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 on detailed peer-reviewed studies completed by the Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG), and is specific to the conditions relevant to the lunar surface.

Summary of Relevant Standards
[V2 6052] Particulate Matter
[V2 6053] Lunar Dust Contamination
[V2 6063] Contamination Cleanup
[V2 7043] Medical Capability
[V2 7082] Surface Material Cleaning

Risks and Hazards Associated with Lunar Dust Exposure:
Medical impact
- Eye irritant
- Abrasive to the skin
- Respiratory system irritant
- Allergenic effects
Damaging to suit mechanisms
- Suit joints/zippers
Habitat environment
- Atmospheric contaminant
- Equipment contamination
- EVA Ops

Source: The Lunar Regolith

Suit Apollo 17, December 1972. Courtesy NASA.
[V2 6052] The system shall limit the cabin particulate matter concentration for total dust to <3 mg/m³, and the respirable fraction of the total dust to <2.5 μm in aerodynamic diameter to <1 mg/m³.

[Rationale: These values were derived by applying a factor of 5 to the OSHA limits for nuisance dusts, which is the best analog for the ordinary dust present in spacecraft. They do not apply to reactive dust, e.g., LiOH or extraterrestrial dust. The factor of 5 is applied to adjust from intermittent occupational exposure to continuous spaceflight exposure.]

[V2 6053] 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/m³ during intermittent daily exposure periods that may persist up to 6 months in duration.

[Rationale: Although the requirement is being conservatively applied to all inhalable particles (all particles ≤10 μm), it is most applicable to dusts in the respirable range (≤2.5 μm) that can deposit more deeply into the lungs. Studies show that the particle size of lunar dust generally falls within a range of 0.02-5 μm.]

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.
- Setting the lunar dust exposure limit with no lower size limit on particles is consistent with how USEPA set the PM₁₀ (≤10 μm particulate) National Ambient Air Quality Standard
Reports from Apollo

Crew Observations
- “Dirt is soft like powdered snow however it clung to everything- suit, cabin h/w, skin, etc.”
- “So dirty can’t see maps on EVA General Comments: The lunar dust was ubiquitous during lunar surface activities.”
- “So much dust on camera can’t get polargraphic filter on.”
- “Rocks existed under the surface dust. easy to trip and fall. The surface is not uniform. Lunar dust is like ground down lead. Similar to the grindings in a pencil sharpener; tenacious; made zipper sticky.”
- “We were quite dirty, lot of dust on suits, particularly up the legs to the knees, and the gloves and arms. Pretty much black like we’d been working in powdered graphite… Seemed to be clinging to us. Banged feet against the strut and a lot of dust fell off our feet. Concerned that once back in orbit they would not be able to remove helmet because of floating dust in zero g; gloves were removed after EVA, hands became contaminated with dust. also got dust particles in the eyes, but it was not difficult to clear the eyes. Wiped down with tissue or towels. Took several days to get fingernail bed clean. Before returning to the CM, stripped down and wiped off with a wet towel.”
- “We dusted but there was still dust everywhere. It smelled like gunpowder, however you would get desensitized to it. Suits would have to be doffed before entering the vehicle.”

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% O2 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 CM 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 LM 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 CSM. 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.

Source: *The Apollo Medical Operations Project*
Reference

Observed Hazards from Lunar Dust:
- Vision obscuration
- Inhalation and irritation
- Allergenic
- Abrasion
- False instrument readings
- Dust coating and contamination
- Loss of traction
- Clogging of mechanisms
- Thermal control problems
- Seal failures

Source: The Effects of Lunar Dust on EVA Systems During the Apollo Missions

Dust morphology

Most of 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

Regolith Composition – The prime constituents are aluminosilicate and other silicate minerals that make up 90 percent by volume of lunar rocks. The lunar rock or soil is also comprised of up to 20 percent of various oxides that can potentially be tapped for oxygen extraction.

- SiO$_2$, TiO$_2$, Al$_2$O$_3$, FeO, MgO, CaO
- Volatiles at the poles, which are not completely understood or characterized on the toxicity to humans

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.

Note: Collections for each Apollo mission were varied and different between each based on the characteristics of the moon in that particular region. Considerations should include the location and proportions of the regolith and compositions.

Source: Micro-Morphology and Toxicological Effects of Lunar Dust.
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.

“Dose-dependent histopathology, including inflammation, septal thickening, fibrosis and granulomas, in the lung was observed at the two higher exposure concentrations. No lesions were detected in rats exposed to <6.8 mg/m³. This 4-week exposure study in rats showed that 6.8 mg/m³ was the highest no-observable-adverse-effect level (NOAEL). These results will be useful for assessing the health risk to humans of exposure to lunar dust, establishing human exposure limits and guiding the design of dust mitigation systems in lunar landers or habitats.” (Lam et. al)

“Small (mean particle diameter = 2.9 ± 1.0 μm), reactive lunar dust particles were used during in vitro testing indicated minimal irritancy potential based on the time required to reduce cell viability by 50% (ET50). Follow-up testing using the Draize standard protocol confirmed that the lunar dust was minimally irritating. Minor irritation of the upper eyelids was noted at the 1-hour observation point, but these effects resolved within 24 hours. In addition, no corneal scratching was observed using fluorescein stain.” (Meyers et. al)

“Benchmark dose methodology was used to analyze data from studies in which rats were exposed over 4 weeks (6 hours/day, 5 days/week) by nose-only inhalation to air and four concentrations of lunar dust, ranging from 2.1 to 61 mg/m³. Biomarkers were measured in bronchial alveolar lavage fluid that was collected at 1 day, 1 week, and 1 and 3 months after exposure. When a species factor of 3 is applied and the duration of exposure is extrapolated to 6 months with daily exposure not exceeding 6 hours, a safe exposure estimate (SEE) for humans of 0.3 – 0.9 mg/m³ is supported by the findings of this study.” (Scully et. al)

Other Studies on Dust Performance and Morphology – includes studies to understand the performance on the surface and interactions with equipment.

“The particle size distribution of the lunar dust from Apollo 17 sample 77051 has been determined using SEM imaging analysis. The size-distribution data features an approximate Gaussian distribution with a single mode at around 300-nm. The reactivation surface area of highly porous “Swiss-cheese” particles is about 26% higher than a sphere. The morphologies of dust grains have been classified based upon their four types: 1) spherical; 2) angular blocks; 3) glass shards; and 4) irregular (ropey or Swiss-cheese). These data will assist the medical researchers in their studies of the toxicological effects of inhalation of lunar dust by humans.” (Park et al.)

“Apollo 11 DDE, deployed 17 m from LM, proved that rocket exhaust caused dust and debris to contaminate the Passive Seismometer, the first scientific instrument deployed by human hands on a celestial body, leading to its severe overheating and premature failure. By contrast, Apollo 12 hardware had collateral dust splashed on it during deployment 130 m from LM.” (O’Brien)
Design Application

Testing and Mitigation of Dust:
- Crew health
  - Medical supplies – eye wash, allergy medications, etc.
  - 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 (ECLSS)
  - Flow rate
  - Particle size removal – HEPA filtration or similar, etc.
- EVA ops
  - 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
- Lunar equipment testing
  - Temperature sensitivity from dust accumulation
  - Incorrect readings or data collection
- Rover design
  - Wheel traction
  - Fenders
- Stowage
  - Location of suit post-EVA
  - Collected dust and regolith

Other Standards for Consideration
V2 3006 Human-Centered Task Analysis
V2 6033 Eye Irrigation Water Quantity
V2 6051 Water Contamination Control
V2 7039 Volume Accommodations
V2 7080 Particulate Control
V2 7082 Volume Allocation
V2 8001 Volume Allocation
V2 9053 Protective Equipment
V2 9054 Protective Equipment Use
V2 11001 Suited Donning and Doffing

Gene Cernan covered in dust following EVA. Note the presence of dust on suit and other surfaces. Courtesy NASA.
Back-Up
Referenced Standards

[V2 3006] Each human spaceflight program or project shall perform a task analysis to support hardware and operations design.

[Rationale: A detailed task analysis of crew required activities is required to determine appropriate human spacecraft designs and layout along with the appropriate operational activities. This task analysis is utilized by numerous other standards such as net habitable volume, cognitive workload, situational awareness, display design, information management, EVA suit mobility, etc.]

[V2 6033] The system shall provide a minimum of 0.5 kg of immediately available potable water for eye irrigation for particulate events, e.g., dust, foreign objects, and other eye irritations.

[Rationale: Eye irrigation is required for spaceflight, based on experience and data from Shuttle, ISS, and Apollo programs. Eyewash capability for particulate events is expected, especially for lunar missions because of the increased risk of exposure to dust on the lunar surface.]

[V2 6051] 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.

[Rationale: While ensuring the delivery of potable water to crewmembers on orbit is important, contamination from sources within the delivery system or from the environment is also possible.]

[V2 6052] The system shall limit the cabin particulate matter concentration for total dust to <3 mg/m$^3$, and the respirable fraction of the total dust to <2.5 μm in aerodynamic diameter to <1 mg/m$^3$.

[Rationale: These values were derived by applying a factor of 5 to the OSHA limits for nuisance dusts, which is the best analog for the ordinary dust present in spacecraft. They do not apply to reactive dust, e.g., LiOH or extraterrestrial dust. The factor of 5 is applied to adjust from intermittent occupational exposure to continuous spaceflight exposure.]

[V2 6053] 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.

[Rationale: This limit was based on detailed peer-reviewed studies completed by the Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG) and is specific to the conditions relevant to the lunar surface, i.e., this requirement would not necessarily be applicable to other missions. The requirement assumes that the exposure period is episodic and is limited to the time before ECLSS can remove the particles from the internal atmosphere (assumed as 8 hours post-introduction). Although the requirement is being conservatively applied to all inhalable particles (all particles ≤10 μm), it is most applicable to dusts in the respirable range (≤2.5 μm) that can deposit more deeply into the lungs. Studies show that the particle size of lunar dust generally falls within a range of 0.02-5 μm.]
Referenced Standards

[V2 6063] The system shall provide a means to remove or isolate released contaminants and to return the environment to a safe condition.

[Rationale: In the event of a contamination event, contaminants are to be removed, isolated, or reduced from the environment to ensure the crew’s health and ability to continue the mission. In some cases such as a spill, vehicle systems may be unable to remove the contaminant; and the crewmembers will have to perform the cleanup themselves. Cleanup of a contamination includes the control and disposition of the contamination.]

[V2 7039] During physiological countermeasure activities, the volume provided shall accommodate a person, expected body motions, and any necessary equipment.

[Rationale: The operational envelope is the greatest volume required by a crewmember to use an exercise device (not the deployed volume of the device). The volume is necessary to permit the crewmember to conduct the countermeasure activities properly to maintain health and fitness.]

[V2 7043] A medical system shall be provided to the crew to meet the medical requirements of NASA-STD-3001, Volume 1, in accordance with Table 15, Medical Care Capabilities.

[Rationale: NASA-STD-3001, Volume 1, includes definitions of the levels of medical care required to reduce the risk that exploration missions are impacted by crew medical issues and that long-term astronaut health risks are managed within acceptable limits. The levels of care and associated appendices define the health care, crew protection, and maintenance capability required to support the crew as appropriate for the specific mission destination and duration, as well as for the associated vehicular constraints. As mission duration and complexity increase, the capability required to prevent and manage medical contingencies correspondingly increases. Very short-duration missions, even if outside low Earth orbit (LEO) are considered as Level I capability medical requirements. The ability to provide the designated level of care applies to all flight phases, including during pressurized suited operations.]

<table>
<thead>
<tr>
<th>Level of Care</th>
<th>Space Environment</th>
<th>Mission Duration</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>LEO</td>
<td>&lt;8 days</td>
<td>Space Motion Sickness, Basic Life Support, First Aid, Private Audio, Anaphylaxis Response</td>
</tr>
<tr>
<td>II</td>
<td>LEO</td>
<td>&lt;30 days</td>
<td>Level I + Clinical Diagnostics, Ambulatory Care, Private Video, Private Telemedicine</td>
</tr>
<tr>
<td>III</td>
<td>Beyond LEO</td>
<td>&lt;30 days</td>
<td>Level II + Limited Advanced Life Support, Trauma Care, Limited Dental Care</td>
</tr>
<tr>
<td>IV</td>
<td>Lunar</td>
<td>&gt;30 days</td>
<td>Level III + Medical Imaging, Sustainable Advanced Life Support, Limited Surgical, Dental Care</td>
</tr>
<tr>
<td>V</td>
<td>Mars Expedition</td>
<td></td>
<td>Level IV + Autonomous Advanced Life Support and Ambulatory Care, Basic Surgical Care</td>
</tr>
</tbody>
</table>
Referenced Standards

[V2 7080] 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.

[Rationale: Manufacture, assembly, or other operations in a terrestrial or partial-g environment may accumulate residue and debris. This residue may then contaminate the spacecraft during flight or reduced-gravity environments. System development specifications are to ensure that crews can access residue accumulations for removal.]

[V2 7082] The system shall contain surface materials that can be easily cleaned and sanitized using planned cleaning methods.

[Rationale: Program requirements are to be established so that surface materials such as highly textured materials are assessed for this feature.]

[V2 8001] The system shall provide the volume (operational envelope) and interior configuration necessary for the crew to perform all mission tasks, using necessary tools and equipment to meet mission goals and objectives and support human performance and behavioral health.

[Rationale: Adequate internal size, in terms of volume and surface area, are to be provided to ensure crewmembers can safely, efficiently, and effectively perform mission tasks, including work, sleep, eat, egress, ingress, maintenance, housekeeping, and other tasks necessary for a safe and successful mission. It is important to consider all types of volume—pressurized, habitable, and net habitable, in accordance with JSC-63557, Net Habitable Volume Verification Method, when determining the amount of volume that is necessary. Confinement, isolation, and stress that can accompany a space mission tend to increase with duration. This creates a psychological need for additional volume. Privacy becomes more important for crewmembers as mission durations become longer. When evaluating the net habitable volume and interior configuration needs of a system, careful consideration should be given to cultural attitudes with regard to the overall work space.]

[V2 9053] Protective equipment shall be provided to protect the crew from expected hazards.

[Rationale: Analyses are to define anticipated hazards and appropriate protective equipment. Protective equipment might include gloves, respirators, goggles, and pressure suits. The equipment is to fit the full range of crewmembers. This might require adjustable gear or multiple sizes (with consideration of the number of crewmembers that may have to use the equipment at the same time.) Because the gear could be used under emergency conditions, it is to be located so that it is easily accessed and is to be simple to adjust and don.]
Referenced Standards

[V2 9054] Protective equipment shall not interfere with the crew’s ability to conduct the nominal or contingency operations that the crew is expected to perform while employing the protective equipment, including communication among crewmembers and with ground personnel.

[Rationale: Analyses are to be performed of the situations and operations in which protective equipment is to be used. This analysis is to define the task demands and the requirements for protective equipment design. Task performance demands might include visibility, range of motion, dexterity, and ability to communicate.]

[V2 11001] The system shall accommodate efficient and effective donning and doffing of spacesuits for both nominal and contingency operations.

[Rationale: Spacesuit donning and doffing is a non-productive activity. Plus, tedious and difficult tasks are more prone to neglect and human error. Finally, rapid donning can be critical in an emergency. System developers need to consider total system design and human accommodation, including emergency scenarios, assess donning task times, and evaluate features such as unassisted donning.]
References