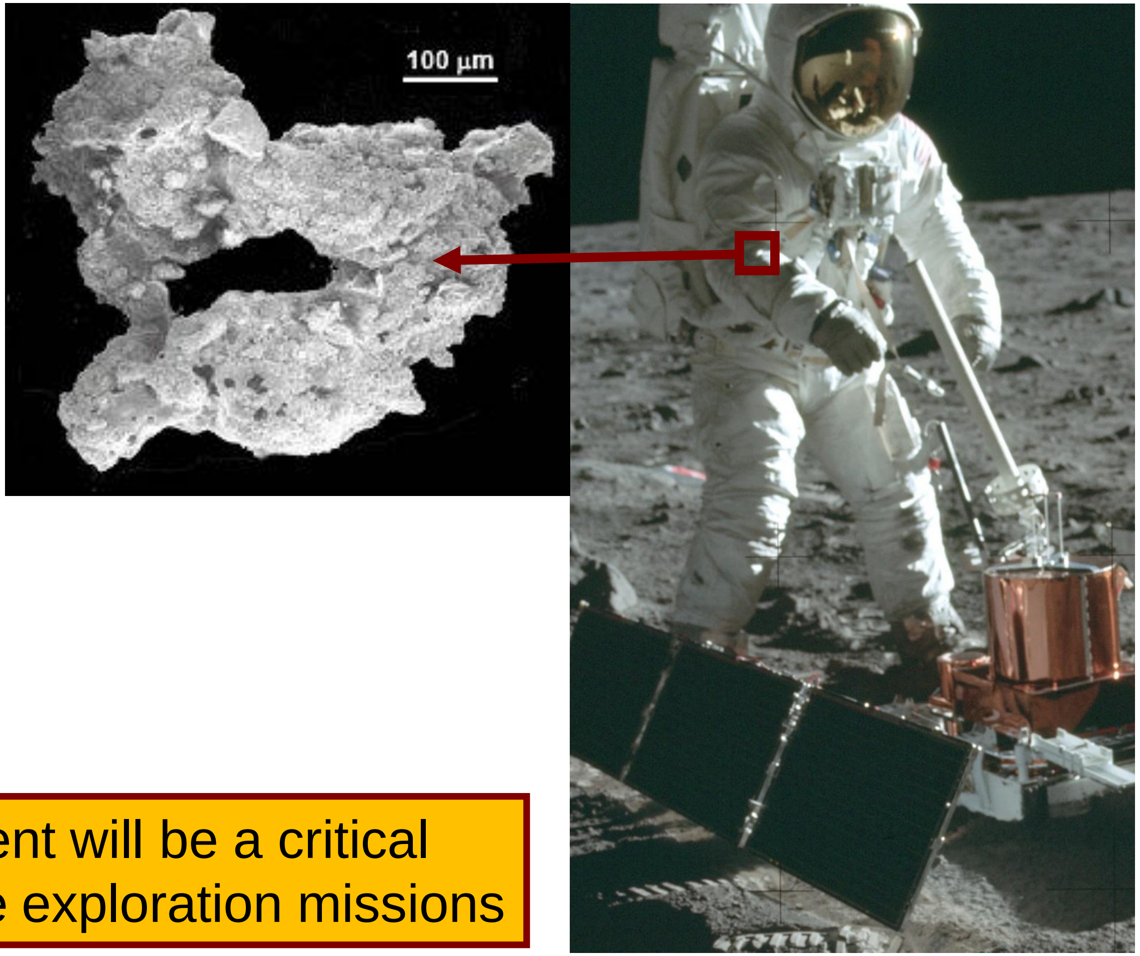
Image credit: NASA

- 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

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

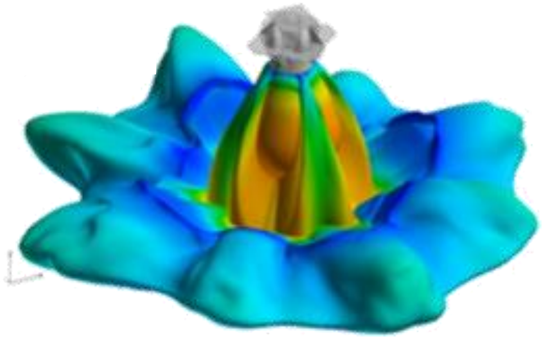
Image Credits Left: NASA **Right:** NASA AS11-40-5951

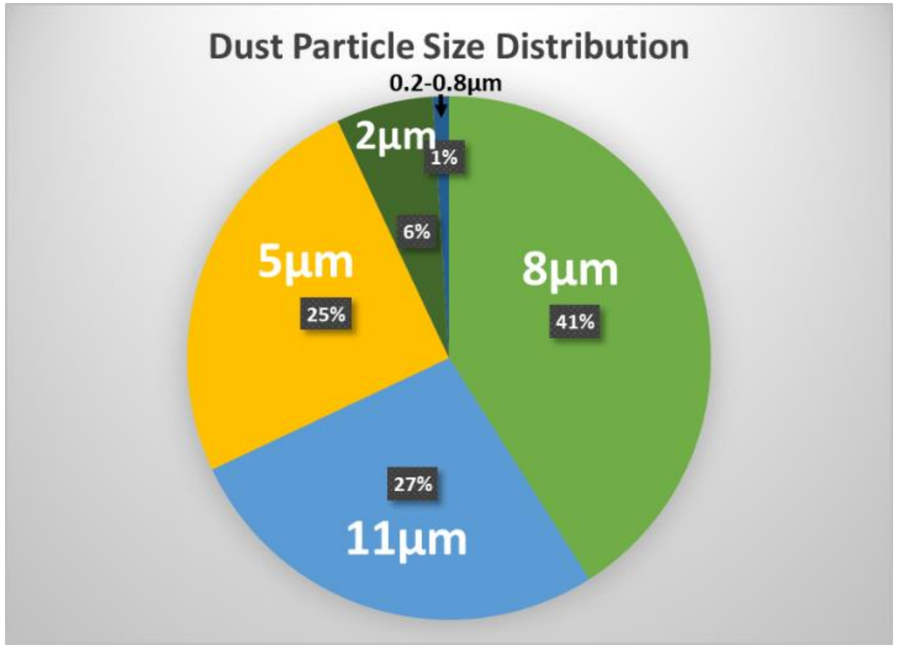
[1] D.J. Loftus, et al., "The Chemical Reactivity of Lunar Dust Relevant to Human Exploration of the Moon," *Planetary Science Division Decadal Survery white paper* (2020).

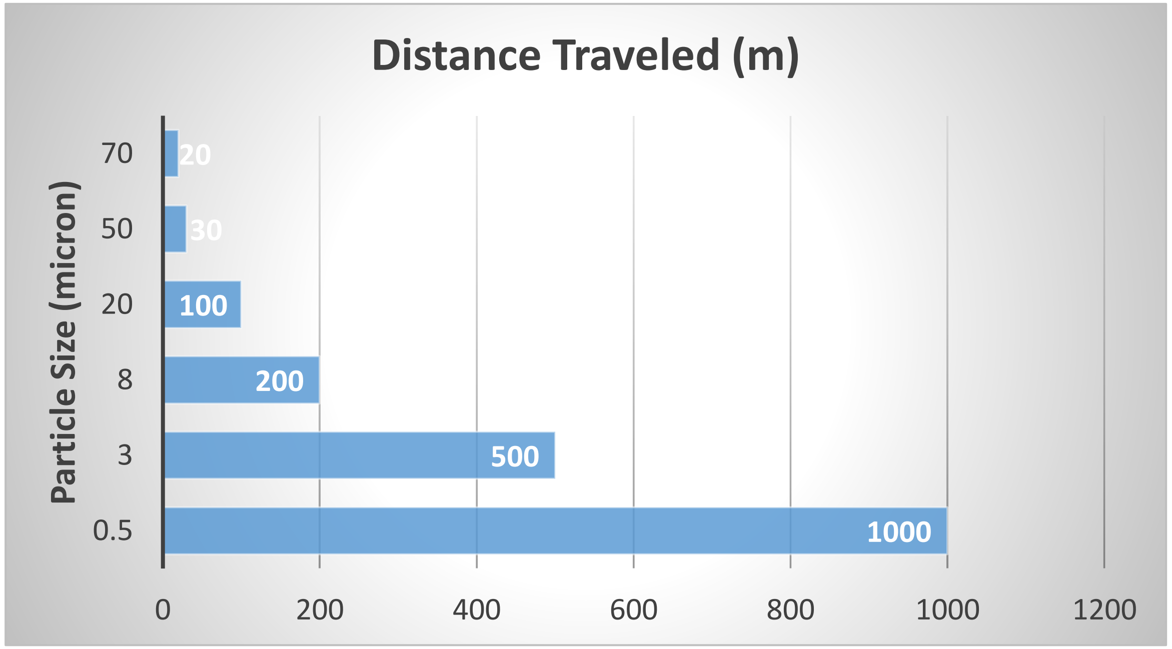
[2] C. Meyer, NASA Lunar Petrographic Thin Section Set (2003).

Plume-Surface Interactions During and After Lunar Landing Events

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







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Lunar Lander Leg Material Selection

- Substrate material considerations for reusable lunar lander leg
  - Mechanical properties
  - Coefficient of thermal expansion (CTE)
  - Space-heritage
- Candidate substrate materials
  - Aluminum alloys
  - Titanium alloys
  - Polymer composites

Material	Density (g/cm^3)	Young’s Modulus (Pa)	Vickers Hardness	Fracture Toughness ($Pa.m^{0.5}$)	CTE (µm/m·°C)
Ti-6Al-4V	4.43	1.15E+11	366	1.14E+8	9.10
Aluminum 2219	2.87	7.57E+10	121	4.50E+7	2.38

Image credit: NASA

Coating Candidates for Mitigating Lunar Dust Abrasion and Adhesion

- Advanced wear-resistant coating applications
  - High-performance machining and tooling
  - Mining and drilling
  - Gears and bearings
  - Armor/defense
- Coating candidate material requirements
  - Low density
  - Substrate compatibility
  - Processability
  - Commercial and market availability

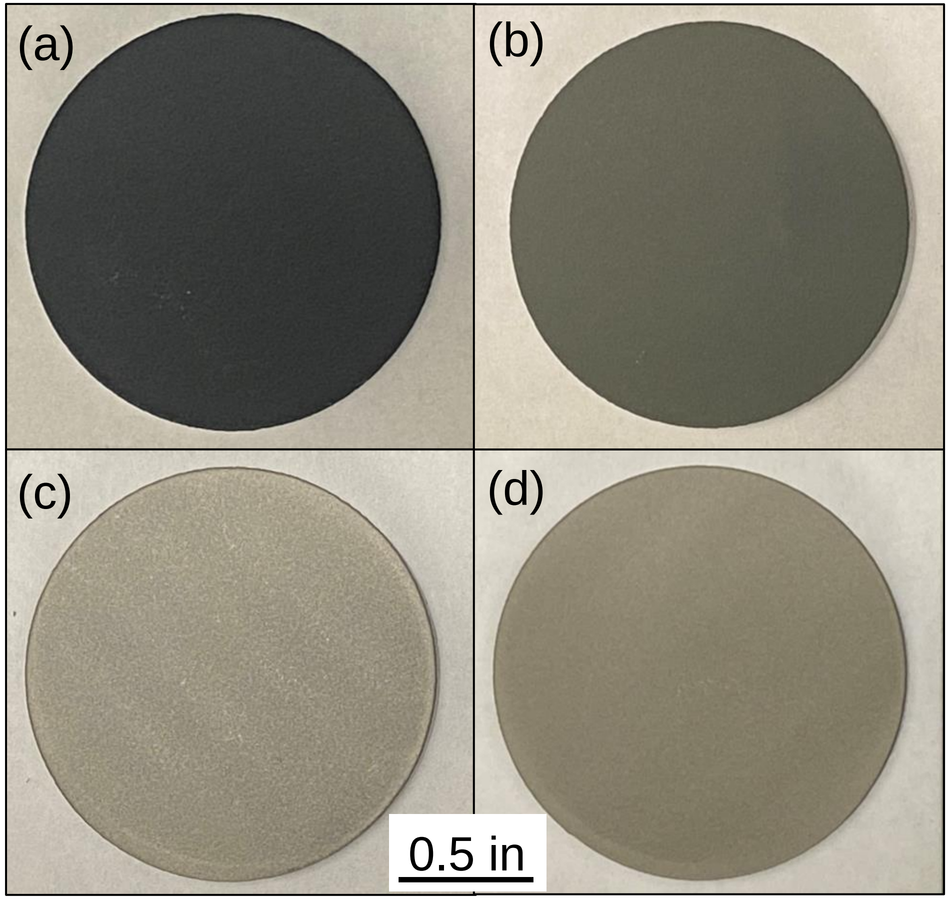
Material	Density (g/cm³)	CTE (µm/m·°C)	Processing Method
Candidate Coating Material Properties			
Alumina	3.76	8.3	APS
Alumina-Titania	3.5	3.9	APS
Boron Carbide	2.53	9.4	Vacuum-PS
Chromium Carbide	6.68	-	HVOF
Chromium Oxide	5.22	3.7	APS
Chrome Carbide/ Nickel Chrome	2.3	6.4	HVOF
Co-Mo-Cr-Si (Tribaloy T-800)	8.6	-	HVOF
Substrate Materials			
Aluminum 2219	2.87	23.8	-
Ti-6Al-4V	4.43	9.1	-

Image credit: NASA

Test Methods for Evaluating Lunar Dust Abrasion and Adhesion

- Coupon-level mechanical property assessment
  - Taber abrasion wear (ASTM D4060)
  - Hardness
    - Room temperature
    - Cryogenic conditions
  - Nanoindentation
    - Young’s modulus
    - Scratch test
  - Lunar dust adhesion test
- Assessing performance in more representative environments
  - Wear under vacuum
  - Particulate erosion rig

➢ Down-select promising ceramic coating for test article

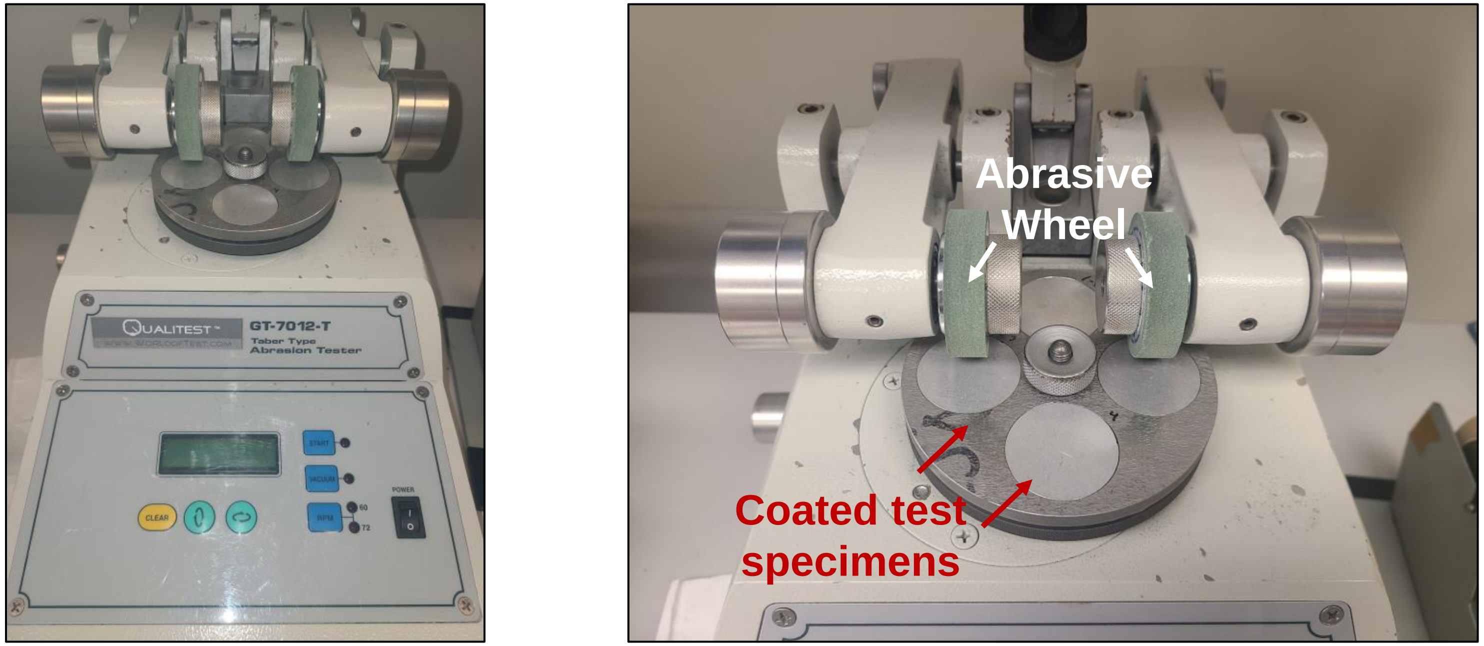


Al6061 substrates coated with (a) alumina-titania (Al_2O_3-TiO_2), (b) chromium oxide (CrO_2), (c) Tribaloy T-800 and (d) chromium carbide-nickel chrome (CrC-NiCr)

image credit: NASA LaRC/Valerie Wiesner

Coupon-Level Mechanical Property Assessment for Abrasion

- Taber abrasion wear (ASTM D4060)
  - Change in coating thickness
  - Weight loss after set number of cycles
  - Wear index value (average mass loss per thousand cycles of abrasion)
- Profilometry to evaluate wear pattern



Taber abraser test setup

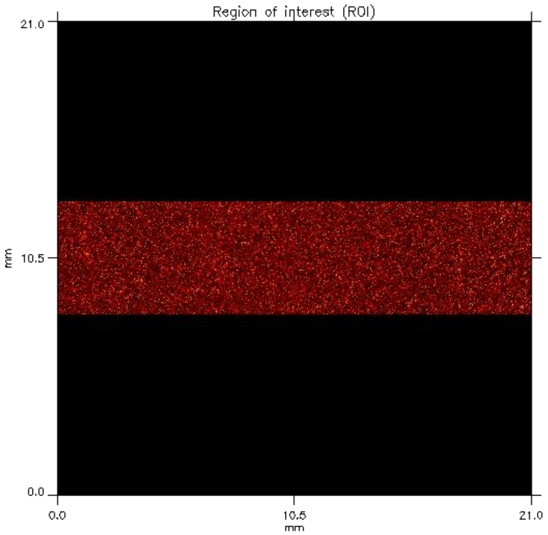
Image credit: NASA LaRC/Chris Wohl

Preliminary Taber Abrasion Results

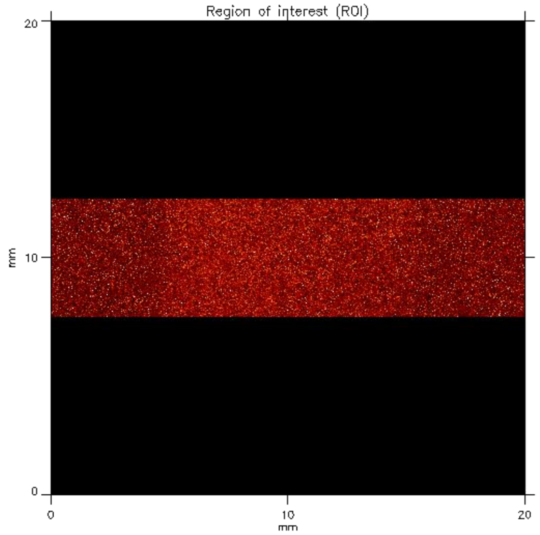
- After 1200 cycles:
  - Weight change inconclusive
  - Minimal change in coating thickness

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

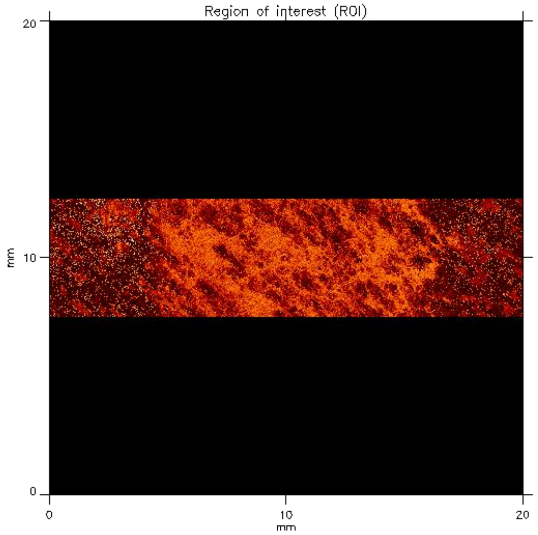
- Profilometry reveals negligible wear pattern



Alumina-titania



Chromium carbide



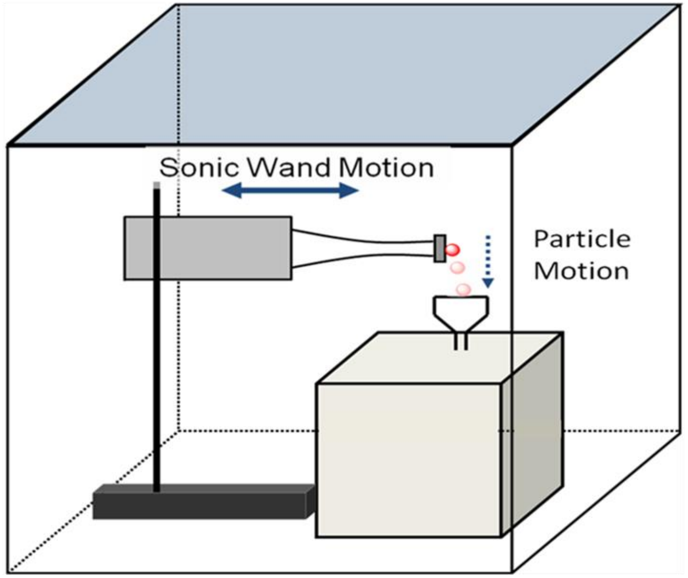
Stainless Steel

- ➢ Taber abrasion testing at higher cycles ongoing

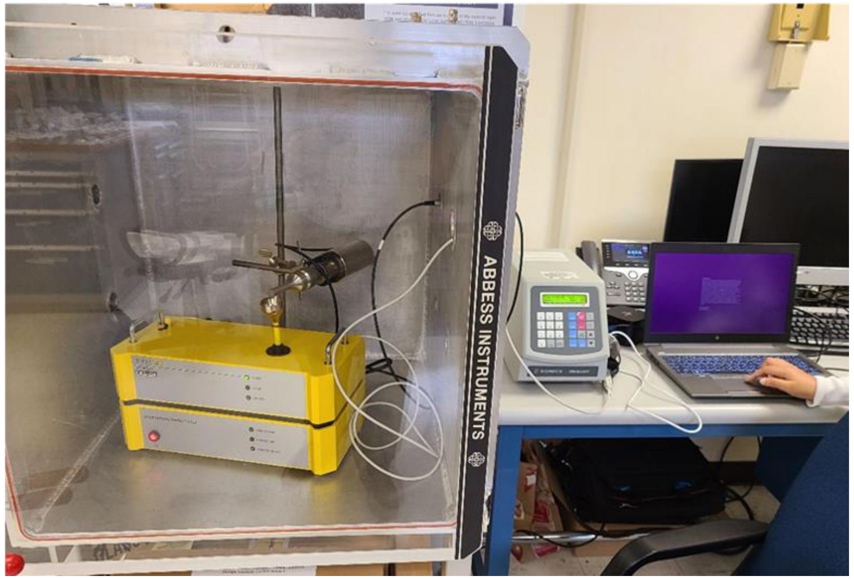
Middle and bottom image credit: NASA LaRC/Chris Wohl

Assessing Lunar Dust Adhesion

- Lunar Dust Adhesion Test
    - Coated specimen mounted on circular sonic wand tip
    - Lunar dust simulant (LHS-1D, <25μm) deposited by aerosolization technique
    - Optical microscopy images taken before and after specimens subjected to sonic wand amplitude



Schematic of lunar dust adhesion test setup



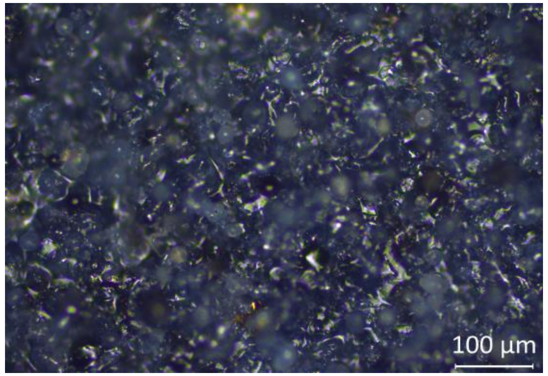
Lunar dust adhesion test setup

Image credit: NASA LaRC/Chris Wohl

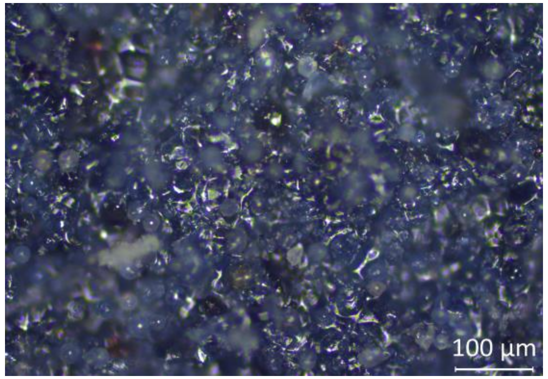
Preliminary Results of Lunar Dust Adhesion Test

- Al_2O_3-TiO_2 ceramic

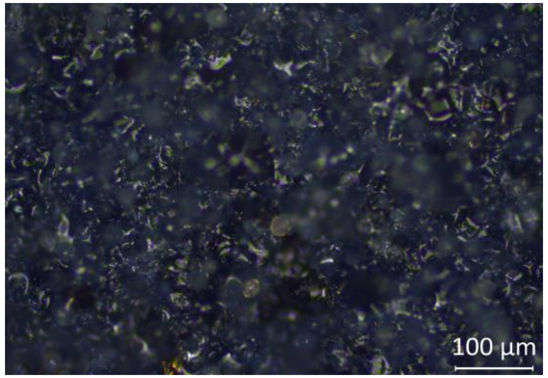
Before dust deposition



After dust deposition

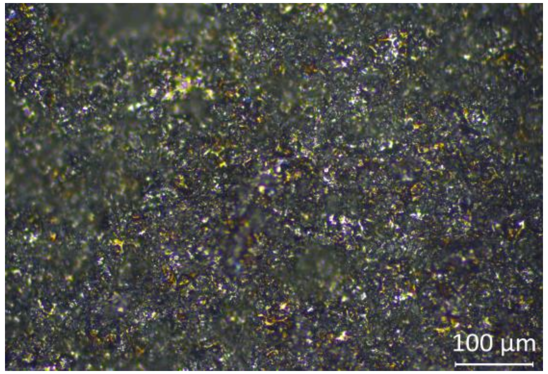


After sonic wand test

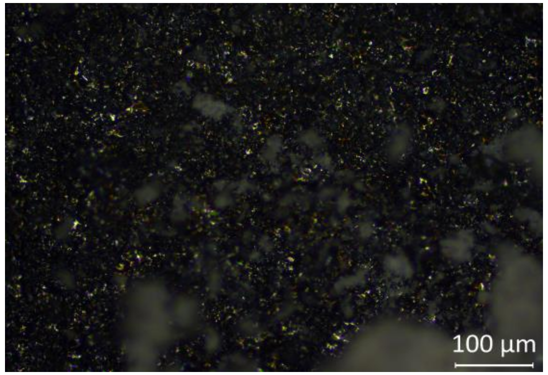


- Cr_2O_3 ceramic

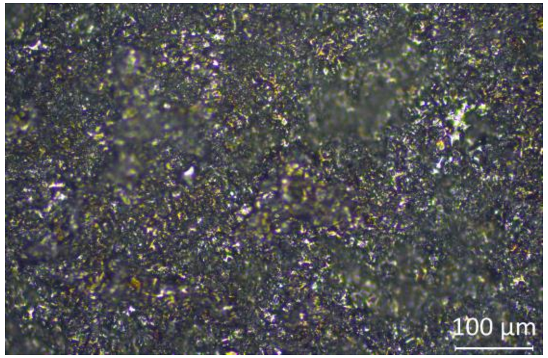
Before dust deposition



After dust deposition



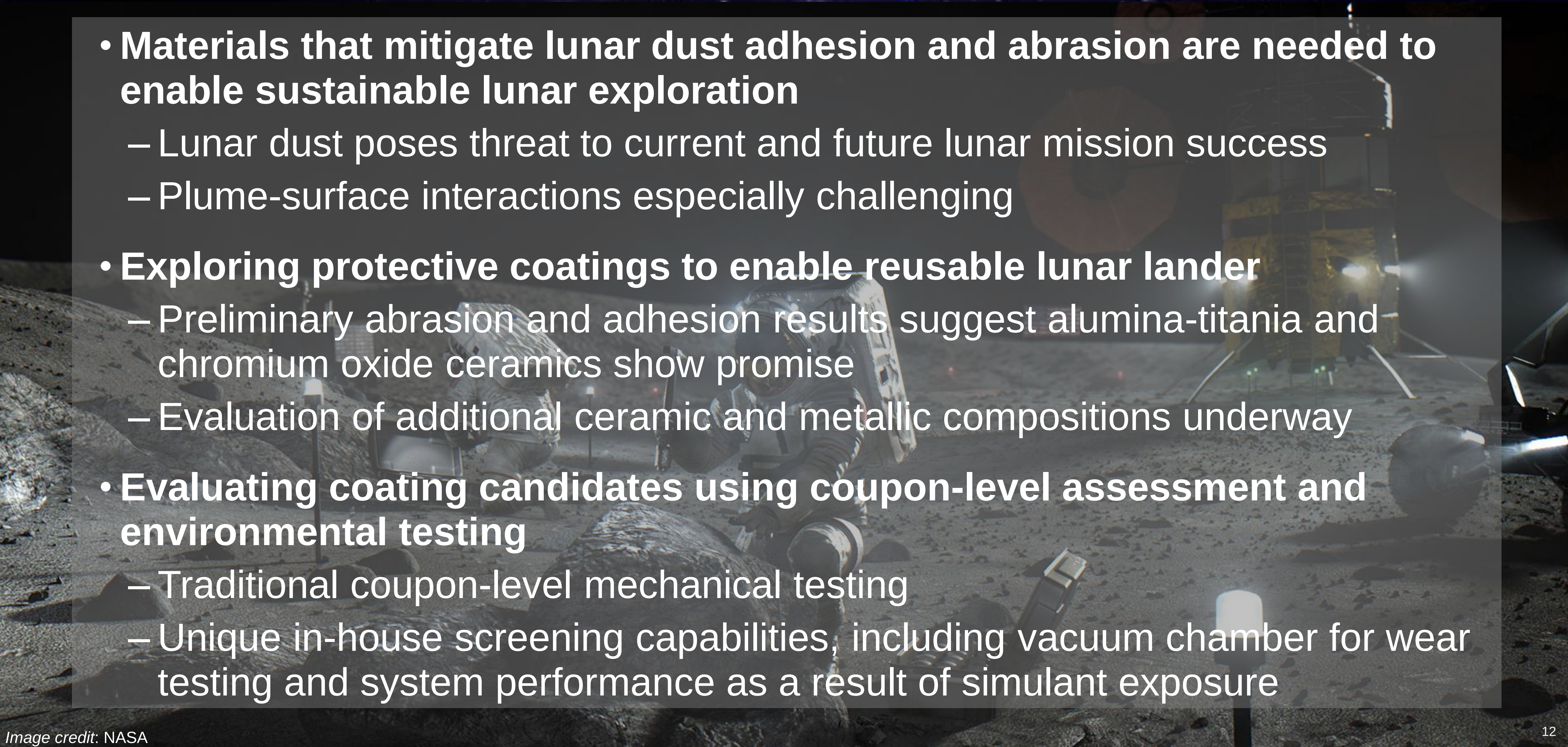
After sonic wand test



➢ Minimal adhesion observed with further analysis underway

Image credit: NASA LaRC

Protective Coatings for Lunar Applications



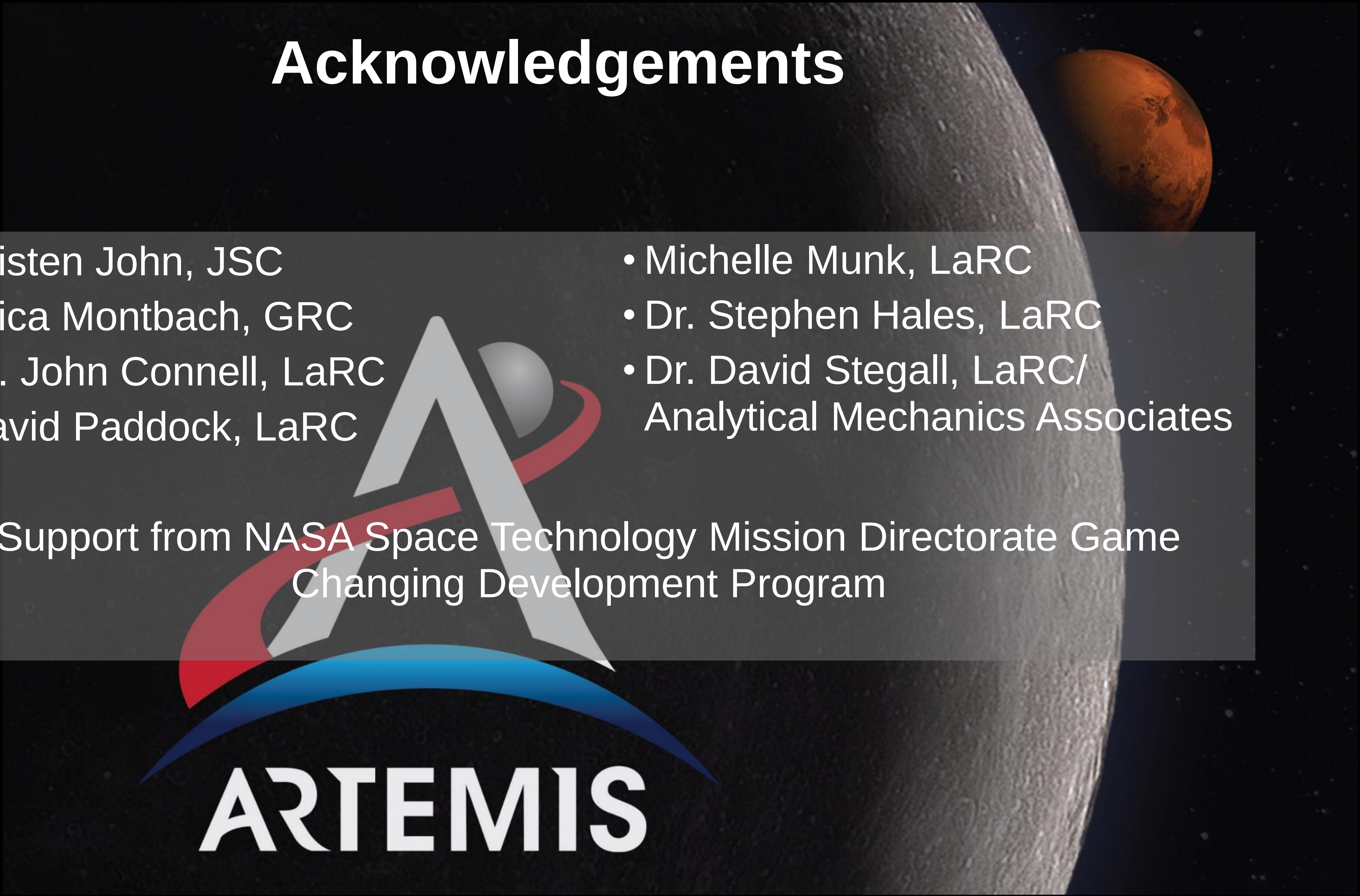
- **Materials that mitigate lunar dust adhesion and abrasion are needed to enable sustainable lunar exploration**
  - Lunar dust poses threat to current and future lunar mission success
  - Plume-surface interactions especially challenging

- **Exploring protective coatings to enable reusable lunar lander**
  - Preliminary abrasion and adhesion results suggest alumina-titania and chromium oxide ceramics show promise
  - Evaluation of additional ceramic and metallic compositions underway

- **Evaluating coating candidates using coupon-level assessment and environmental testing**
  - Traditional coupon-level mechanical testing
  - Unique in-house screening capabilities, including vacuum chamber for wear testing and system performance as a result of simulant exposure

Image credit: NASA

Acknowledgements



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