Lunar Dust: Characterization and Mitigation

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Abstract. Lunar dust is a ubiquitous phenomenon which must be explicitly addressed during upcoming human lunar exploration missions. Near term plans to revisit the moon as a stepping stone for further exploration of Mars, and beyond, places a primary emphasis on characterization and mitigation of lunar dust. Comprised of regolith particles ranging in size from tens of nanometers to microns, lunar dust is a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects. The environmental and anthropogenic factors effecting the perturbation, transport, and deposition of lunar dust must be studied in order to mitigate it's potentially harmful effects on exploration systems. The same hold true for assessing the risk it may pose for toxicological health problems if inhaled. This paper presents the current perspective and implementation of dust knowledge management and integration, and mitigation technology development activities within NASA's Exploration Technology Development Program. This work is presented within the context of the Constellation Program's Integrated Lunar Dust Management Strategy. This work further outlines the scientific basis for lunar dust behavior, it's characteristics and potential effects, and surveys several potential strategies for its control and mitigation both for lunar surface operations and within the working volumes of a lunar outpost. The paper also presents a perspective on lessons learned from Apollo and forensics engineering studies of Apollo hardware.

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PRINCIPAL AUTHOR'S BIO (~50 WORDS)

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Definition

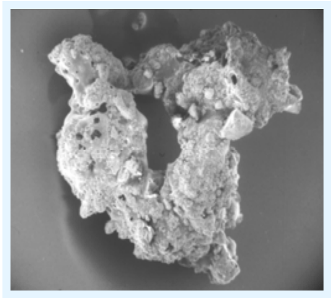
Lunar Regolith: *The layer of unconsolidated rocky material overlying the entire surface of the Moon ranging in thickness from ~1 meter to tens of meters formed by impact processes* - physical desegregation of larger fragments into smaller ones and modified by space weather over time.

Formation Processes:

Meteroid bombardment – makes things smaller

Agglutinate formation – makes things bigger

Exposure of fresh bedrock



Size Nomenclature

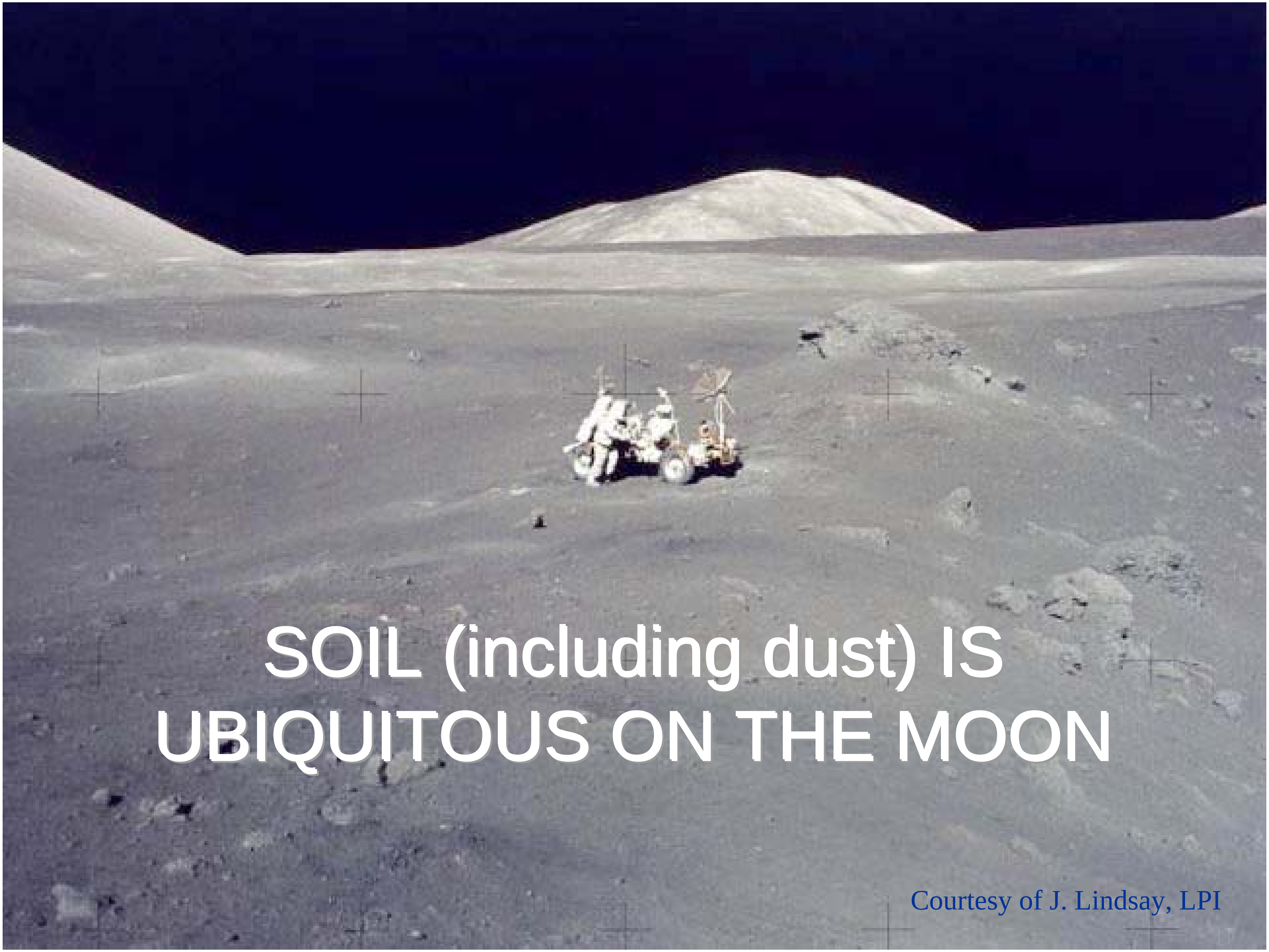
Lunar Regolith - Boulders to Microscopic

Lunar Soil - Particle fraction $\leq$ 1cm diameter

Lunar Dust - Particle fraction $\leq$ 20µm diameter

Respirable Fraction - <10µm diameter in 1g, possibly larger in 1/6g

Submicron Fraction - Large numbers of fine (<1 µm) to ultrafine (<100 to ~20 nm) particles: high number density between 100 and 200nm


SOIL (including dust) IS UBIQUITOUS ON THE MOON
Courtesy of J. Lindsay, LPI

Apollo Experience

- Lunar Regolith Posed Many Operational Challenges
  - Surface obscuration during lunar module descent
  - Dust Coating and Contamination
    - Anthropogenic sources
    - Surface Systems Effects
      - Lunar Rover
        - Thermal control
      - EVA Suits and Mechanisms
        - Abrasion and wear
        - Seals
  - Crew efficiency
    - Maintenance and cleaning
  - Human Exposure
    - Inhalation and irritation

Lunar Regolith Management Technology and Capability Needs

- Site Preparation – Roads, landing site, construction materials, radiation shielding
  - In-situ microwave sintering
  - Waste recycling
  - Temporary mats
  - Fixative or adhesives
  - Vibration
- Hard and soft goods surface coatings
  - Coatings that attract and/or repel dust
  - Abrasion resistant coatings
  - Strippable coatings
  - Easy don and doff over-garments
- Compressed gas extraction
  - Storage
  - Re-use
  - Cleaning systems
- Automated cleaning systems
  - Electrostatic
  - Magnetic
  - Vacuum
  - HEPA Filtration
  - Self cleaning connectors
- Manual cleaning systems
  - Non-abrasive brushes that remove very small particles
  - Magnetic and or electrostatic wand
- Crew and equipment translation systems
  - Pressurized articulating jet ways
  - Vacuum transfer

Addressed by ETDP Dust Project

Addressed by other ETDP Projects

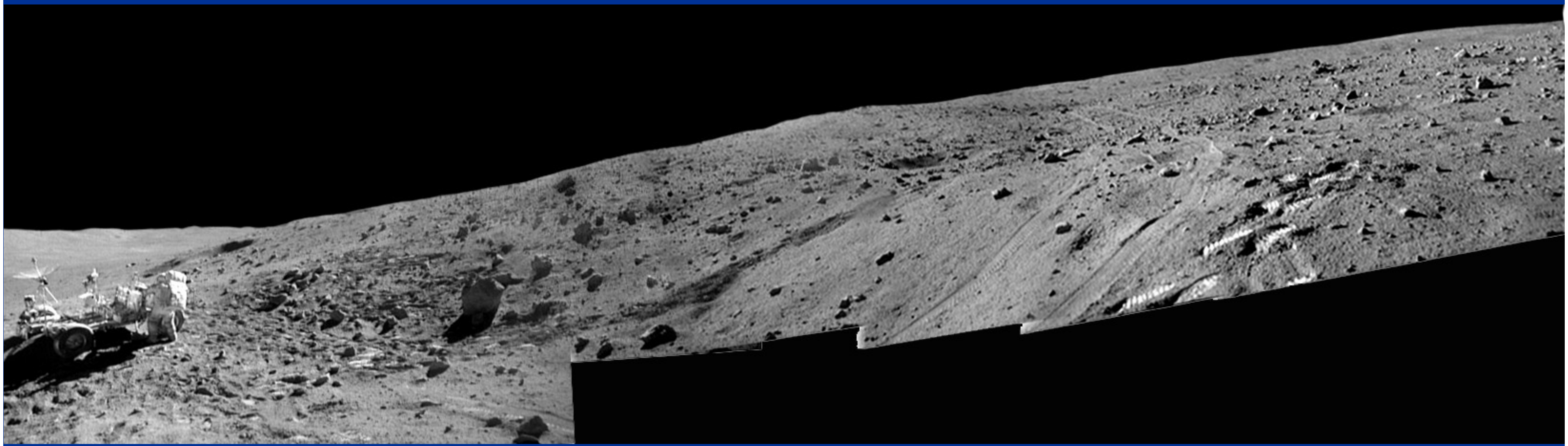
Exploration Technology Development Program
Dust Project - Technical Content Summary

- Dust Mitigation Technology Development
  - Mechanical Components and Seals
    - Dust Tolerant Bearings, Gimbal/Drive Mechanisms
  - Materials and Coatings
    - Abrasion resistant materials, surface coatings
  - Dust Mitigation for Habitat/Airlock Applications
    - CO_2 shower
    - SPARCLE
    - Industry Solicitation
  - Dust Mitigation for Surface System Applications
    - Electrostatic curtain
    - Protection of Thermal Control Surfaces
    - Self Cleaning Solar Arrays

Exploration Technology Development Program
Dust Project Technical Content Summary

- Engineering Design Environments
  - Simulant Characterization, Definition, and Requirements
    - Proves regolith characterization methodology
    - Establishes dust simulant figures of merit (FOMs)
    - Characterizes current simulants to assess applicability for technology development, integration, and testing
  - Regolith Characterization
    - Addresses knowledge gaps and guides simulant definition and FOMs
  - Environment Characterization
    - Analytically assesses lunar surface environment and applies to engineering design and technology development, integration, and testing
  - Forensic Engineering Investigations

The Lunar Surface is Not JSC-1…



The lunar surface is a complicated environment produced by impact processes over billions of years and continually modified.

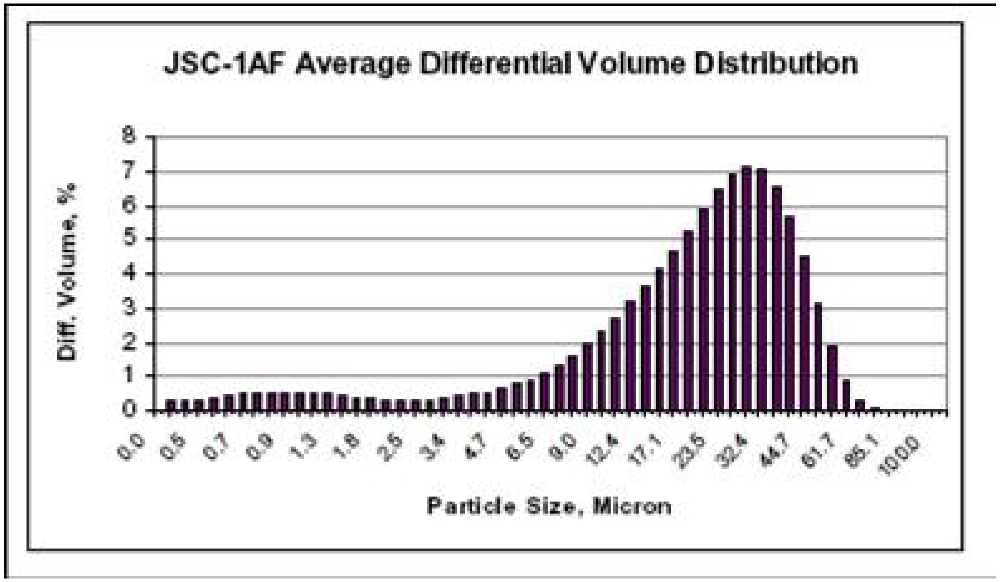
There is no simulant that reproduces the properties of the bulk regolith and there is no single simulant that reproduces all of the properties of the fine-fraction.

Courtesy of J. Plescia, Applied Physics Laboratory

Simulant and Regolith Characterization

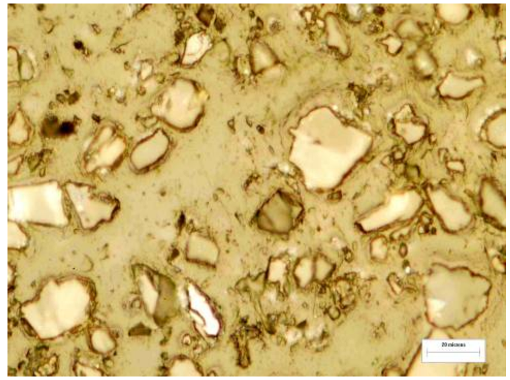
- Physical Properties to be Assessed
  - Particle size and shape
  - Adhesion, Hardness, Abrasivity
  - Surface Energy, Chemistry and Reactivity
  - Dielectric function and Conductance
  - Charge capacity and electrostatics
  - Magnetic Susceptibility
  - Tribocharging

Simulant Fidelity - for example: JSC-1af significantly underrepresents the fine and unltrafine fraction of lunar regolith



Apollo Forensic Engineering Investigation

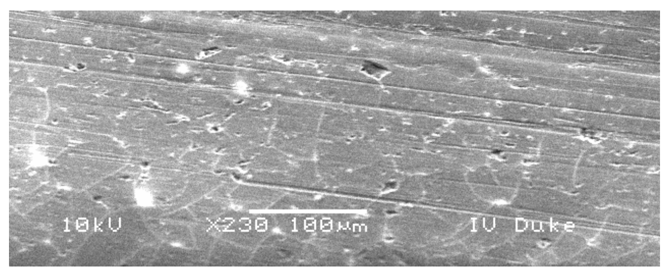
- **Objective:** To obtain useful data on the effects of lunar dust exposure on Apollo equipment and space suits.
  - *Results will be used to guide dust mitigation technology development and to help develop models for the effects of dust exposure on materials and systems*
- **Approach:**
  - Examination of spacesuits at the Smithsonian Institution by XRF and tape peels to reveal trapped dust
  - Inspection of LiOH cartridge filters
  - Disassembly and Inspection of IVA/EVA glove seal bearings and races
  - Chemical analysis of polymer degradation in suit materials
  - Direct SEM imaging of exposed surfaces of an EVA glove
  - SEM analysis of dust samples vacuumed from suits upon return to Earth



Optical Micrograph of lunar dust vacuumed from Apollo suit

Initial visit to Smithsonian to evaluate condition of artifacts, such as the Apollo 17 suit shown above

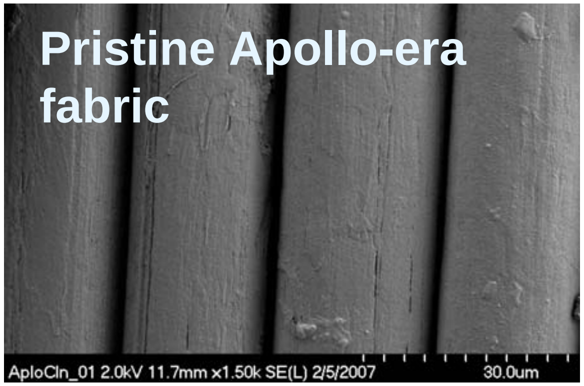
Electron micrographs from GRC showing damage to the outer layer of Alan Bean's Apollo 12 suit

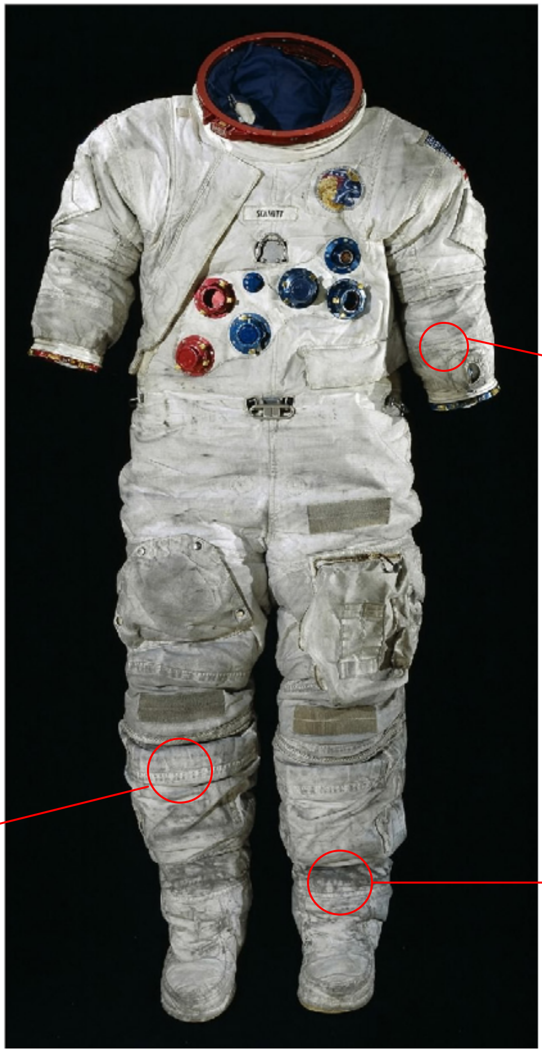


SEM image of inner bearing race from Apollo 12 IVA glove (not lunar exposed control case)

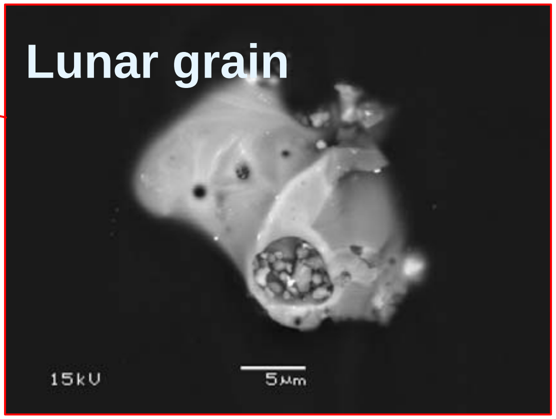
NAS-DIRT (NASA and Smithsonian Dust Investigation Research Team) Results

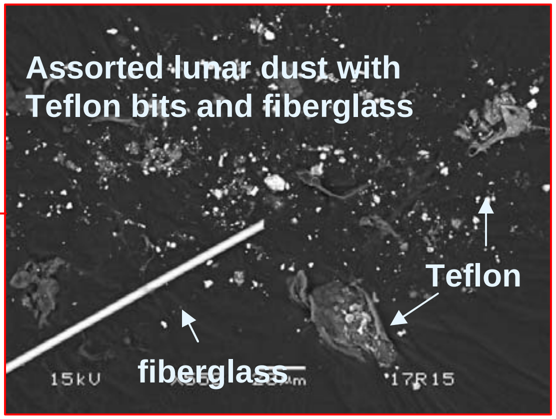
Apollo 12 - Investigations of fabric from lunar EVA suit worn by Alan Bean show damage that was incurred in the lunar environment



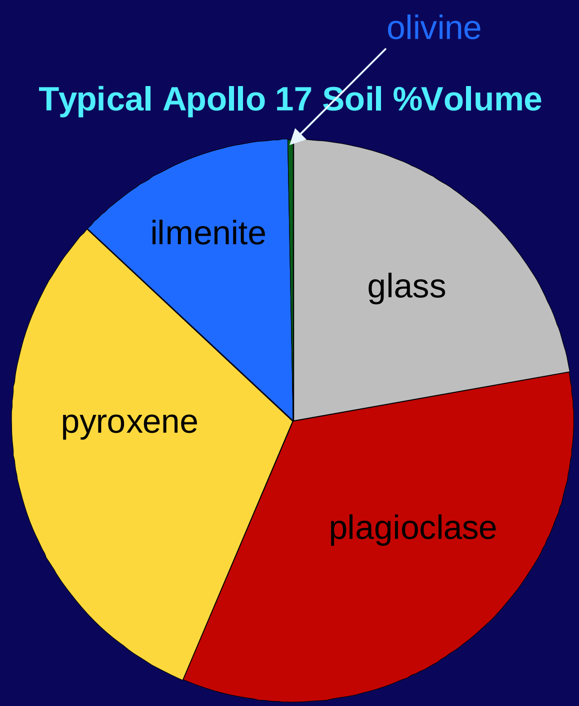


Apollo 17 – Tape peel samples off lunar EVA suit reveal the size distribution and mineralogy of adhered lunar material, as well as material from degradation of the suit fabric itself.

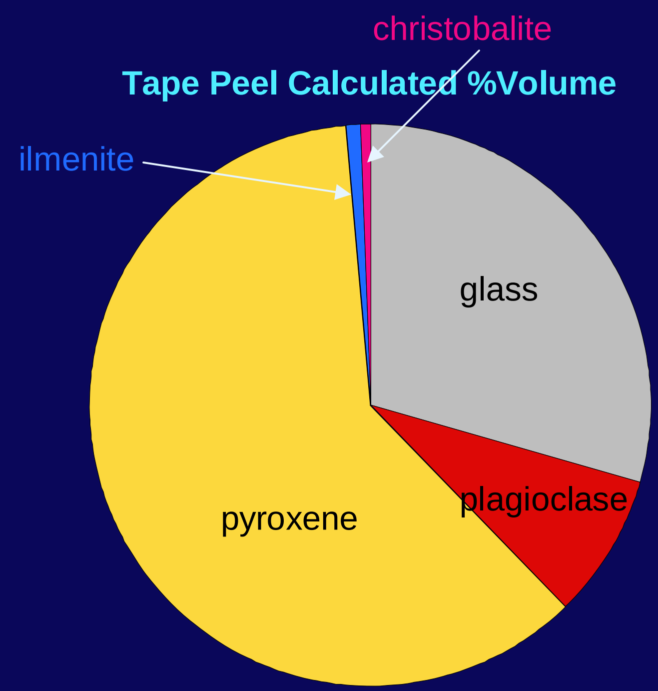




Mineralogy of Suit Tape Peel Samples



Breakdown by percent volume of lunar grain types for grain sizes between 20-90 microns from Apollo 17 (Mare soils 72501,76501, and 78221)*.

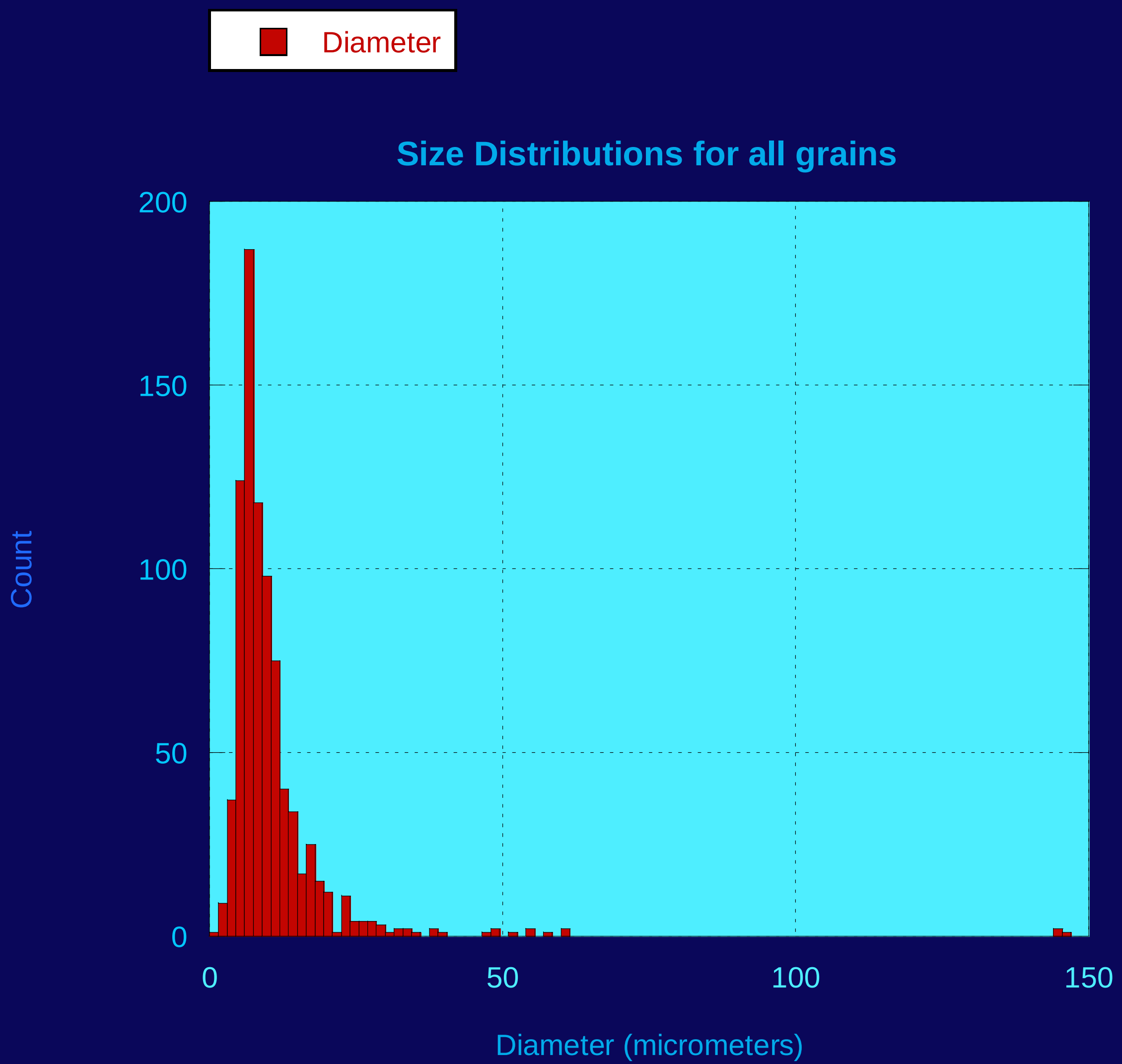


Breakdown by percent volume for each lunar grain type calculated from the tape peels for sizes greater than 2 microns**

*Papike et. al. 1982

**J. Anneliese Lawrence, Marshall University John F. Lindsay, Lunar and Planetary Institute Sarah K. Noble, NASA-JSC

Grain Size of Suit Tape Peel Samples



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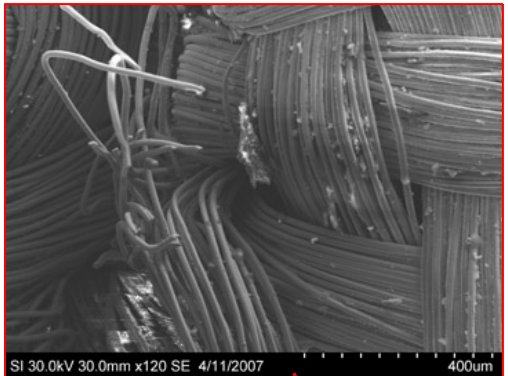
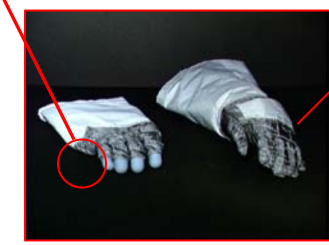
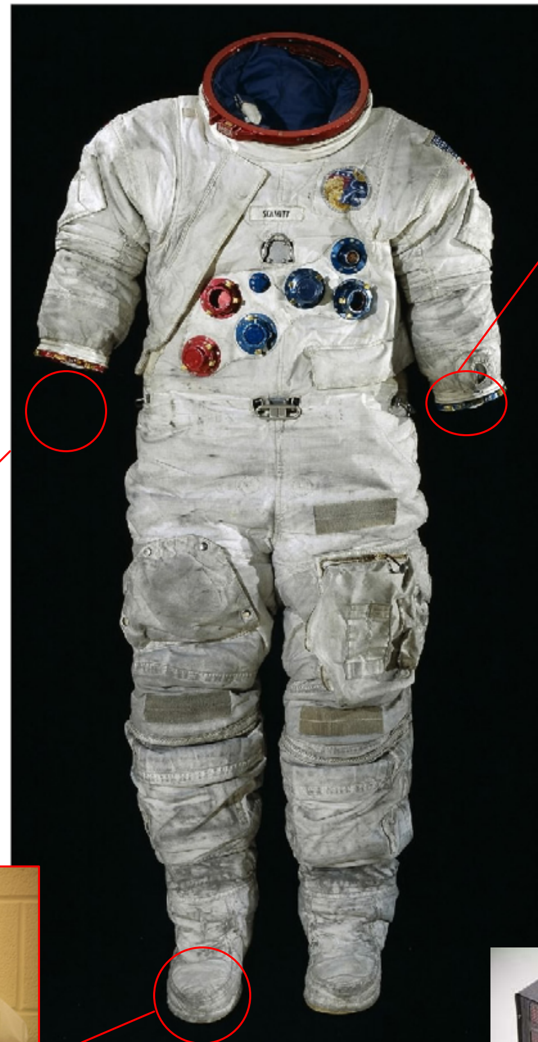
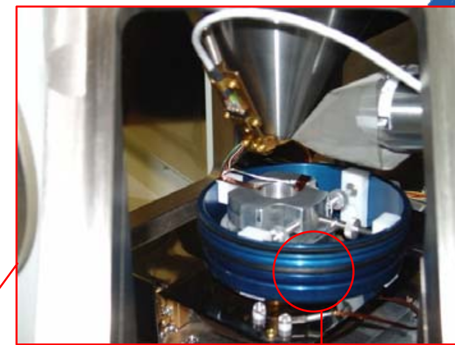
NAS-DIRT Results Continued

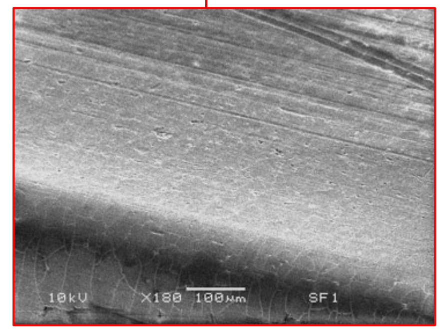




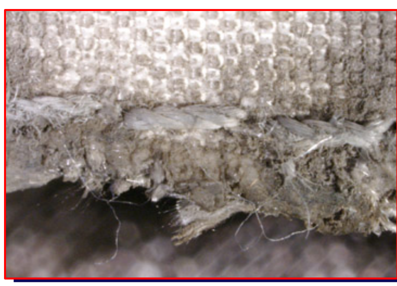
SEM and optical imaging of the gloves and boots show wear patterns from exposure to lunar dust







SEM imaging of rotating pressure seals on glove disconnects provide insight on wear patterns of bearings and seals



Investigation of air filters shows what material was airborne in cabin

Summary

- Vision for Space Exploration plans to resume human missions to the moon, of extended duration, require a strategic approach to management of lunar regolith
- Layered engineering solutions, based on improved understanding of the integrated lunar environment, can allow safe and sustainable mission operations
- The ETDP Dust Project will provide improved understanding of relevant lunar environment characteristics, and develop mitigation technologies required to address gaps in current capabilities