
DUST
MITIGATION

Dust Characterization Needs for Dust Mitigation

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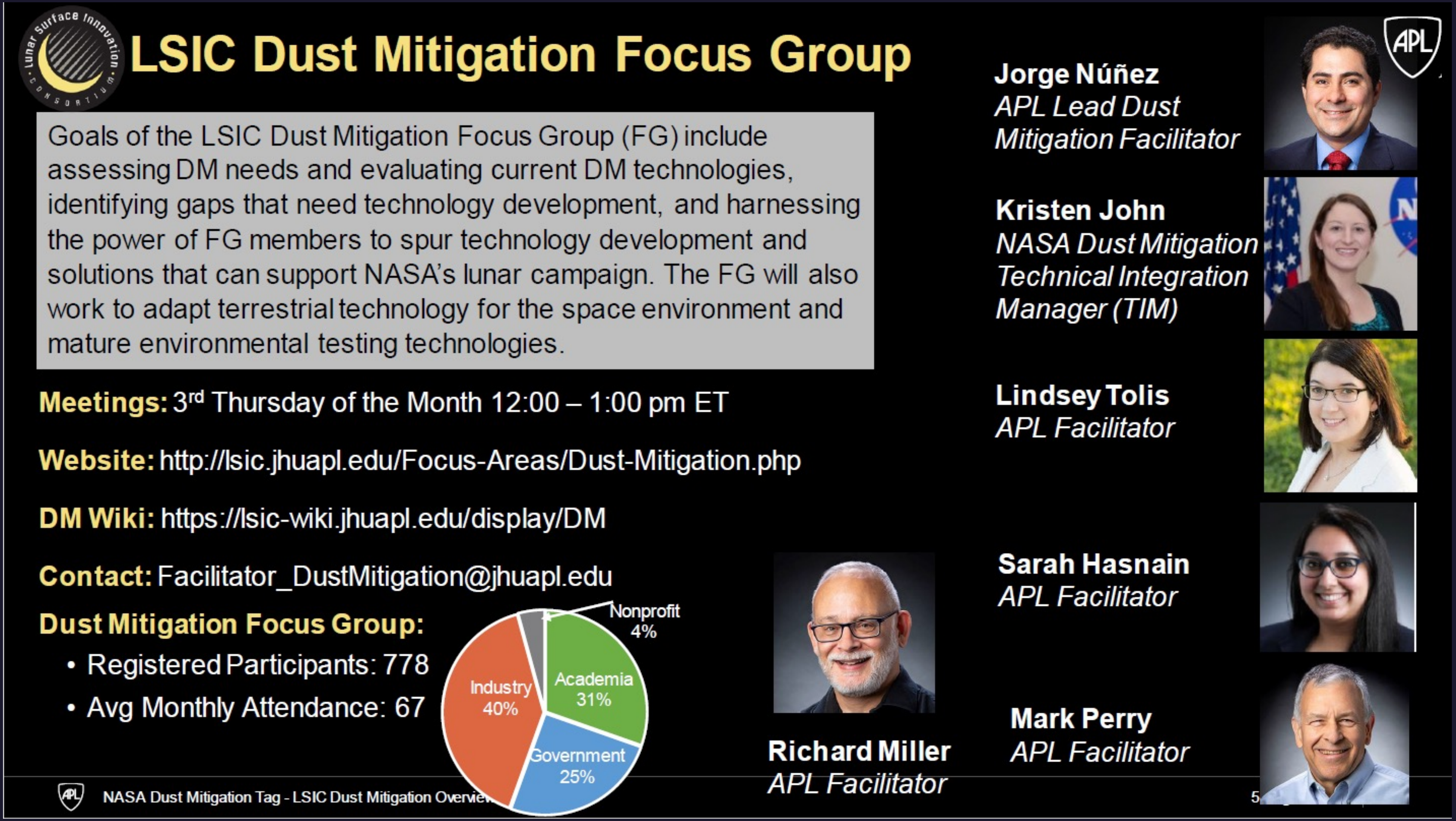
NASA ARTEMIS SPACECRAFT PERFORMANCE EX2 CONCEPT ENGINEERING

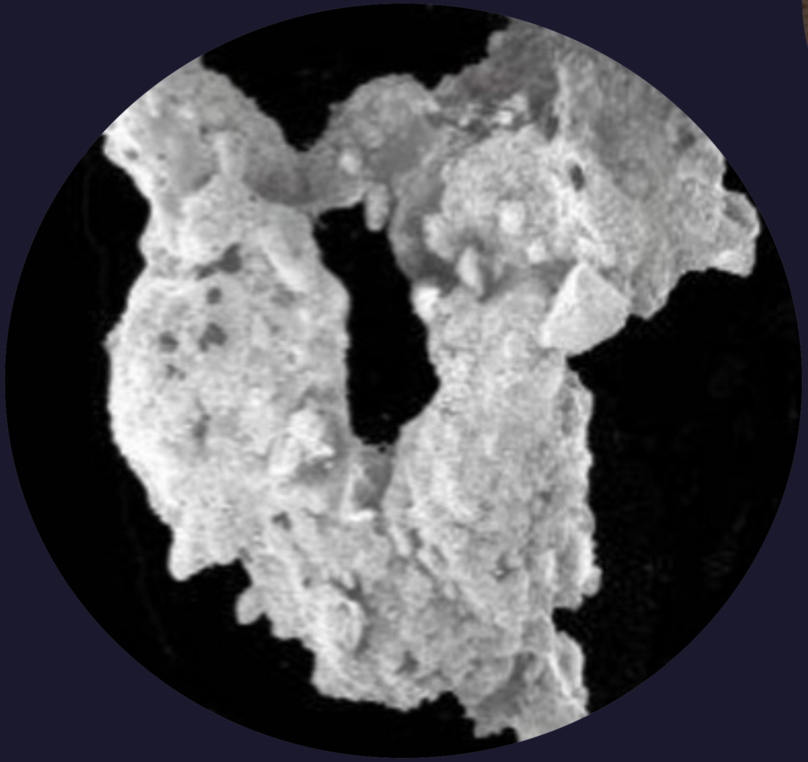
LSIC

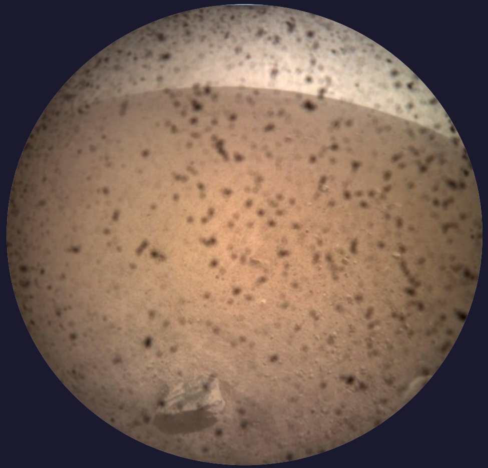
- Provides independent analysis/review of Dust Mitigation technology development.
- NASA's conduit to industry and academia.
- Provides Systems Engineering functions to help perform studies, address needs.



LSIC = Lunar Surface Innovation Consortium

Agenda





Dust, the dust problem, and dust mitigation

Dust characterization needs

Adhesion experiment

Dust accumulation sensor

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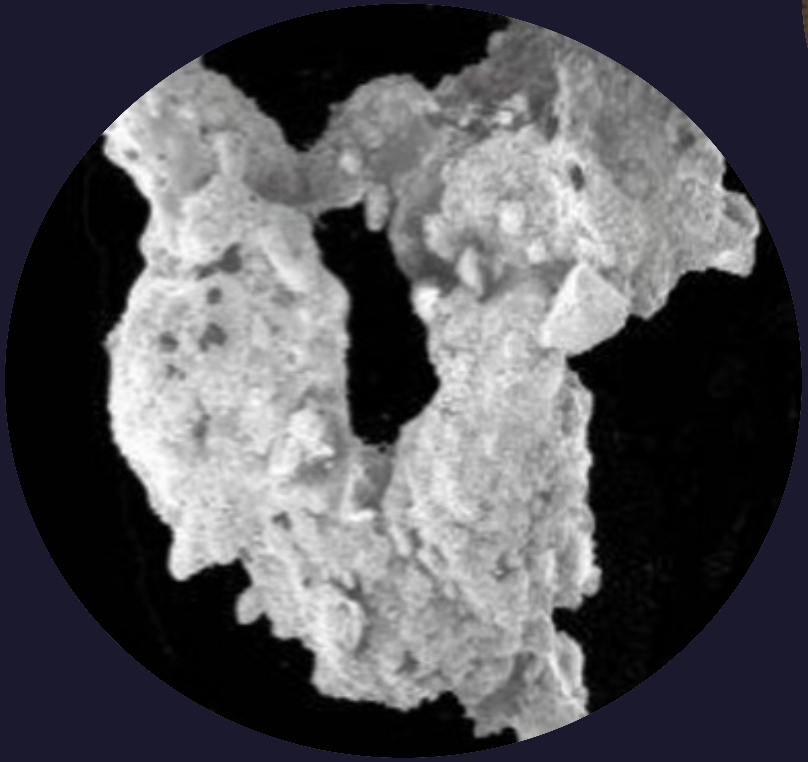
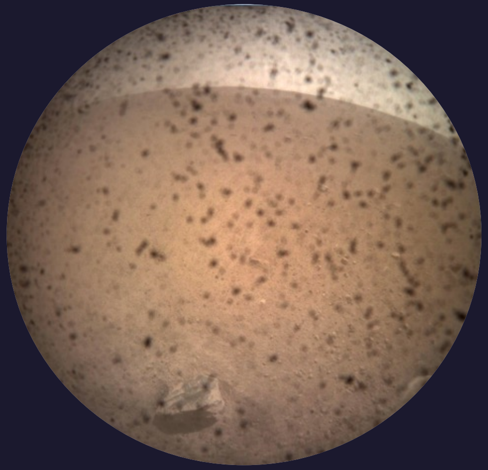
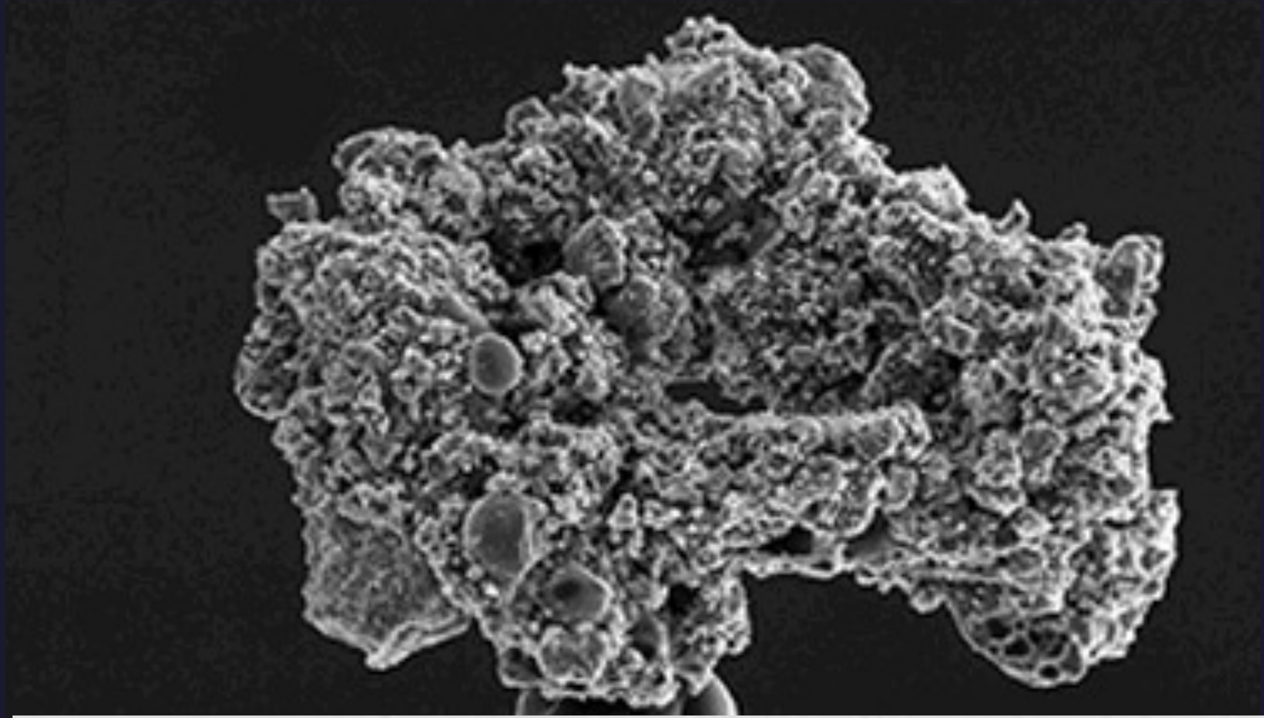
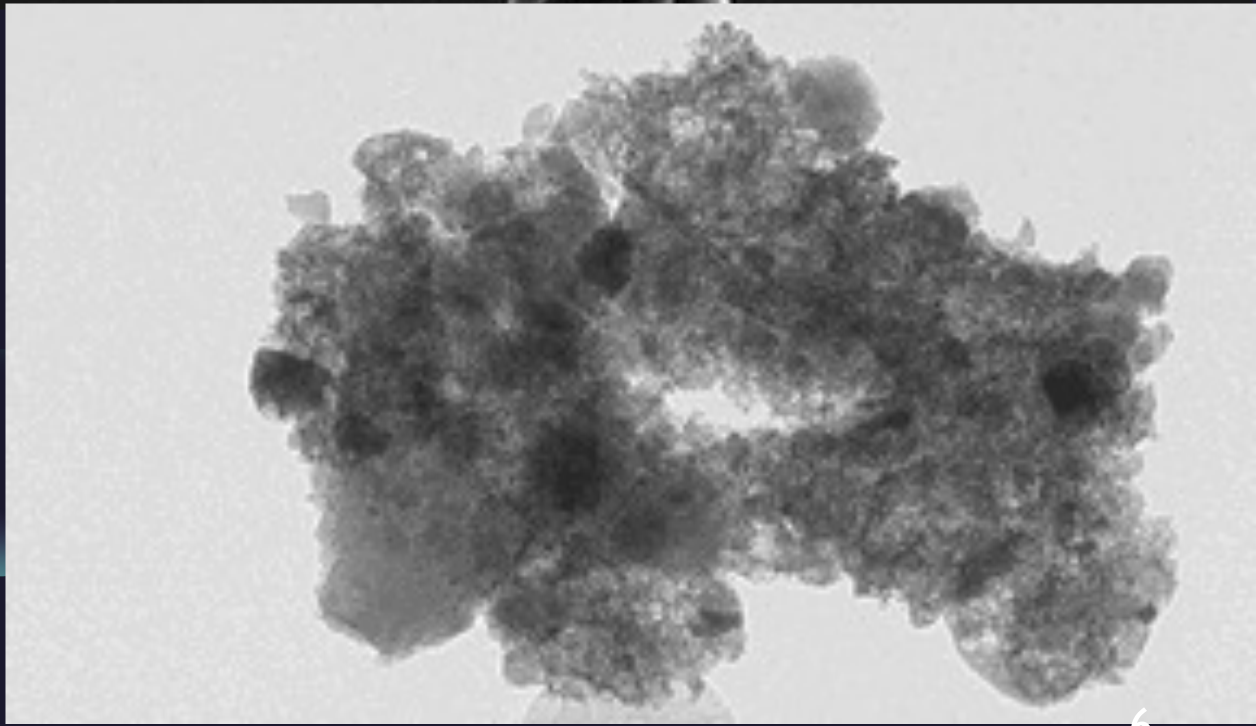




Assumption

- You are already aware of the dust and that dust will be a problem…
- But in case you're not…





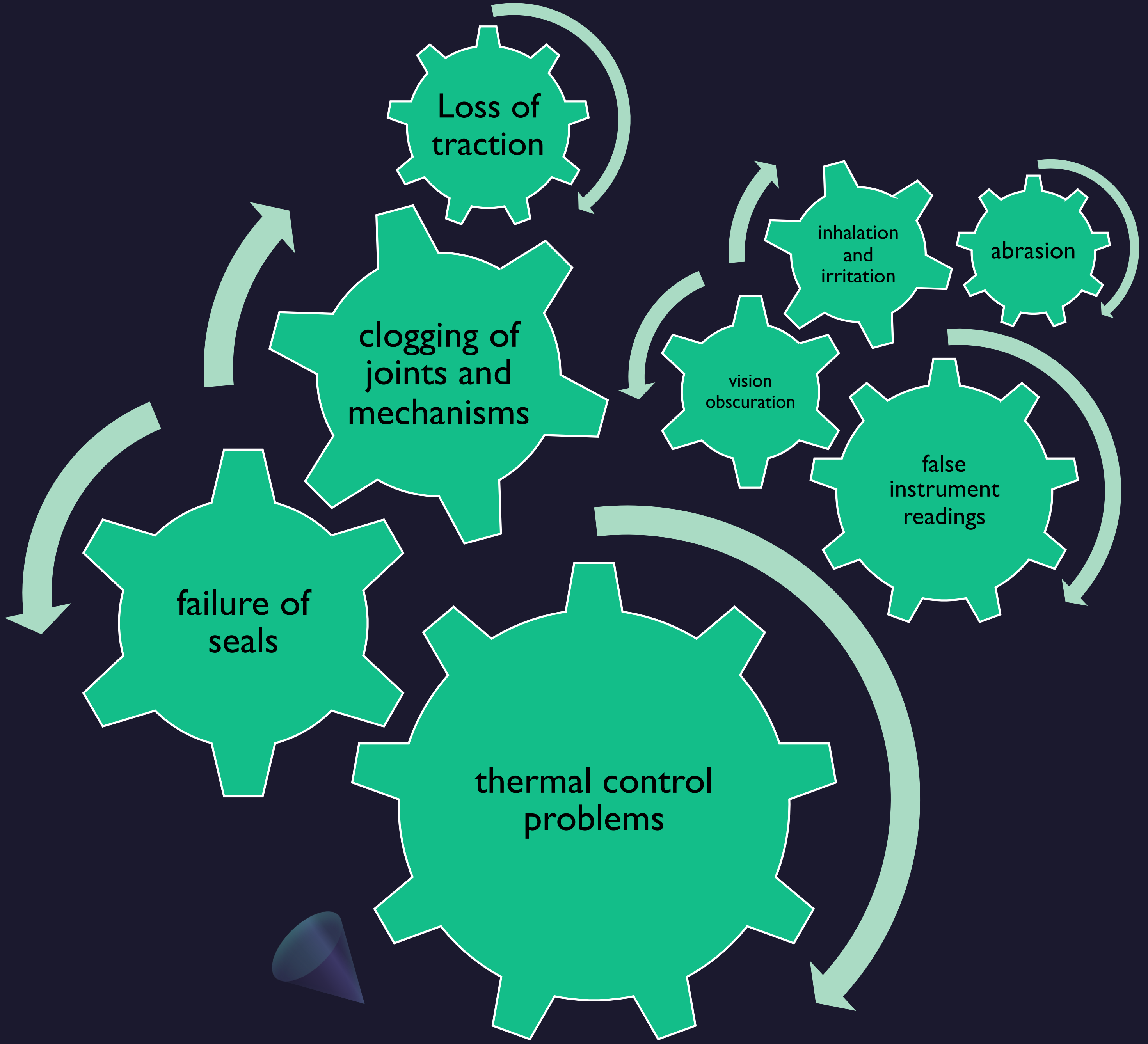
Courtesy of LeHigh University, Department of Materials Science and Engineering

Why is dust such a problem?

- **Electrostatic** and ferromagnetic in an environment with no natural grounding… so it sticks to anything carrying a charge.
- **Fine-grained**, with a significant fraction that is smaller than the human eye can resolve... so visibly clean isn't clean.
- **Jagged**, so it scratches and abrades everything from suit fabrics to human lungs.
- **Widely varied -** we only really know about the composition of dust in the places we've been.
- **Unpredictable** - behavior of lunar dust in space is governed by different forces than on earth.
- **Difficult to analyze** because the behavior can't be replicated without low gravity and zero atmosphere, making model validation difficult.

Assumption

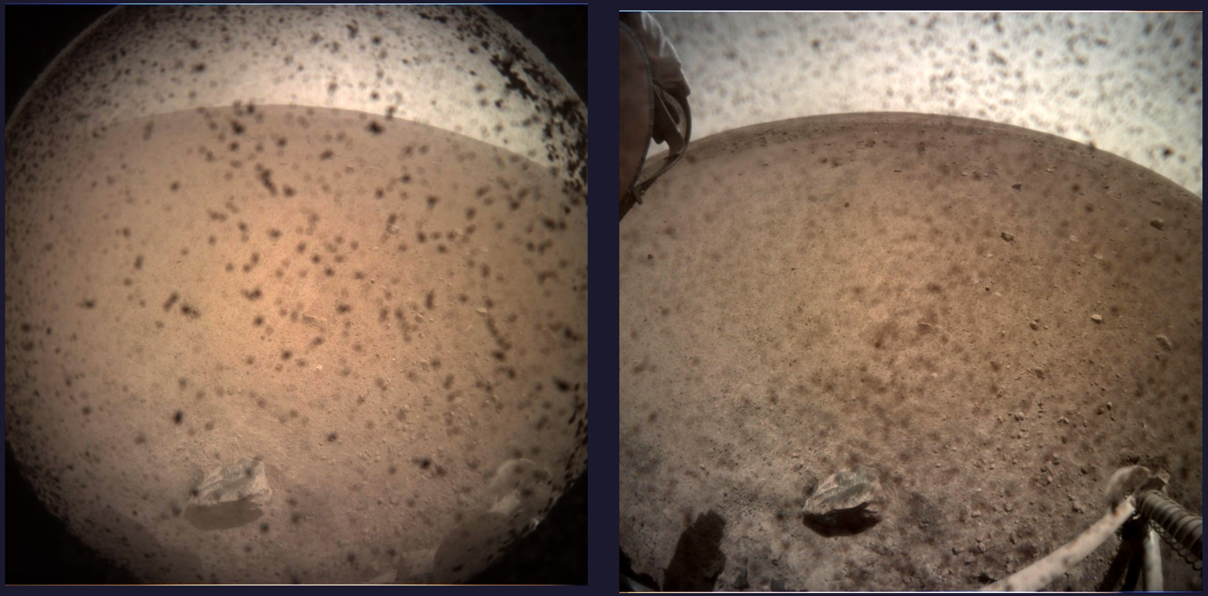
- You know that Apollo alerted us to some of the challenges from the dust
- But in case you're not…



Reference: NASA/TM—2005-213610
The Effects of Lunar Dust on EVA Systems During the Apollo Missions by James R. Gaier

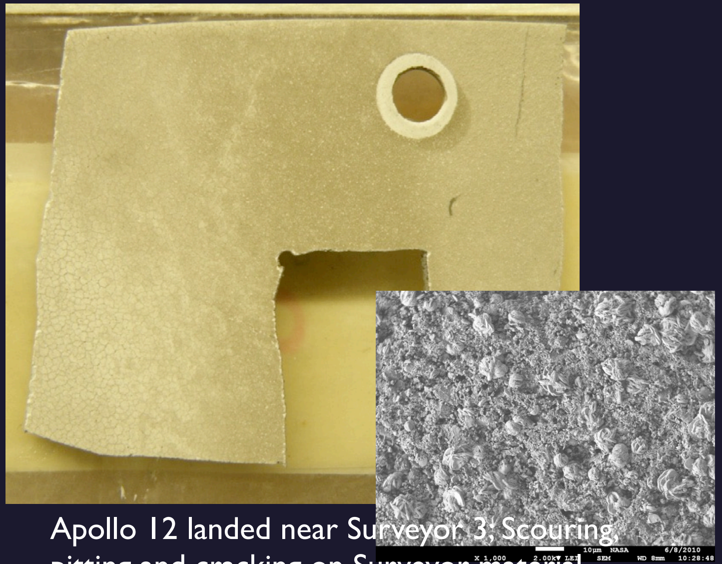
Assumption

- You are already aware of the potential impacts from plume surface interactions (PSI)
- But in case you're not…
  - Plume-surface interactions (PSI) occur when a rocket engine exhaust (or other gas jet) interacts with a planetary surface
  - PSI effects will be a **large** contributor for lunar dust accumulation on any descending vehicle
  - Regolith ejecta poses a hazard to spacecraft and to surrounding assets



Mars Insight - Material breached lens cover

Ejecta streams visible during Apollo 11 landing



Apollo 12 landed near Surveyor 3: Scouring pitting and cracking on Surveyor material coupon & SEM image (See Immer et al. 2010)

Good resource: Mehta et al. 2011, Rocket Plume Interactions for NASA Landing Systems

"When large systems fail, it is due to multiple faults that occur together in an unanticipated interaction, creating a chain of events in which the faults grow and evolve."

Source: National Academy of Sciences,
Why do errors happen?
ncbi.nlm.nih.gov

Examples in history:

Columbia, Challenger, Three Mile Island

Interesting reads: Henry Petroski – To Engineer is Human & Design Paradigms

A confluence of environmental factors

How does dust impact hardware?

Power

Dust accumulation on solar panels leads to reduction in available power.

Communications

Communication equipment can be covered in dust.

Thermal

Dust coats thermal radiators and equipment increases in temperature.

Optics

Optics concerns include accumulation on cameras/optics as well as concerns for thermal optical properties (transmittance, reflectance, and absorptance).

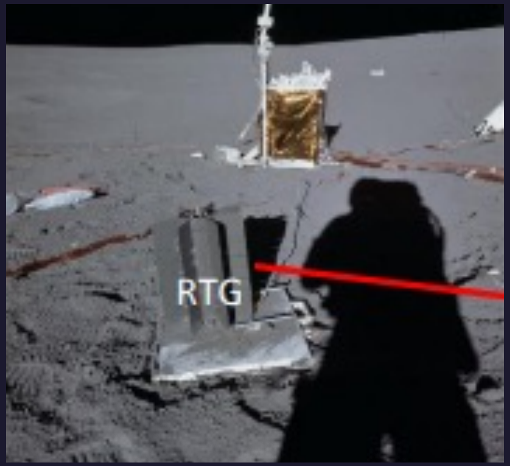
What to do about it?

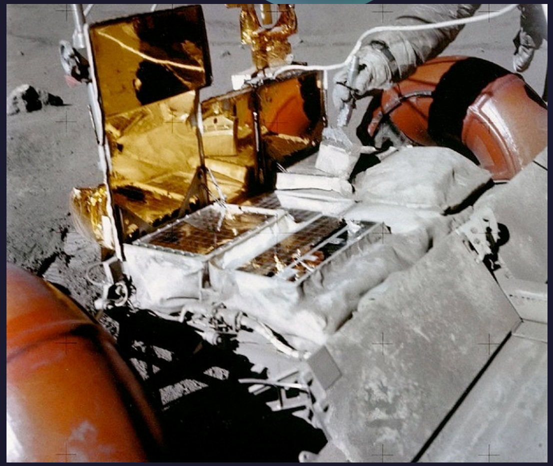
NASA-STD-1008 provides guidance on how to test for this. (Sections on dust testing for thermal & optical testing.)

The Best Practices "Guidebook" discusses potential solutions to mitigate these challenges.

Another one bites the dust

Lessons learned from the surface…





Apollo astronauts could not avoid getting dust on deployed ALSEP Experiments

Lunokhod 2 robotic rover only lasted through 4 lunar temperature cycles

Dust was a problem on the space suits, communications, TV cameras, and other equipment

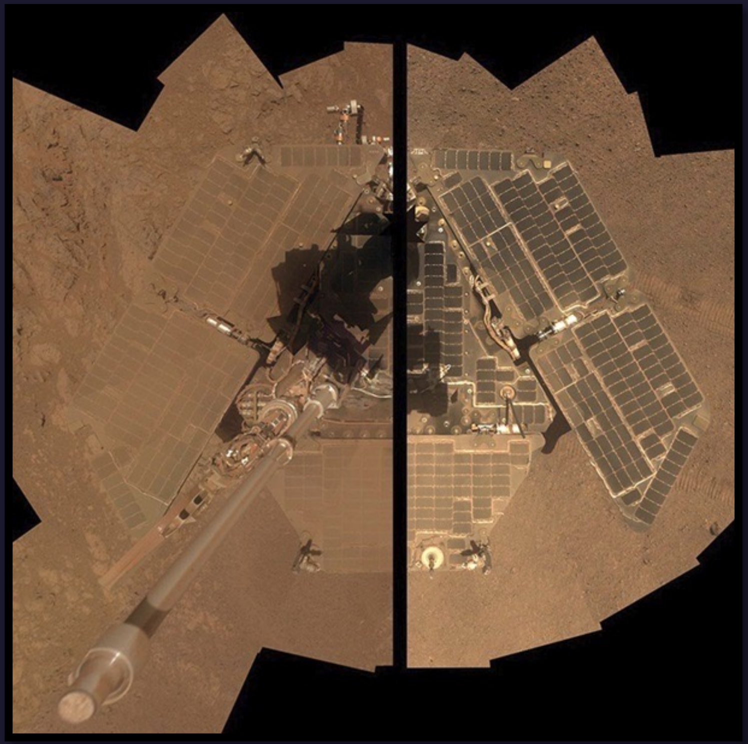
Dust accumulated on the radiators of the battery for the LRV of Apollo 16

The Apollo astronauts encountered marked degradation of performance in heat rejection systems for the lunar roving vehicle, science packages, and other components. – Jim Gaier

An insulating layer of dust on radiator surfaces could not be removed and caused serious thermal control problems. NASA/TM—2005-213610

Lunar Dust on Power & Thermal Systems

- Power connectors & heat exchangers → internal clogging, scratching
- Heat rejection/radiators → performance degradation, lower efficiency, system overheat
- Reflective and other surfaces → compromised by excessive dust, mirrors obscured
- Power generation/solar arrays → solar thermal conversion effects such as heat absorption, reduced power output
- PV arrays, cells, sensors → reduced power output, lower efficiency
    - Modeling and ground-based analysis shows power output from PV cells is cut in half by a covering of less than **3 mg/cm²**; measurements from the Sojourner rover on Mars found that PV cells lost efficiency of **0.28%/day** owing to dust deposition.



Mars Opportunity Rover

Did radiators degrade during Apollo?

Yes!

Apollo 12 Temperatures measured were approximately 68 °F higher than expected (3-16)

Apollo 15 LRV batteries ran 68 to 78°F high because dust accumulation on radiators (94)

Apollo 16 Instrument performance degraded by overheating due to dust on radiators (4-10, 4-19)

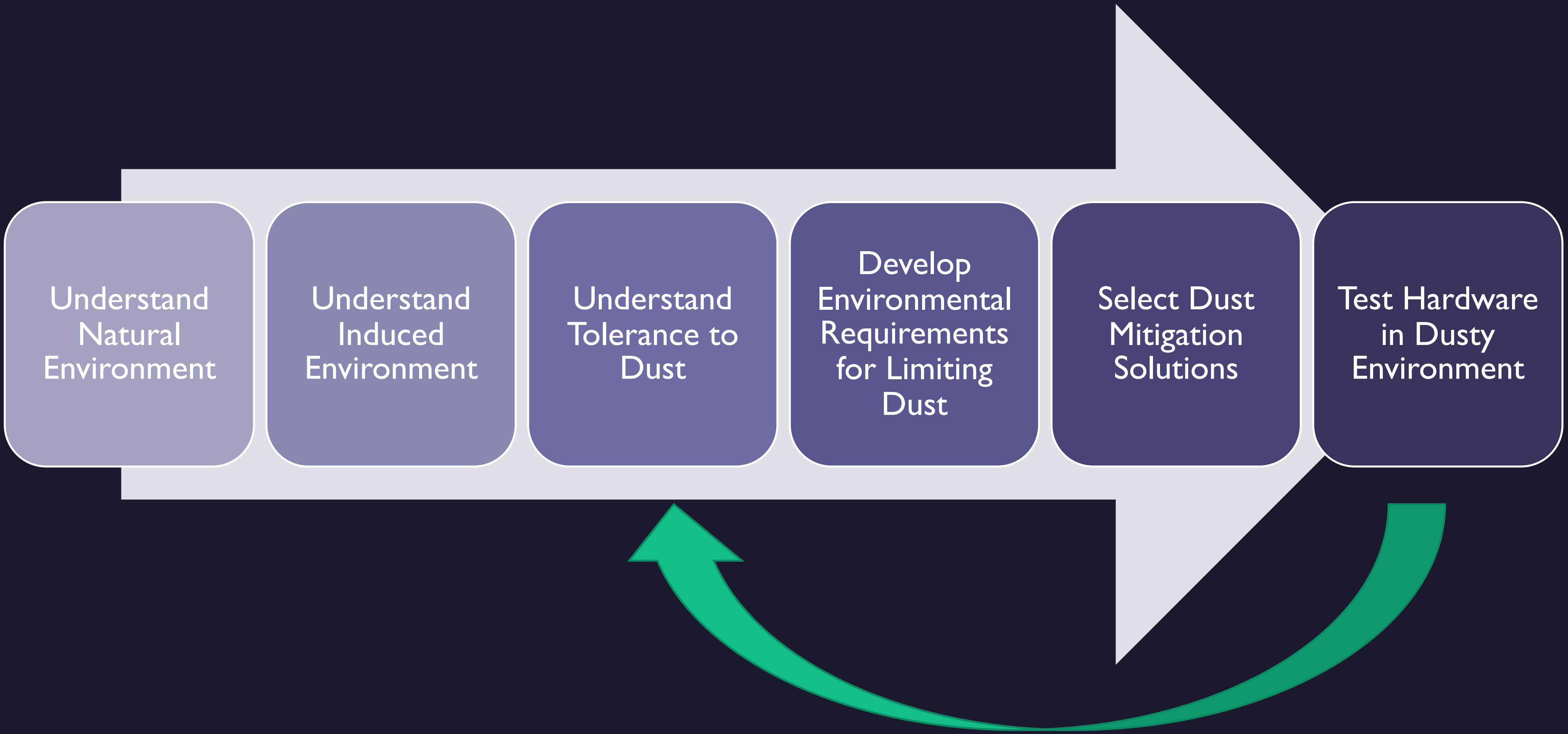
Apollo 16 Dust on Lunar Rover battery mirrors caused overheating (9-42)

Apollo 17 Instrument shut down when terminator passing to mitigate dust collection (15-29)

So you're going to the surface?

It sure would be nice if you had a…

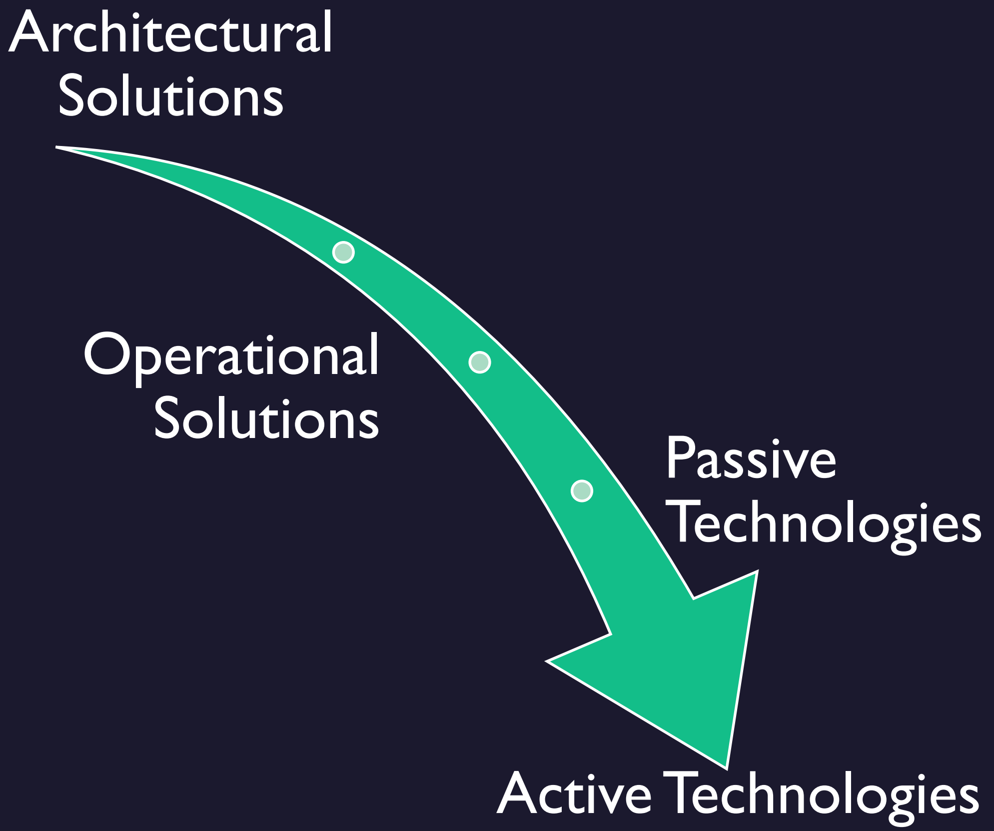
Dust Mitigation Strategy



Dust Mitigation Strategy

Dust management

1. Tolerating dust exposure
2. Detecting/monitoring dust
3. Controlling entry of dust into vehicles/systems
4. Removal of dust



Dust Mitigation Solutions

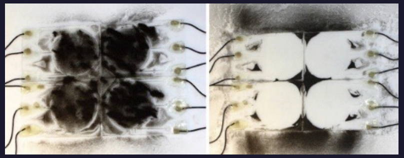
Architectural Solutions

Operational Solutions

Passive Technologies

Active Technologies

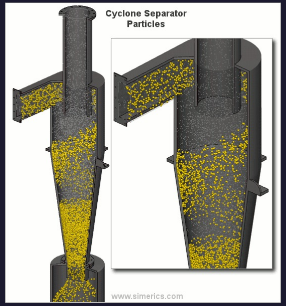
- <u>Active technology solutions:</u>
- **Electrostatics**
- **Compressed air**
- Vacuums
- **Electrodynamic dust shield**

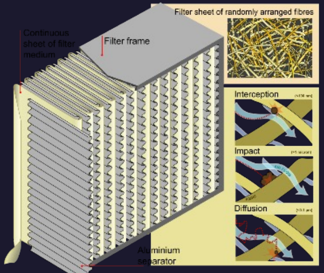


<u>Architectural & Operational solutions:</u>

- Suitports
- Severable airlocks
- Mud-rooms
- Porches
- Landing Site Selection
- **Prepared Landing Pad**
- Optimized EVA and **traverse planning**

- <u>Passive technology solutions:</u>
- HEPA filters
- Cyclone separators
- Softwalls
- **Low-energy surface coatings**
- Coveralls/aprons/**covers**
- Dust tarps
- Brushes
- Tape
- Wipes





Dust Mitigation Technology “Swimlanes”

Dust Mitigation Efforts at NASA

Testing with Dust?

1. Look at Available Dust Testing Papers & Publications
2. Review Current Dust Testing Efforts
3. Read the Dust Mitigation Best Practices Guide
4. Understand the NASA Standard for Dust Testing

   https://standards.nasa.gov/standard/NASA/NASA-STD-1008

5. Select your Simulants (Simulant Advisory Committee)

   https://ares.jsc.nasa.gov/projects/simulants/
   https://lsic.jhuapl.edu/Resources/Lunar-Simulants.php

6. Identify your Facilities (LSIC Facilities Directory)
   https://lsic-wiki.jhuapl.edu/display/CD

Simulants

"What simulant should I use for testing?"

One of the most common questions we get

Simulant selection is critical to performing relevant tests

Simulant Characteristics to Consider

Aerosol Ingestion Testing: *PSD, Hardness, Morphology*
Abrasion Testing: *Hardness, Morphology, PSD*
Optical Testing: *Opacity, PSD, Albedo*
Thermal Testing: *Thermal Conductivity, Emissivity*
Mechanisms Testing: *Hardness, Morphology, Electrostatic Charging, PSD*
Seals and Mating Surfaces Testing: *Hardness, Morphology, PSD*
Reactivity Testing: *Chemical Composition, Morphology, PSD*
Electrostatic Properties: *Electrical Conductivity, Tribocharging, Permittivity*
PSI Testing: *Geotechnical, Electrostatics, Chemical Composition*

Per Lunar Dust Testing Standards, vetted with NASA Simulant Advisory Committee

Solution: Talk to the NASA Simulant Advisory Committee

https://ares.jsc.nasa.gov/projects/simulants/

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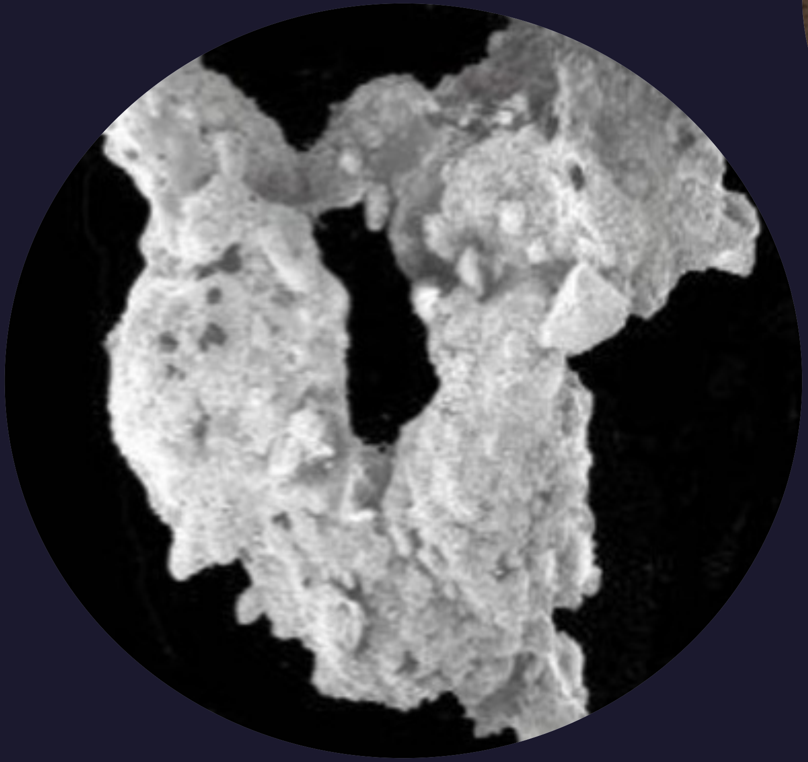

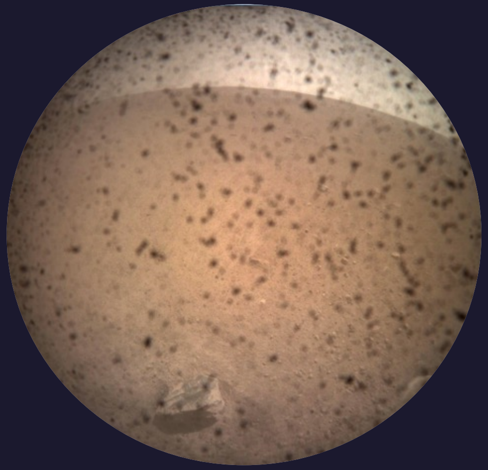

Defining "Dust"

From NASA-STD-1008

Dust: For the purpose of this NASA Technical Standard, we define "dust" pragmatically as the regolith size fraction that poses any functional or longevity concerns or risks to hardware, components, or systems. This is defined by an upper particle size bound and includes smaller particles. Estimates of source size fractions are given in this NASA Technical Standard for various dust transport mechanisms. The unit micrometer (μm) is used to define dust sizes in this NASA Technical Standard.

Note: The definition of "dust" can have different meanings to different scientific groups, and the word "dust" has been used to characterize anything from a very specific size particle distribution to nearly all of the particulate matter in a given sample/volume. Various definitions of dust have been used widely in NASA official documents and in other scientific documents. However, when designing, developing, and testing technologies and systems for dealing with the particulate matter, it is not ideal to have two classes: one for dust and one for larger- or smaller-sized particles.

Or simply put: All lunar particulate that will need to be mitigated.

Our Goal

- The goal of this information collection process is to create a list of dust characterization needs based on scientific and engineering knowledge gaps that will aid in the design and survival of designed and future systems, and address the challenges related to defining the lunar environment and mitigating lunar dust effects on systems and operations.

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- The goal of this information collection process is to create a list of dust characterization needs based on scientific and engineering knowledge gaps that will aid in the design and survival of designed and future systems, and address the challenges related to defining the lunar environment and mitigating lunar dust effects on systems and operations.

requirements, risks, hazard controls, mission success

capability gaps, technology gaps, program and project needs, etc

SLS-SPEC-159 DSNE

dust mitigation technologies or strategies

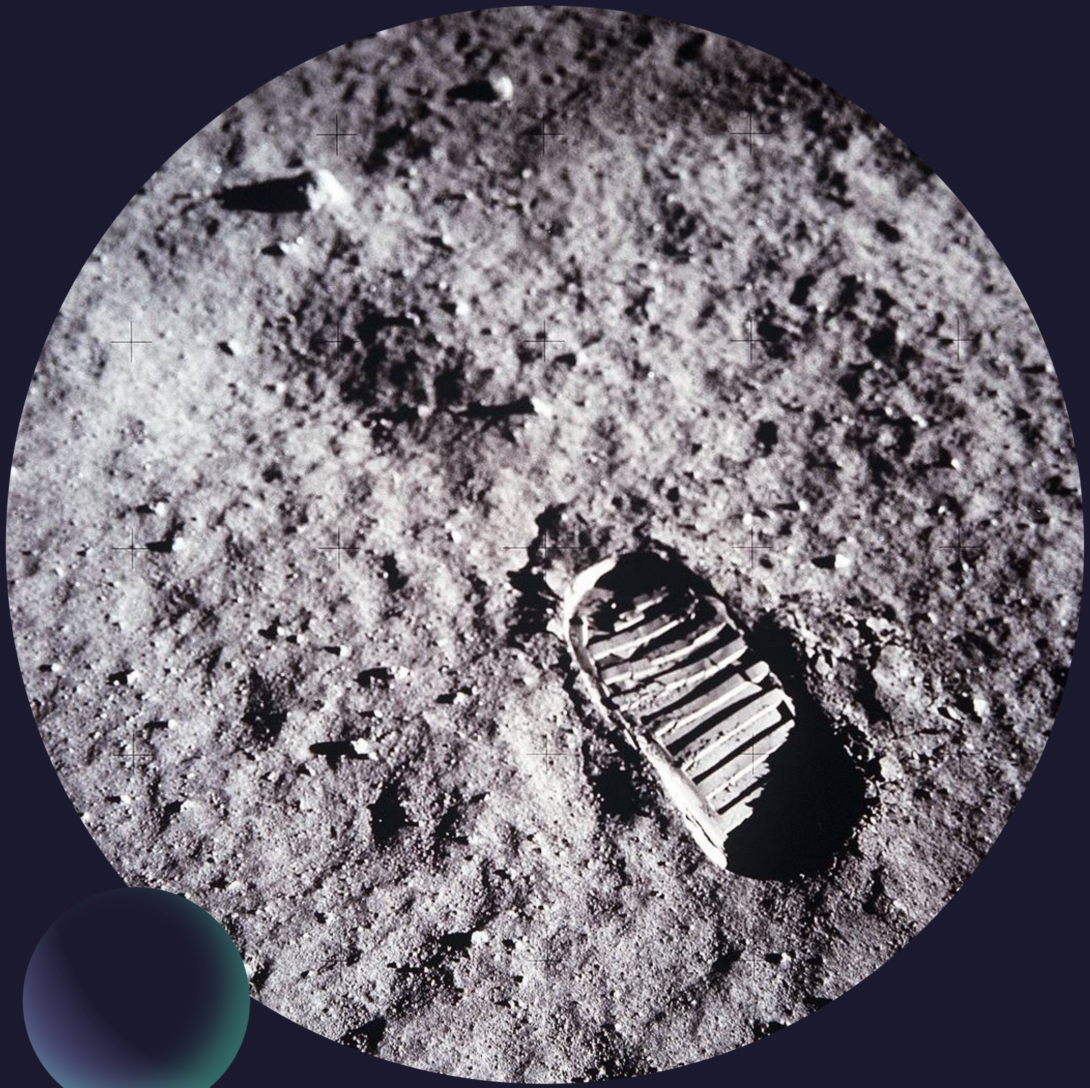
NASA-STD-1008 (i.e. testing)

+use the data to inform models

Why are we here at DAP?

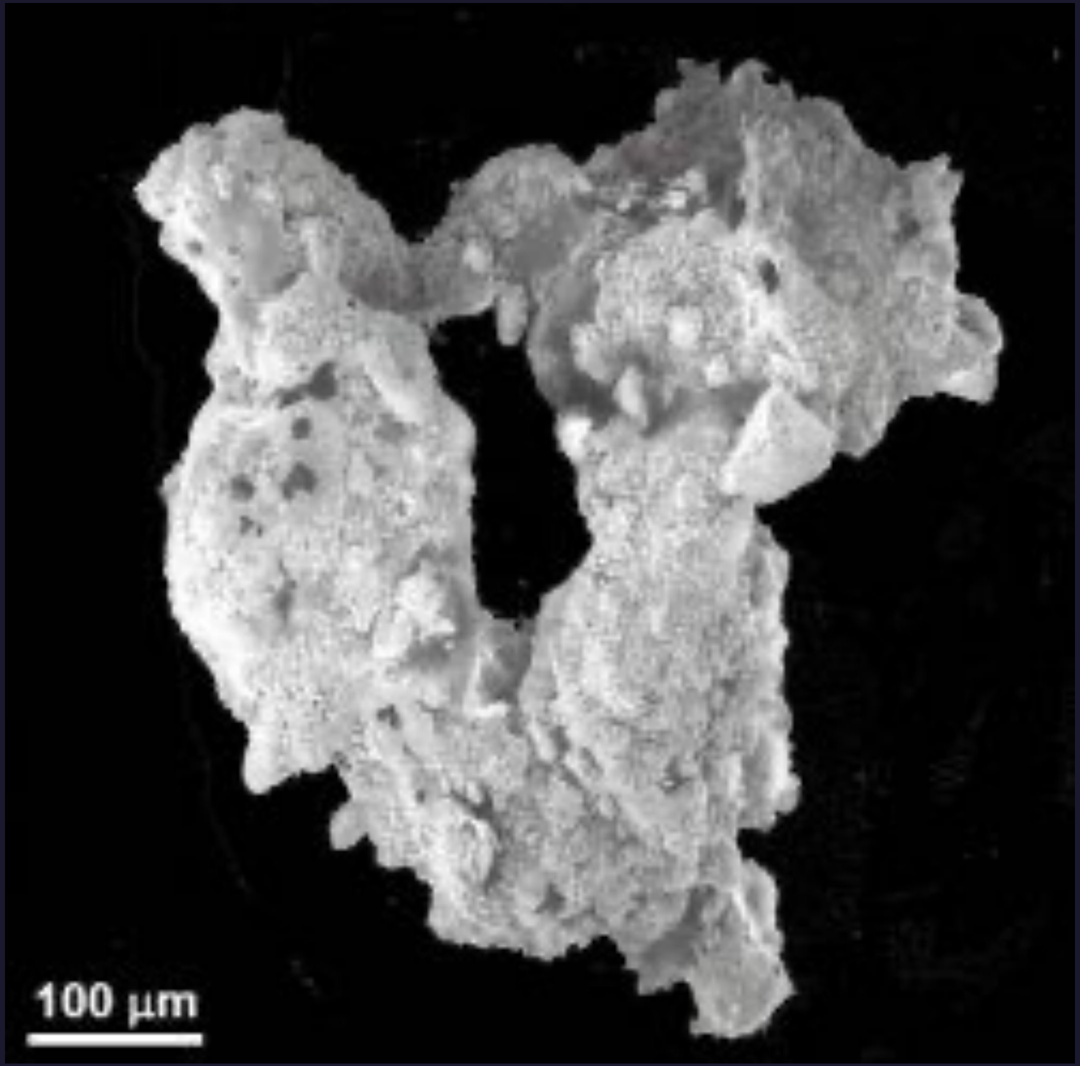
- It is expected, through the course of currently planned or future lunar surface mission instrumentation, payloads, lab experiments, or analysis, that some of these unknowns will be characterized

- We need the science community to help us connect the dots between our "needs" and the potential sources for "answers"



First step: start with upcoming missions

Identify this stuff and figure out how to apply toward future mission/hardware success



Sources of our list

- NASA-STD-1008
- SLS-SPEC-159 DSNE
- 2020 publication "The Impact of Lunar Dust on Human Exploration"
- PSI white paper
- Gaps identified within NASA programs and projects

What is NASA-STD-1008?

- "Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments" approved by the Office of the NASA Chief Engineer on 2021-09-21 through an Agency-wide review and is publicly available at https://standards.nasa.gov/standard/nasa/nasa-std-1008
- "The purpose of this NASA Technical Standard is to establish **minimum** requirements and provide effective guidance regarding methodologies and best practices for testing systems and hardware to be exposed to dust in dust laden and generating environments. The intent is **to facilitate consistency and efficiency** in testing space systems, subsystems, or components with operations and missions in dusty environments."

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-1008

Approved: 2021-09-21

CLASSIFICATIONS AND REQUIREMENTS FOR TESTING SYSTEMS AND HARDWARE TO BE EXPOSED TO DUST IN PLANETARY ENVIRONMENTS

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Table 3—Planetary Pressurized Lunar Sources of Dust and Associated Dust Parameters

PP Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Extravehicular Activity (EVA) Suit Cross-Hatch Transported Dust	<500 µm [TBR] [1]	50 g per suit per EVA[2][3][5]	10 g/m^3 per suit per EVA [2][3][4]	Variable [6]	N/A
Hardware Cross-Hatch Transported Dust	<500 µm [TBR] [1]	Variable g/m^2 [2]	Variable g/m^3 [2]	Variable [6]	N/A

Section 4 provides estimated dust parameters and references for each estimate.

Section 5 describes testing methods and facility needs.

What is NASA-STD-1008?

- "Classifications ar… be Exposed to D… of the NASA Chi… review and is pub… https://standards.…
- "The purpose of … requirements and … and best practices … dust in dust laden … facilitate consis… subsystems, or co… environments."

1.2 Applicability

This NASA Technical Standard is applicable to any system, subsystem, or component that will be exposed to planetary dust (refer to definition in section 3.2 in this NASA Technical Standard). There are four different environments in which hardware may be exposed to dust: planetary external (PE), planetary pressurized (PP) volumes, in-space pressurized (SP) volumes, and in-space external (SE). In this NASA Technical Standard, the environments are referred to as working dust environments. The word "pressurized" does not necessarily imply habitable. Where applicable, habitable volumes are identified in the text of this NASA Technical Standard.

This NASA Technical Standard allows for broad usage for missions to the Moon, Mars, and small bodies (e.g., asteroids) when working with dust or regolith. However, section 4.2 (Sources of Dust) and section 5.4 (Simulants) have been broken into Lunar, Martian, and Small Bodies sections, with the Martian and Small Bodies sections currently marked as reserved.

The environmental conditions defined in this NASA Technical Standard (sources of dust, particle sizes, system surface, and/or volumetric loading) are based on estimates from current data sets or studies. Future insight into these environments through missions, technology demonstrations, laboratory studies, modeling, or analyses may unveil new definitions, at which time this NASA Technical Standard will be revised. Appendix A provides context for why it is necessary to test and examine the effects of dust on hardware and systems as it relates to the operational environment.

…vides estimated …s and references …te.

Section 5 describes testing methods and facility needs.

NASA-STD-1008 Section 4

SECTION 4. Dust Requirements & Standards

4.1 Dust Impact Assessment Process

4.2 Sources of Dust

a. Planetary External (PE)

b. Planetary Pressurized (PP)

c. In-Space Pressurized (SP)

d. In-Space External (SE)

Table provided for each section that contains guidance on particle size, surface accumulated loading, volumetric loading, dust velocity, and charge to mass ratio. It provides this information for various sources of dust depending on the environment.

a. PE – Human generated surface transported dust, rocket plume dust, natural charged dust transport, natural impact ejecta

b. PP – EVA suit cross-hatch transported dust, hardware cross-hatch transported dust

c. SP – micro-G free floating dust, micro-G surface adhering dust

d. SE – rocket plume dust, natural charged dust transport, natural impact ejecta

Table 2—Planetary External Lunar Sources of Dust and Associated Dust Parameters

PE Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Human-Generated Surface Transported Dust	<500 µm [1]	<40 g/m^2 [TBR][11]	N/A	<10 m/s (22.4 mph) [2]	0.1 nC/g - 10 nC/g [15]
Rocket Engine Plume Dust [9, 13]	<10,000 µm [3][12][20]	TBR [21]	10^8 - 10^{13} particles/m^3 [4][15] [20]	<4500 m/s (10,066 mph) [13]	>1000 nC/g
Natural Charged Dust Transport [5]	<1000 µm [16]	Combined Loading Case [17, 19]	TBR [6]	Variable [18]	~ 10,000 nC/g [7]
Natural Impact Ejecta [12]	<10,000 µm	Combined Loading Case [17, 19] or 0.01 g/m^2/day [14]	TBR [10]	<2380 m/s (5324 mph) [8]	~ 10,000 nC/g [7]

Notes:

1. Estimated maximum particle size displaced by Apollo lunar rover.
2. Reference NASA-CR-4404, Lunar dust transport and potential interactions with power system components. The Apollo lunar rovers were designed to travel at a maximum of 3.56 m/s (8 mph) (reference Backer, 1971; Hsu and Horanyi, 2012) with particle speeds of up to 7.12 m/s (16 mph) in the forward direction. A 45° trajectory would yield the maximum horizontal distance of 31 m (103 ft) from the wheel's initial location. Consider the maximum speed at which an Artemis Lunar Terrain Vehicle could travel.
3. Reference Lane, et al., 2008; Morris, et al., 2015.
4. Reference Immer, et al., 2011a. Analysis of digitized Apollo Lunar Module (LM) descent videos estimates plume lofted dust sheets contained 10^8-10^{13} particles/m^3 and were blown radially away from the descent engine at angles of 0-3° above the surface. Volumetric loading as a mass density should be determined by the user based on their choice of simulant.
5. Reference Colwell, et al., 2009.
6. Charged dust transport on the lunar surface is an area of ongoing research, and dust loading has not been quantified in situ.
7. Reference Colwell, et al., 2007.
8. The finest particles are ejected at velocities exceeding the 2.38 km/s (5324 mph) escape velocity of the Moon (see section 5.1.1 of this NASA Technical Standard).

9. The effects of rocket engine exhaust on a planetary body are a subject of ongoing research. Values in this section are estimates. Dust may theoretically be accelerated up to the velocity of the rocket exhaust but is likely slower. Actual dust velocities will depend on regolith properties and the exhaust flow field. On average, there is an inverse relationship between particle size and particle velocity. Particles larger than 1 cm may be moved or lofted, but the effects of large particle impacts are outside the scope of this NASA Technical Standard. See section 4.2, Table 5, In-Space External Lunar Sources of Dust and Associated Dust Parameters, Note 5 in this NASA Technical Standard for additional considerations.
10. Loading due to impact ejecta is sparse. Model development is underway (see Note 14) to quantify this type of loading at the surface. Since impact ejecta is lofted at a relatively high angle, impacts to surface assets from particles on escape trajectories are unlikely.
11. Maximum estimated dust movement observed in Apollo walking and rover video archives.
12. Rocks as large as 10 cm or more can be moved, while dust- to sand-size particles in the upper few cm of regolith in the area surrounding the LM were blown several kilometers away, leaving the coarser, presumably more compact, underlying regolith exposed (reference Immer, et al., 2008; Lane, et al., 2008; Metzger, et al., 2011).
13. Exhaust velocity of a liquid oxygen/liquid hydrogen (LOX/LH2) engine. May be treated as an example maximum. See Note 9.
14. Estimated from NASA-SP-8013, Meteoroid Environmental Model. Updated model is under development which will be available in a future revision of SLS-SPEC-159H, Cross-Program Design Specification for Natural Environments (DSNE), section 3.4.8.2.
15. Reference Jackson, et al., 2011, 2015.
16. Colwell, et al., 2007 notes the historical distinction between soil particles (<1 cm diameter), fines (<1 mm), and dust (< 100 µm); and the paper considers phenomena on particles <1 cm in size. Suggested upper bound is set by pragmatic concerns but may be altered by the user as needed.
17. Combined natural calculated to be 1.0 g/m^2/year (Hollick and O'Brien, 2013).
18. Lofted dust vertical velocities will depend on individual particle size, density, and location in ballistic trajectory in the lunar gravity field.
19. Few individual measurements have been made of the two natural distribution cases, but combined cases exist (Li, et al., 2019) where the value of 6.5×10^{-6} g/m^2 were seen at the Chang'E-3 landing site.
20. Planned hot-fire ground tests and modeling efforts will provide ejecta PSD and bulk density (volumetric loading) parameters. These science-scale and human-scale lander tests are planned for mid-FY22 and mid-FY24.
21. Future PSI investigations could provide test data using characterized coupons to help address the gap of surface accumulated loading from rocket engine plume dust.

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Notes:

1. Apollo 17 suit maximum particle size (NASA/TP-2009-214786). This value may change with new suit materials and/or designs.
2. These values may vary depending on program requirements. In some cases, the requirement for EVA suit cross-hatch transported dust and hardware cross-hatch transported dust may be combined.
3. Assuming 50 g of dust per crewmember per EVA based on EVA to Human Landing System (HLS) requirements.
4. Assuming dust concentration is 50 g spread evenly throughout 5 m^3 habitable volume. Value can be adjusted for different dust concentrations and habitable volumes. Assuming all dust on suit becomes airborne in habitable space, the concentration of airborne lunar dust would be 10 g/m^3 per suit per EVA. It is expected that post EVA remediation efforts will reduce the transferred dust loading on each individual EVA, but that a net buildup over multiple EVAs will occur.
5. This cell contains a mass rather than surface loading, which should be converted to an areal mass density before use in the Dust Class ID. This cell may be interpreted by: (1) dividing the dust mass by the surface area of the EVA suit, if suit loading is desired; or (2) dividing the mass by the affected interior surface area.
6. Aerosol particles travel with the same velocity as free airflow (in cabin or ducting). Particles impact onto surfaces at interruptions to free flow (e.g., sharp bends in the airstream).

Table 4—In-Space Pressurized Lunar Sources of Dust and Associated Dust Parameters

SP Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Microgravity Free Floating Dust	<100 µm [TBR] [1][2]	Variable [5]	0.0016 g/m^3 short duration; 0.0003 g/m^3 long duration [3][4]	N/A	N/A
Microgravity Surface Adhering Dust	<100 µm [TBR] [1][2]	Variable [5]	0.00001 g/m^3	N/A	N/A

Notes:

1. Assumes pre-launch dust remediation. Particle size varies depending on application. For human health, inhalable particles are considered <10 µm, with the respirable range being <2.5 µm. NASA STD-3001, Volume 2 outlines allowable dust mass concentrations for human exposure.
2. Future missions will verify this value.
3. Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG) Report. These values are typically time-weighted averages. Peak initial values may be higher.
4. Ranges from 0.3 mg/m^3 for long duration (30+ days) and 1.6 mg/m^3 for short duration (~7 days).
5. Surface accumulated loading for in-space pressurized assets is likely to be driven by mission architecture.

Table 5—In-Space External Lunar Sources of Dust and Associated Dust Parameters

SE Lunar Sources of Dust	Particle Size (μm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge-to-Mass Ratio (nC/g)
Rocket Plume Dust [4]	TBR [8]	TBR [8]	TBR [8]	<4500 m/s (10,066 mph) [5]	>1000 nC/g
Natural Impact Dust Transport (Surface Ejecta)	<10 μm [1]	Variable [7]	$<10^{-2}$ particles / m^3 [3]	10 m/s-1000 m/s (22.4 mph-2240 mph)	N/A
Surface Returned Vehicle Transported Dust [9]	<100 μm	40 g/m^2 [9]	TBR [9]	TBR [9]	TBR [9]

Notes:

1. The on-orbit lunar dust environment has been measured between 3 km (1.86 mi) and 250 km (155 mi) altitude. This NASA Technical Standard does not distinguish between natural particle sources but states the approximate measured upper bound on particle size. See SLS-SPEC-159H, sections 3.4.2.2.3.2 - 3.4.2.2.3.4, for more details on the lofted dust environment on orbit.
2. Reference Colwell, et al., 2007.
3. Non-standard units should be converted to a volumetric loading based on the PSD selected by the program/project. See SLS-SPEC-159H, sections 3.4.2.2.3.2 - 3.4.2.2.3.4, for more details on the ejected dust environment on orbit.
4. Analysis of digitized Apollo LM descent videos estimated plume-lofted dust sheets contained 10^8-10^{13} particles/m^3 and were blown radially away from the descent engines at angles of 0-3° relative to the surface (reference Immer, et al., 2011a). The finest particles are blown at velocities reaching up to 3 km/s (6711 mph), exceeding the 2.38 km/s (5324 mph) escape velocity of the Moon (reference Lane, et al., 2008; Metzger, et al., 2011).
5. The effects of plume-surface interactions are areas of ongoing research. Dust ejected from a rocket landing may theoretically accelerate up to the exhaust gas velocity. This example velocity is taken from a liquid oxygen/liquid hydrogen (LOX/LH2) engine. Actual dust velocities will depend significantly on architecture and concepts of operation. Dust will be more dispersed at higher altitudes. On average, there is an inverse relationship between particle size and particle velocity. See section 4.2, Table 2, Planetary External Lunar Sources of Dust and Associated Dust Parameters, Notes 9 and 13 in this NASA Technical Standard, for additional justification and considerations.
6. Lofted dust vertical velocities will depend on individual particle size, density, and location in ballistic trajectory in the lunar gravity field.
7. Depends on amount of supplied dust, flight path, and adhesive materials properties of surface of deposition.
8. Future PSI investigations or modeling could provide data to help quantify expected particle size, surface accumulated loading, and volumetric loading from rocket engine plume dust.
9. This represents dust transferred from a mating visiting vehicle from a surface excursion. The mating can be from docking or berthing. At the time of this writing, little is known about the transfer of dust from a surface lander to an orbiting platform. Future modeling will constrain expected particle size, surface accumulated loading, and volumetric loading from vehicle transported dust.

What is the DSNE?

SLS-SPEC-159: Cross-Program Design Specification for Natural Environments (DSNE)

Latest revision available on NTRS

National Aeronautics and Space Administration

SLS-SPEC-159
REVISION I
EFFECTIVE DATE: OCTOBER 27, 2021

CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)

Approved for Public Release; Distribution is Unlimited
The electronic version is the official approved document.
Verify this is the correct version before use.

1.2 Purpose

The DSNE completes environment-related specifications for architecture, system-level, and lower-tier documents by specifying the ranges of environmental conditions that must be accounted for by NASA ESD Programs. To assure clarity and consistency, and to prevent requirements documents from becoming cluttered with extensive amounts of technical material, natural environment specifications have been compiled into this document. The intent is to keep a unified specification for natural environments that each Program calls out for appropriate application.

Example programmatic requirement:
The “system” shall meet all safety, functional, performance, utilization, and mission objectives during and after exposure to natural environments as defined in SLS-SPEC-159 Cross-Program DSNE.

3.0 Natural Environment Specification

3.1 Prelaunch - Ground Processing Phases

3.2 Launch Countdown and Earth Ascent Phases

3.3 In-Space Phases

3.4 Lunar Surface Operational Phases

3.5 Entry and Landing Phases

3.6 Contingency and Off-Nominal Landing Phases

3.7 Recovery and Post-Flight Processing Phases

3.8 Interplanetary Space Specification

3.9 Mars Orbit Specification

3.10 Mars Atmosphere and Surface Phase Specification

3.11 Mars Moon Specification

3.12 Near Earth Asteroid Specification

3.4 Lunar Surface Operational Phases

3.0 Natural Environment Specification

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- 3.2 Launch Countdown and Earth Ascent Phases
- 3.3 In-Space Phases
- **3.4 Lunar Surface Operational Phases**
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- 3.6 Continge
- 3.7 Recover
- 3.8 Interplar
- 3.9 Mars Or
- 3.10 Mars A
- 3.11 Mars M
- 3.12 Near E

3.4 Lunar Surface Operational Phases

- 3.4.1 Lunar Surface Geological and Geomorphological Environment
- **3.4.2 Lunar Regolith Properties**
- 3.4.3 Luna
- 3.4.4 Luna
- 3.4.5 Opt
- 3.4.6 Luna
- 3.4.7 Luna
- 3.4.8 Luna
- 3.4.9 Lunar Illumination
- 3.4.10 Lunar Neutral Atmosphere

3.4.2 Lunar Regolith Properties

- 3.4.2.1 General Description of the Lunar Regolith
- 3.4.2.2 Particle Size and Shape
- 3.4.2.3 Mechanical Properties of Lunar Regolith
- 3.4.2.4 Derived Physical Properties

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Table 3.4.2.3-1 Summary of bulk regolith properties taken as representative of typical lunar characteristics based on prior landed missions and sample properties.

Property	Value	Units	Notes	DSNE Section	Sources
Bulk Density (ρ)	1.58 ± 0.05: 0-30 cm 1.74 ± 0.05: 30-60 cm	g cm^{-3}	Intercrater areas	3.4.2.3.1	Carrier et al. 1991
Relative Density (D_R)	74 ± 3: 0-30 cm 92 ± 3: 30-60 cm	%	Intercrater areas	3.4.2.3.2	Carrier et al. 1991
Specific Gravity (G) [equivalent to particle density (ρ_P; g/cm^3)]	3.1	Dimensionless or g/cm^3	Based on limited number of bulk samples. This is the recommended value.	3.4.2.3.3	Carrier et al. 1991
Typical highlands particle density (ρ_P_highlands)	2.75 ± 0.1	g/cm^3	Highlands or polar regions. Based on limited number of bulk samples.	3.4.2.3.3	Kiefer et al., 2012
Typical mare particle density (ρ_P_mare)	3.35 ± 0.1	g/cm^3	Mare regions. Based on limited number of bulk samples.	3.4.2.3.3	Kiefer et al., 2012
Porosity (n)	49 ± 2: 0-30 cm 44 ± 2: 30-60 cm	%	Calculated	3.4.2.3.4	Carrier et al. 1991
Void Ratio (e)	0.96 ± 0.07: 0-30 cm 0.78 ± 0.07: 30-60 cm	-	-	3.4.2.3.4	Carrier et al. 1991
Permeability			Firing of Surveyor vernier		Choate

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For section 3.4, numerous published data sets from orbiting spacecraft and analysis of Apollo and other sample return missions were used. References are cited for all design environment data.

Chapter 9 of Lunar Sourcebook

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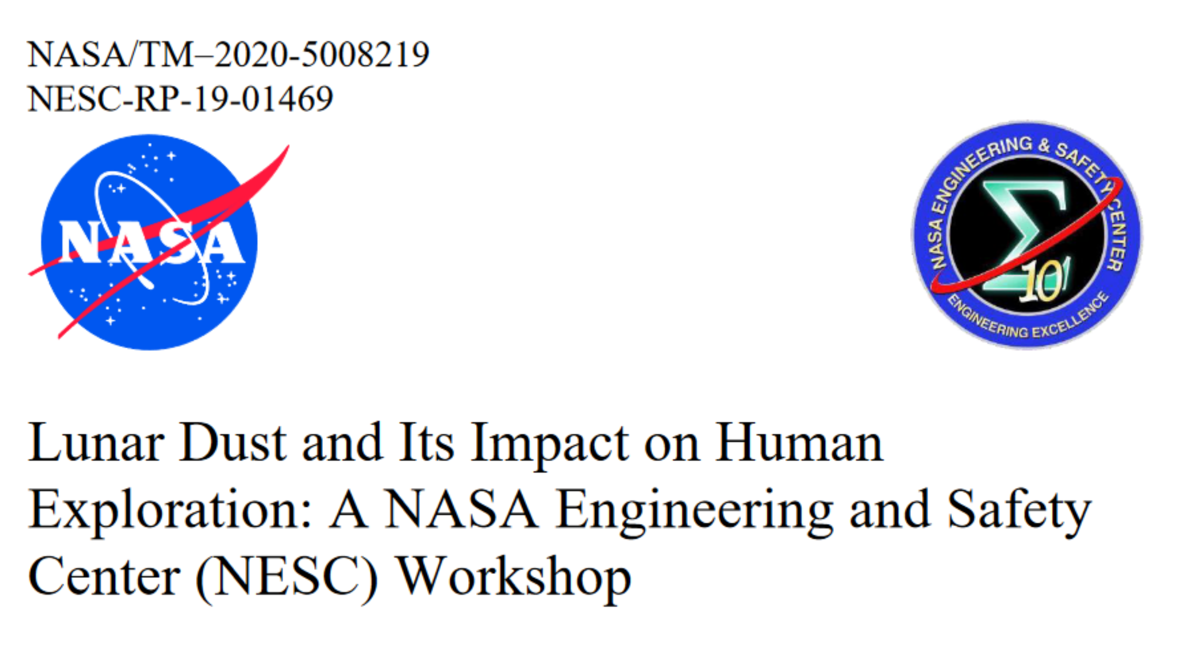
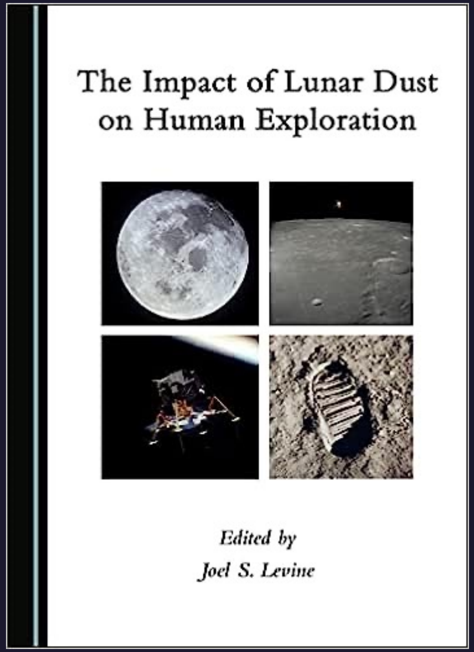
“The Impact of Lunar Dust on Human Exploration”
NESC Workshop in February 2020

- Section 7.0 Findings, Observations, and NESC Recommendations
  - A Finding is a technical fact statement about the topic.
  - An Observation is a refinement of, or extraction from a Finding, or a noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed.
  - A Recommendation identifies “what” is to be done and “when” (if appropriate). It should refrain from providing direction on “how” actions are to be accomplished.


NASA/TM–2020-5008219
NESC-RP-19-01469

Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop



Findings

- F-1. Characteristics of the finest fraction (<45 microns size) of the lunar soil are not well understood. The knowledge gap increases with decreasing particle size. Further, there is insufficient knowledge of the variation in dust characteristics (e.g., chemical composition, mineralogy, etc.) of particles < 45 microns size across lunar geological regions.
- F-2. Apollo and LADEE have obtained particle size distributions, but the work/analyses are not widely known in the lunar dust community.
- F-3. There is uncertainty in the electrical charging properties of the lunar surface and individual particles.
- F-4. Little knowledge exists on the electrical charge of regolith particles on and above the lunar surface due to the interactions with the solar wind, and magnetospheric plasmas, and photoemission and secondary electron emissions.
- F-5. The triboelectric charging of regolith particles in contact with other particles is not well understood. Also, the effects of triboelectric charged particles in contact with human made materials is unknown.
- F-6. There is uncertainty about electrical conductivity, dielectric properties and dielectric breakdown of lunar soil under lunar environmental conditions (e.g., temperature, vacuum conditions).
- F-7. There is limited knowledge about the physics of astronaut/spacesuit charging and discharging in the lunar surface plasma environment, as well as its potential consequences to astronaut and equipment safety during surface operations.
- F-8. Identification and mitigation of electric potential interactions (compatibilities) between suits and hardware in the lunar dust environment need to be considered.

- F-9. There is limited knowledge on the effects from the “operation/design factors” on arcing and arcing consequences. Specific guidelines for mitigating dusty spacesuit electrostatic charging are not readily available.
- F-10. Adhesion and cohesion properties of lunar dust are not well understood.
- F-11. Passive solutions to dust mitigation are system dependent. There is information lacking with regard to how lunar dust will interact with materials being considered for lunar operations.
- F-12. There is no comprehensive plan to set up a network of dust measurement instruments in future missions to obtain a spatio-temporal distribution of particle concentrations.
- F-13. Thermal conductivity and thermal insulative properties of lunar dust in the lunar environment are not adequately known.
- F-14. There is uncertainty in the packing, porosity and permeability and other bulk properties (e.g., shear strength, angle of repose, coefficient of friction, etc.) of lunar soil and its variation with geographic location and depth are not known.
- F-15. A full description of in-situ lunar dust surface chemistry will be necessary in order to build accurate toxicological models and to create authentic simulants, but will require in-situ measurement of equilibrium surface chemistry due to the difficulty of replicating the lunar environment in terrestrial laboratories.
- F-16. Real-time monitoring of airborne particulates, including lunar dust, in lunar habitats and vehicles is required to assess and mitigate crew health risk.
- F-17. There has been little discussion and work, coordinated agency-wide, of cabin (Lunar lander, Gateway, even spacesuit – if needed) air cleaning systems.

- F-18. Our knowledge of collateral dust transfer is insufficient to effectively design mitigation strategies. Also, the physics of natural dust transfer, particularly across the day/night terminator and at the edges of permanently shadowed regions, is not known with sufficient fidelity to determine whether mitigation efforts need to be focused in that direction.
- F-19. Multiple landing vehicles in close proximity will create dust layers on neighboring vehicles.
- F-20. There is insufficient information with regard to the effect of lunar dust deposition on optical, or thermal surface performance.
- F-21. The bristle brush used during Apollo did not adequately clean critical surfaces such as lenses and radiator panels, leading to equipment failures.
- F-22. Optical constants and spectral properties of dust-sized particles from UV through far-IR under relevant lunar temperature and vacuum conditions are needed for measuring the local dust environment.
- F-23. While gaps exist, LADTAG provided significant toxicological data to guide setting permissible exposure limit for spaceflight.
- F-24. The presence and nature of specific allergens and irritants in lunar dust has not been established.
- F-25. It is unclear whether there is sufficient pristine respirable dust fraction in the NASA JSC Lunar Sample Laboratory Facility to perform additional animal toxicology studies for landing sites relevant to upcoming missions.
- F-26. Lunar dust dissolves in aqueous solutions, such as those found in the human body, and in that process releases a variety of materials, including potentially reactive metals, the extent to which this represents a risk warrants further evaluation.

- F-27. It is known fine particulates (PM 2.5) are deposited predominately in lung periphery in reduced gravity.
- F-28. Inclusion of a capability for respiratory monitoring and diagnosis would be beneficial for medical operations to monitor the impact of lunar dust exposure.
- F-29. There appears to be little coordinated discussions across the agency to identify the impact of lunar dust on mechanisms, seals, connectors, and solar panels. Nor are there cleaning systems identified.
- F-30. There is uncertainty in the magnetic properties of the dust as particle size decreases and nanophase iron content increases.
- F-31. There is uncertainty concerning the behavior of volatiles on controlling the properties of dust particles.
- F-32. There is uncertainty concerning the bonding and adsorption of regolith particles with volatiles under lunar conditions.
- F-33. Volatile materials are present in permanently shadowed areas at the lunar poles and may present a hazard to crews and their equipment or valuable resources.
- F-34. No industry-standard set of NASA requirements and oversight mechanisms exist for the manufacturing, quality control, and validation of lunar dust simulants.

Observations

- O-1. The general characteristics and distribution of lunar dust particles have not been well characterized for the smallest fraction of particles (<10 microns) that impacts human health and well-being (e.g., respiration and eye irritations). Additionally, particle size distributions <45 microns, which will affect hardware performance, have not been well characterized. (F-1)
- O-2. Measurements of the electrical charging properties of the lunar surface and individual particles have not been sufficiently examined to support human surface operations of increasing frequency or duration. (F-3)
- O-3. While charging/electrostatic discharging has been studied extensively for spacecraft on-orbit, the charging situation on lunar surface is different because of the lunar dust environment. Dust accumulation and the wear and tear of spacesuit by dust will enhance the severity of differential charging on spacesuit surface. This increases the probability of electrostatic discharge and arcing on spacesuit.
- O-4. Concerns were expressed by panel members regarding how the agency will address the change from mechanical systems used during Apollo to ubiquitous modern electronics today in vehicles, suits, and habitats, etc. The dusty environment will surely provide a challenge. (F-3, F-4, F-7, F-8)
- O-5. Change from mechanical systems to modern electronics since Apollo.
- O-6. Initial studies have demonstrated that electrostatic/dielectric breakdown are likely occur to dusty spacesuits under many of the space plasma conditions on lunar surface. However, the consequences of arcing/breakdown on spacesuit and astronaut have not been investigated. There has been no “quantitative” assessment of the risks associated with charging/arcing. (F-7, F-9)

- O-7. Initial study shows, in addition to plasma environment, charging, and dust coverage, arcing onset are also influenced by many operation/design factors, such as material property, material outgassing, seal/suit leakage, leakage during the opening/closing of the hatch, water sublimation and other details of spacesuit design, etc. Such operation/design factors need to be carefully considered during the quantitative assessment of the risks. Current design guidelines on spacecraft charging/arcing are developed for "clean" spacecraft on-orbit (e.g., make the spacecraft surface uniformly conductive, etc.) (F-9)
- O-8. Thermal conductivity and thermal insulative properties of lunar dust in the lunar environment have only been detected at a few sites where missions have landed. (F-13)
- O-9. The packing, porosity and permeability and other bulk properties (e.g., shear strength, angle of repose, coefficient of friction, etc.) of lunar soil has only been measured at a few Apollo landing sites. (F-14)
- O-10. Surface physiochemical activation is a significant factor in determining particulate. Surface physiochemical activation is a significant factor in determining particulate toxicology in terrestrial materials. Chemical reduction of simulant raises oxidative damage markers in in vitro studies. This is not involved in LADTAG results; direct dry dust exposure to trachea in rodents is the preferable exposure route. (F-15)
- O-11. ROS toxicity studies of individual mineral phases show that slight chemical differences in individual mineral phases can strongly affect toxicity. (F-15).
- O-12. While mass-based particulate load measurement is necessary at a minimum to protect crew health, a means to identify in real time the nature of particle types (cabin vs. lunar dust) contaminating the cabin air would be desirable.
- O-13. The impact of aerosols resulting from dust particles-liquid interactions (e.g., cleaning fluids, breath, etc.) in enclosures (cabins, spacesuits) has not been estimated.

- O-14. Although much was learned about collateral dust transfer during the Apollo Program, the flux of dust transfer during different surface operations, the role of dust cohesion, and how human activities affect the cohesive and adhesive properties of the surface layer of regolith, and the mechanisms by which lunar surface operations will transfer dust are poorly understood (all operational environments - zero g/inside/outside, etc.)
- O-15. A campaign of landing vehicles on the lunar surface is planned to establish a human presence on the Moon. As described in the Lunar Dust Workshop, vehicle landing activities will produce significant dust from propulsion ejecta.
- O-16. Although from the Apollo excursions into permanently shadowed regions and analysis of rover and foot tracks the flux of natural dust transfer is thought to be insignificant compared to collateral transfer, its magnitude has not been quantified so natural dust transfer could pose a risk to extended missions.
- O-17. Surfaces may look optically clean but are dirty, leading to equipment failure.
- O-18. Early Artemis landings are planned at 6.5 days, whereas later Artemis missions will be in the range of 30-180 days on surface. The LADTAG PEL is appropriate for the short-stay Artemis missions but gaps in toxicological analysis may pertain to long-stay Artemis missions.
- O-19. Nickel is a cause of allergic contact dermatitis and has known toxicological effects via inhalation and oral route. It is present on the Moon in lower concentrations than on Earth, however, allergic reactions are more dependent on host sensitivity than on allergen concentrations. Irritant reactions may resemble allergic reactions, but are more dependent on irritant concentrations and less specific to an individual.
- O-20. 2% of the airborne particulate contamination on the ISS is composed of nickel-bearing material.
- O-21. It is possible to separate in situ and transport to Earth sufficient quantities of lunar dust in the <100-micron size.

- O-22. Materials given off by lunar dust in aqueous solution may be released in a concentrated burst, due to the high surface area of dust agglutinates and mostly glass adherent nanoparticles that dissolve rapidly due to their small size and high surface to volume ratio.
- O-23. Most animal studies looking at dust toxicity did not control for deep lung deposition. There is evidence of weakened immune system during long-duration spaceflight. There are no studies looking at combined effect of lunar dust and a weakened immune system.
- O-24. Magnetic properties as particle size decreases and nanophase iron content increases have not been well characterized.
- O-25. Measurements on the behavior of volatiles on controlling the properties of dust particles do not exist.
- O-26. Measurements on the bonding and adsorption of regolith particles with volatiles under all lunar conditions do not exist.
- O-27. Volatile materials detected in cold-traps on the Moon [AGU report], especially in permanently shadowed polar craters, may include ammonia, mercury, hydrogen sulfide, methane, carbon monoxide, as well as resources such as water and carbon dioxide. The VIPER mission will analyze volatiles at the south lunar pole.

NESC Recommendations

- R-1. Measure lunar dust particle size and shape distribution, chemical composition, mineralogy, chemical reactivity, electrical charge, mobilization, migration, and deposition from 45 to 0.1 micron across lunar geological regions. (F-1 to F-4, F-6, F-9) [SMD, HEOMD, STMD] PRIORITY: Very High. (Panels 1, 2, 3)
- R-2. Produce a review article that integrates the LADEE particle size distribution (0.3 -10 μm) near the lunar surface to altitude with Apollo data. (F-2) [NESC] PRIORITY: High. (Panel 3)
- R-3. Measure electrical charge using Apollo samples to simulated interactions with solar wind plasma, photoemissions, and secondary electrons. (F-4) [HEOMD, SMD] PRIORITY: Very High. (Panel 1)
- R-4. Measure tribocharging for particle-particle and particle-material charging using Apollo samples. (F-5) [SMD, HEOMD] PRIORITY: High. (Panel 1)
- R-5. Measure electrical conductivity and dielectric properties of Apollo samples under lunar environmental conditions. (F-6) [SMD, HEOMD] PRIORITY: High. (Panel 1)
- R-6. Investigate spacesuit charging/discharging by physics-based modeling and laboratory experiments. (F-7) [HEOMD] PRIORITY: Medium. (Panel 3)
- R-7. Produce guidelines delineating and mitigating electric potential interactions between space suits and hardware in the lunar dust environment. (F-8) [HEOMD, Industry] PRIORITY: Medium. (Panel 3)
- R-8. Initiate experiments to characterize lunar dust cohesion as well as adhesion to relevant materials (e.g., metals, fabrics, plastics, electronics, filters, etc.). Establish adhesion testing procedures for the materials and a data base containing the results. (F-10) [HEOMD, Universities] PRIORITY: High. (Panel 1, 3)

- R-9. Measure lunar dust thermal conductivity using Apollo samples and future in situ measurements on the lunar surface. (F-13) [HEOMD] PRIORITY: Medium. (Panel 1)
- R-10. Perform laboratory experiments and measurements to quantify the bulk lunar dust properties under lunar environmental conditions (e.g., hard vacuum, lunar surface temperature, and reduced gravity conditions). (F-14) [HEOMD, SMD) PRIORITY: Medium. (Panel 1)
- R-11. Support studies on the characterization of the surface physiochemical activation of lunar dust and generation of ROS and other potentially toxic products. (F-15) [HEOMD] PRIORITY: High. (Panel 2)
- R-12. Ensure that real-time dust monitoring solutions relevant to human health exist in Gateway and Human Lander System requirements. (F-16) [HEOMD] PRIORITY: High. (Panel 2)
- R-13. Develop routine and innovative dust remediation systems (e.g., as filtration, ESPs, photo-ionizers, enhanced ESPs, electret filters, etc.) for lunar application. (F-17) [STMD, HEOMD] PRIORITY: Very High. (Panel 3)
- R-14. Perform laboratory experiments, model and simulation on dust transfer, in-situ measurements (validation and iteration). (F-18) [STMD, SMD, Universities] PRIORITY: High. (Panel 3)
- R-15. A strategy for distributing landing vehicles on the lunar surface must address ejecta effects on/from neighboring vehicles. (F-18, F-19) [HEOMD] PRIORITY: Medium. (Panel 3)
- R-16. Initiate/support a laboratory program to characterize the effect of lunar dust deposition on optical and thermal surfaces. (F-11, F-13, F-20, F-21) [HEOMD, STMD] PRIORITY: Very High. (Panel 3)
- R-17. Perform refractive index measurements of mare and highlands mineral components from the far-UV through the far-IR using Apollo samples. (F-22) [SMD, HEOMD] PRIORITY: Low. (Panel 1)

- R-18. Support studies including those using return materials from short-stay Artemis missions to better inform potential risks for exposure on the longer-duration Artemis missions. (F-23) [HEOMD and OCHMO] PRIORITY: Very High. (Panel 2)
- R-19. Support studies on characterization of lunar dust to address potential allergens, including metal allergens such as nickel. (F-24) [HEOMD and OCHMO] PRIORITY: Medium. (Panel 2)
- R-20. Consult with the NASA Astromaterials Research and Exploration Science Division and report on the amount and accessibility of respirable-size lunar dust for studies of chronic toxicity, and make recommendations for such studies. (F-25) [HEOMD] PRIORITY: Medium. (Panel 2)
- R-21. Support analytical studies on dissolution of lunar dust in aqueous environments. (F-26) [HEOMD] PRIORITY: Medium. (Panel 2)
- R-22. Support toxicological studies to address deep pulmonary deposition of particles in fractional gravity. (F-27) [HEOMD] PRIORITY: Medium. (Panel 2)
- R-23. Support studies to address the development of respiratory health monitoring focused on lunar dust and other particulate deposition in the respiratory system. (F-28) [HEOMD and OCHMO] PRIORITY: Medium. (Panel 2)
- R-24. Organize an Agency-wide, coordinated effort (working groups, technical discipline teams, etc.) to discuss, develop, and select for deployment, device (including suits) cleaning technologies. (F-17, F-20, F-29) [STMD] PRIORITY: Very High. (Panel 3)
- R-25. Measure the magnetic properties and how they vary with particle size and composition using existing Apollo and future in situ measurements on the lunar surface. (F-31) [STMD, SMD, Universities] PRIORITY: Low. (Panel 1)

- R-26. Perform laboratory experiments to quantify how the presence of volatiles impact the bulk characteristics of regolith and dust under relevant environmental conditions. Also, quantify the nature of volatile bonding with particular emphasis on water. (F-31, F-32) [STMD, SMD, Universities] PRIORITY: High. (Panel 1)
- R-27. Assess the results from the VIPER mission for remaining gaps in knowledge relevant to the Artemis program, and to the preservation of gas volatiles in samples. (F-33) [HEOMD] PRIORITY: Medium. (Panel 2)
- R-28. Identify the most qualified group within NASA and/or other agencies that will develop an industry-standard set of NASA requirements and oversight mechanisms for the manufacturing, quality control, and validation of lunar dust simulants. (F-34) [HEOMD and OCHMO] PRIORITY: Very High. (Panel 2)

Needs from the PSI community

Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars

A White Paper submitted to the Planetary Science Decadal Survey 2023-2032

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Key Recommendation: All future landed missions on the Moon and Mars must have dedicated measurements of plume-surface interactions, and this data must be made publicly available so we can gain a better understanding of the effects of rocket exhaust on planetary surfaces and can plan for protecting hardware surrounding landing sites.

Watkins et al. 2021 white paper, Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars, https://doi.org/10.48550/arXiv.2102.12312

Outstanding questions and strategic knowledge gaps…needed to better model PSI, ensure safe landings, and understand physical alterations at the landing sites.

- What are the size distributions, volumes, and velocities of particles lofted by exhaust plumes? How far do they travel?
- How much dust (mass, particle size) remains lofted after engine shut-down, at what altitude and distribution, and for how long?
- What physical changes occur to the surface in the landing zone?
- What is the nature of contamination of regolith around the landing site? What is the maximum lateral and horizontal range of contamination and how does contamination vary based on different propellants?
- How does PSI differ in different landing terrains?
- Does a fraction of plume gas compounds become part of the lunar atmosphere for extended periods of time, or permanently, and could this affect scientific investigations of the processes that create the lunar exosphere/atmosphere?
- What effects do lander size and engine configuration have on PSI?
- How does the mass/volume/size/velocity/flux of dust particles lofted in the exhaust plume evolve through repeated landings/launches within a zone of interest? Are hazards mitigated or increased with repeated landings/launches?
- How far away from nearby hardware must a landing take place to ensure the safety of the emplaced infrastructure?
- How important will landing pads / prepared surfaces be for repeat missions to an area, and how effective will they be over time?

Other sources for list

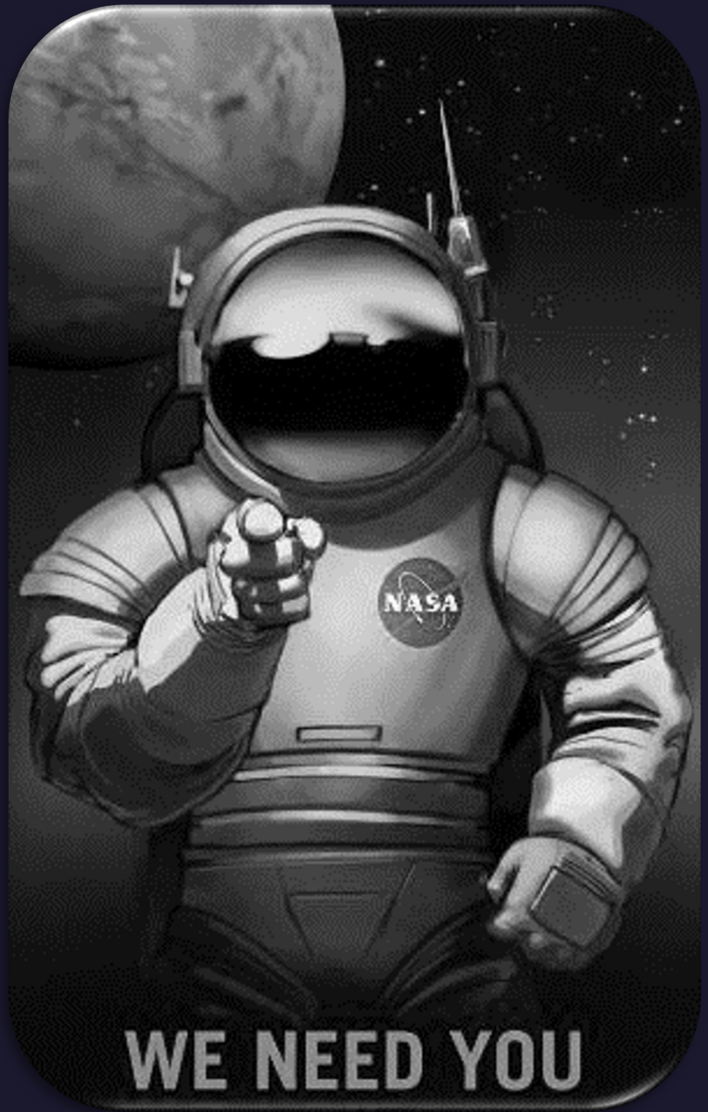
- Known gaps identified within NASA programs, mission directorates, and projects
    - HLS, Gateway, Orion, EHP
    - STMD, ESD, SMD
    - CLPS landers and payloads
    - Other industry and academic partners
    - Any future surface asset!
- Gaps identified by LSIC Dust Mitigation team
- Lunar simulant limitations
- Dust parameters needed to improve modeling efforts
- Cross-reference our needs with those of ISRU, Excavation and Construction, and other areas
- What are we missing? Please reach out to me!

What's next?

- Firm up current "needs" list; consolidate; prioritize
- Identify potential sources for "answers"
  - Vision: our own dusty version of a science traceability matrix that starts with our dust measurement objectives and ties back to potential instrument/mission requirements and data products
- Communicate our needs to the community; Work closely with LEAG, LSIC, and lunar science community
- Advocate for relevant efforts
- Identify overlap between our needs and upcoming mission data (e.g. data from payload X from mission Y will address need Z)
- Figure out best way to inform future hardware design with newfound data; turn around lessons learned quickly

But, really, what's next?

- Perhaps a workshop or TIM? Maybe something similar to a LEAG Special Action Team?
- Thoughts? Please let me know!



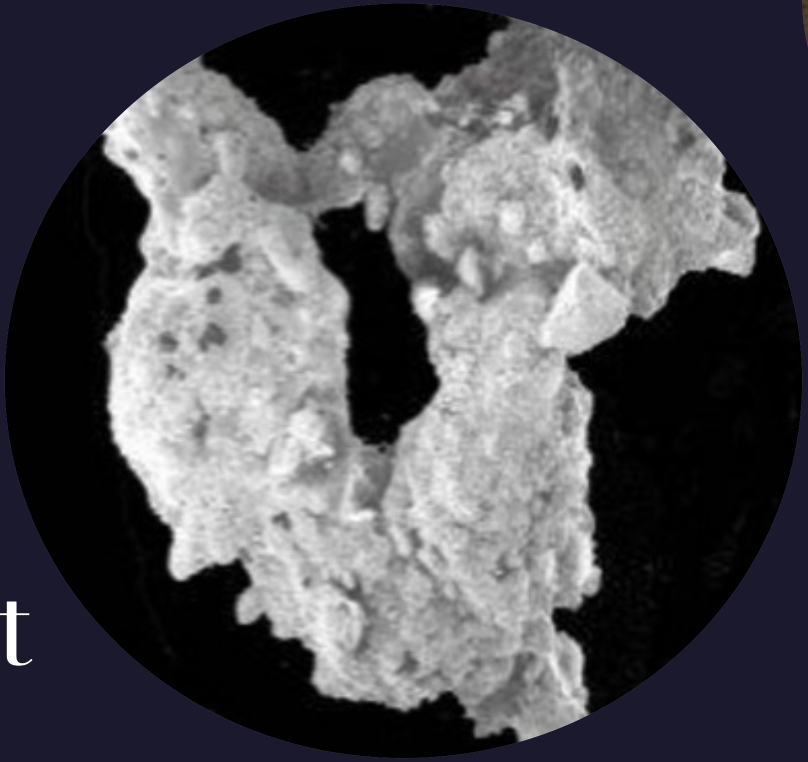
Agenda

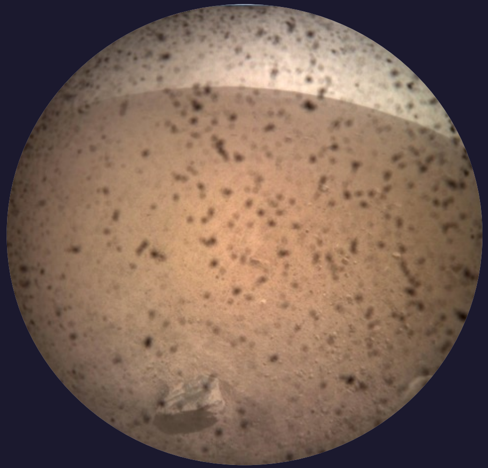
Dust, the dust problem, and dust mitigation

Dust characterization needs

Adhesion experiment

Dust accumulation sensor





Adhesion Experiment – Past

A semi-quantitative dust adhesion experiment measured <45 µm JSC-1/1A lunar simulant on four materials (bare aluminum, anodized aluminum, Ortho fabric and Z93P painted aluminum)

ELSEVIER

Acta Astronautica
Volume 199, October 2022, Pages 25-36

Adhesion of lunar simulant dust to materials under simulated lunar environment conditions

Donald C. Barker [a], Andres Olivas [a], Ben Farr [b], Xu Wang [b], Charlie R. Buhler [c], Jeremy Wilson [a], John Mai [a]

Lunar dust adhesion was demonstrated using centripetal force measurement profile.

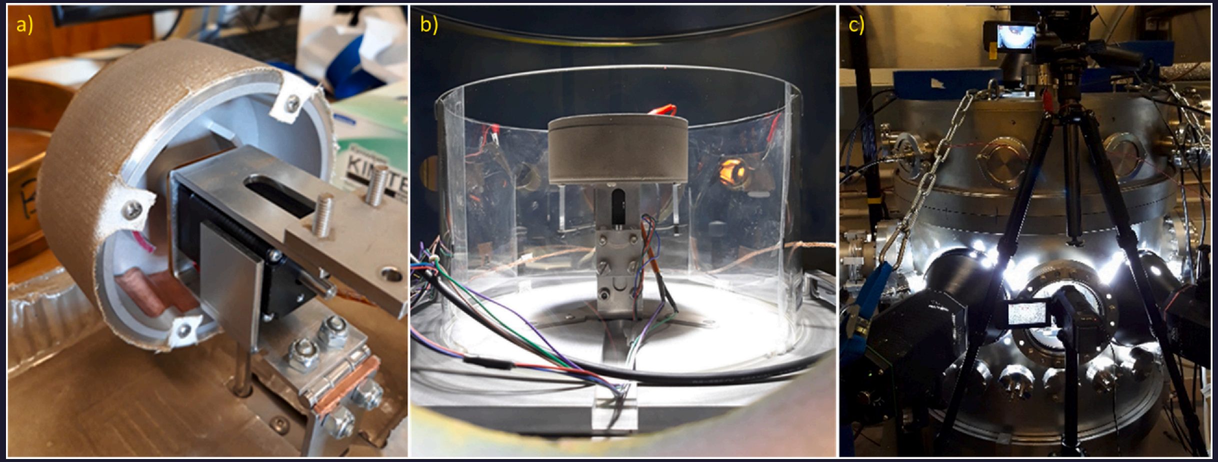
Measured material adhesion differences between just vacuum (~10^{-6} Torr) versus vacuum with UV light for all four materials.

A quadratic dependence of adhesion force with particle sizes remaining on final rotation was found in the range of 0.1 to 3 µm.

Finest of the fine dust will likely remain attached to all materials planned for use in the lunar environment.

Adhesion Experiment – Present

- A fully automated version of this experiment is currently in development.
  - Apply dust under stabilized environmental chamber conditions (an automation challenge) – i.e. vacuum, charging and UV.
- Enhance experiment to reduce error bars & use different simulants.
- Modeling efforts need adhesive force per surface material, function of particle size

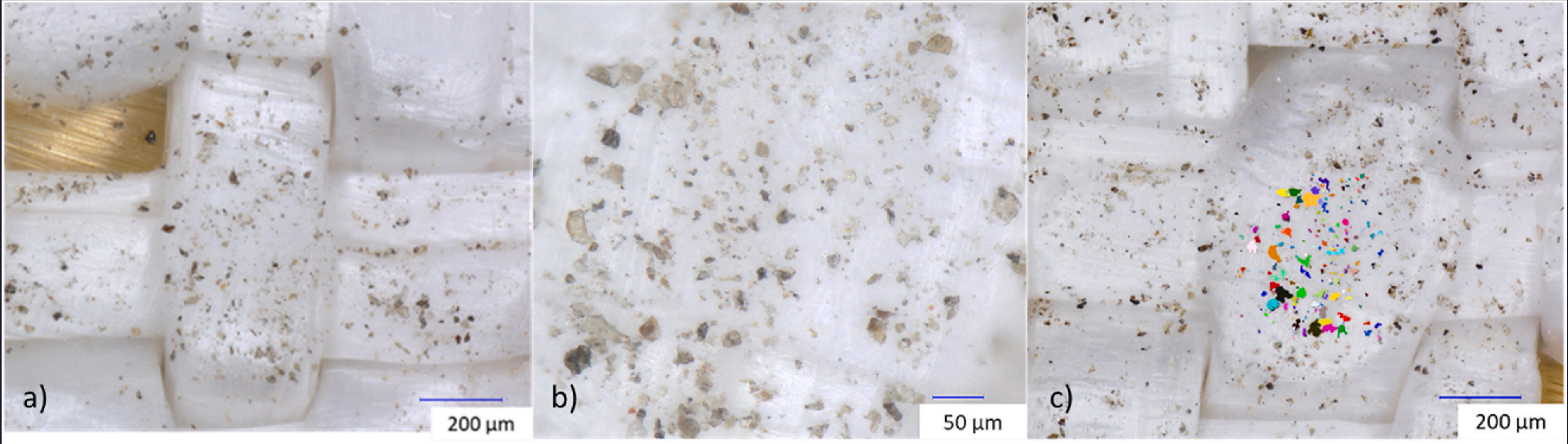


Previous experimental setup

Adhesion Experiment – Future

Goal: Measure adhesion properties of all materials desired to be used on the lunar surface.

Given Experimental Test Stand Success: Full up testing of materials in dusty-plasma chamber would result in a table of material adhesion values vs. simulant types (using multiple simulants).



Images a) and b) show dust that remained on the Ortho fabric after final 400 g rotation (No UV). Image c) shows an example of particle size identification and estimation.

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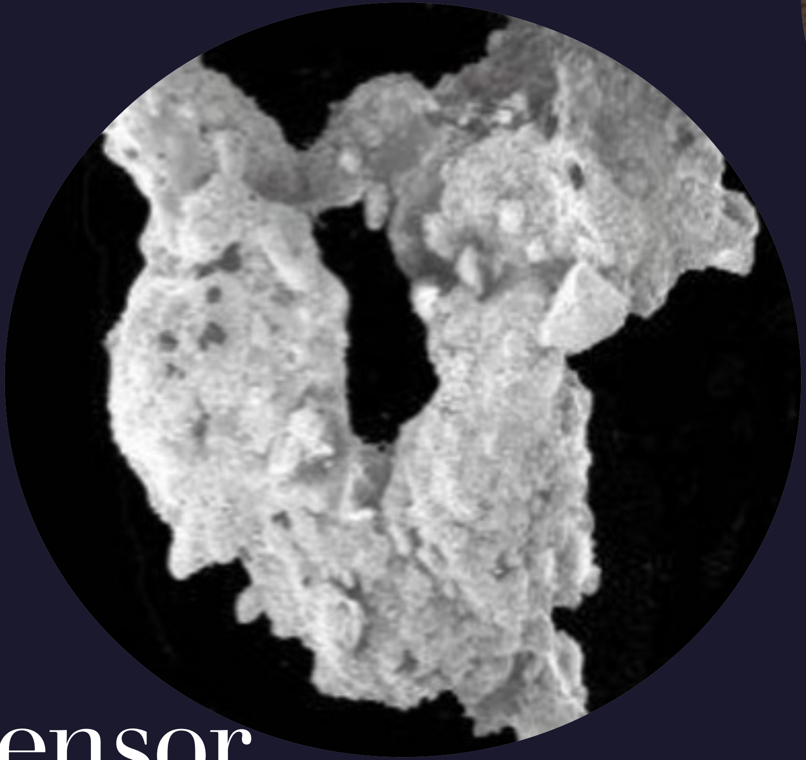
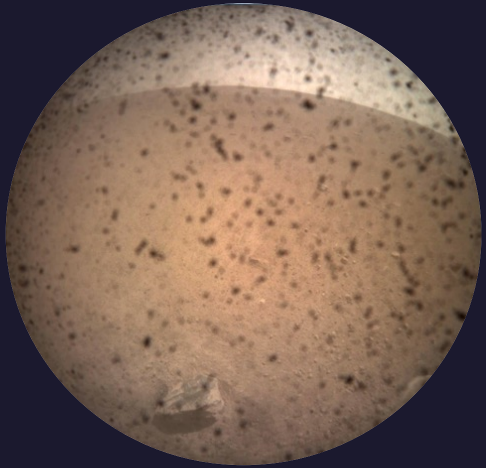
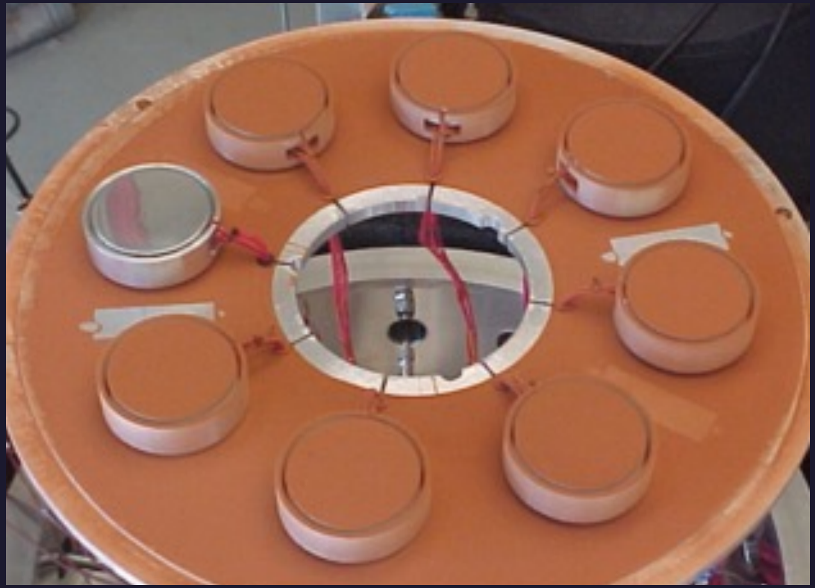




Lunar Dust Level Sensor & Effects on Surfaces (LDES)

- Quantify the effects of lunar dust on external surfaces, materials, and system performance (e.g. radiators); develop a sensor to measure in-situ local dust accumulation using reverse engineering.
- Perform ground testing to determine impacts of dust on radiator heat rejection.
- Test sensor on lunar surface to measure dust accumulation on key systems, study dust transfer on external surfaces, and assess material degradation.

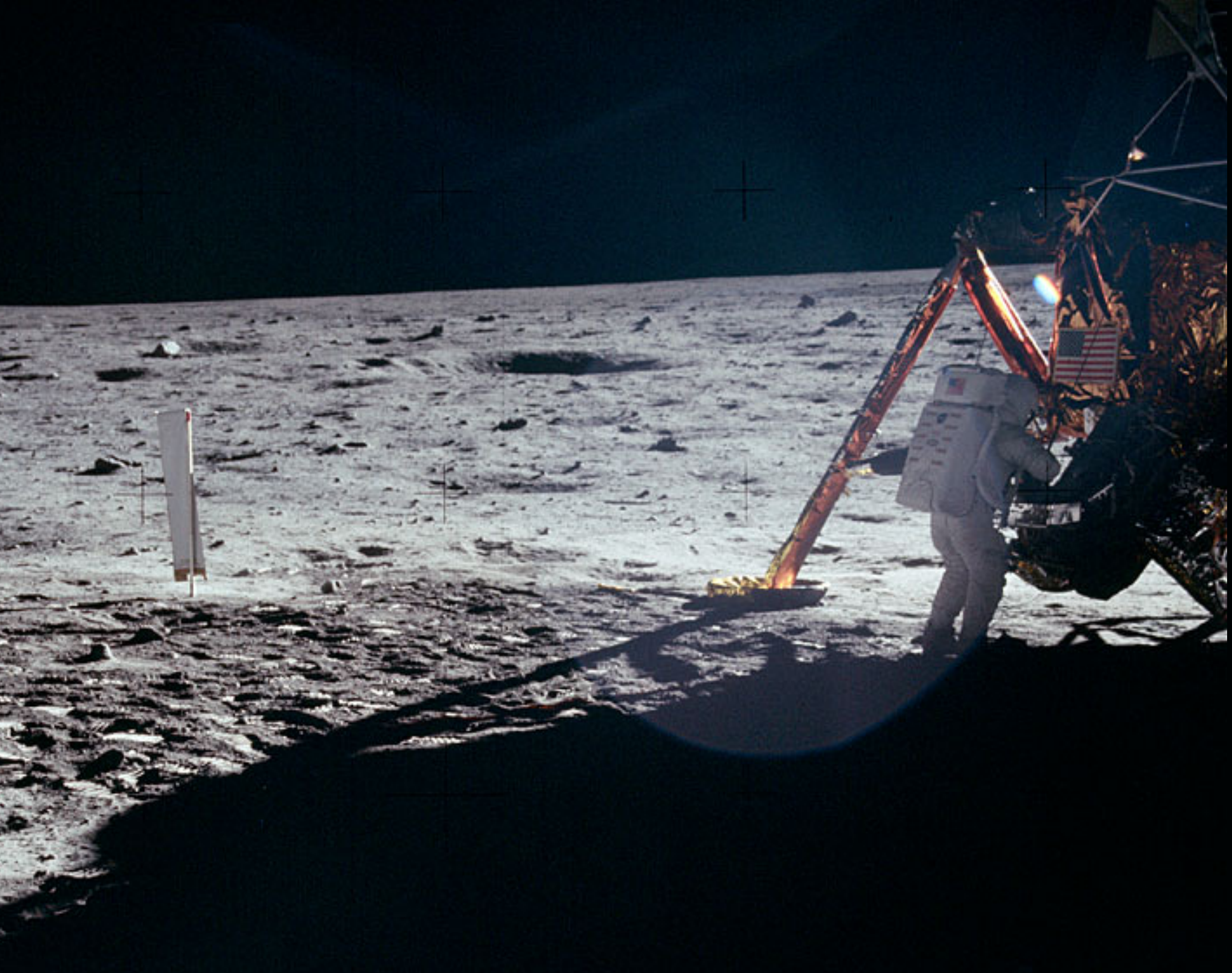


"I'm at the foot of the ladder. The LM [Lunar Module] footpads are only depressed in the surface about 1 or 2 inches, although the surface appears to be very, very fine grained, as you get close to it, it's almost like a powder; down there, it's very fine.... I'm going to step off the LM now.

That's one small step for (a) man. One giant leap for mankind.

As the—The surface is fine and powdery. I can—I can pick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a small fraction of an inch. Maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine sandy particles."

- Neil A. Armstrong Tranquility Base (Apollo 11), July 20, 1969



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Questions?

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