

Dust-Proofing the Future: Materials Challenges for Lunar Exploration

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Overview: Lunar Dust Tolerant Materials

- **Return to the Moon: Lunar environment**
- **Impact of lunar dust on exploration**
- **Testing and characterization for lunar dust tolerant applications**
 - Abrasive wear
 - Erosive wear
 - Environmental testing
 - Space flight exposure
 - Dust adhesion
- **Ongoing and future efforts**



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.

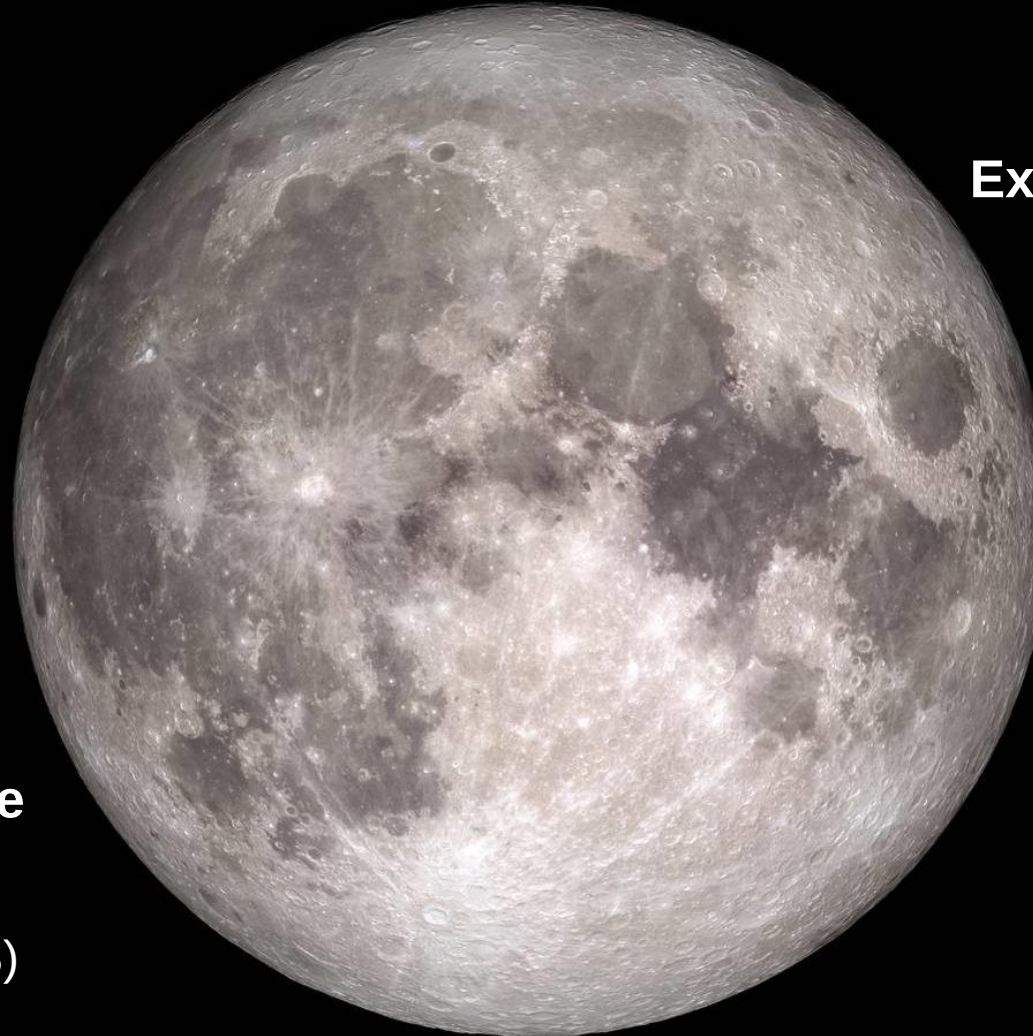


Lunar Environment

Low gravity
1/6th of Earth's gravity

Lack of atmosphere
 10^{-12} Torr (10^{-15} atm)

Elevated radiation exposure
~200x more than Earth's
~2.6x higher than that of
International Space Station (ISS)



Extreme temperature variation
127°C (260°F) to
-173°C (-280°F)

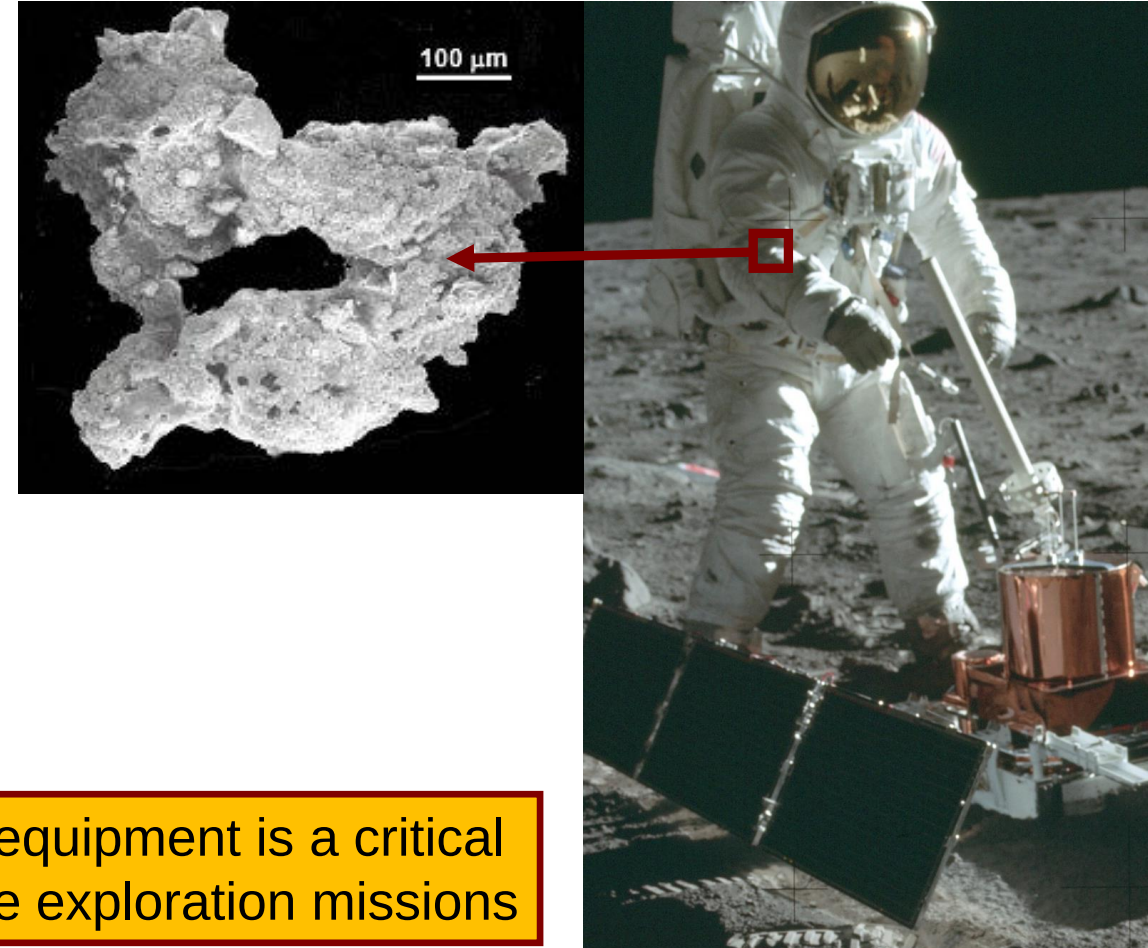
Lunar regolith
Average particle size 72 μm
Of regolith by weight,
50% < 50 μm
20% < 20 μm
1% < 1 μm



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 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 – 100 μm -sized particles
 - Nominal density $\sim 1.5 \text{ g/cm}^3$
 - Irregular, jagged morphology
 - Electrostatically 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

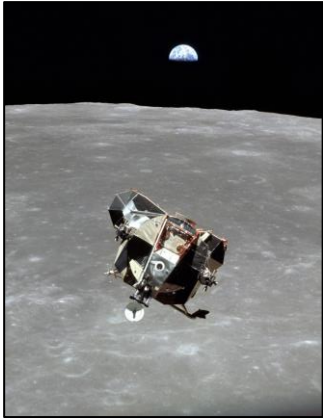
[1] D.J. Loftus, et al., "The Chemical Reactivity of Lunar Dust Relevant to Human Exploration of the Moon," *Planetary Science Division Decadal Survey white paper* (2020).

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



Dust-Proofing the Future: Lessons from the Apollo Missions

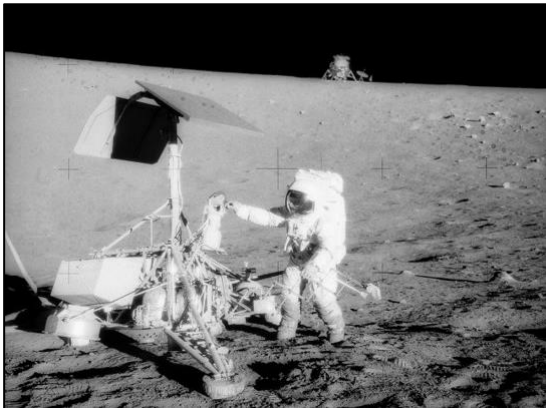
Land: Plume surface interactions (PSI)



Apollo 11 lunar module



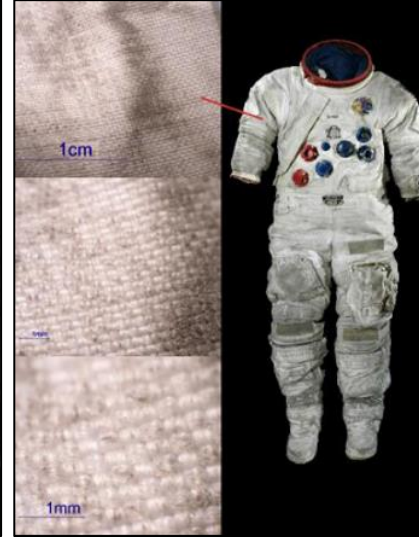
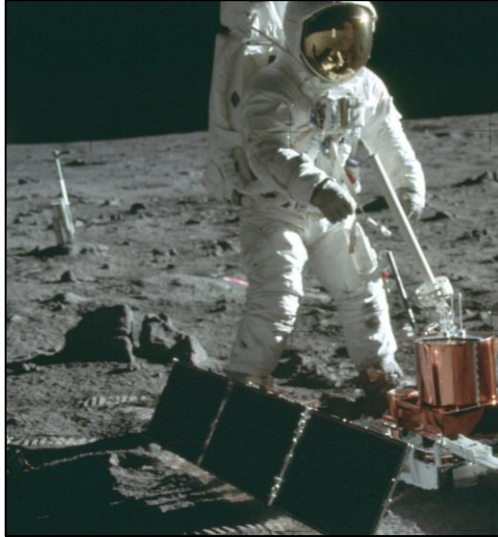
Regolith ejecta from Apollo 12 landing resulted in **scouring**, **pitting** and **cracking** of nearby Surveyor III's aluminum spacecraft structure



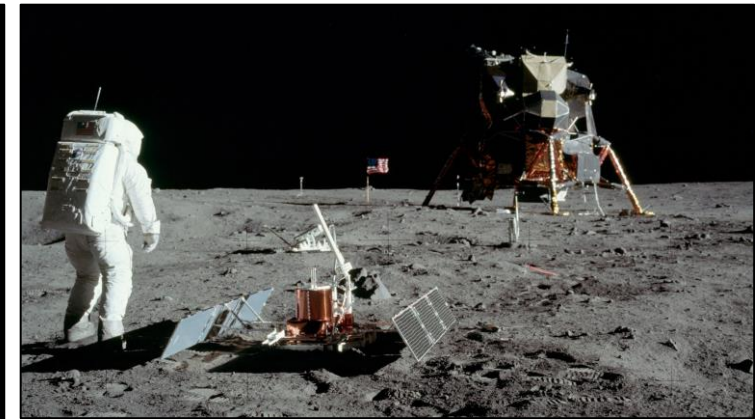
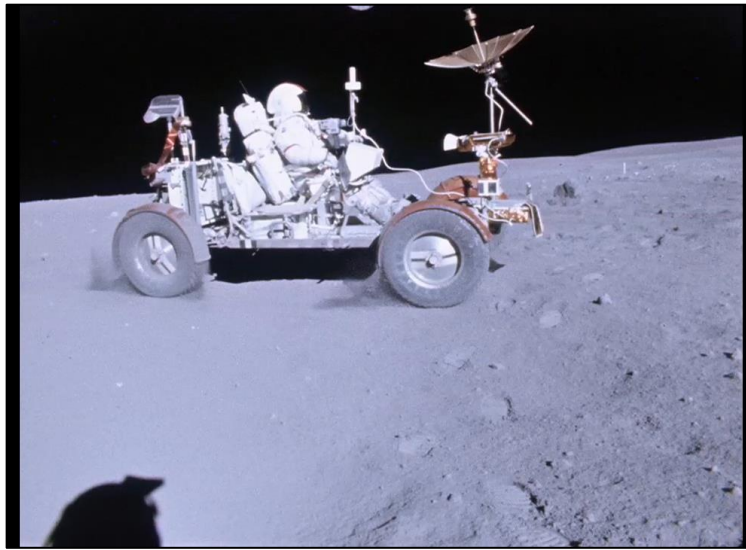
Apollo 12 extravehicular activity (EVA) showing Apollo 12 Lunar Module and Surveyor 3 spacecraft



Explore: Human-generated surface transported dust



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

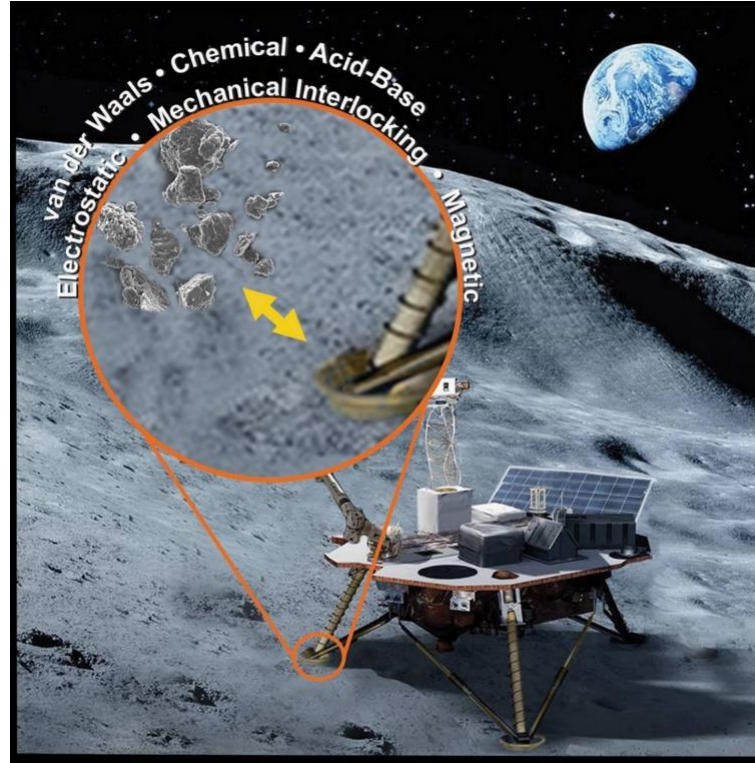


What strategies can be used to manage lunar dust?



Material Design and Selection for Lunar Applications

Dust Mitigation = Must Remove



Dust Management = Must Tolerate



Goal: Engage aspects of lunar dust from mitigation to management



Materials Discovery for Lunar Dust Tolerant Applications

Novel materials and architectures

- Laser ablation patterning of ceramics
- Spray deposition of graphene/polymer coatings
- Laser powder bed fusion of ternary metal borides
- Longer-term application (>10 years)

Protective coatings and materials

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

Testing and characterization

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



Coating Candidates for Mitigating Lunar Dust Abrasion and Adhesion

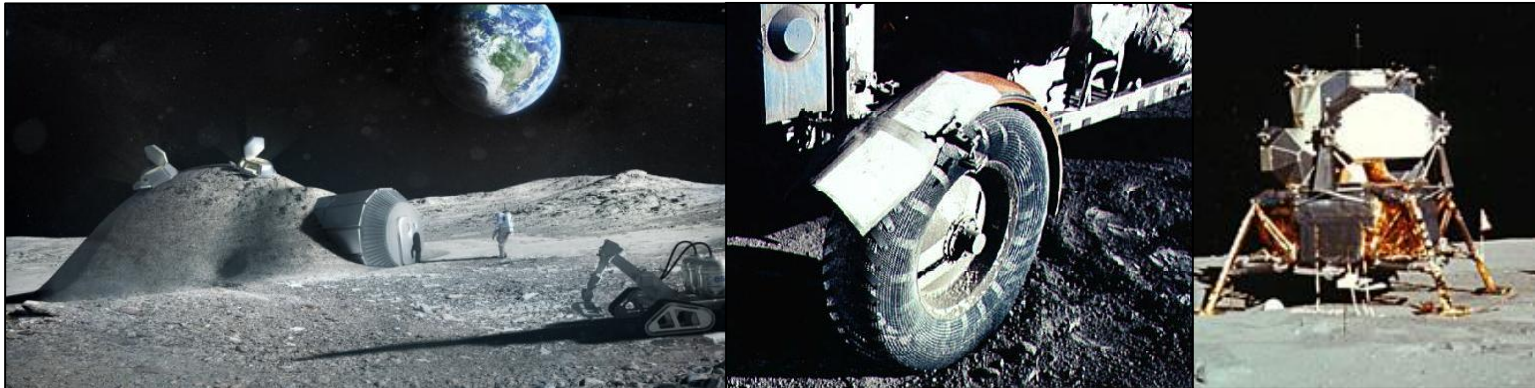
Material	Density (g/cm ³)	CTE* (μm/m·°C)	Processing Method
Substrate Materials			
Aluminum 6061	2.7	23.6	-
Ti-6Al-4V	4.43	9.1	-
Candidate Coating Material Properties			
Chromium Carbide (Cr ₃ C ₂)	6.68	-	HVOF
Chromium Oxide (Cr ₂ O ₃)	5.22	3.7	APS
Chrome Carbide-Nickel Chrome (CrC-NiCr)	2.3-3.1	6.4	HVOF

- **Coating applications**

- High-performance machining and tooling
- Mining and drilling
- Gears and bearings
- Armor/defense

- **Coating candidate material requirements**

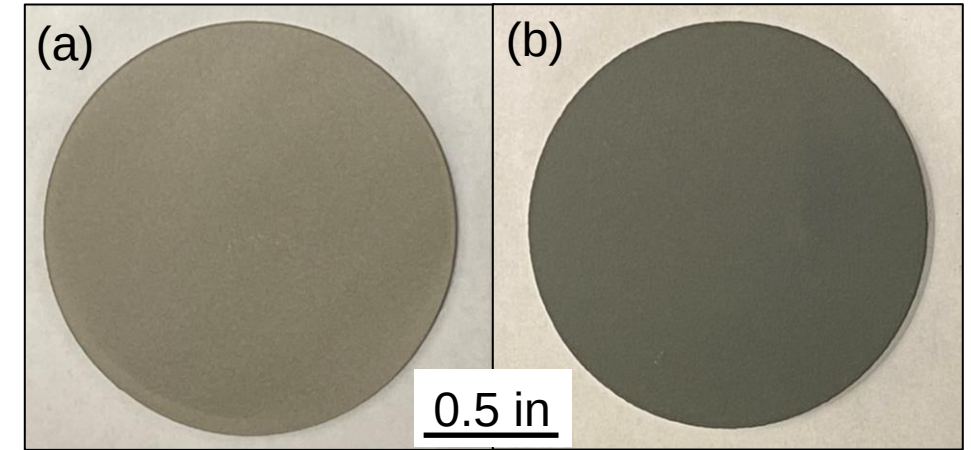
- Low density
- Substrate compatibility
- Processability
 - Air plasma spray (APS)
 - Vacuum plasma spray (PS)
 - High velocity oxygen fuel (HVOF)



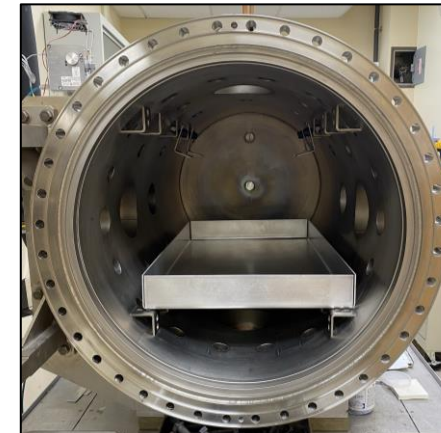


Test Methods to Evaluate Lunar Dust Abrasion, Adhesion and Environment

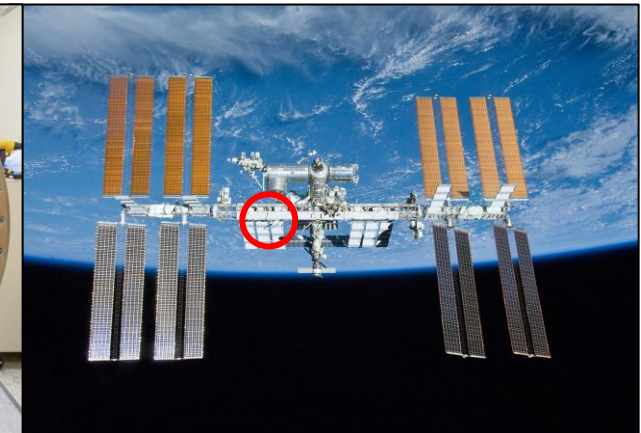
- Coupon-level mechanical property assessment
 - Pin-on-disk tribometry (ASTM G99)
 - Taber abrasion (ASTM D4060)
 - Cryogenic solid particle erosion
 - Thermal shock
 - Hardness
 - Surface roughness and adhesion properties
 - Profilometry
 - Goniometry
 - Lunar dust adhesion test
 - Environmental testing
 - Surveying Lunar dust Influence on Device Efficacy (SLIDE) environmental testbed
 - Materials International Space Station Experiment (MISSE-16)
- Test article development



Al6061 substrates coated with (a) CrC-NiCr and (b) CrO₂



SLIDE environmental testbed

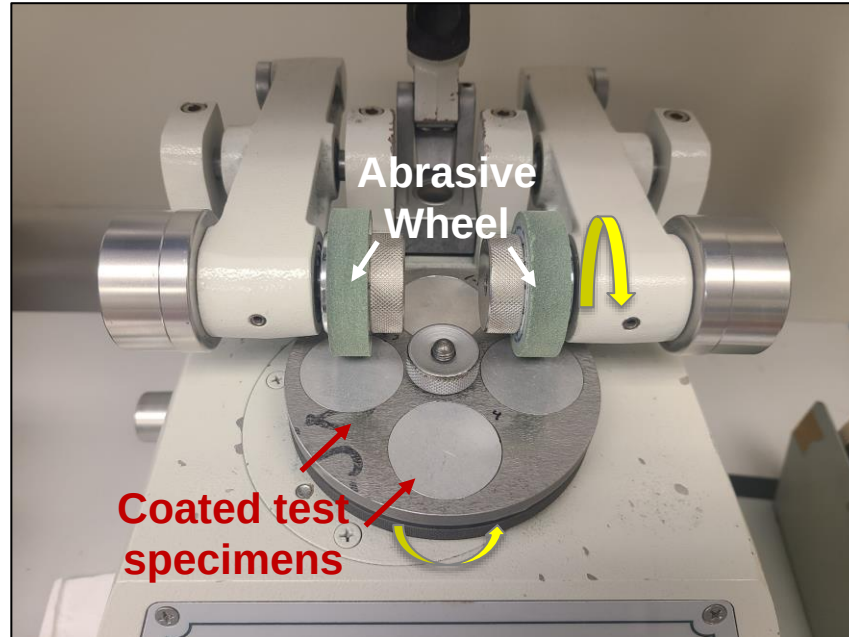


Location of MISSE-16 on International Space Station

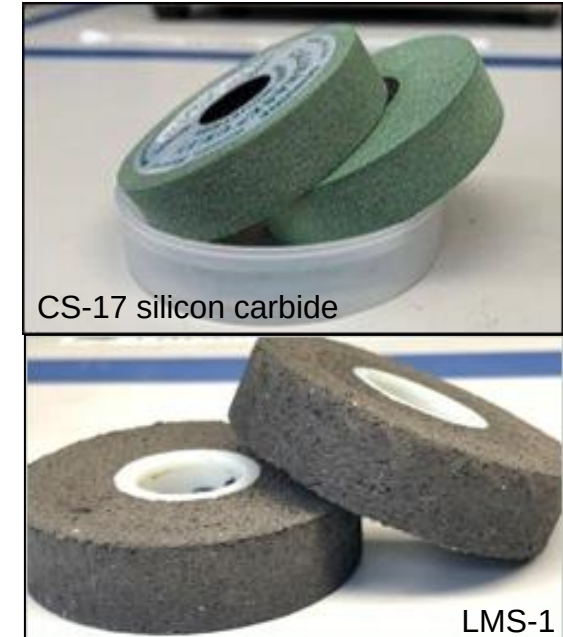


Taber Abrasion (ASTM D4060)

- QualTest GT-7012-T Taber Type Abrasion Tester
- Lower rotating abrasive wheel onto specimen fixed in spinning specimen mount for 400, 1200 and 5000 cycles
 - Measure decrease in coating thickness using Eddy current instrument
 - Track weight loss before and after cycles



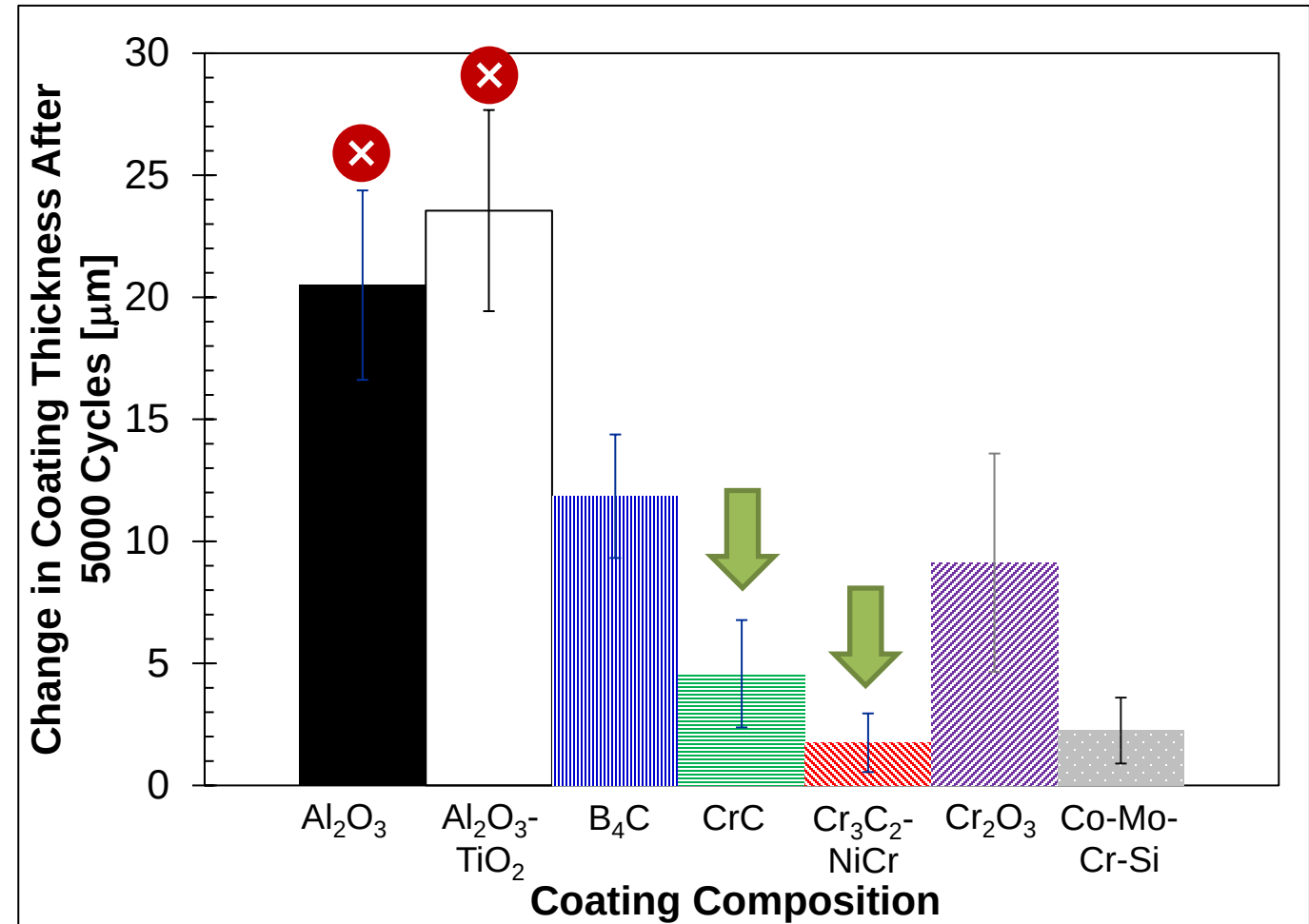
Taber abrasion test setup





Taber Abrasion Results

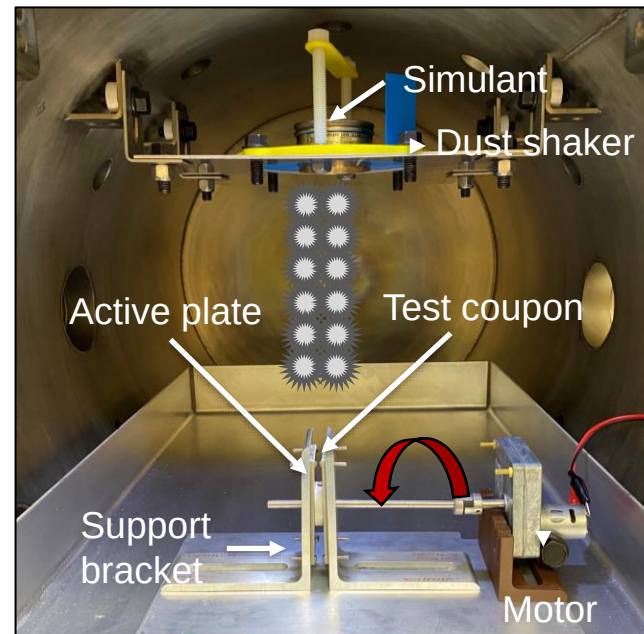
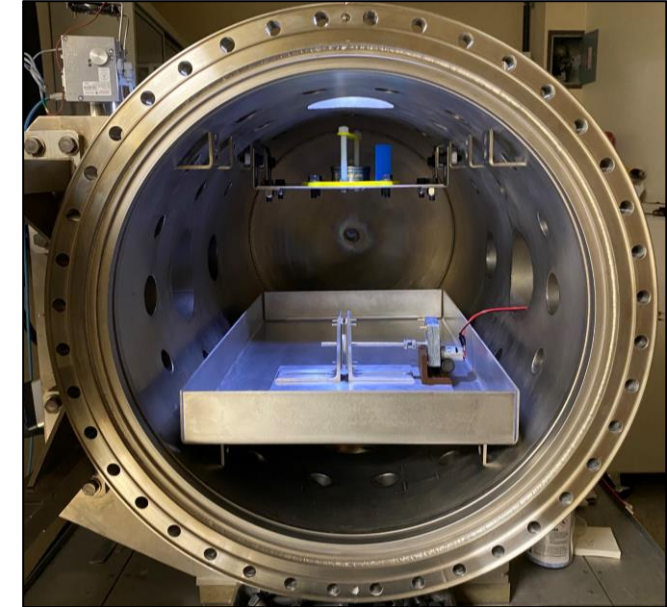
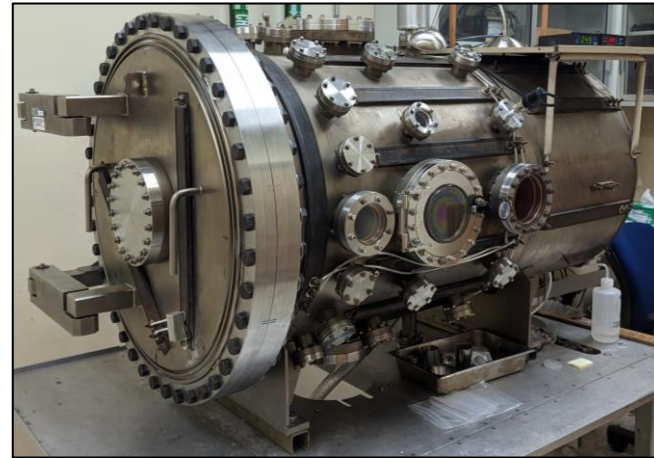
- After 5000 cycles:
 - Change in coating thickness varied with composition
 - Weight change inconclusive across all compositions
- Alumina-titania ($\text{Al}_2\text{O}_3\text{-TiO}_2$) showed greatest decrease in coating thickness
 - $23.6 \mu\text{m} \pm 4.1 \mu\text{m}$
- CrC-NiCr exhibited smallest decrease in coating thickness
 - $1.75 \mu\text{m} \pm 1.2 \mu\text{m}$
- Lunar dust simulant-based abrasive wheels





Characterizing Wear by Lunar Dust in Vacuum

- Surveying Lunar Dust Influence on Device Efficacy (SLIDE) chamber
 - Wear caused by dust (e.g., lunar, Martian, standard, etc.)
 - High vacuum ($>10^{-6}$ Torr)
 - Temperature fluctuations (ambient to -190° C)
 - Ultraviolet (UV) radiation
- Configurable to accommodate variety of materials, mechanisms and abrasives relevant to lunar applications



Simplified pin-joint mechanism inspired by Lunar Surface Manipulation System (LSMS)

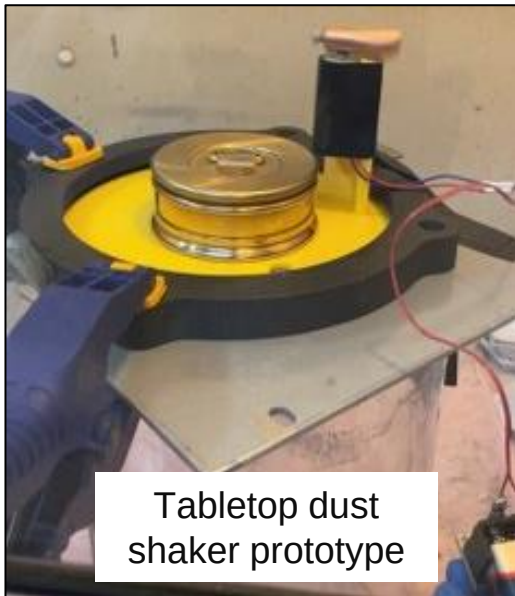


SLIDE Chamber Dust Shaker

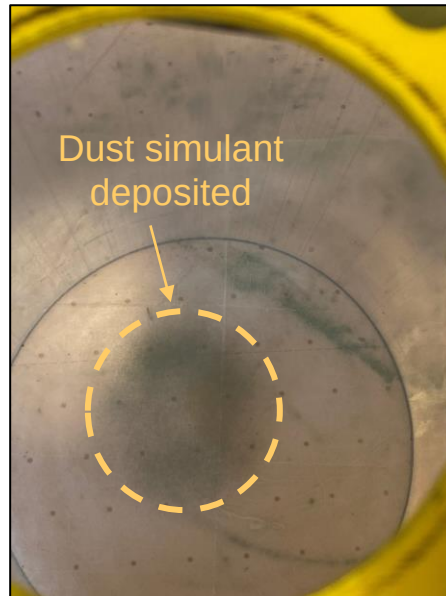
- Dust shaker releases tailorable amounts of lunar dust simulant
 - Sieve: mesh opening of $106\text{ }\mu\text{m}$
 - Shaker mechanism: rotating copper weight powered by electric motor
 - Surface accumulated loading
 - Human-generated surface transported dust: $<40\text{ g/m}^2$ [1]
 - SLIDE chamber dust shaker: $\sim 40\text{ g/m}^2$ after 15 seconds



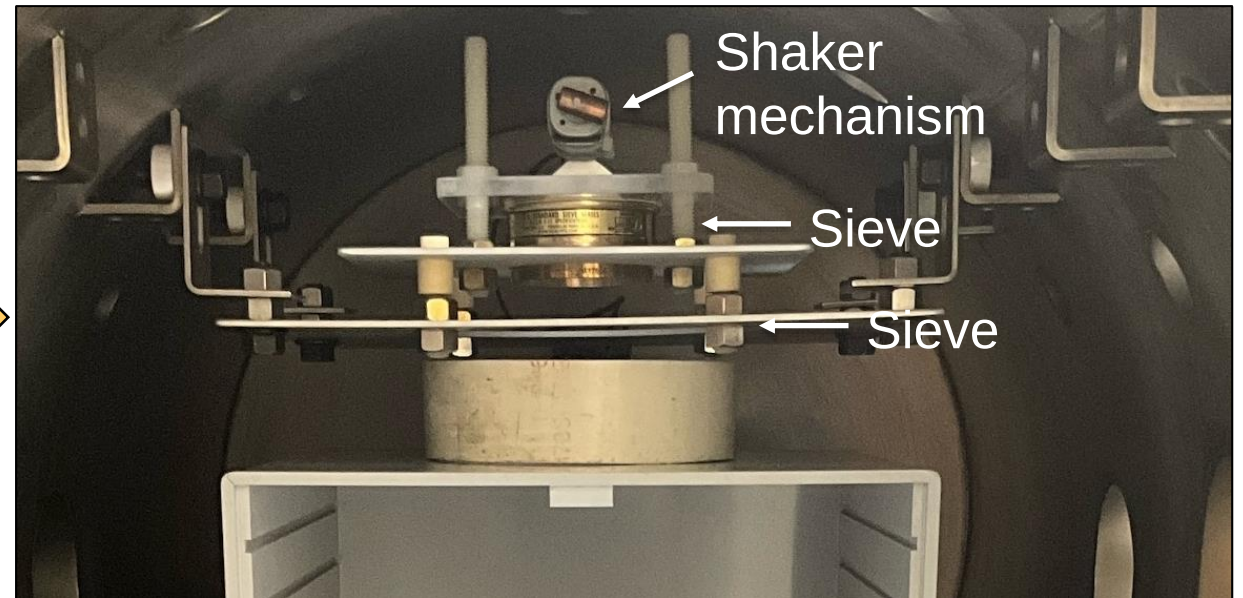
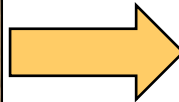
Sieve with 3-in. diameter



Tabletop dust shaker prototype



Dust simulant deposited



Shaker mechanism

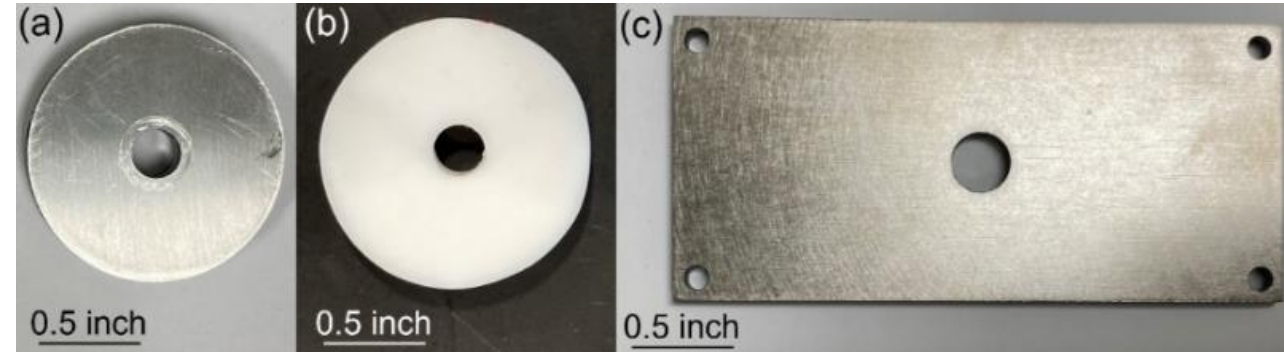
Sieve

Sieve

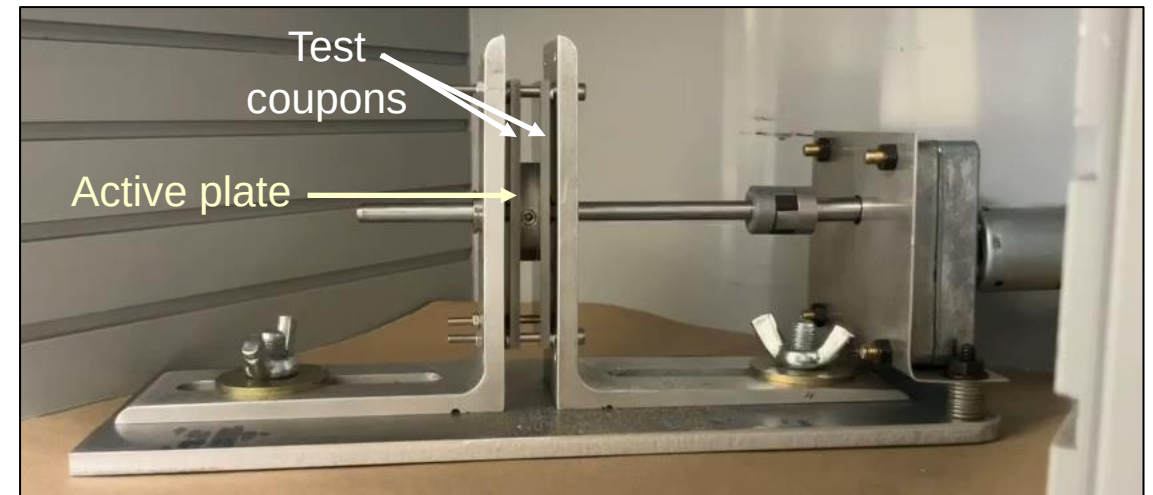


Pilot Assessment of Material Wear Performance

- Test coupon
 - Ti-6Al-4V
 - CrC-NiCr coating
 - Boron carbide
 - Molybdenum aluminum boride
 - Active plate
 - Polytetrafluoroethylene (PTFE)
 - Aluminum 6061 alloy (Al6061)
 - SLIDE test conditions
 - Vacuum: $\sim 10^{-5}$ Torr
 - Lunar simulant type: LHS-1D
 - Active plate rate of rotation: 1.3 RPM
 - Test duration: 5000 cycles
 - Materials characterization
 - Optical microscopy
 - Profilometry
- Compare results of SLIDE-tested coupons with baseline data from standard methods



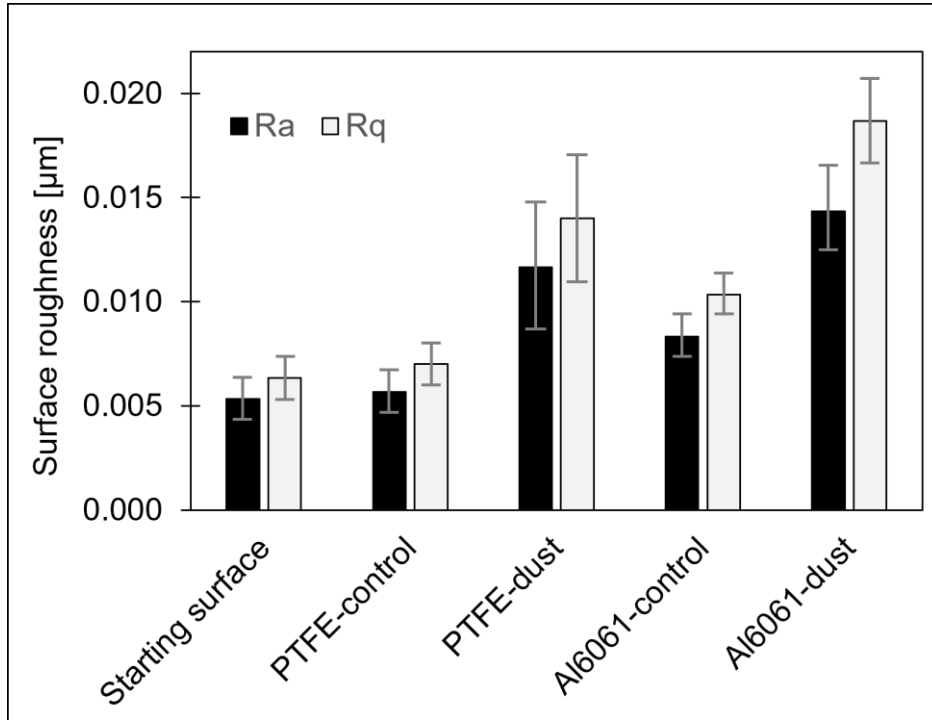
(a) Al6061 Active Disc, (b) PTFE Active Disc and (c) Ti-6Al-4V Test Coupon



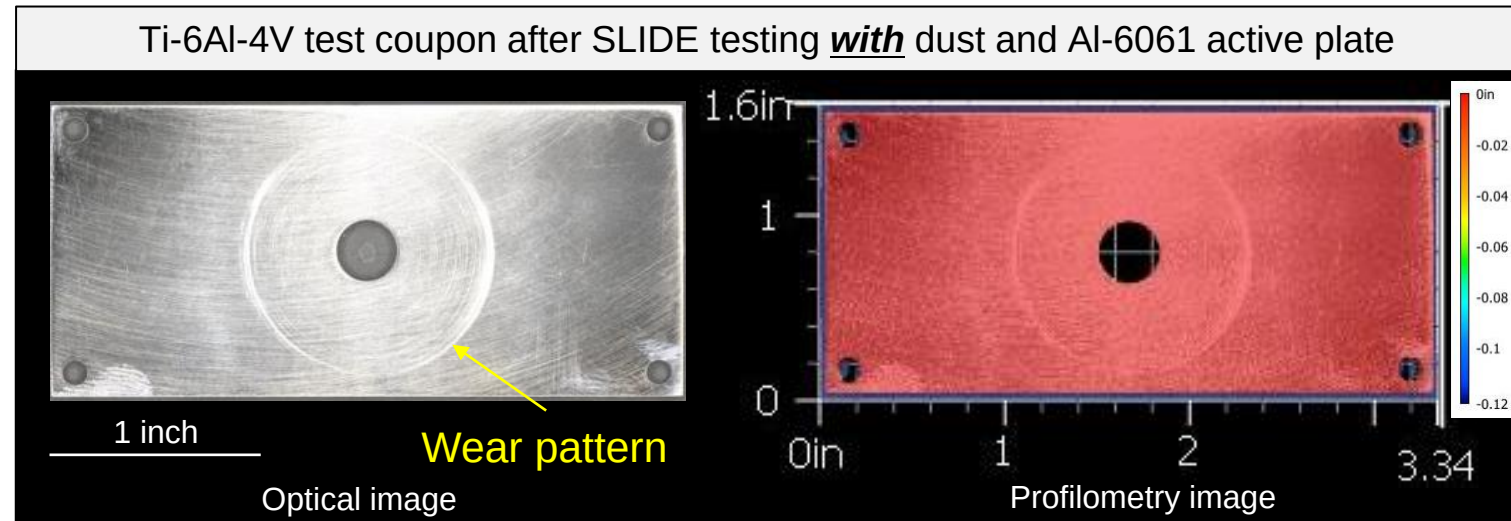
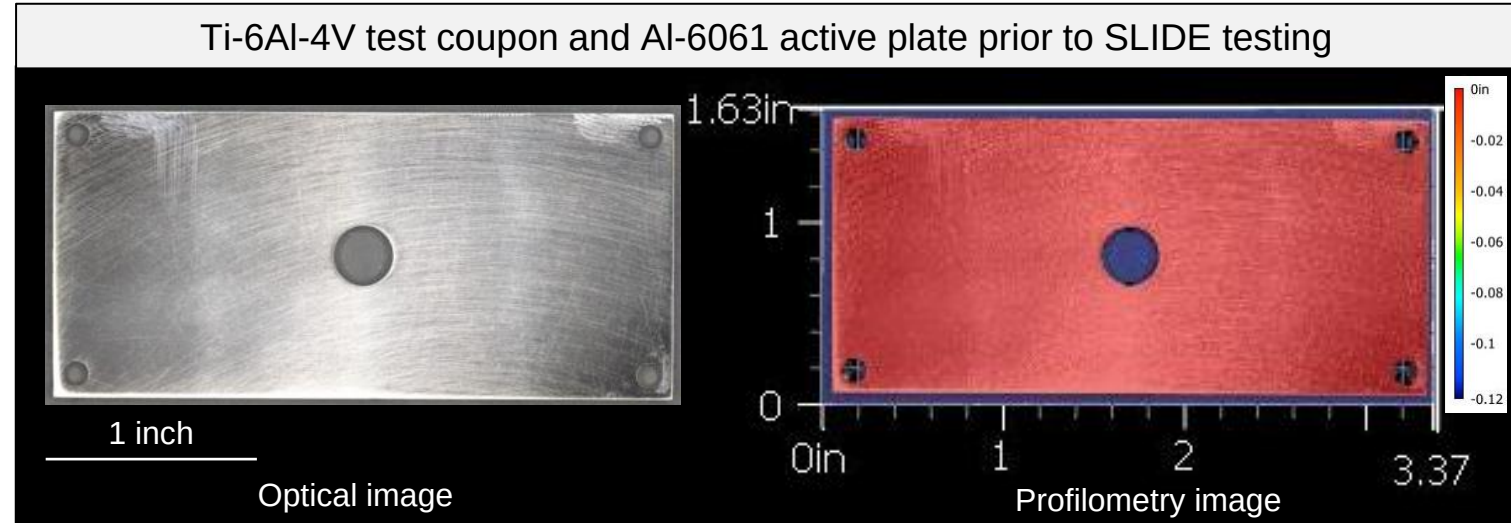
Test comprised of Al6061 active plate and Ti-6Al-4V test coupons without dust



Pilot Assessment of Material Wear Performance



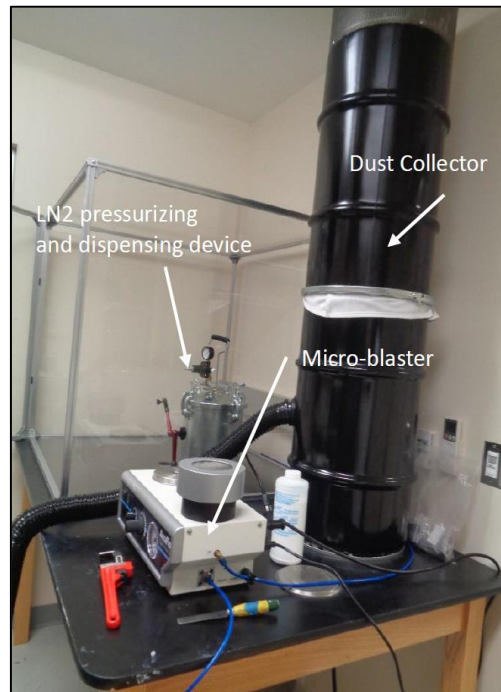
- Introduction of lunar dust simulant resulted in a higher degree of wear of the Ti-6Al-4V surface than in wear tests without lunar dust simulant



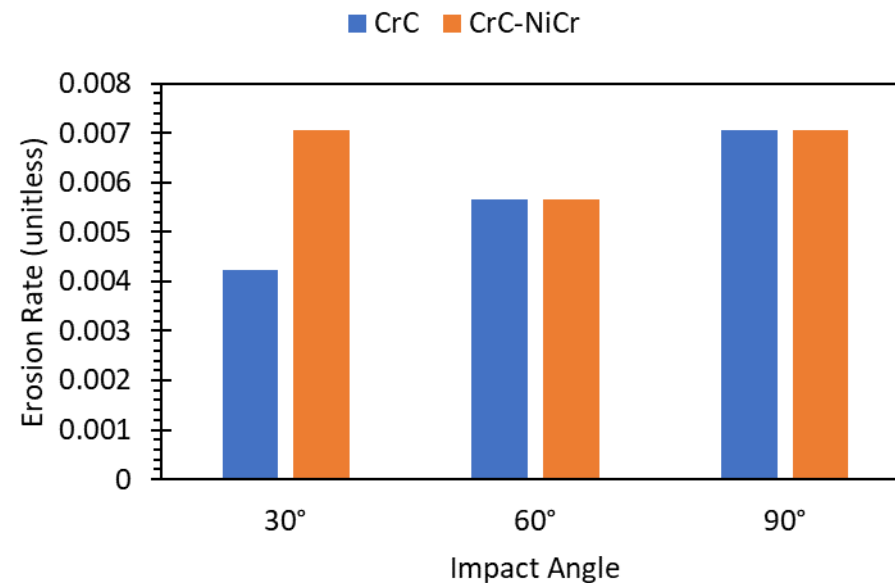


Cryogenic Solid Particle Erosion (SPE)

- Custom-built instrument enabling cryogenic test conditions (-175°C to -160°C) during controlled particle erosion
- Volcanic soil (18- μm diameter) from Mauna Kea, Hawaii Island, Hawaii
 - Impact angles of 30° , 60° , and 90° evaluated during 30-second particle exposure

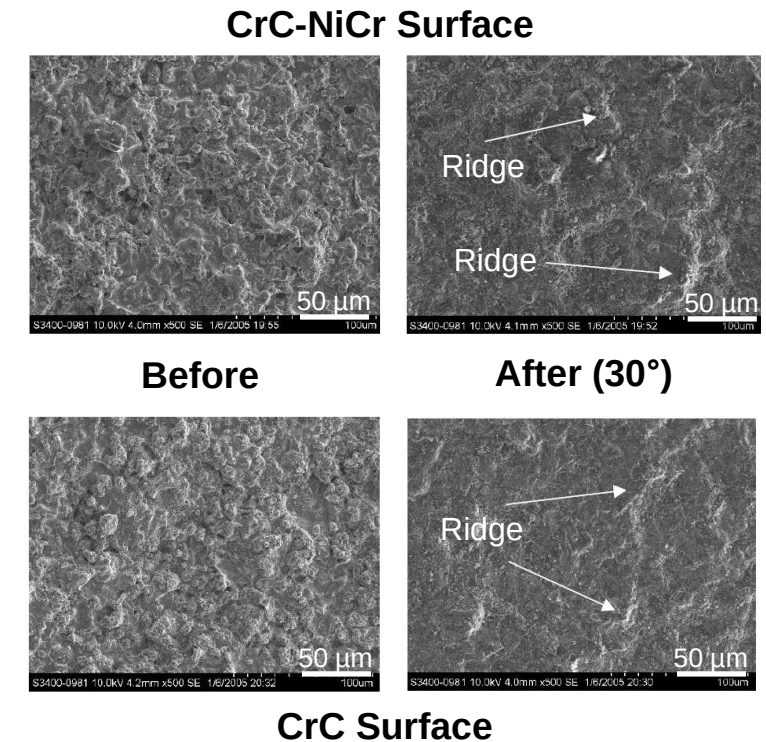


Cryogenic SPE Instrument



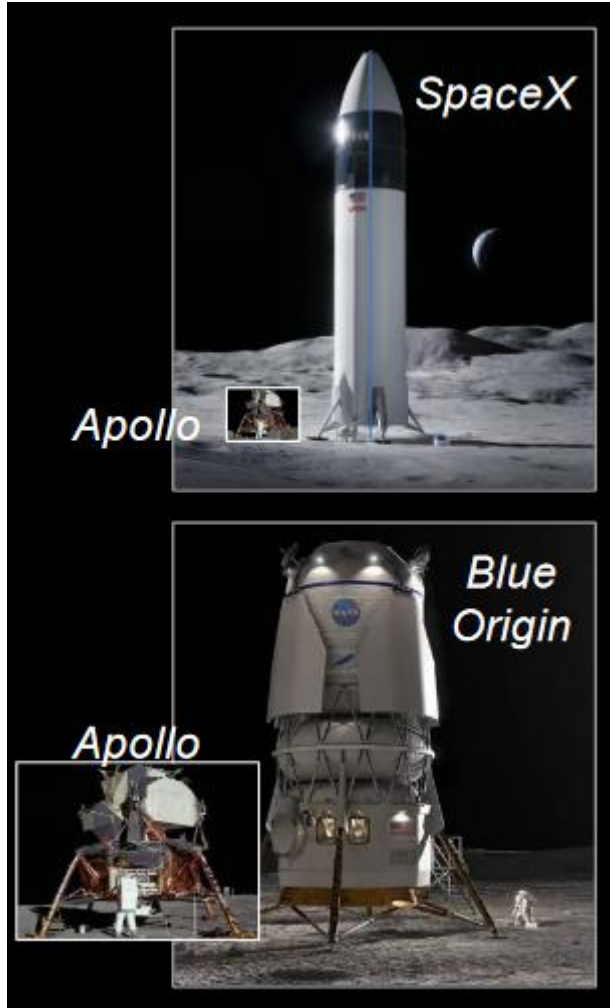
Erosion Rate for Al_2O_3 was 470% greater at 60°

Erosion Rates





Testing for Plume Surface Interactions (PSI)



Human Landing System (HLS)
lander concepts

Limited experimental data on lunar dust particle velocities and angles of impingement

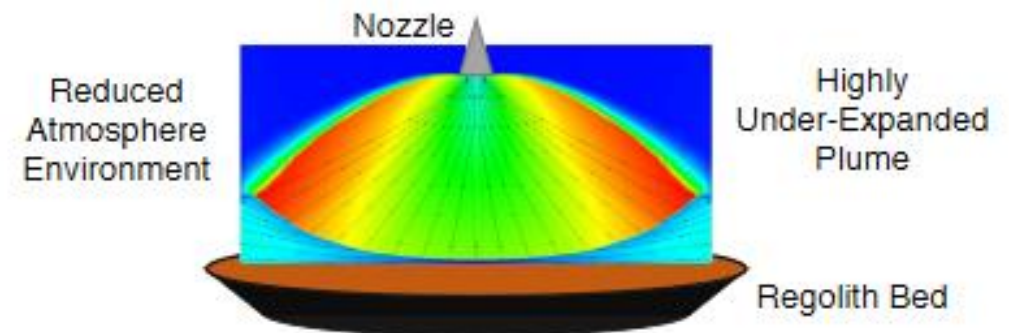
- Nano- to micrometer-sized particle sizes
- Within 50 m of landing site, particle velocity estimates 300 m/s to 2000 m/s

Ground-based testing opportunity: PSI test campaign (2025-26)

- Passive experiment to expose materials relevant to lunar applications to PSI-like environment (e.g., erosion, impact)



LaRC 60-foot vacuum sphere

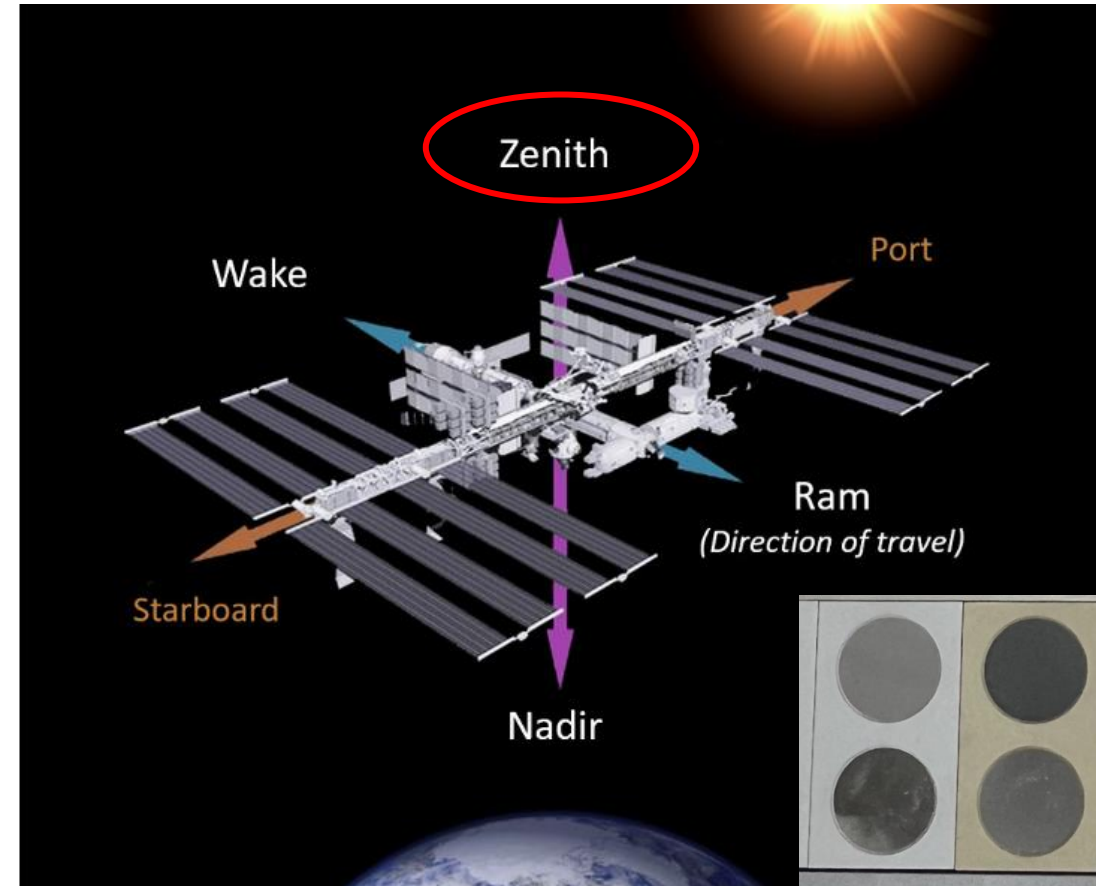


Schematic of PSI test setup



Assessing Materials Performance in Low-Earth Environment (LEO)

- MISSE-16
 - Zenith positions for six-month exposure
 - Maximum solar ultraviolet (UV) radiation
 - Atomic oxygen fluence $\sim 10^{20}$ atoms/cm²
 - ~ 3380 thermal cycles (-14°C to 32°C)
 - Specimens returned for ground-based analysis
- Pre- and post-exposure characterization
 - Surface characteristics and microstructure
 - Optical properties Solar absorptance
 - Infrared emittance
 - Dust adhesion

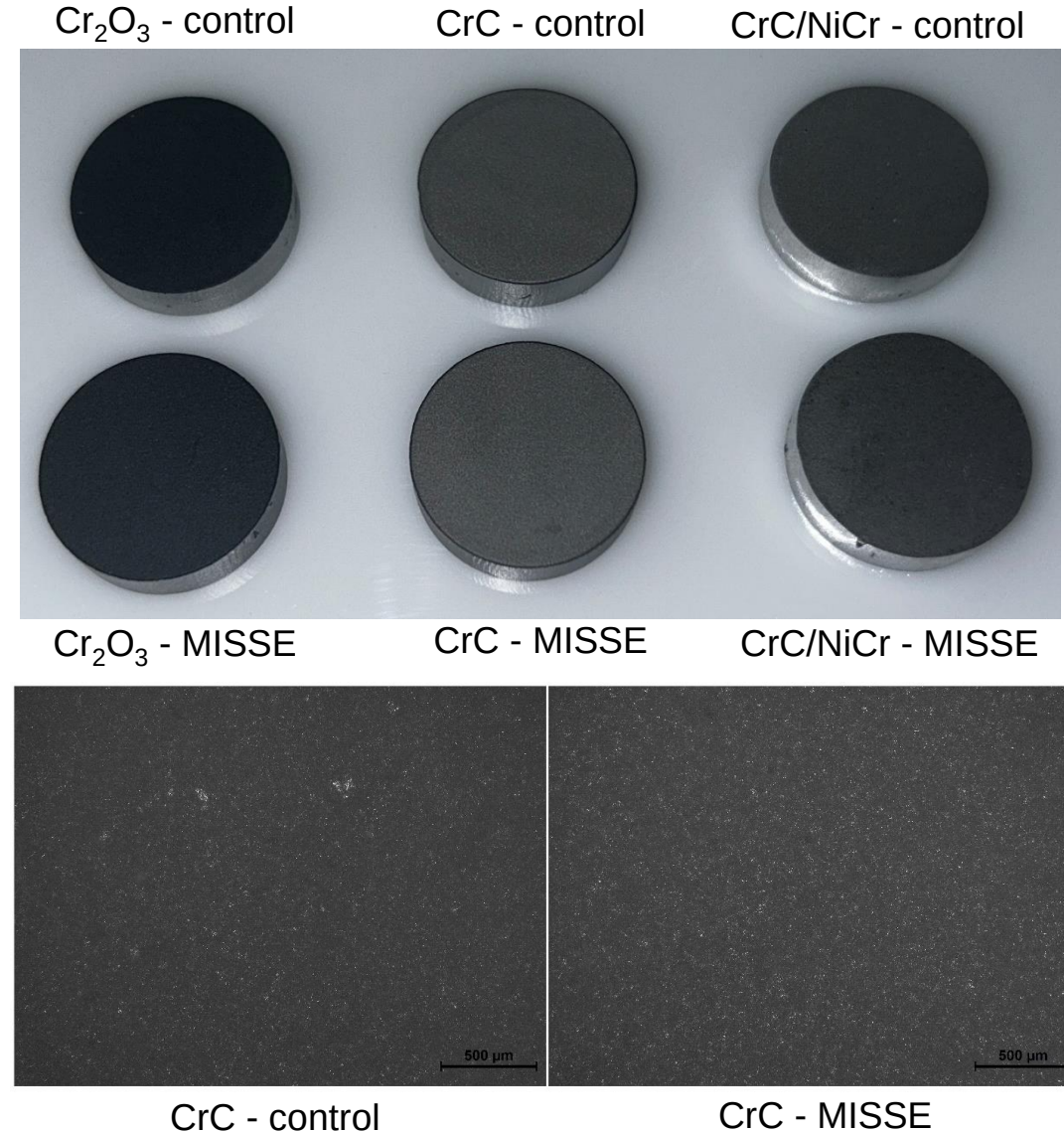


ISS schematic with inset of specimens flown on MISSE-16

Surface Characteristics

- No discernible change in surface features
 - Optical microscopy
 - Scanning electron microscopy
- Increase in surface roughness parameters after exposure
 - Average roughness: R_a
 - Root mean square roughness: R_q

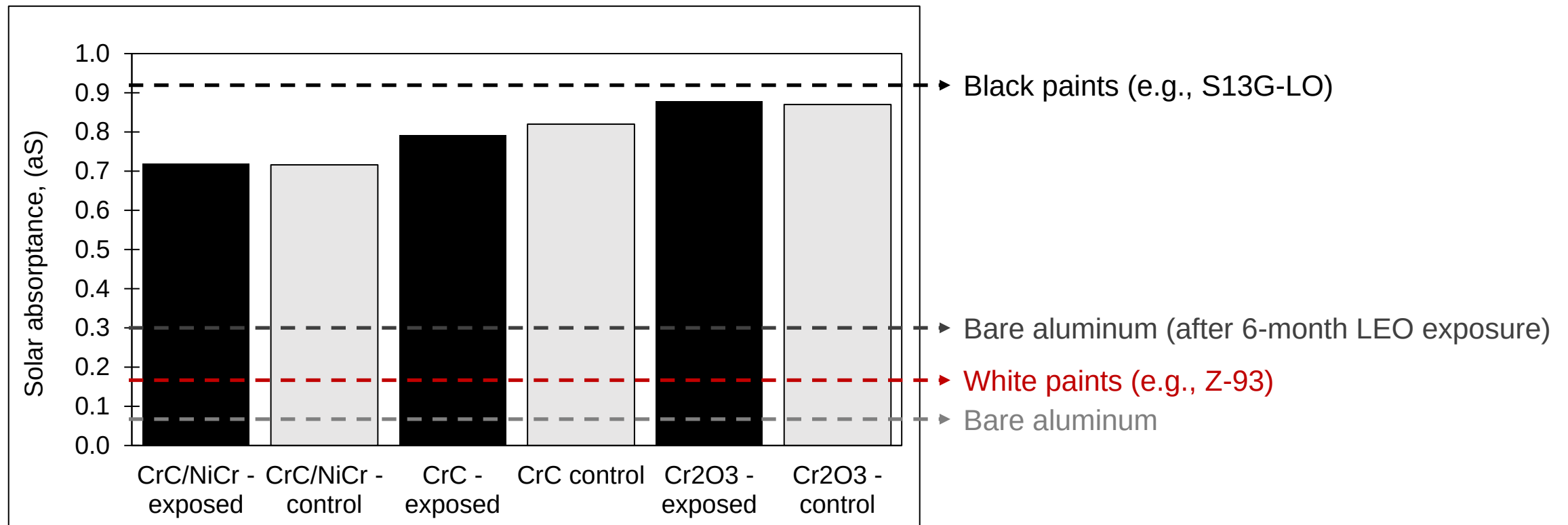
Sample	sRa (μm)	sRq (μm)
CrC – MISSE	0.822	1.086
CrC – control	0.860	1.083
Cr ₂ O ₃ – MISSE	1.350	1.674
Cr ₂ O ₃ – control	1.1301	1.641
CrC/NiCr – MISSE	1.308	1.639
CrC/NiCr – control	1.289	1.633





Optical Properties: Solar Absorptance

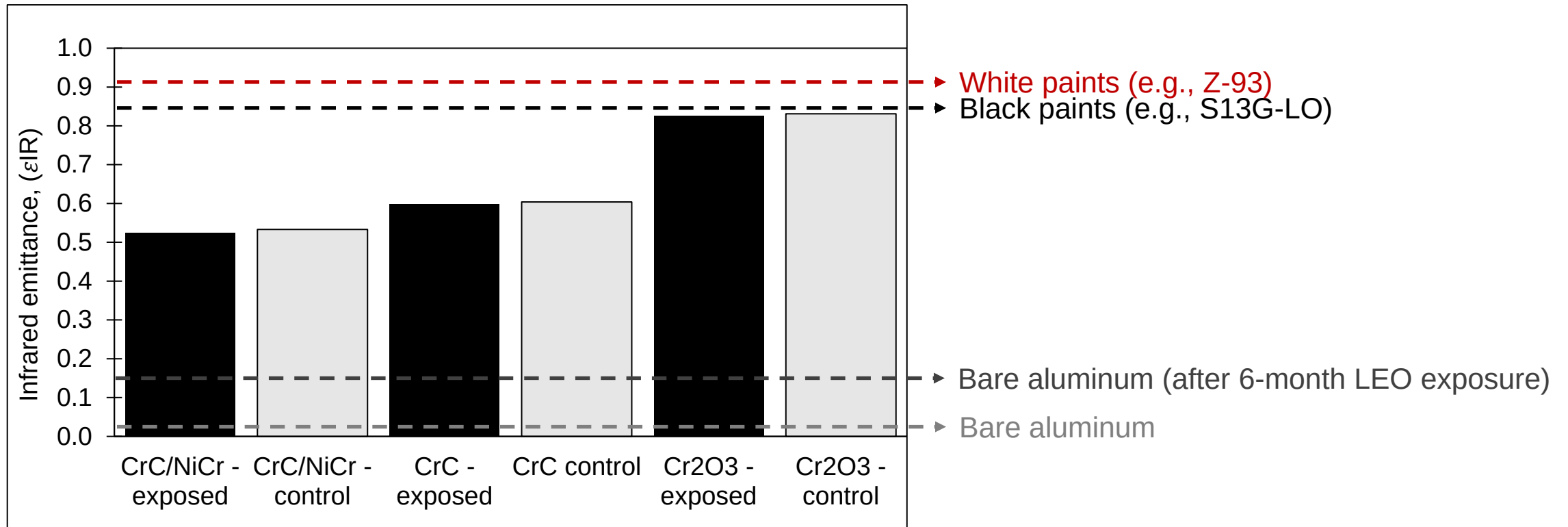
- Solar absorptance (a_S) values before and after LEO exposure varied $<3.4\%$
 - CrC/NiCr: a_S increased by 0.003 (0.4%)
 - CrC: a_S decreased by 0.028 (3.4%)
 - Cr_2O_3 : a_S increased by 0.009 (1.0%)





Optical Properties: Infrared Emittance

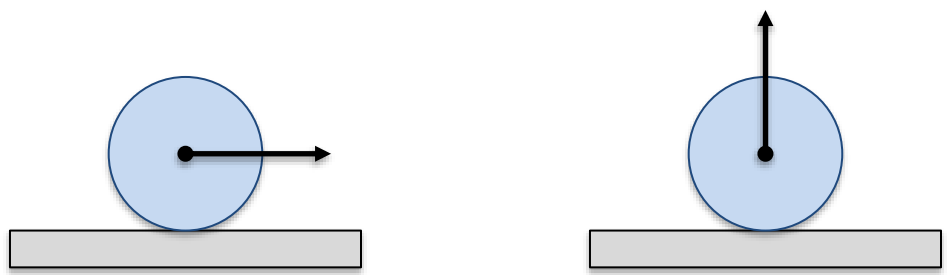
- Infrared emittance (ϵ_{IR}) values before and after LEO exposure varied by <1.7%
 - CrC/NiCr: ϵ_{IR} decreased by 0.009 (1.7%)
 - CrC: ϵ_{IR} decreased by 0.006 (1.0%)
 - Cr_2O_3 : ϵ_{IR} decreased by 0.005 (0.6%)





Centrifuge Adhesion Testing

Centrifugal Force Vector

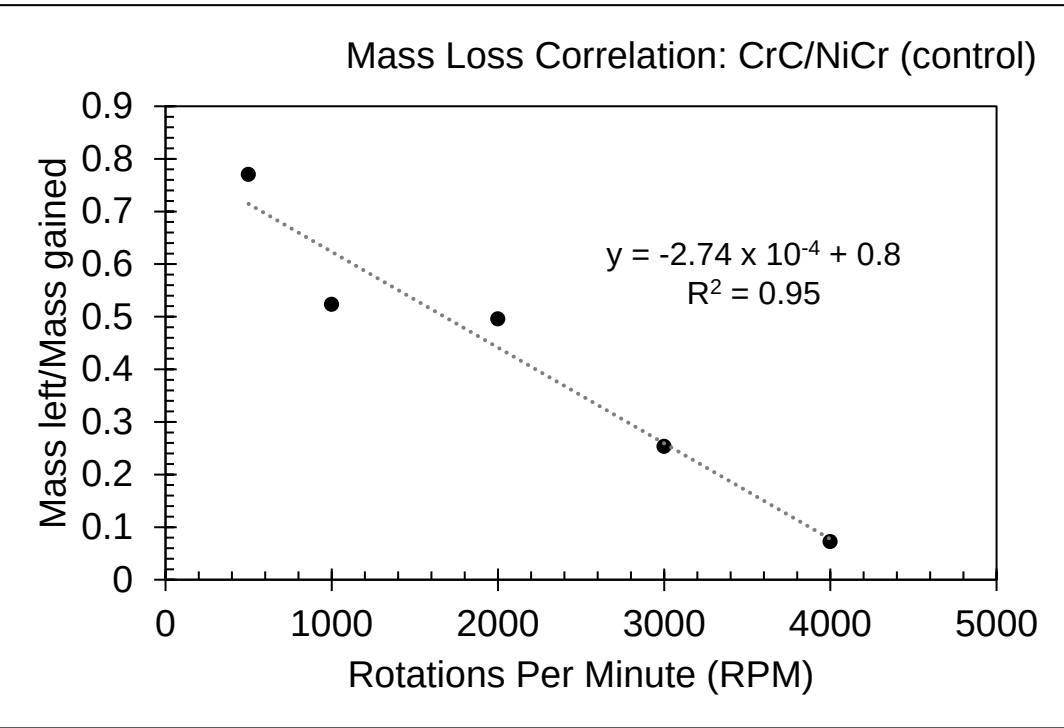


Mass Loss Coefficient

Mass Remaining $\longrightarrow$
Mass Gained $\longrightarrow$

$$\frac{m_1}{m_0} = -\mu\omega$$

Angular Velocity



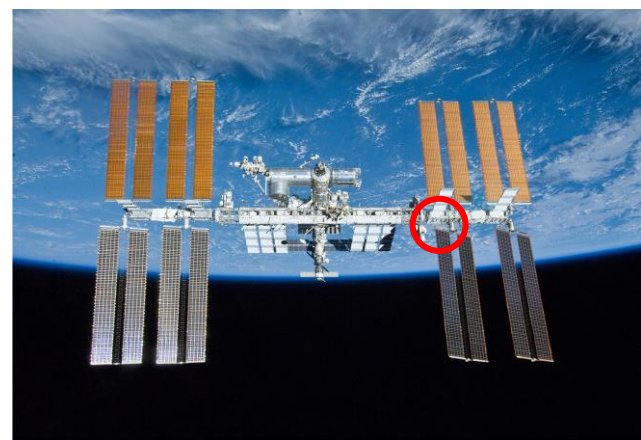
Material	Mass Loss Coefficient ($\times 10^{-4}$)	Zero Mass at RPM	Low Dust adhesion ↓ High
CrC/NiCr (control)	2.74	3650.2	
CrC (MISSE)	2.58	3924.8	
CrC (control)	2.55	3926.5	
CrC/NiCr (MISSE)	2.40	4174.5	



Current Efforts and Upcoming Opportunities

Low-earth orbit (LEO)

- MISSE-16
 - o Additional microstructural analysis ongoing
- MISSE-20
 - o Specimen integration complete and ready for launch (tentatively Oct. 30, 2024)
 - o Wake position for six-month exposure
 - o Specimens returned for ground-based analysis

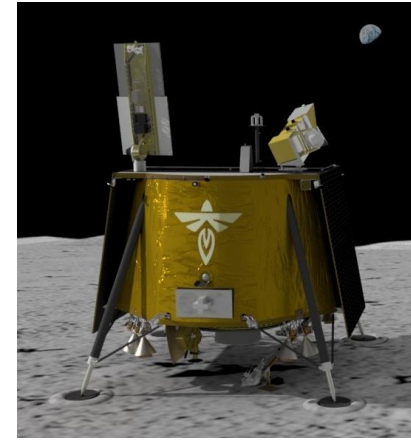


Location of MISSE-16 on International Space Station

Lunar surface

- Regolith Adherence Characterization (RAC) Payload and PlanetVac Instrument (2025)
 - o Mare Crisium location
 - o Direct exposure in lunar environment
- Optical observation throughout duration of exposure
- Specimens remain on Moon upon conclusion of mission

MISSE-16	MISSE-20
Cr_2O_3	B_4C
Cr_3C_2	MoAlB
CrC/NiCr	8YSZ
	SiC
Lunar Surface	
CrC/NiCr	



Artist rendering of Firefly Aerospace Blue Ghost Lander



Mare Crisium planned landing site



Protective Coatings for Lunar Applications

- **Lunar dust poses threat to current and future lunar mission success**
 - Materials that mitigate and manage lunar dust adhesion and abrasion are needed to enable sustainable lunar exploration
- **Test methodologies are critical to advance technologies to enable sustainable crewed presence on the Moon**
 - Traditional coupon-level mechanical testing
 - Accessible environmental testing for abrasion and erosion
 - Dust adhesion screening methods
 - Flight tests and exposures
- **Processing, manufacturing and testing opportunities**

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The Artemis logo features a stylized white 'A' with a red swoosh and a blue swoosh. A small grey sphere is positioned at the top of the 'A'.

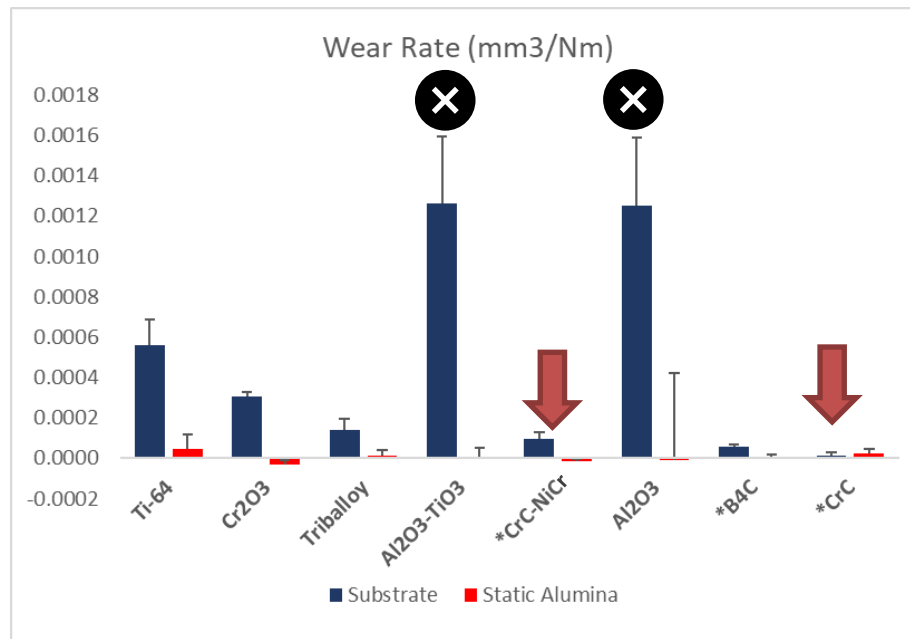
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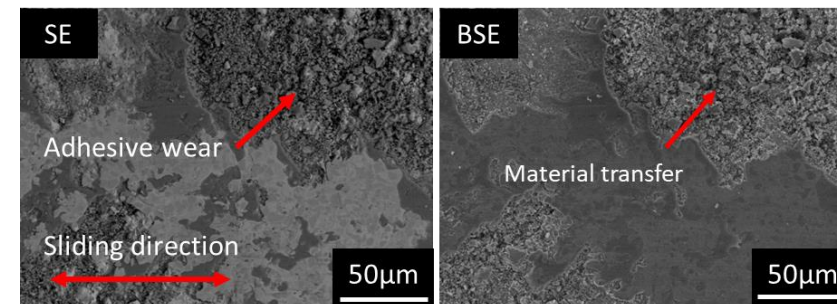


Pin-on-Disk Tribometry (ASTM G99)

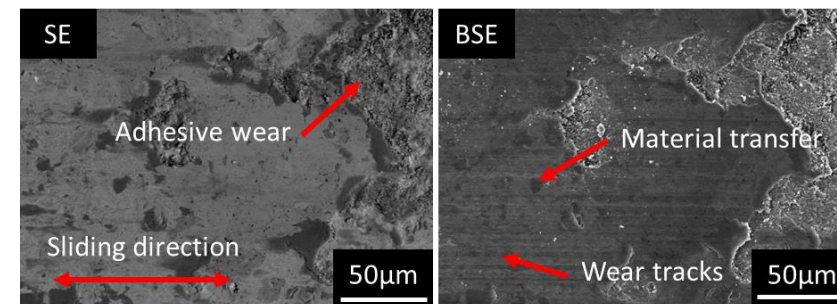
- CSM Instruments, model TRB
- Speed: 20 cm/s, Load: 5 N, Sliding distance: 100 m (+900 m for wear rate < 0.0001 mm³/Nm)
 - Determination of wear rate (quantitative) and analyze material transfer (qualitative)



Wear Rates



CrC-NiCr Surface

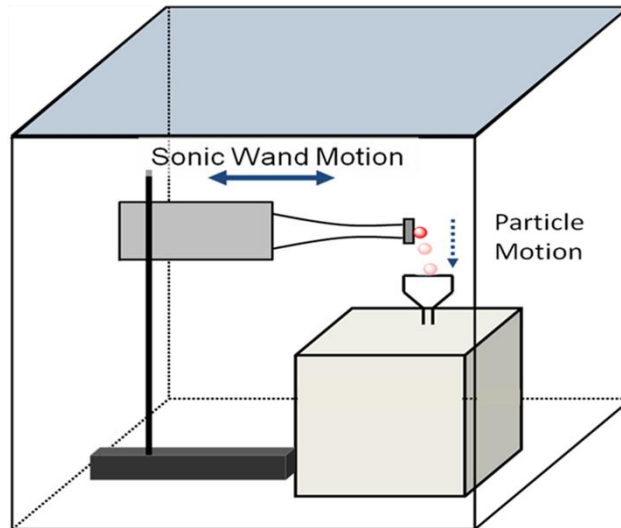


CrC Surface

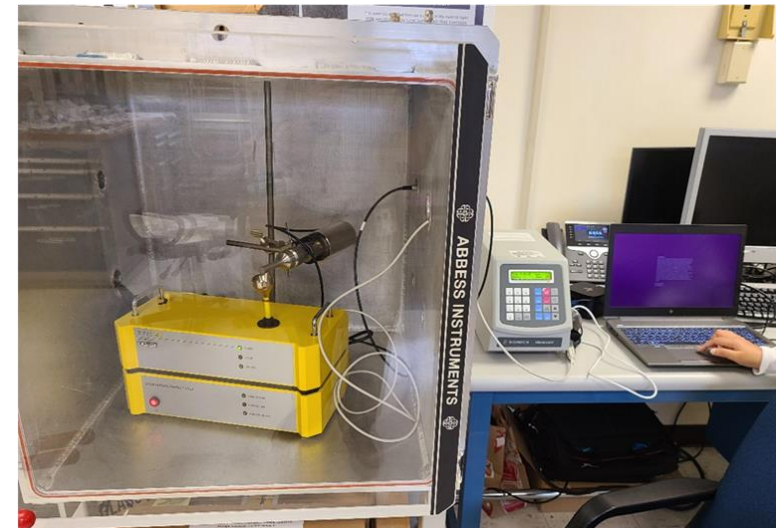


Assessing Lunar Dust Adhesion

- Lunar Dust Sonic Wand Adhesion Test
 - Coated specimen mounted on circular sonic wand tip
 - Lunar dust simulant (LHS-1D, $< 25 \mu\text{m}$) deposited by aerosolization technique
 - Optical microscopy images taken before and after specimens subjected to sonic wand amplitudes:
 1. 20% of sonic wand amplitude for 2 seconds, twice
 2. 20%-40% sonic wand amplitude for 2 seconds



Schematic of lunar dust adhesion test setup



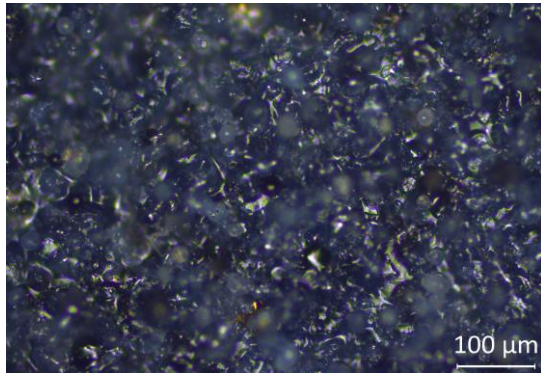
Lunar dust adhesion test setup



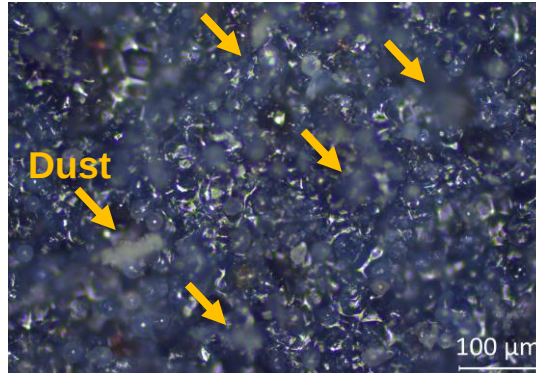
Preliminary Results of Lunar Dust Adhesion Test

- $\text{Al}_2\text{O}_3\text{-TiO}_2$ coating (APS)

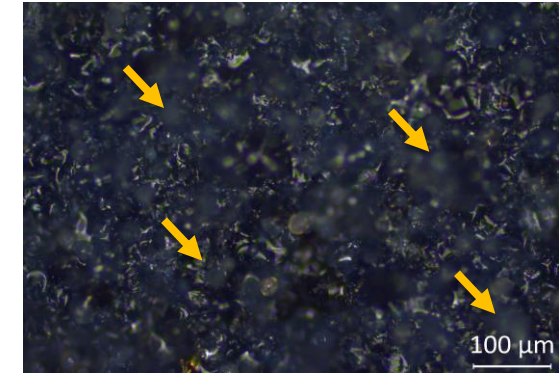
Before dust deposition



After dust deposition

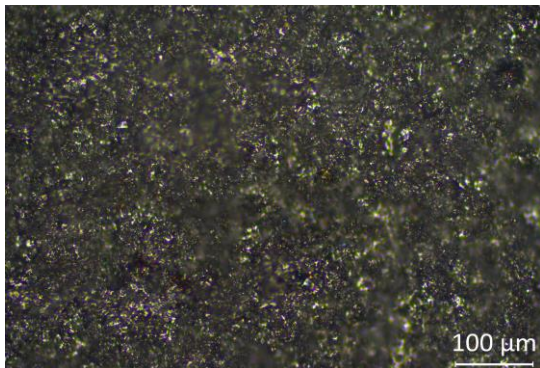


After sonic wand test



- $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating (HVOF)

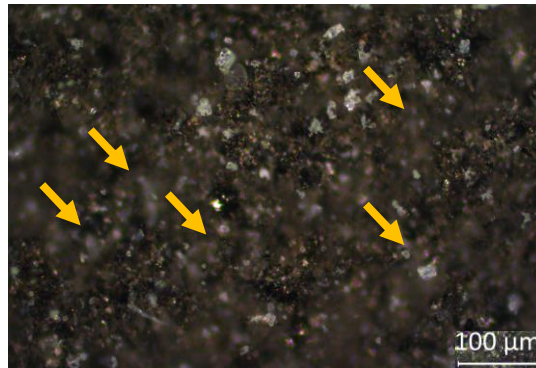
Before dust deposition



Dust
application



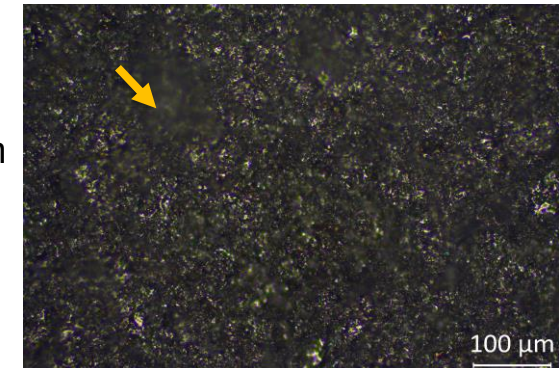
After dust deposition



Sonication



After sonic wand test



➤ Minimal adhesion observed with further analysis underway