Protective Coatings for Lunar Dust Tolerance

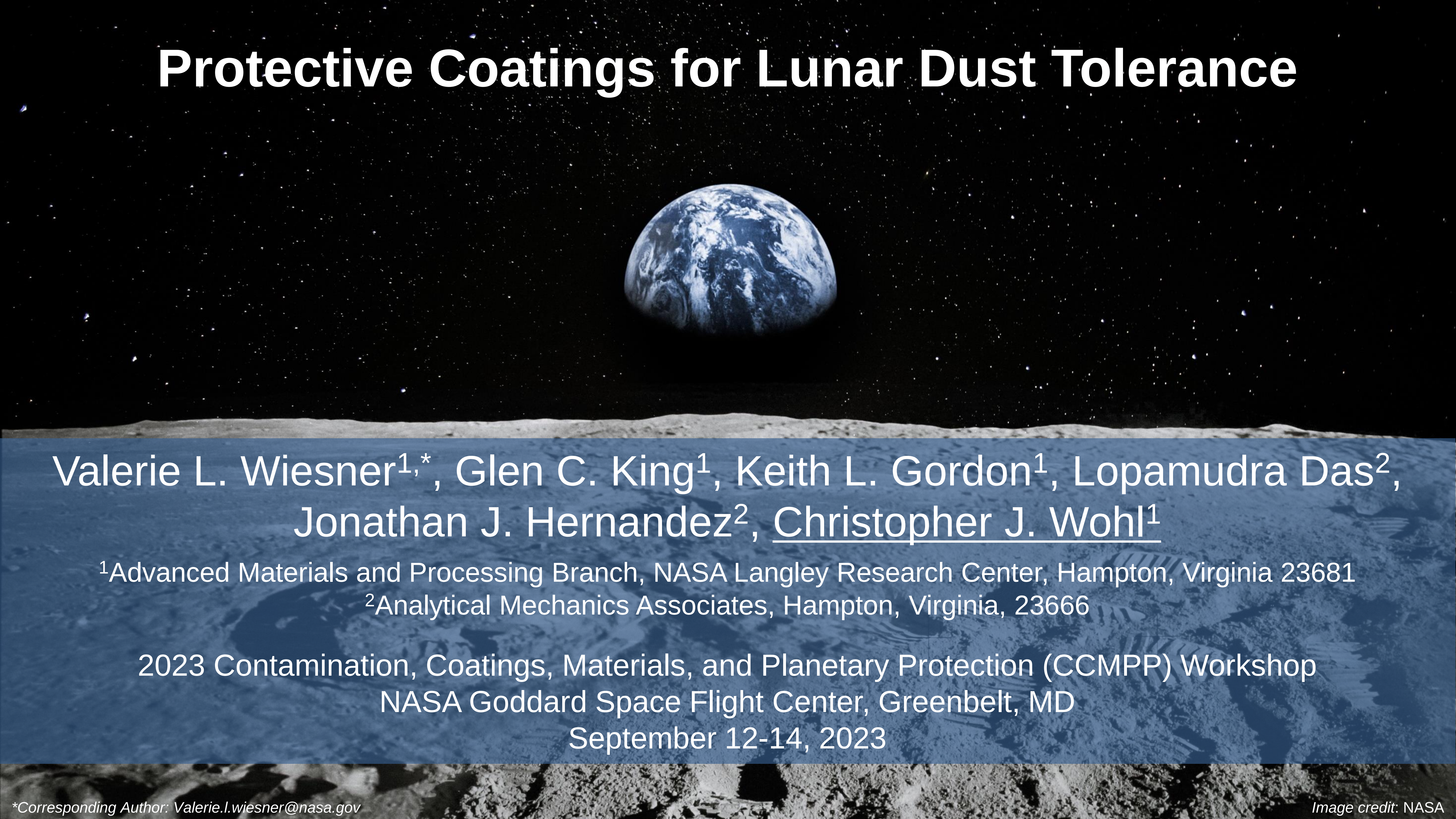

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Image credit: NASA

Overview: Protective Coatings for Lunar Dust Tolerance

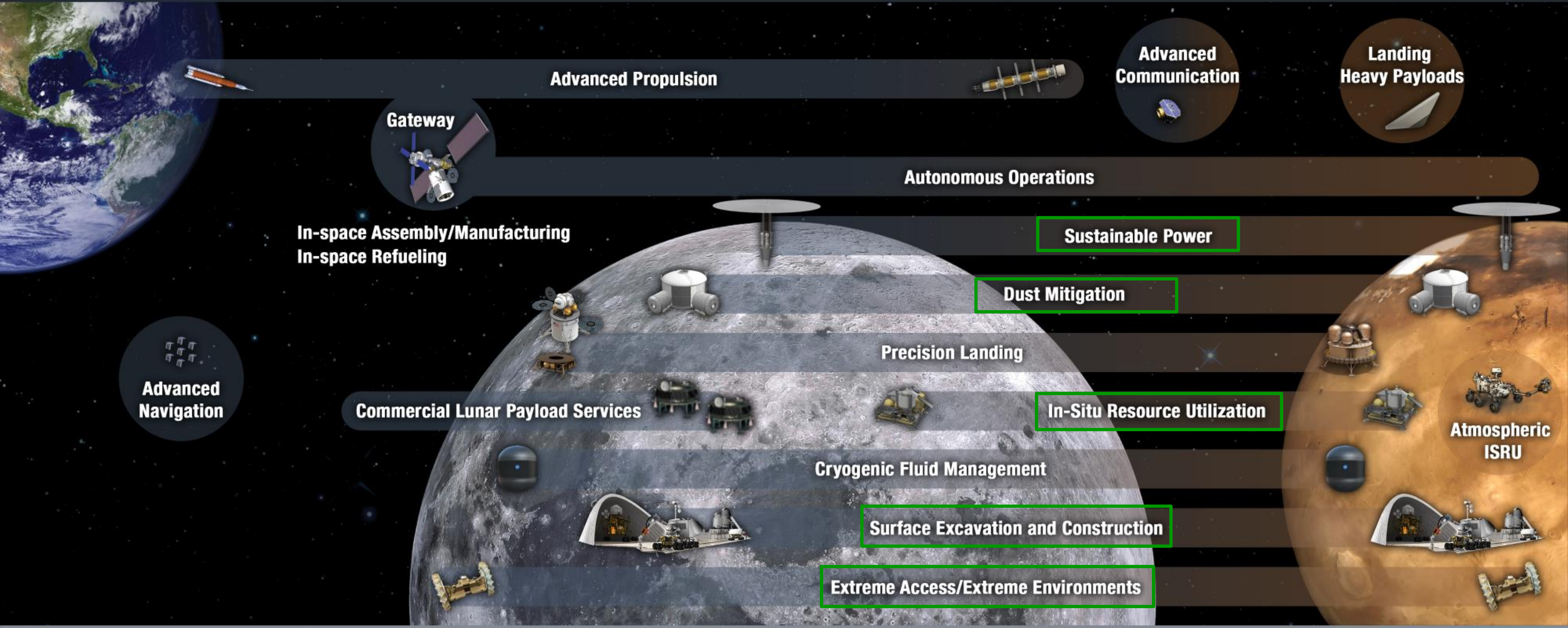
- **Return to the Moon: Artemis Missions and beyond**

- **Materials development for lunar dust tolerant applications**
  - Protective coatings for near-term use
  - Testing and characterization

- **Ongoing and future efforts**
  - Preliminary results
  - Processing and manufacturing opportunities

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]

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



Advanced Propulsion

Advanced Communication

Landing Heavy Payloads

Gateway

Autonomous Operations

In-space Assembly/Manufacturing
In-space Refueling

Sustainable Power

Dust Mitigation

Precision Landing

Advanced Navigation

Commercial Lunar Payload Services

In-Situ Resource Utilization

Atmospheric ISRU

Cryogenic Fluid Management

Surface Excavation and Construction

Extreme Access/Extreme Environments

2020 203X

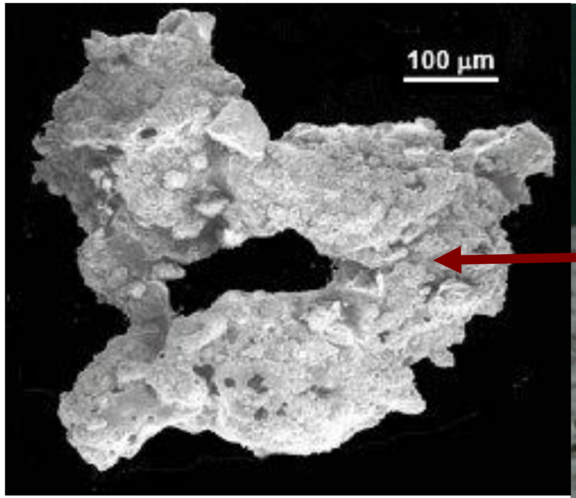
Lunar Surface Innovation Initiative (LSII)

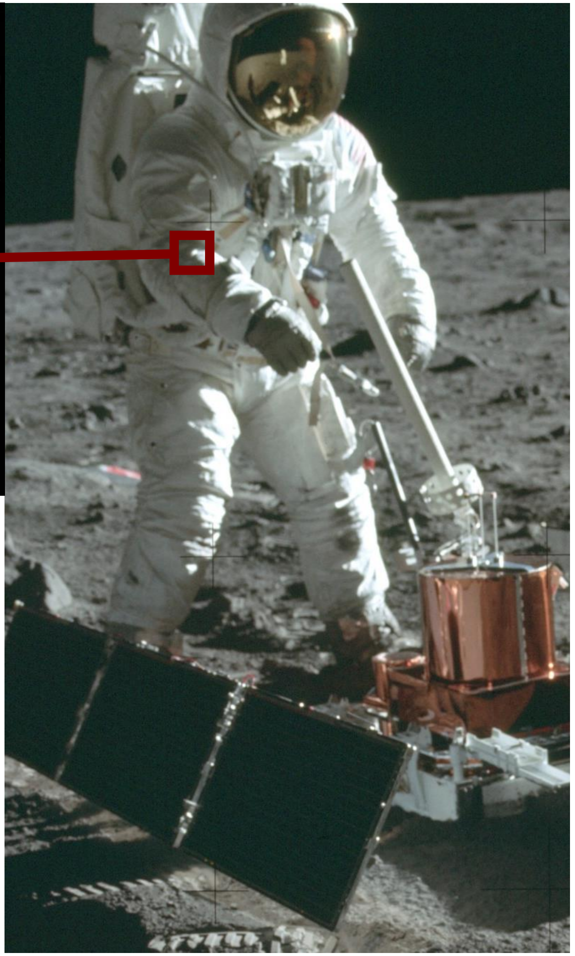
Image credit: NASA

Lunar Dust Composition and Characteristics

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

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





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

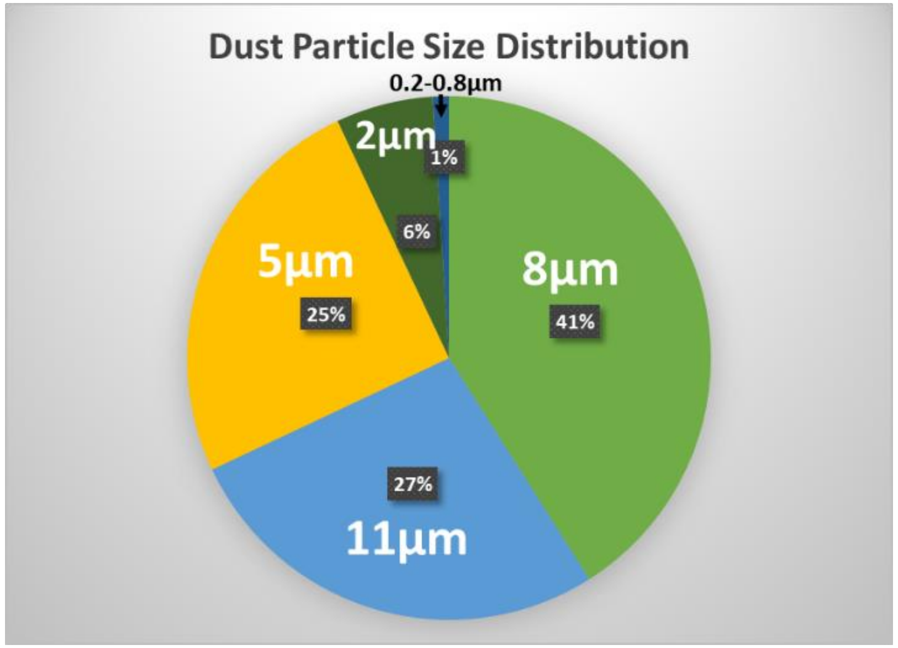
Image Credits Left: NASA **Right:** NASA AS11-40-5951

[1] D.J. Loftus, et al., “The Chemical Reactivity of Lunar Dust Relevant to Human Exploration of the Moon,” *Planetary Science Division Decadal Survey 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 50 m of landing site, particle velocity estimates 300 m/s to 2000 m/s



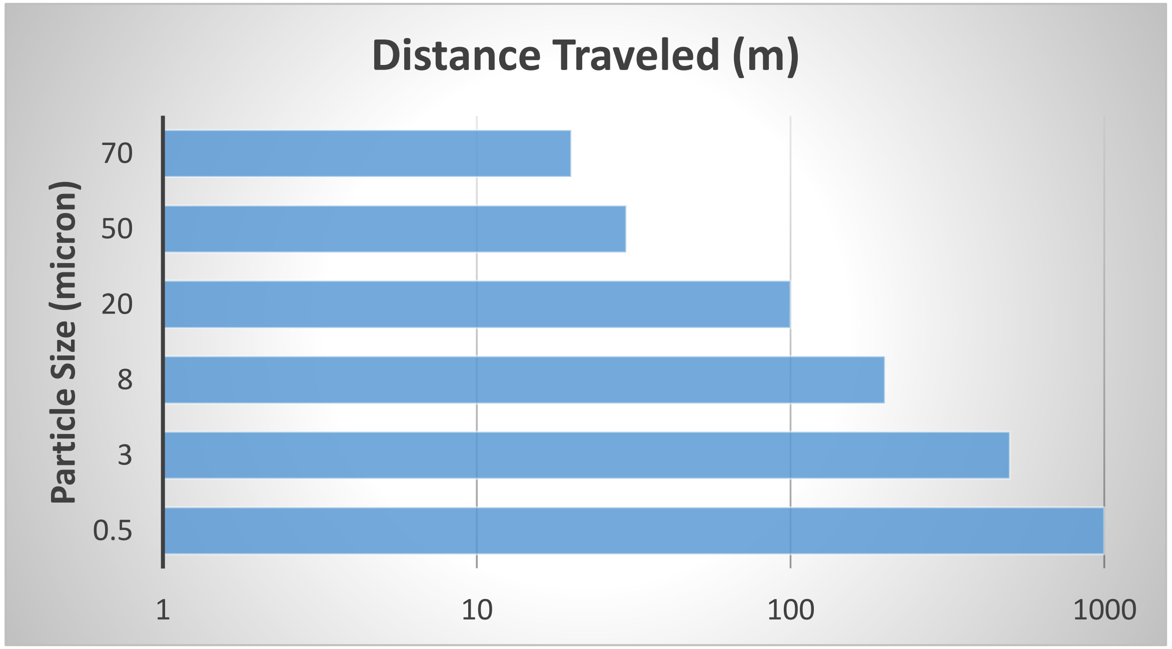


Image Credits Top Right: NASA MSFC/Peter Liever; *Bottom Left:* NASA LaRC; *Bottom Right:* NASA Lunar Surface Wear Map https://plumesurfacewearmap.larc.nasa.gov/

Materials Development for Lunar Dust Tolerant Applications

Novel materials and architectures

- Additive manufacturing (AM) of transition metal borides
  - Feasibility assessment to produce coatings and bulk materials
- Longer-term application (>10 years)

Protective coatings and materials

- Commercial-of-the-shelf (COTS) coating compositions
  - Ceramics
  - Metals
- Near-term application (<10 years)

Testing and characterization

- Coupon-level mechanical property assessment
- Surface roughness and adhesion properties
- Material performance in representative environments
- Flight experiments

Coating Candidates for Mitigating Lunar Dust Abrasion and Adhesion

Material	Density (g/cm³)	CTE (μm/m·°C)	Processing Method
Substrate Materials			
Aluminum 6061	2.7	23.6	-
Ti-6Al-4V	4.43	9.1	-
Candidate Coating Material Properties			
Alumina (Al_2O_3)	3.76	8.3	APS
Alumina-Titania (Al_2O_3-TiO_2)	3.5	3.9	APS
Boron Carbide (B_4C)	2.53	9.4	Vacuum-PS
Chromium Carbide (CrC)	6.68	-	HVOF
Chromium Oxide (Cr_2O_3)	5.22	3.7	APS
Chromium Carbide-Nickel Chromium (CrC-NiCr)	-	6.4	HVOF
Co-Mo-Cr-Si (Tribaloy T-800)	8.6	-	HVOF

- **Coating applications**
  - High-performance machining and tooling
  - Mining and drilling
  - Gears and bearings
  - Armor/defense
- **Coating candidate material requirements**
  - Low density
  - Substrate compatibility
  - Processability
    - Air plasma spray (APS)
    - Vacuum plasma spray (PS)
    - High velocity oxygen fuel (HVOF)

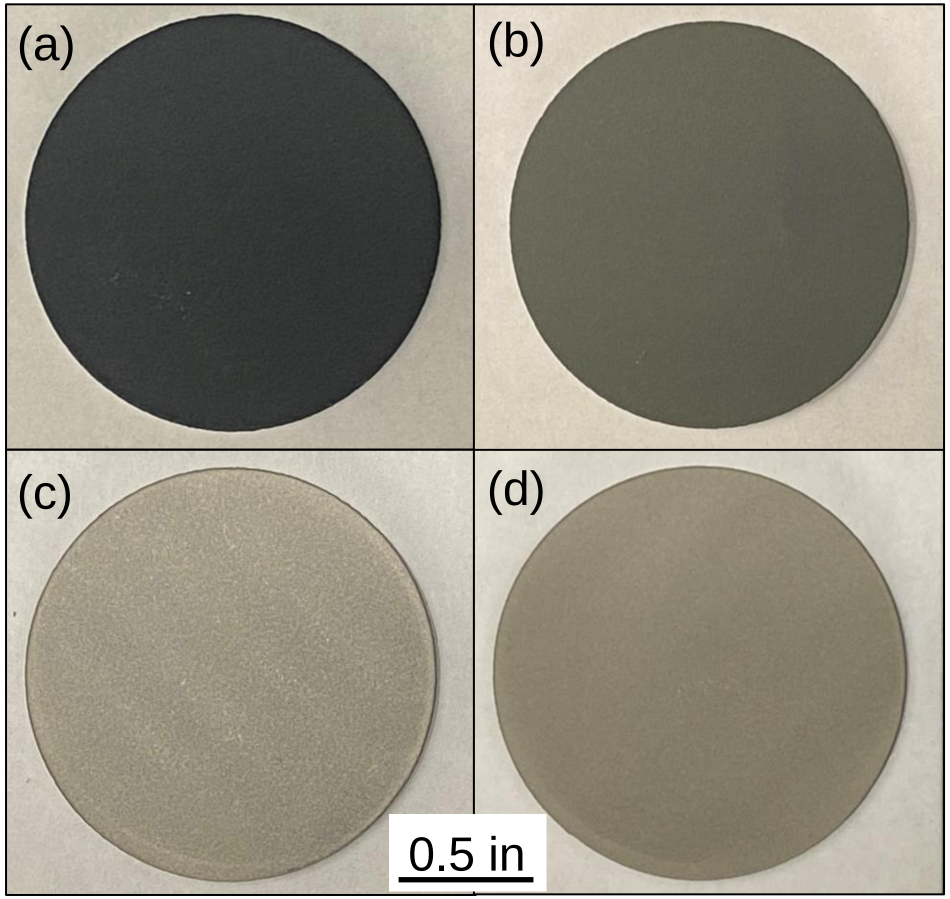
CTE: Coefficient of thermal expansion

Test Methods to Evaluate Lunar Dust Abrasion and Adhesion

- Coupon-level mechanical property assessment
  - **Taber abrasion (ASTM D4060)**
  - **Pin-on-Disc Tribometry**
  - Thermal shock
  - Hardness

- Assessing performance in more representative environments
  - **Particulate erosion rig**
  - Wear under vacuum
  - **Flight experiments**

- Down-select promising ceramic coating for test article



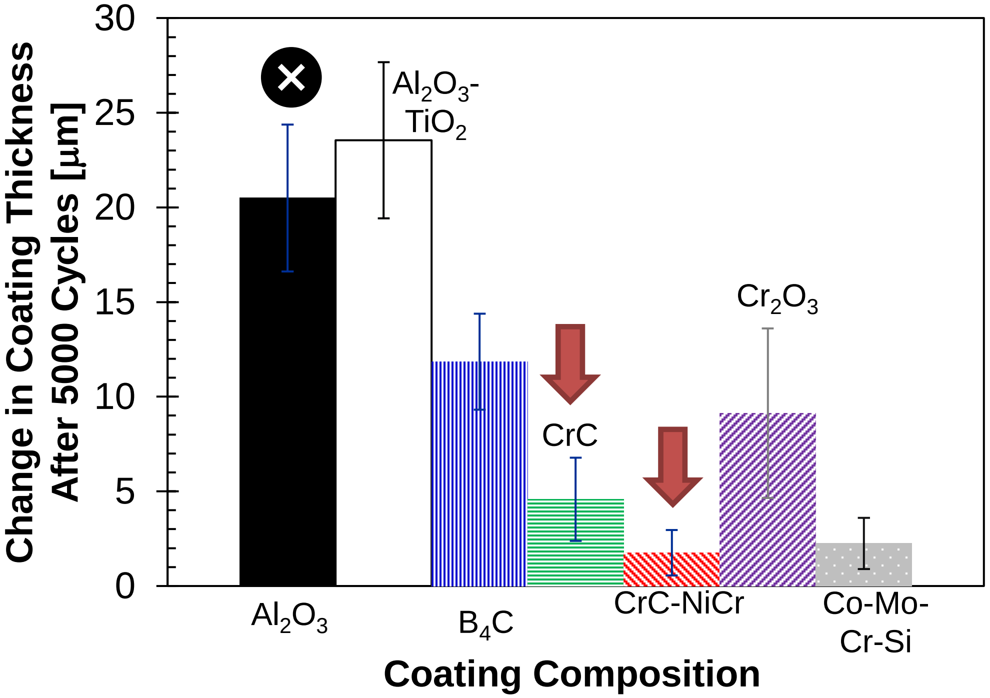
Al6061 substrates coated with (a) Al_2O_3-TiO_2, (b) CrO_2, (c) Co-Mo-Cr-Si and (d) Cr_3C_2-NiCr

image credit: NASA

Taber Abrasion (ASTM D4060)

- QualTest GT-7012-T Taber Type Abrasion Tester
- Lower rotating abrasive wheel onto specimen fixed in spinning specimen mount for up to 5000 cycles
  - Measure decrease in coating thickness using Eddy current instrument
  - Track weight loss before and after cycles

Taber abrasion test setup

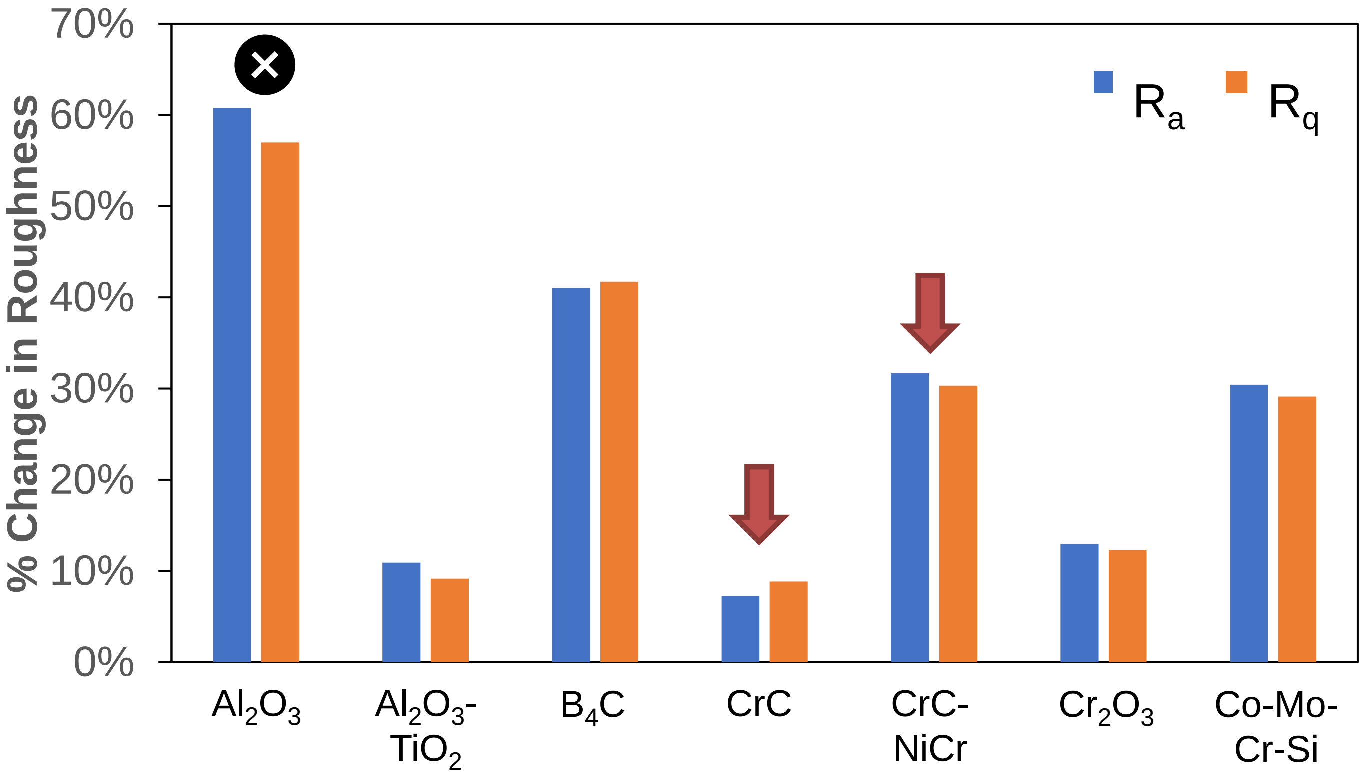


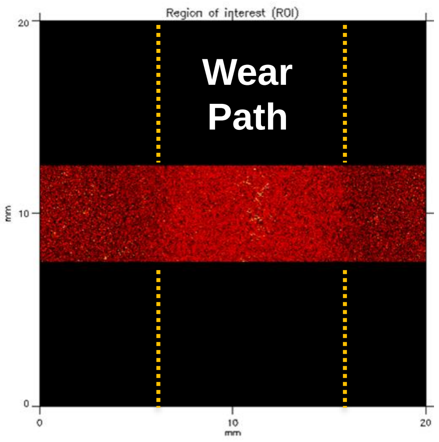
- After 5000 cycles:
  - Change in coating thickness varied with composition
  - Weight change inconclusive across all compositions
- Al_2O_3-TiO_2 showed greatest decrease in coating thickness
  - 23.6 µm ± 4.1 µm
- CrC-NiCr exhibited smallest decrease in coating thickness
  - 1.75 µm ± 1.2 µm

Image credit: NASA

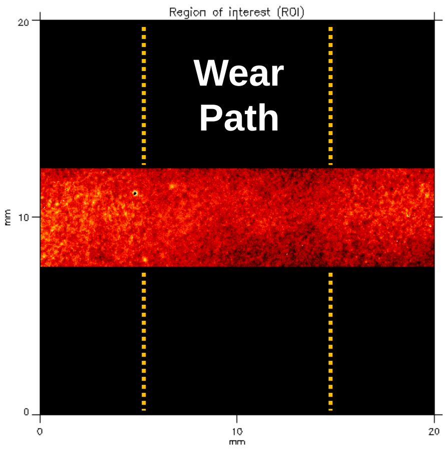
Change in Surface Roughness of Coatings After Taber Testing

- Notable decrease in R_a and R_q values observed in all compositions
  - Largest decrease in values observed in alumina (Al_2O_3) coating
    - R_a: 5.77 µm to 2.26 µm
  - Smallest decrease in values observed in CrC and Al_2O_3-TiO_2 coatings
    - CrC R_a: 2.51 µm to 2.33 µm
    - Al_2O_3-TiO_2 R_a: 6.53 µm to 5.82 µm





Al_2O_3

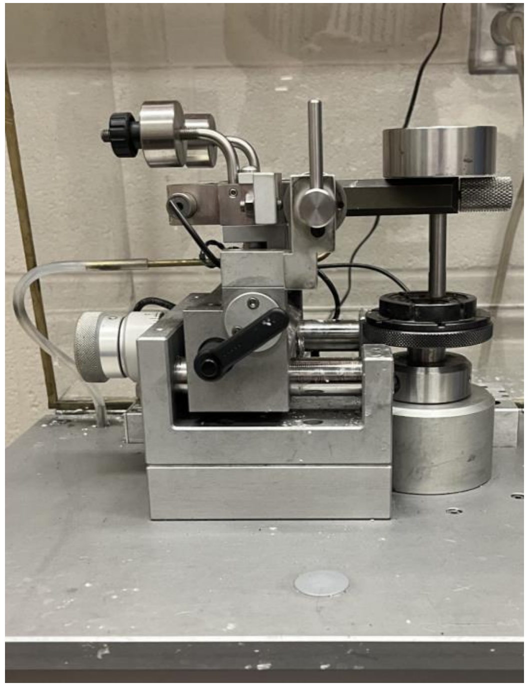


CrC

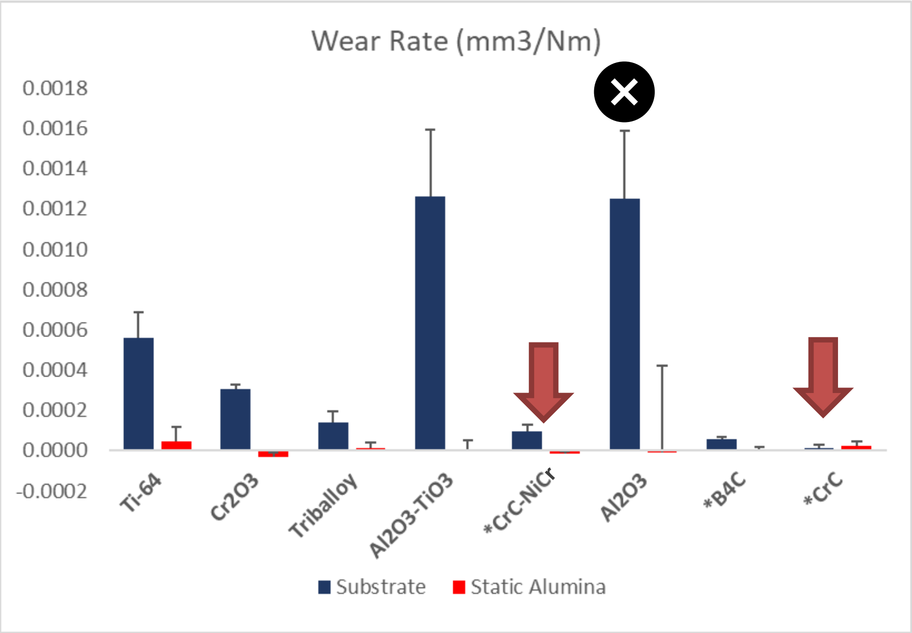
- R_a: Average roughness
- R_q: Root mean square roughness

Pin-on-Disc Tribometry (ASTM G99)

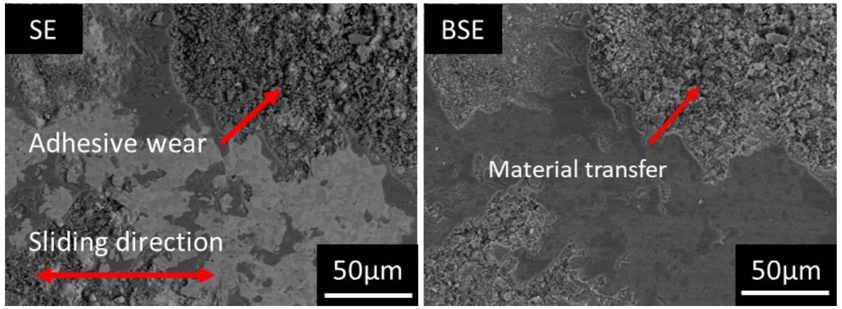
- CSM Instruments, model TRB
- Speed: 20 cm/s, Load: 5N, Sliding distance: 100 m (+900m for wear rate < 0.0001 mm3/Nm)
    - Determination of wear rate (quantitative) and analyze material transfer (qualitative)



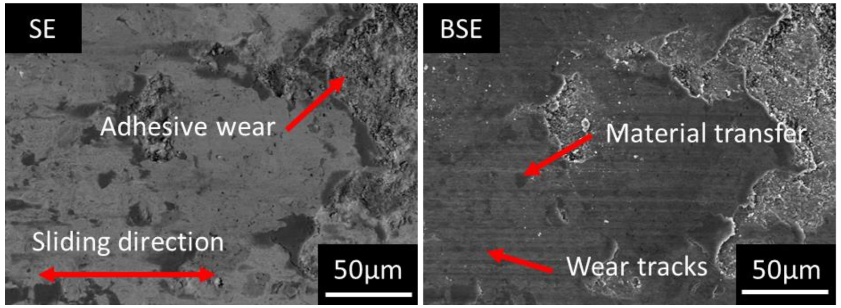
CSM Instruments, model TRB



Wear Rates



CrC-NiCr Surface



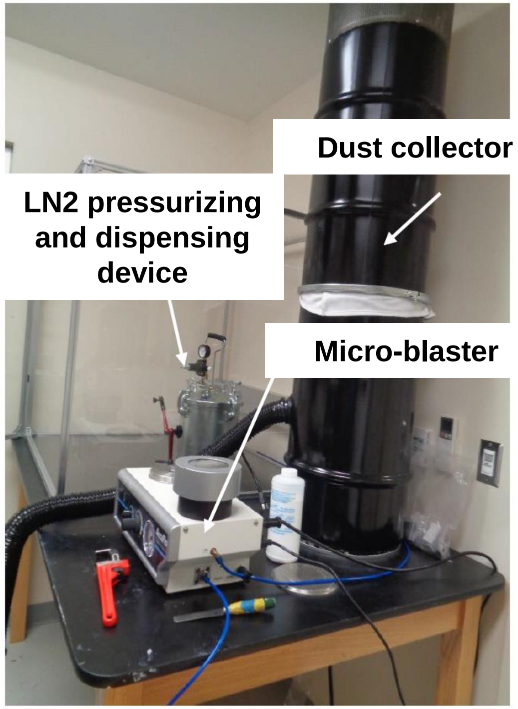
CrC Surface

Image credit: Prof. Surojit Gupta and Mackenzie Short, SAA1-32507

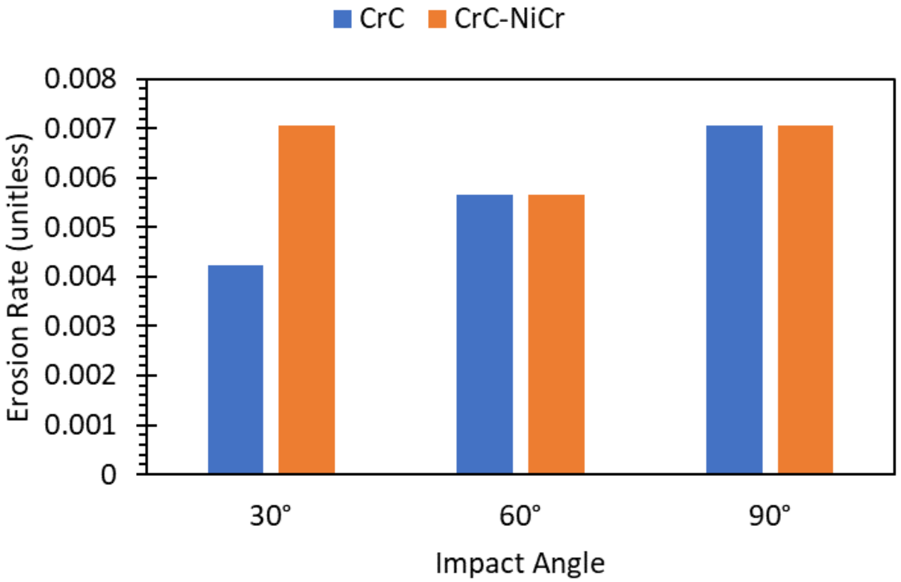
SE: Secondary electron, BSE: Back-scattered electron

Cryogenic Solid Particle Erosion (SPE)

- Custom-built instrument enabling cryogenic (liquid nitrogen, LN2) test conditions during controlled particle erosion
- Volcanic soil (18 μm diameter) from Mauna Kea, Hawaii Island, Hawaii
  - Impact angles of 30º, 60º, and 90º evaluated during 30 s particle exposure



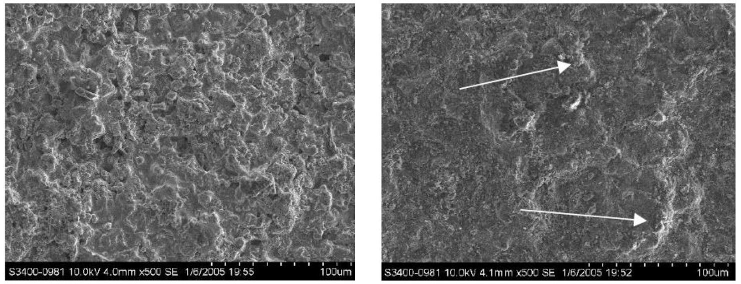
Cryogenic SPE Instrument



Erosion Rate for Al_2O_3 was 470% greater at 60º.

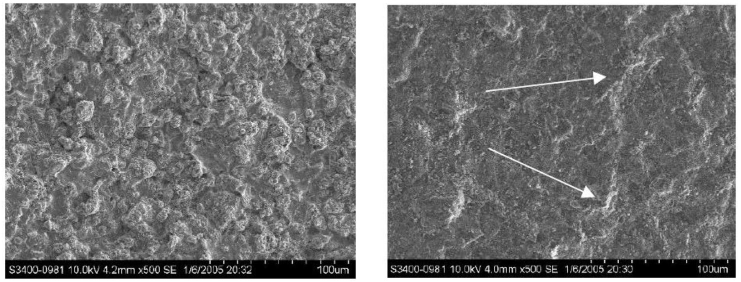
Erosion Rates

CrC-NiCr Surface



Before Wear **After Wear**

CrC Surface

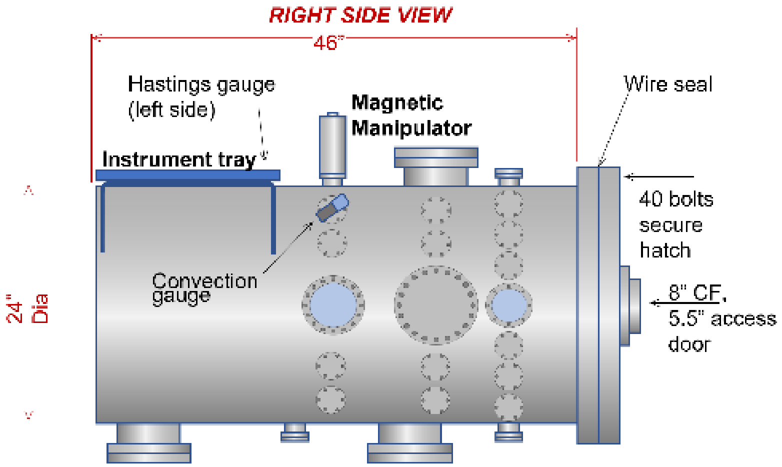


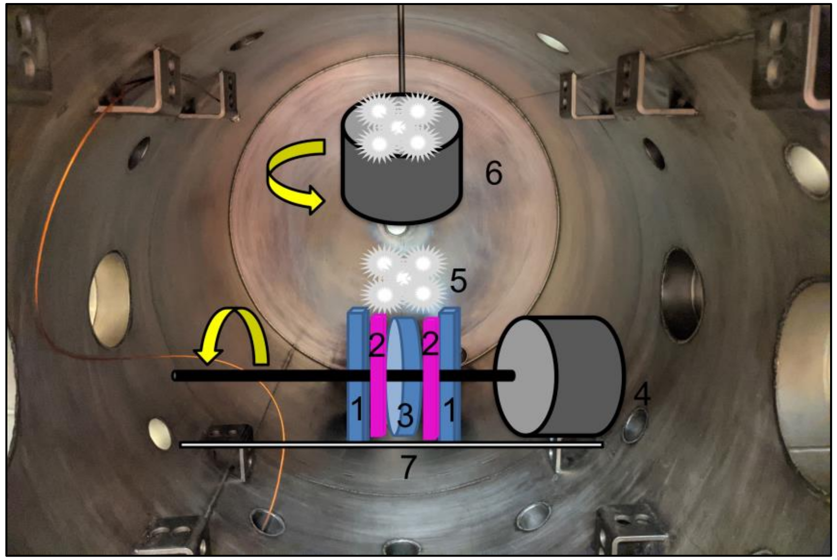
Before Wear **After Wear**

Image credit: Prof. Getu Hailu, NASA EPSCoR R3 Recipient, Award Number 80NSSC21M0137

Characterizing Wear by Lunar Dust Simulant in Vacuum

- Surveying Lunar Dust Influence on Device Efficacy (SLIDE) chamber
  - Subject materials to wear caused by lunar dust in vacuum
- Leverage ASTM standards
  - Taber abrasion (ASTM D1044)
  - Pin abrasion (ASTM G132)
  - Falling sand abrasion (ASTM D968)
  - Wear testing with ball on disc (ASTM G99)
- Configurable to accommodate variety of mechanisms relevant to application





<u>SLIDE chamber components</u>

1. Supporting Bracket
2. Testing Coupons
3. Active Plate
4. Motor
5. Lunar Simulant
6. Dust Shaker
7. Container (Cross Section View)

Image credit: NASA

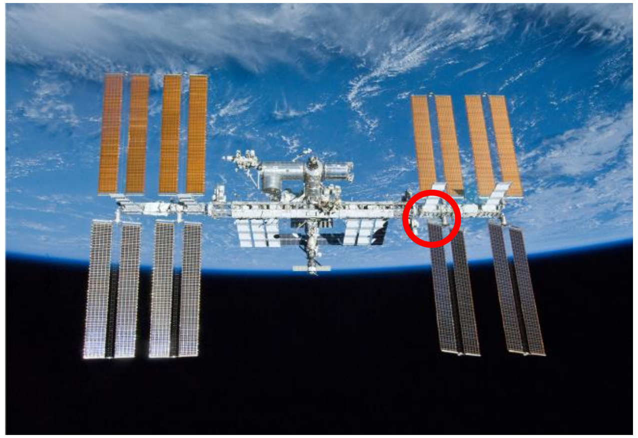
Assessing Materials Performance in Extreme Environments

Low-earth orbit (LEO)

- MISSE-16 (Materials ISS Experiment Flight Facility) (returned on April 15, 2023, CRS-27)
- Sun facing: Zenith position for six-month exposure to:
  - Solar ultraviolet radiation
  - Atomic oxygen in low Earth orbit (minor)
- Optical images collected throughout duration
- Specimens returned for ground-based analysis

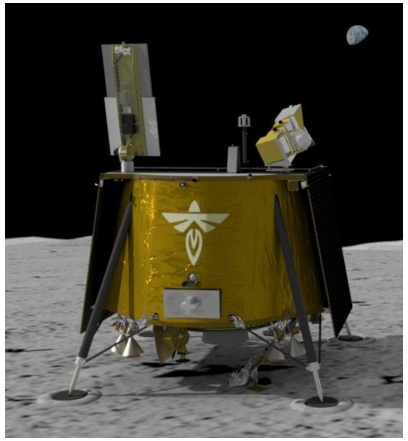
Lunar surface

- PlanetVac Instrument on Firefly Aerospace Blue Ghost Lander (2024)
  - Mare Crisium location
  - Direct exposure in lunar environment
- Optical observation throughout duration of exposure
- Specimens remain on Moon upon conclusion of mission



Location of MISSE-16 on International Space Station (ISS)

Coating Compositions	Exposure Type
Cr_2O_3	LEO
CrC	LEO
CrC-NiCr	LEO Lunar surface



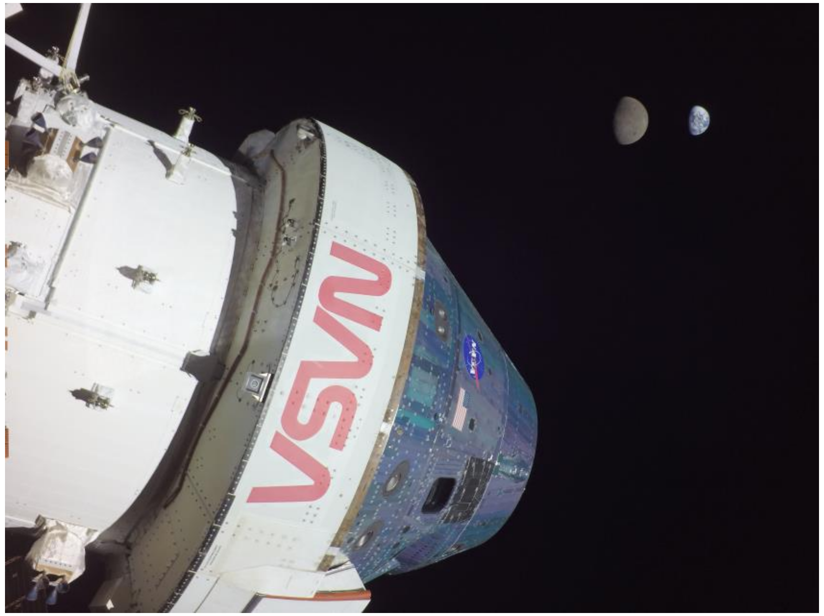
Artist rendering of Firefly Aerospace Blue Ghost Lander

Mare Crisium planned landing site

Image credits: NASA

Protective Coatings: On-going and Future Efforts

- Cr_3C_2-NiCr shows notable promise as protective coating
  - Exhibited lowest change in coating thickness after Taber abrasion testing
  - Possessed low as-processed surface roughness and lunar dust adhesion (data not shown)*
  - Yielded very low tribometry and cryogenic SPE erosion rates
- Microstructural and compositional evaluation
  - Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) of coating cross-sections
  - Phase analysis via X-ray diffraction (XRD)
- Thermal and mechanical properties
  - Quench testing
  - Room temperature hardness
  - Cryogenic hardness
- Extreme environment testing
  - Wear testing in vacuum
  - Exposure in LEO and lunar surface environments

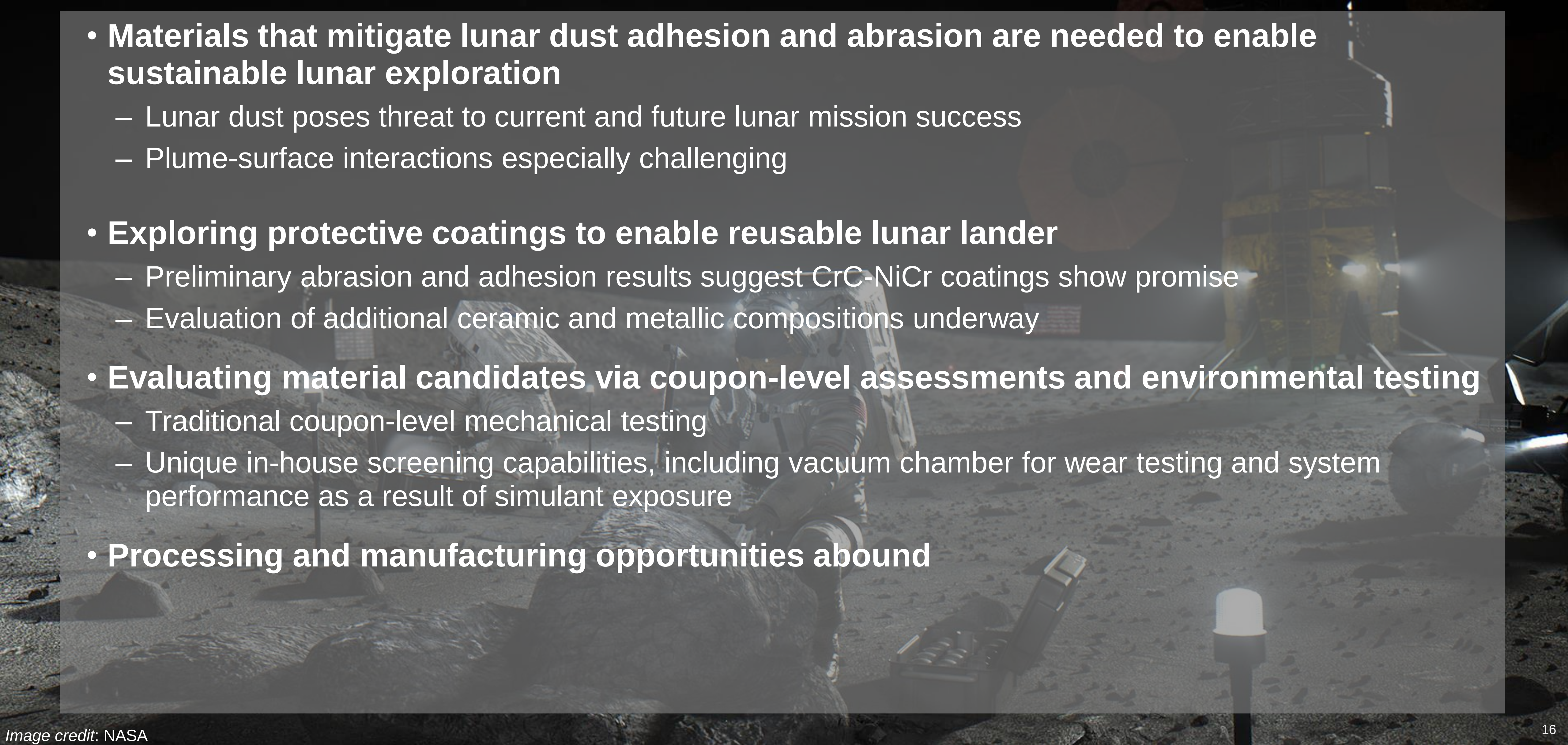


Material technologies for use on future Artemis Missions (image captured during 2022 Artemis I Mission)

Image credits: NASA

*Wiesner, Valerie L. et al., Materials Discovery for Lunar Dust Tolerant Applications, ICACC 2023, January 22-27, Daytona Beach, Fl, 2023.

Materials Development for Lunar Dust Tolerant 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 CrC-NiCr coatings show promise
  - Evaluation of additional ceramic and metallic compositions underway
- **Evaluating material candidates via coupon-level assessments 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
- **Processing and manufacturing opportunities abound**

Image credit: NASA

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- Michelle Munk, LaRC
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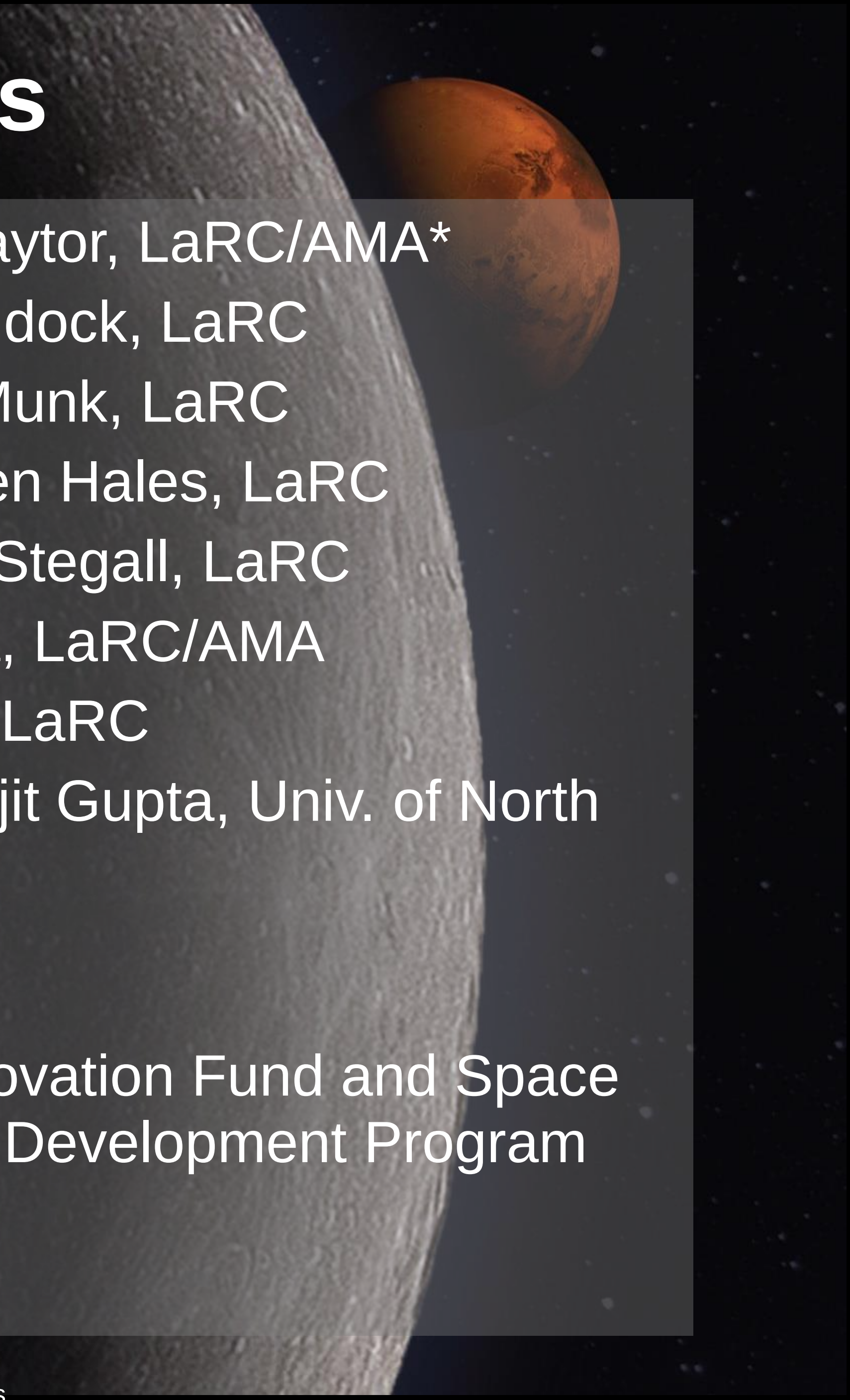
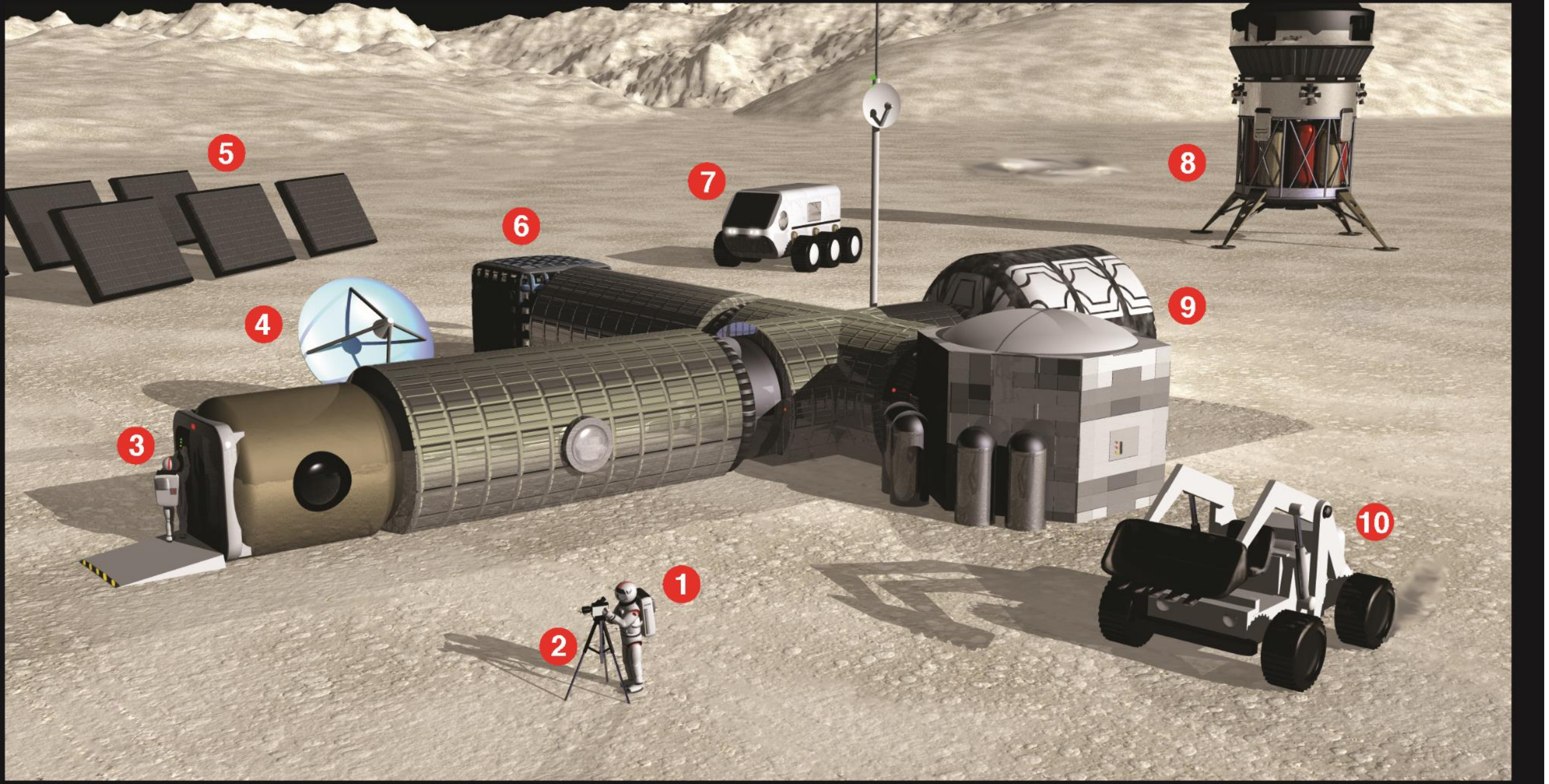


Image credit: NASA

*NIA: National Institute of Aerospace, JSC: Johnson Space Center, GRC: Glenn Research Center, AMA: Analytical Mechanics Associates

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

Surface Roughness of As-processed Coatings

- FormFactor (FRT) of America Microprof 100 Profilometer
  - Data collected on pristine as-processed coating surface
    - 10 µm between data points
    - 40 µm between data lines

- R_a: Average of individual heights and depths from mean elevation of profile
- R_q: Root mean square of individual heights and depths from mean line

  - Al_2O_3-TiO_2, Al_2O_3 and B_4C had highest R_a and R_q values
  - CrC, Co-Mo-Cr-Si and CrC-NiCr possessed lowest R_a and R_q values

Material	**R_a (µm)**	**R_q (µm)**
Al_2O_3	5.77	7.27
Al_2O_3-TiO_2	6.53	8.03
B_4C	5.50	7.02
CrC	2.52	3.21
Cr_2O_3	4.31	5.38
CrC-NiCr	4.06	5.09
Co-Mo-Cr-Si	3.28	4.12