NASA-STD-3001 Technical Brief

Lunar Dust

OCHMO-TB-011
Rev C

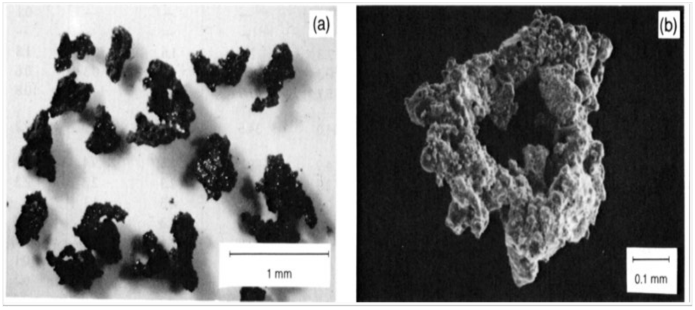
Relevant Technical Requirements

NASA-STD-3001 Volume 1, Rev C
[V1 3004] In-Mission Medical Care

NASA-STD-3001 Volume 2, Rev D
[V2 3006] Human-Centered Task Analysis
[V2 6023] Trace Constituent Monitoring and Alerting
[V2 6051] Water Contamination Control
[V2 6053] Lunar Dust Contamination
[V2 6061] Environment Cross-Contamination
[V2 6063] Contamination Cleanup
[V2 6109] Water Quantity
[V2 6153] Celestial Dust Monitoring
[V2 7043] Medical Capability
[V2 7080] Particulate Control
[V2 7082] Surface Material Cleaning
[V2 8001] Volume Allocation
[V2 9053] Protective Equipment
[V2 11126] Suit Materials Cleanability

Executive Summary

Lunar dust exposure during the Apollo missions has provided insight and many years of research of an extraterrestrial environment that has not been visited by humans since 1972. Due to the unique properties of lunar dust (and other celestial bodies), there is a possibility that exposure could lead to serious health effects (e.g., respiratory, cardiopulmonary, ocular, or dermal harm) to the crew or impact crew performance during celestial body missions. Limits have been established based largely on detailed peer-reviewed studies completed by the Lunar Airborne Dust Toxicity Advisory Group (LADTAG). Research on lunar dust is ongoing, and emergent considerations (e.g., the presence of toxic volatiles in permanently shadowed regions, allergenic potential of dust) will be appropriately addressed as the risk is more clearly understood. The role of dust mitigation and monitoring is also highlighted here, as these contribute to the ability to characterize crew exposures and minimize risk.



Source: The Lunar Regolith

Background

Recommendations from Crew:

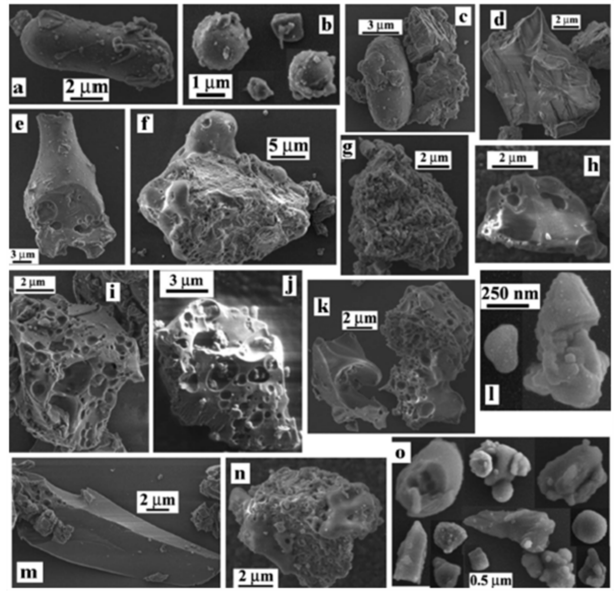
Protect the suit zipper function. The lunar dust was difficult to clear from the zipper and impaired normal function on each subsequent lunar EVA for some missions. The abrasive nature of the dust scored the metal connections, primarily circumferentially on the bearing surfaces. The lunar dust exposure did not result in a breach of the sealing capability of the suit, however repeated exposures may increase this risk.

Provide an airlock for ingress/egress. Designing an airlock to separate the vehicle hatch from the habitation area could decrease the risk of tracking lunar dust into the lunar module.

Have the ability to clean body and rinse eyes/nasal passages of dust. The lunar dust was ubiquitous in the vehicle cabin and was very difficult to clear from the hands. In each case, ocular irritation occurred that required copious saline irrigation to treat.

Medication availability. Nasal congestion was experienced by most crewmembers, and was attributed to the 100% O_2 environment, dust, and viral exposures preflight. Actifed was used and provided moderate relief. Lunar crews stated that symptoms resolved on lunar surface after initial exposure to dust only to return when reentering the crew module as the particulates floated throughout the cabin in microgravity.

Design an efficient method for clearing the lunar dust from the vehicle cabin. Lunar dust particles floated everywhere in the lunar module upon return to microgravity. Dust particles floated into crewmembers' eyes, nose, and lungs, which prompted the Apollo 12 crew to keep their helmets on prior to docking with the crew service module. The dust did not appear to be filtered from the environment through ventilation/LiOH system although the vacuum cleaner that was used beginning with Apollo 14 seemed to help clear the larger particles.



Lunar Dust Characteristics

- Range from ~0.02 µm -10 µm
- Predominantly 0.02-5 µm.
- 95% <2 µm in diameter. 40% <0.1 µm.
- 0.1-0.3 µm is a prevailing fraction
- Smaller particles are the most deeply respirable and potentially impactful on crew health, although they represent a minimal mass fraction.

Risks and Hazards Associated with Lunar Dust Exposure:

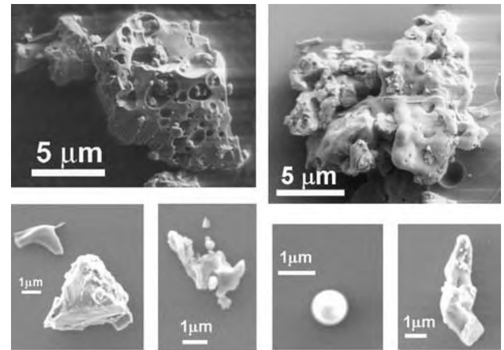
Medical impact
- Eye irritant
- Abrasive to the skin
- Pulmonary system toxicity
- Possible allergenic effects (research pending)

Habitat environment
- Atmospheric contaminant
- Equipment contamination
- EVA Ops

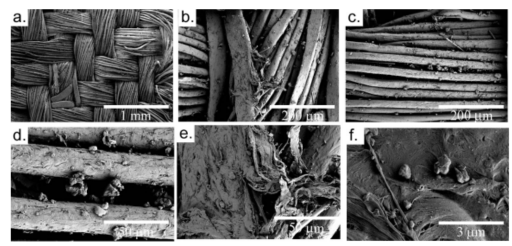
Background

Dust Morphology – Most lunar dust particles show sub-angular to angular shapes with sharp edges. There are four prominent shapes: 1) spherical; 2) angular blocks; 3) glass shards; and 4) irregular (ropey or Swiss-cheese). In particular, submicron bubbles and cracks are present in most grains. This causes a multiplication of the reactivation surface area.

- Similar to volcanic ash – Arizona volcanic ash is used as a simulant
- Fine/Ultrafine particles that range from ~0.02 to 10 microns with 95% less than 2 microns
  - Particles 10 µm and below are expected to be readily entrained and aerosolized in the cabin airflow



Source: Micro-Morphology and Toxicological Effects of Lunar Dust

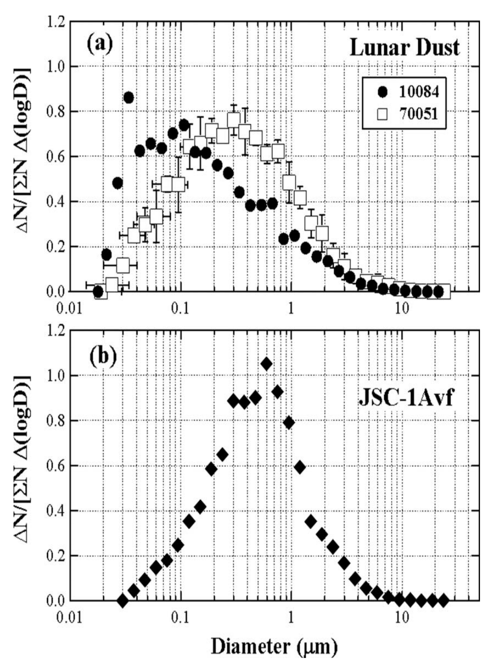


Source: Lunar Dust Effects on Spacesuit Systems

Regolith Composition – The prime constituents are aluminosilicate and other silicate minerals that make up 90 percent by volume of lunar rocks. There are varying amounts, typically low, of Crystalline Silica (free SiO_2) minerals, Quartz, Tridymite, Cristobalite, which have higher toxicity, lower exposure levels and are highly regulated in terrestrial (earth) environment. Very location and mineralogy/geology dependent.

The lunar rock or soil is also comprised of up to 20 percent of various oxides that can potentially be tapped for oxygen extraction.

- Silicone dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), iron(II) oxide (FeO), magnesium oxide (MgO), and calcium oxide (CaO)
- Volatiles at the poles, which are not completely understood or characterized on the toxicity to humans



Source: Park et al, 2008 Characterization of Lunar Dust for Toxicological Studies: Particle Size Distribution

Lunar Surface –

Mare – volcanic, basaltic areas that are relatively flat with few craters

Highlands – primary crust, anorthositic that is heavily cratered and rough

Behavior – Has an electrostatic charge due to the FeO, as well as possible surface reactivity from solar wind, solar flares, galactic cosmic rays, micrometeoroids, large thermal cycles, and ultrahigh vacuum.

Reference Data

Human Health Studies – includes various intratracheal and inhalation exposures via in vitro and in vivo studies, as well as abrasive studies to determine impact to the skin and eyes. Additional research is needed to understand surface reactivity, acute toxicity, and cardiovascular risks.

Apollo experience provided limited evidence that lunar dust was a potential health concern but was clearly a dust management challenge for other spacecraft systems. The short-term nature of Apollo precluded firmer health conclusions based on that experience alone.

From 2005-2013 NASA invested significant research and risk assessment effort (Lunar Airborne Dust Toxicity Advisory Group, LADTAG) to develop toxicity guidelines that could be applied in controlling/assessing crew lunar dust exposures. External/Internal experts formed the team, which included toxicological, geological, chemical, and risk assessment experts.

LADTAG employed standard rodent toxicity testing with actual lunar dust (Apollo 14), along with known mineral dusts (positive/negative controls) for comparison. Exposures were conducted 6 hrs/day, 5 days, week, over a 4-week period.

Lung inflammation, septal thickening, and other signs of respiratory system toxic challenge were seen in rodents exposed to lunar dust, with negative consequences increasing with exposed dose. These are the same types of effects that could occur in spaceflight crew if lunar dust were not properly controlled. Results showed that lunar dust was moderately toxic, in comparison with other reference dusts.

Standard risk assessment procedures were following in extrapolating the LADTAG rodent findings to protect crew exposures during intermittent dust exposures over an assumed 6-month mission. LADTAG determined that lunar dust would adhere to “Haber’s Rule” (which states that concentration and allowable exposure duration are proportionally and inversely related). This assumption allows for expression of equivalent risk for other exposure durations and conditions (e.g., continuous exposure scenario) that may be more relevant to the specific lunar mission under evaluation (e.g., 7-day or 30-day mission exposure scenarios).

A7-L Pressure Suit with lunar dust, Apollo 11

Reference Data

[V2 6053] Lunar Dust Contamination The system shall limit the levels of lunar dust particles less than 10 µm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m^3 during intermittent daily exposure periods that may persist up to 6 months in duration.
From: NASA-STD-3001 Volume 2, Rev D

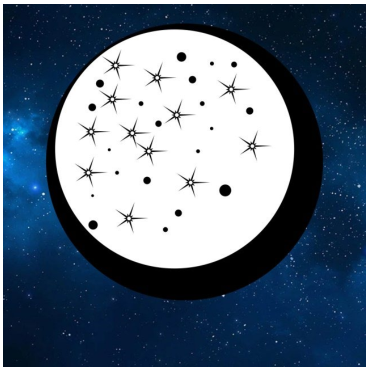
Adherence to the exposure limit will minimize adverse impacts to the crew respiratory system, which is believed to be the most sensitive aspect of lunar dust exposures from a health perspective. Risk of eye abrasion and skin irritation (e.g., EVA gloves, under fingernails) are relevant to lunar dust, but are handled by other overarching operational controls and assessment procedures. Research is ongoing on lunar dust, including on other adverse health effects such as its allergenic potential.

The selection of Apollo 14 regolith was strategic and was intended to allow the toxicity study findings to be as broadly applicable to other lunar landing locations as possible. Thus, it is acceptable to apply this standard when assessing surface dust exposure at the lunar south pole without incorporating additional conservatism.

Relatively recent findings have suggested that some lunar samples may contain toxic volatile constituents (e.g., hydrogen sulfide, ammonia, mercury) that are trapped in lunar polar ice. These are not expected to be relevant to normal regolith encountered by the crew and are not expected to be carried back into a habitable volume as part of the lunar dust matrix. Inadvertent releases resulting from strategic samples (e.g., subsurface samples, permanently-shadowed regions) can be a very real concern but are mitigated through proper containment and are handled separately from this particular lunar dust standard.

Risk to the crew respiratory system is best reflected by average exposures to lunar dust, and time to effect are generally on the order to weeks to months of exposure under most circumstances relevant to lunar missions. Thus, acute limits for lunar dust are not being set at this time. Limiting peak exposures may be key in controlling long-term lunar dust averages, however. Peak exposures can also be mitigated through operational controls (e.g., temporary dust masks, goggles) that may be used to preclude superficial physiological responses (e.g., eye irritation, sneezing) to liberate lunar dust particles (or another general particulate).

[Risk of Adverse Health and Performance Effects of Celestial Dust Exposure]



Gene Cernan covered in dust following EVA. Note the presence of dust on suit and other surfaces.

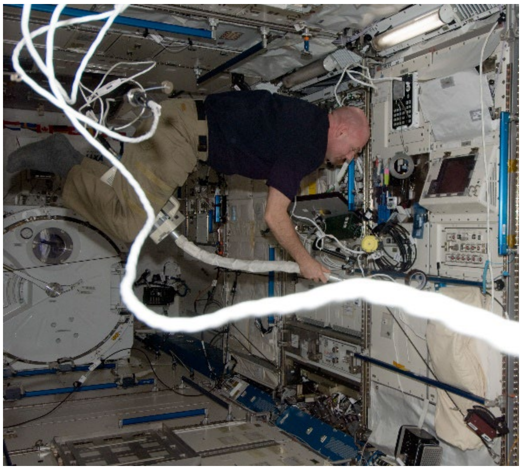
Application

Monitoring

Dust monitoring is key in assessment and tracking of crew exposure levels for lunar dust, and to inform any medical responses or anomaly resolution activities during a mission. This data is also used post-mission to provide an occupational exposure record. Additionally, lunar dust monitoring provides verification and optimization of controls, and in providing objective measurement data for maturation of mitigation concepts.

There are available commercial particulate monitoring technologies that can likely be employed (with minimal spaceflight adaptations) to provide inflight measurement data. Necessary data will include the particle sizes of the dust and the mass concentration that are used to demonstrate attainment of the health-based standard. Dust monitoring is likely to be needed situationally (e.g., assessing cabin clearing after EVA introduction, anomaly assessment), rather than as a continuous monitored environmental parameter.

[V2 6153] Celestial Dust Monitoring and Alerting The vehicle shall monitor celestial dust and alert the crew locally and remotely when they are approaching defined limits.
From: NASA-STD-3001 Volume 2, Rev D



ESA astronaut Andre Kuipers uses a vacuum cleaner during housekeeping operations on the ISS

Design Testing and Mitigation of Dust

Crew Health
- Medical supplies – eye wash, allergy medications, etc.[1,2]
- Personal hygiene supplies – cleansing products, water, towels, etc.

Habitable Area
- Cleaning materials – vacuum, ability to wipe/remove dust from surfaces
- Equipment interactions – antistatic capabilities, etc.

Air Filtration/Environmental Control Life Support System (ECLSS)[3]
- Flow rate
- Particle size removal – HEPA filtration or similar, etc.

Extravehicular Activity (EVA) Operations
- Interactions with dust
- Mechanisms of dust transport

Post-EVA Activities
- Suit cleaning before/after vehicle entry
- Suit stowage

Suit Design
- Joints/mechanisms
- Entry method
- Outer material
- Ability to be cleaned and methods for cleaning

Rover Design[4]
- Wheel traction
- Fenders

Stowage
- Location of suit post-EVA
- Collected dust and regolith

1. Pharmaceuticals and Medications Technical Brief
2. Medical Care Technical Brief
3. ECLSS Technical Brief
4. Extraterrestrial Surface Transport Vehicles Technical Brief

Back-Up

Major Changes Between Revisions

Rev B → Rev C

- Updated information to reflect the revisions to language throughout both volumes of NASA-STD-3001.
- Updated/added website links due to new NASA website launch

Rev A → Rev B

- Updated entire slide deck to new formatting.
- Added details to Slide 4 on regolith

Original → Rev A

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev C.

Referenced Technical Requirements

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

NASA-STD-3001 Volume 1 Revision C
[V1 3003] In-Mission Preventive Health Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, individual crewmember needs, clinical practice guidelines, flight surgeon expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses consider the needs and limitations of each specific vehicle and design reference mission (DRM) with particular attention to parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, and behavioral care, are to include, but are not limited to: (see NASA-STD-3001, Volume 1 Rev C for full standard).

NASA-STD-3001 Volume 2 Revision D
[V2 3006] Human-Centered Task Analysis Each human spaceflight program or project shall perform a human-centered task analysis to support systems and operations design.
[V2 6023] Trace Constituent Monitoring and Alerting The system shall monitor trace volatile organic compounds (VOCs) in the cabin atmosphere and alert the crew locally and remotely when they are approaching defined limits.
[V2 6051] Water Contamination Control The system shall prevent potable and hygiene water supply contamination from microbial, atmospheric (including dust), chemical, and non-potable water sources to ensure that potable and hygiene water are provided.
[V2 6053] Lunar Dust Contamination The system shall limit the levels of lunar dust particles less than 10 µm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m^3 during intermittent daily exposure periods that may persist up to 6 months in duration.
[V2 6061] Environment Cross-Contamination The system shall provide controls to prevent or minimize (as appropriate) biological cross-contamination between crew, payloads and vehicles to acceptable levels in accordance with the biosafety levels (BSL) defined in JPR-1800.5, as well between crew, payloads, vehicles and extraterrestrial planetary environments with the extent of application specific to individual planetary bodies and special locations thereon.
[V2 6063] Contamination Cleanup The system shall provide a means to remove or isolate released chemical and biological contaminants and to return the environment to a safe condition.
[V2 6153] Celestial Dust Monitoring and Alerting The vehicle shall monitor celestial dust and alert the crew locally and remotely when they are approaching defined limits.
[V2 7043] Medical Capability A medical system shall be provided to the crew to meet the medical requirements of NASA-STD-3001, Volume 1.
[V2 7080] Particulate Control The system shall be designed for access, inspection, and removal of particulates that can be present before launch or that can result from mission operations.
[V2 7082] Surface Material Cleaning The system shall contain surface materials that can be easily cleaned and sanitized using planned cleaning methods.
[V2 8001] Volume Allocation The system shall provide the defined habitable volume and layout to physically accommodate crew operations and living.
[V2 9053] Protective Equipment Protective equipment shall be provided to protect the crew from expected hazards.
[V2 11126] Suit Materials Cleanability The suit materials (internally and externally) shall be compatible with the expected cleaning materials and methods.

Reference List

1. Natural Environments Definition for Design. (2016). NASA Technical Reports Server Technical Memorandum-218229.
2. Agui JH and Stocker DP. NASA Lunar Dust Filtration and Separations Workshop Report. National Aeronautics and Space Administration, Glenn Research Center. December 2009. TM-2009-215821.
3. Anderton R, Posselt B, Komorowski M, Hodkinson P. (2019). Medical considerations for a return to the Moon. Occupational Medicine, 69: 311–313.
4. Geotechnical Properties of Lunar Soil. (2005). Lunar Geotechnical Institute, Lakeland, FL. https://www.lpi.usra.edu/lunar/surface/carrier_lunar_soils.pdf
5. Khan-Mayberry N. (2008). The lunar environment: Determining the health effects of exposure to moon dusts. Acta Astronautica, 63.
6. Lam C, Scully RR, Zhang Y, Renne RA, Hunter RL, McCluskey RA, Chen BT, Castranova V, Driscoll KE, Gardner DE, McClellan RO, Cooper BL, McKay DS, Marshall L, and James JT. (2013). Toxicity of lunar dust assessed in inhalation-exposed rats. Inhalation Toxicology, 25(12): 1–18.
7. Lunar Dust Effects on Spacesuit Systems. (2008). NASA/TP-2008-000000. Lyndon B. Johnson Space Center, National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090015239.pdf
8. Lunar Exploration Initiative: Parameters of Lunar Soils. (2006). David A. Kring. https://www.lpi.usra.edu/science/kring/lunar_exploration/briefings/lunar_soil_physical_properties.pdf
9. Lunar Regolith. (2003). NASA Lunar Petrographic Educational Thin Section Set. https://curator.jsc.nasa.gov/lunar/letss/regolith.pdf
10. Lunar Sourcebook, Chapter 7: The Lunar Regolith. David S. McKay, Grant Heiken, Abhijit Basu, George Blanford, Steven Simon, Robert Reedy, Bevan M. French, and James Papike. https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter07.pdf
11. Meyers VE, Garcia HD, Monds K, Cooper BL and James JT. (2012). Ocular toxicity of authentic lunar dust. BMC Ophthalmology, 12: 26.
12. Park JS, Lui Y, Kihm KD, Taylor LA. (2006). Micro-Morphology and Toxicological Effects of Lunar Dust. Lunar and Planetary Science XXXVII. https://www.lpi.usra.edu/meetings/lpsc2006/pdf/2193.pdf
13. Scully RR, Lam C and James JT. (2013). Estimating safe human exposure levels for lunar dust using benchmark dose modeling of data from inhalation studies in rats. Inhalation Toxicology, 25(14): 785-93.
14. Stubbs TJ, Vondrak RR and Farrell WM. (2005). A Dynamic Fountain Model for Lunar Dust. Lunar and Planetary Science XXXVI. https://www.lpi.usra.edu/meetings/lpsc2005/pdf/1899.pdf
15. The Apollo Experience Lessons Learned for Constellation Lunar Dust Management. (2006). NASA/TP-2006-213726. Lyndon B. Johnson Space Center, National Aeronautics and Space Administration. https://www.hq.nasa.gov/alsj/TP-2006-213726.pdf
16. The Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations. (2007). NASA/TM-2007-214755. Lyndon B. Johnson Space Center, National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070030109.pdf
17. The Effects of Lunar Dust on EVA Systems During the Apollo Missions. (2005). NASA/TM—2005-213610. Glenn Research Center, National Aeronautics and Space Administration. https://history.nasa.gov/alsj/TM-2005-213610.pdf
18. Updates to the Risk of Adverse Health and Performance Effects of Celestial Dust Exposure. (2019). Human Systems Risk Board CR-SA-01787. NASA.