Risk of Adverse In-Mission Health and Performance Effects and Long-Term Health Effects Due to Celestial Dust Exposure (Dust Risk)
(Revision C.1)

Human System Risk Board (HSRB)

HSRB CR SA-07566
Approved: 2/13/2025

Risk Custodian Team

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Risk Record

- This package:
  - Provides updated evidence
  - Provides updated likelihood x Consequence (LxC) scores assessed against new assumptions and evidence base
  - Considers and clarifies the risk implications from data from dusts collected during Apollo and non-crewed missions

- This information (including incorporated changes based on today's [Feb 8, 2024] discussion) with the HSRB, will be released via change request (CR).

This information was previously reviewed/dispositioned at:

Meeting	Date	Outcome/Direction
SMOCB/ BRESCB	12/11/23	Approved

Contents

1. Risk Title and Statement

- **Risk Title:** Risk of Adverse In-Mission Health and Performance Effects and Long-Term Health Effects Due to Celestial Dust Exposure

- **Risk Statement:** Given the unique properties of lunar and other celestial bodies' dust, there is a possibility that exposure could lead to serious health effects (e.g., respiratory, cardiopulmonary, ocular, or dermal harm) or to crew performance impacts during celestial body missions.

2. Risk History

Item	Date	Outcome/Status
HSRB Risk Presentation	2/13/2025	**Decisional** – CR SA-07566 HSRB DAGtionary Updates and DAG Corrections; CR approved with modifications. Rev C.1
HSRB Risk Presentation	3/7/2024	**Decisional** – CR SA-06806, Rev C approved-out-of-board (Evals unanimous concurs)
HSRB Risk Presentation	2/8/2024	**Informational** – Content reviewed by HSRB. Approval for release in CR.
CMB Risk Presentation	2/9/2022	**Decisional** – CMB concurred on 12/9/21 risk posture and updates
HSRB Risk Presentation	12/9/2021	**Decisional** – CR Approved with Mods; Rev B (DAG update included in this CR)
Risk Evaluated via CR	10/15/2021	CR Evaluation period ended 10/29/21
HSRB Risk Presentation (CR Kickoff)	10/7/2021	**Informational** – Content reviewed by HSRB. Approval for release in CR.
HSRB Risk Presentation (CR Approval)	8/29/2019	**Decisional –** CR Approved with Mods.; Rev A
Risk Evaluated via CR	6/26-8/1/2019	**Decisional** – Content reviewed via CR to update risk
HSRB Risk Presentation (CR Kickoff)	6/20/2019	**Informational** – Content reviewed by HSRB. Approval for release in CR.
HSRB Risk Finalized	1/27/2015	**Decisional** – Risk baselined in BPS system
HSRB Risk Presentation	10/27/2014	**Decisional** – CR 14-008 Approved with Mods. Approved risk baseline.
Risk Evaluated via CR	10/2/2014	**Decisional** – To baseline integrated risk (includes Lunar and other celestial bodies)
HSRB Lunar Standard Presentation	2/26/2014	**Informational** – Described lunar dust standard refinement and a preliminary risk summary of celestial dust exposure based on JSC 66705 process
Risk Evaluated via CR	9/9/2009	**Decisional** – Approved with Mods – with LxC Assessment – Content baseline 10/04/2010.
HSRB Risk Presentation	8/25/2009	**Informational** – Content reviewed by the HSRB. Approval for release via out-of-board CR* (The original risk proposed and approved for baseline was "Risk of Adverse Health Effects of Lunar Dust Exposure")

3. Executive Summary

- Assessments using primary human blood immune cells indicated no evidence for allergenic effects of lunar dust. Although allergenic response to lunar dust appears unlikely, it cannot be definitively ruled out for all design reference missions (DRMs). Further study is necessary to fully assess sensitization potential.

- The Space Mission Directorate (SMD) geology team released a position paper that clarified the mission conditions that would lead to an encounter with hazardous volatiles from samples collected from the permanently shadowed region (PSR) of the Moon. This has no impact on DRM risk posture, it informs sample containment and mission-specific risk decisions.

- The recent successful landing of the Indian Space Agency Rover (Chandrayaan-3) at the lunar south pole has resulted in reports of sulfur in lunar regolith samples, which is consistent with the body of historical evidence.

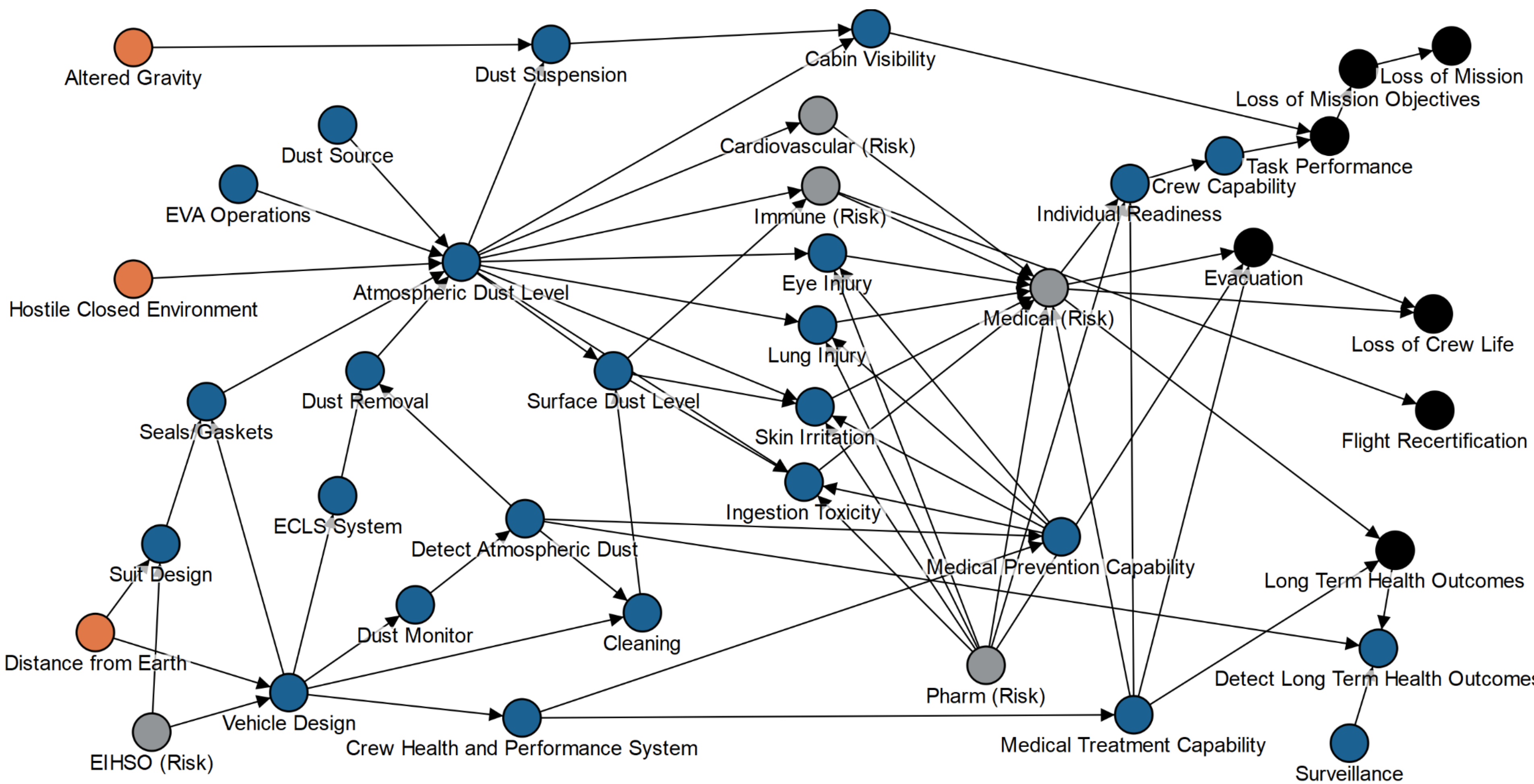
- New evidence includes a recently released manuscript describing the toxicity mechanism of lunar dust, which adds to a broader debate regarding the toxicity mechanism induced by particulate matter. This paper has no direct impact to the LxC for the dust risk.

- Acute exposures to celestial dust may warrant more thorough assessment. Additional research and development in this area is probably justified to better inform operational response and planning to support crew health and performance (CHP).

- Reductions in LxC scores were proposed for several lunar DRMs, resulting in some colors changing from yellow to green. These changes were justified by the risk custodial team based on the negative allergen findings and the new celestial dust monitoring requirement in NASA Standard (Std) 3001.

- Martian DRM was retained as an LxC of 4x4 (Red). The Mars Sample Return (MSR) campaign slated for 2030s will include at least one sample of Martian regolith. This is a unique opportunity to gain insight into the toxicity of Martian dust and to work with the MSR team to address gaps in knowledge.

4. Dust Risk Directed Acyclic Graph



Narrative of Dust Directed Acyclic Graph (DAG)

- This DAG centers around **Atmospheric Dust Levels** that can occur within vehicles after extravehicular activity (**EVA) Operations** on celestial bodies. During **EVA Operations**, **Dust Sources** from the lunar or Martian surface can result in dust being carried into a vehicle or habitat, potentially on space suits. The extent to which this will occur depends on the **Vehicle Design**, the **Suit Design**, and the **Seals and Gasket** designs that are included to prevent dust entry into a vehicle. This is dependent on human systems integration architecture **(EIHSO Risk),** including the crew's ability to operate dust contaminated equipment.
- If dust gets into a vehicle or habitat, the extent of exposure that a crew faces depends on several factors:
  - The level of **Dust Suspension** that occurs in the vehicle atmosphere
  - The **Surface Dust Level** that builds up when dust settles from the atmosphere onto vehicle surfaces: The capability for **Dust Monitoring** that enables crews to **Detect Atmospheric Dust** levels must be included in the environmental control and life support **System** (**ECLSS)** to determine if prompt **Dust Removal** (filtration) and **Cleaning** of surfaces is required.
- Inappropriate levels of **Dust Suspension** in the atmosphere can lead to issues with **Cabin Visibility,** which can affect performance when piloting vehicles, especially when returning to microgravity. Equipment to be used for surface operations must be designed to be maintainable and repairable by crew, in situ. This can also lead to several health challenges that affect **Crew Capability**.
  - Dust exposure can lead to **Eye Injury**, **Lung Injury,** and **Skin Irritation, all of** which can progress to affect the **Medical (Risk)**. Most evidence suggests that the medical issues are likely to be minor during a mission.
  - Dust that gets into food or pharmaceuticals may lead to **Ingestion Toxicity**, especially in the case of Martian dust containing perchlorates.
  - Some evidence exists that the **Cardiovascular (Risk) and Immune (Risk)** may be affected by exposure to celestial dust, but currently, this remains at the speculative level.
- Countermeasures can include the following:
  - **Medical Prevention Capabilities** such as artificial tears, skin coverings, etc.
  - **Medical Treatment Capabilities** including creams and ointments to treat skin irritation and medical eye drops to address eye irritation or injury. Antibiotics may be required if secondary infection develops.
- **Long-Term health Outcomes** may include pneumonoconiosis, hypersensitivity conditions, autoimmune disorders, and cancers, however, the current level of evidence indicates the occurrence of these outcomes will be low. Post-mission and post-career **Surveillance** of these types of conditions can enable us to **Detect Long Term Health Outcomes** and better characterize the magnitude of risk in the long-term health domain.

5. Risk Summary

Risk Title: Risk of Adverse In-Mission Health and Performance Effects and Long-Term Health Effects Due to Celestial Dust Exposure

Risk Custodian Team: T. McCoy, S. Keprta, T. Springer

Risk Statement: Given the unique properties of lunar and other celestial bodies' dust, there is a possibility that exposure could lead to serious health effects (e.g., respiratory, cardiopulmonary, ocular or dermal harm) or to crew performance impacts during celestial body missions.

Primary Hazard: Hostile Closed Environment

Secondary Hazard: Altered Gravity, Distance from Earth

Countermeasures:
Monitoring Airborne dust monitoring in habitable volumes, inflight pulmonary function testing*
Prevention: Health Standard, engineering design /filtration, Personal Protective Equipment (PPE)
Intervention: In-flight pharmaceuticals, nasal irrigation*

*Countermeasures that are not yet operational but are being investigated

Contributing Factors: Celestial body surface, vehicle design, suit design, seals, and gaskets, ECLS system, EVA operations, atmospheric dust, surface dust, cleaning capability.

State of Knowledge: Results from NASA rodent-based research coupled with expert review has determined that for six months of episodic exposure to lunar dust the exposure standard (NASA STD 3001, Volume 2) should be 0.3 mg/m3, which is tailorable based on the duration of mission exposure. This standard is based on inhalation toxicity studies of lunar dust (actual Apollo 14 samples with low crystalline silica content and characterized for heavy metals) and assumes that the exposure period is episodic and limited to the time before ECLSS can remove the particles from the internal atmosphere (assumed as 8 hours after introduction). The recommended standard protects the respiratory system from injury caused by inhaled lunar dust and is set to also be adequately protective of other relevant health endpoints. More lunar dust particles will likely be deposited in the peripheral areas of the lung than inside the lung when exposures occur during the mission in contrast to deposits incurred in Earth gravity, but it is assumed this is offset by equivalent reductions in overall dust loading in microgravity; an assumption that is subject to further scientific research. This standard may be refined, or new standards created for other celestial body dust exposure based on the dust composition and mission profile. Lunar polar ice subsurface regolith may contain volatiles of toxicological concern (e.g., mercury, ammonia, hydrogen sulfide) that are unlikely to be retained in dust on suits, etc., but must be assessed to ensure appropriate containment if samples are being stored in a habitable environment. Weight of evidence suggests allergic reactions are unlikely, although this potential is difficult to rule out entirely.

Summary of LxC Drivers: Likelihood is low for lunar orbit (LO) missions. For lunar orbit + surface (LOS), the likelihood of effects to both long-term health (LTH) and operations (Ops) is higher due to the potential for repeated introduction of dust and longer stays on the planetary surface. The likelihood also increases given the lack of dust monitoring during short- duration missions; a capability that should be included in system design and planning for long-term missions. For Mars Planetary, the likelihood is high due to the lack of proven systems, operational strategies, and standards to protect crews from dust. Martian dust storms and the Martian atmosphere are contributing challenges. Consequence Lunar: Characterized as a significant impact to performance with loss of some mission objectives due to acute effects (watery eyes, upper airway sensitivity, ocular irritation, and potential allergen response). These impacts may be magnified as lunar exposure is extended (>30 days). LTH effects could include unknown return to baseline because health effects from chronic exposure to lunar dust may lead to irreversible compromised pulmonary function and possible damage to organs other than the lung. Lack of monitoring excludes the ability to detect exposures that persist above the NASA 3001 Standard. Lunar volatiles in some samples can pose a health risk if improperly contained.

Risk Disposition Rationale per DRM: Accepted with Monitoring for LOS short DRMs. LOS long **Requires Mitigation** because of the greater potential for exposure to lunar dust and because existing uncertainties dictate a higher risk. Mars Planetary is reflected as **Requires Characterization**—this is based, in part, on uncertainty regarding the characterization of Martian dust and exposure potential. Additionally, the potential absence of a prior analogue mission that demonstrates an adequately controlled and well characterized environment for these longer missions is a driver. This can be mitigated through a demonstrated performance history with dust control (including monitoring) with well-designed lunar missions.

DRM Categories	Mission Type and Duration	LxC Ops	Risk Disposition	LxC LTH	Risk Disposition
Low Earth Orbit	Short (<30 days)	N/A		N/A	
	Long (30 days to 1 yr)	N/A		N/A	
Lunar Orbital	Short (<30 days)	1X2	Accepted	1x2	
	Long (30 days to 1 yr)	1X2	Accepted	1x2	
Lunar Orbital + Surface	Short (<30 days)	2X1	Accepted w Monitoring	2x2	Accepted w/ Monitoring
	Long (30 days -1 yr)	3X3	Requires Mitigation	3x4	Requires Mitigation
Mars	Preparatory (<1 yr.)	N/A		N/A	
	Planetary (730-1224 d.)	4x4	Requires Characterization	4X4	Requires Characterization

6. LxC Quick look

Previous (approved December 2021)

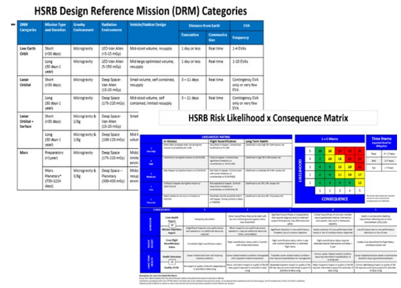
DRM Categories	Mission Type and Duration	LxC Ops	Risk Disposition	LxC LTH	Risk Disposition
Low Earth Orbit	Short (<30 days)	N/A		N/A	
	Long (30 days -1 yr)	N/A		N/A	
Lunar Orbital	Short (<30 days)	1X2	Accepted	1x2	
	Long (30 days -1 yr)	1X2	Accepted	1x2	
Lunar Orbital + Surface	Short (<30 days)	2X2	Accepted	2x3	Requires Mitigation
	Long (30 days -1 yr)	3X3	Requires Mitigation	3x4	Requires Mitigation
Mars	Preparatory (<1 yr.)	N/A		N/A	
	Planetary (730-1224 d.)	4x4	Requires Characterization	4X4	Requires Characterization

Current (approved March 2024)

DRM Categories	Mission Type and Duration	LxC Ops	Risk Disposition	LxC LTH	Risk Disposition
Low Earth Orbit	Short (<30 days)	N/A		N/A	
	Long (30 days -1 yr)	N/A		N/A	
Lunar Orbital	Short (<30 days)	1X2	Accepted	1x2	
	Long (30 days -1 yr)	1X2	Accepted	1x2	
Lunar Orbital + Surface	Short (<30 days)	2X1	Accepted with Monitoring	2x2	Accepted with Monitoring
	Long (30 days -1 yr)	3X3	Requires Mitigation	3x4	Requires Mitigation
Mars	Preparatory (<1 yr.)	N/A		N/A	
	Planetary (730-1224 d.)	4x4	Requires Characterization	4X4	Requires Characterization

Consequence lowered due to negative allergen findings and assumption that lunar dust monitoring will be available.

No proposed LxC change for DRM due to sensitization potential, acute considerations, integrated dust experience during short-duration DRM.



7. Assumptions

All LxC assessments:

- Assume that NASA Standards 3001 have been met
- Countermeasures equivalent to current International Space Station countermeasures are in use
- Based on the HSRB LxC Matrix and the HSRB DRM categories
- Additional assumptions are documented below

DRM Categories	Mission Type and Duration	Assumptions
Low Earth Orbit (LEO)	Short (<30 days)	
	Long (30 d-1 yr.)	
Lunar Orbital	Short (<30 days)	
	Long (30 d-1 yr.)	
Lunar Orbital + Surface	Short (<30 days)	• Volatiles may be present for specific missions to the PSR of the Moon. It is assumed that containment will be commensurate with mission-specific risk. • Acute responses (including performance effects) to dust exposure will be addressed through developed mitigation and prevention strategies.
	Long (30 d-1 yr.)	• Volatiles may be present for specific missions to the PSR of the Moon. It is assumed that containment will be commensurate with mission-specific risk. • Acute responses (including performance effects) to dust exposure will be addressed through developed mitigation and prevention strategies.
Mars	Preparatory (<1 year)	
	Planetary (730-1224 days)	

Current countermeasures in use:

<u>Monitoring:</u>
Airborne dust in habitable volumes, inflight pulmonary function

<u>Prevention:</u>
Health standard, engineering design, dust filtration, PPE, gaskets, ECLSS, EVA operations, cleaning of atmospheric and surface dust

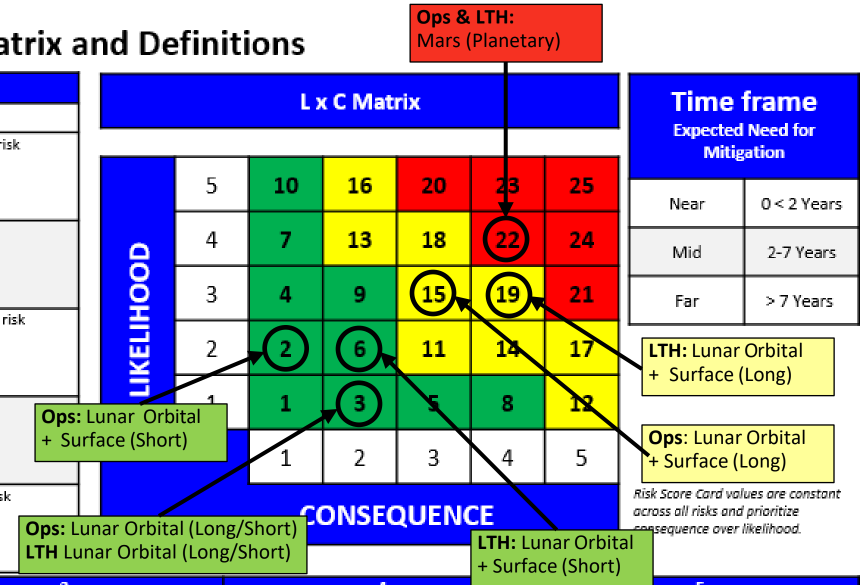
<u>Intervention:</u>
In-flight pharmaceuticals, nasal irrigation*

*Not operational, but included for further evaluation

8. HSRB Risk Likelihood x Consequence Matrix

Human System Risk Board Risk Matrix and Definitions

LIKELIHOOD RATING	In-Mission	Flight Recertification	Long Term Health
5 Very High	More likely to happen than not during the mission or probability (P) >10%	Very likely to happen. Controls are insufficient or P> 10%	Likelihood is very high OR >10% excess risk
4 High	Likelihood is high during the mission or 1%<P≤10%	Likely to happen. Controls have significant limitations or uncertainties or 1%<P≤ 10%	Likelihood is high OR 6-10% excess risk
3 Moderate	May happen during the mission or 0.1%<P≤1%	Not likely to happen. Controls exist with some limitations or uncertainties or 0.1%<P≤1%	Likelihood is moderate OR 3-6% excess risk
2 Low	Unlikely to happen during the mission or .01%<P≤0.1%	Not expected to happen. Controls have minor limitations or uncertainties or 0.01%<P≤0.1%	Likelihood is low OR 1-6% excess risk
1 Very Low	Nearly certain to not occur in-mission or P≤0.01%	Extremely remote possibility that it will happen. Strong controls in place or P≤0.01%	Likelihood is very low OR < 1% excess risk



Time frame Expected Need for Mitigation	
Near	0 < 2 Years
Mid	2-7 Years
Far	> 7 Years

Risk Score Card values are constant across all risks and prioritize consequence over likelihood.

CONSEQUENCES		1	2	3	4	5
IN MISSION	Crew Health Impact	Temporary discomfort	Minor injury/illness that can be dealt with by crew without ground support, minor crew discomfort	Significant injury/illness or incapacitation that requires diagnosis and/or treatment support from ground, may affect personal safety	Critical injury/illness of one crew member requiring extended medical intervention and support, may result in temporary disability	Death or permanently disabling injury/illness affecting one or more crewmember (LOCL/LOC)
	OR					
	Mission Objectives Impact	Insignificant impact to crew performance and operations – no additional resources required	Minor impact to crew performance and operations – requires additional resources (time, consumables)	Significant reduction in crew performance, threatens loss of a mission objective	Severe reduction of crew performance that results in loss of multiple mission objectives	Loss of mission due to crew performance reductions or loss of crew
FLIGHT RECERT	Crew Flight Recertification Status	Immediate flight recertification status	Flight recertification status within 3 months with limited intervention	Flight recertification status within 1 year with nominal intervention or restricted flight status	Flight recertification status requires extended medical intervention and takes > 1 year	Unable to be Recertified for Flight Status, premature career end
LONG TERM HEALTH	Health Outcomes	Career related short term self-resolving medical conditions	Career related medical conditions manageable with outpatient medical treatments	Treatable career related medical condition that requires hospitalization for management	Chronic career related medical condition requiring intermittent hospitalization or nursing care	Career related premature death or permanent disability requiring institutionalization
	OR					
	Quality of Life	No impact on quality of life OR independence in activities of daily living	Minor, short-term impact on quality of life OR rare support required for activities of daily living	Moderate long-term impact on quality of life OR may require some time-limited support for activities of daily living	Major long-term impact on quality of life OR requires intermittent support for activities of daily living	Chronic debilitating impact on quality of life OR requires continuous support for activities of daily living

Assumptions for Long Term Health Risk Matrix:

- *Long Term Health extends from the end of the post mission time period and covers an astronaut's lifetime.*
- *Conditions considered within the LTH Risk Matrix are those that 1) are related to the astronaut career, 2) are beyond those expected as part of natural aging, and 3) include acute, chronic and latent conditions.*
- *Quality of Life is defined as impact on day-to-day physical and mental functional capability and/or lifetime loss of years*

9. Risk Postures

Lunar Orbital (< 30 Days) Operations

1x2	Accepted

- **LxC Drivers for Likelihood:** Assuming that NASA Std 3001 Standards are in place and adequate ECLSS design and operation, only a remote probability exists that crewmembers will experience impacts or performance issues during a mission.
- **LxC Drivers for Consequence:** Impacts would likely be limited to minor eye irritation or temporary throat irritation, therefore, impacts are best characterized as temporary discomfort.
- **Rationale for Risk Disposition:** A lunar orbital scenario inherently involves a low risk of developing effects from exposure to lunar dust due to the lack of a regular source that introduces dust into the vehicle. Visiting vehicles from the lunar surface may bring lunar dust, but these impacts should be isolated and manageable with system filtration.
- **DRM Specific Assumptions:**
- **DRM Specific Evidence/Level of Evidence:** 1 (Strong)

Lunar Orbital (< 30 Days) Long-Term Health

1x2	Accepted

- **LxC Drivers for Likelihood:** A remote probability exists that crewmembers will experience long-term health consequences (e.g., fibrosis, pulmonary impairment).
- **LxC Drivers for Consequence:** Impacts would likely be limited to minor eye irritation or temporary throat irritation, therefore, impacts are best characterized as temporary discomfort. The availability of lunar dust monitoring would be helpful in ruling out lunar dust if crew experience non-attributable adverse health outcomes after a mission.
- **Rationale for Risk Disposition:** A lunar orbital scenario inherently involves a low risk of developing effects from exposure to lunar dust due to the lack of a regular source that introduces dust into the vehicle. Visiting vehicles from the lunar surface may bring lunar dust, but these impacts should be isolated and manageable with system filtration.
- **DRM Specific Assumptions:** NASA Std 3001 Standards are in place and ECLSS design and operation are adequate
- **DRM Specific Evidence/Level of Evidence:** 1 (Strong)

Lunar Orbital (30 d – 1 yr) Operations

1x2	Accepted

- **LxC Drivers for Likelihood:** A remote probability exists that crewmembers will experience health impacts or performance issues during a mission.
- **LxC Drivers for Consequence:** Impacts would likely be limited to minor eye irritation or temporary

throat irritation, therefore, impacts are best characterized as temporary discomfort. More significant health consequences are not expected to develop, given the limited potential for introducing dust into the vehicle and our understanding of lunar dust toxicity from ground research.

- **Rationale for Risk Disposition:** A lunar orbital scenario inherently involves a low risk of developing effects from exposure to lunar dust, due to the lack of a regular source that introduces dust into the vehicle. Visiting vehicles from the lunar surface may bring lunar dust, but these impacts should be isolated and manageable with system filtration.
- **DRM Specific Assumptions:** NASA Std 3001 Standards are in place and ECLSS design and operation are adequate
- **DRM Specific Evidence/Level of Evidence:** 2 (Moderate)

Lunar Orbital (30 d – 1 yr) Long Term Health

1x2	Accepted

- **LxC Drivers for Likelihood:** A remote probability exists that crewmembers will experience health impacts or performance issues during a mission.
- **LxC Drivers for Consequence:** Impacts would likely be limited to minor eye irritation or temporary throat irritation, therefore, impacts are best characterized as temporary discomfort. More significant health consequences are not expected to develop, given the limited potential for introducing dust into the vehicle and our understanding of lunar dust toxicity from ground research.
- **Rationale for Risk Disposition:** A lunar orbital scenario inherently involves a low risk of developing effects from exposure to lunar dust due to the lack of a regular source that introduces dust into the vehicle. Visiting vehicles from the lunar surface may bring lunar dust, but these impacts should be isolated and manageable with system filtration.
- **DRM Specific Assumptions:** NASA Std 3001 Standards are in place and ECLSS design and operation are adequate
- **DRM Specific Evidence/Level of Evidence:** 2 (Moderate)

Lunar Orbital + Surface(< 30 Days) Operations

2x1	Accepted with Monitoring

- **LxC Drivers for Likelihood:** A **low probability** exists that crewmembers will experience health impacts or performance issues during a mission.
- **LxC Drivers for Consequence:** Characterized as a **minor impact** to performance or mission objectives due to brief and resolvable effects (watery eyes, upper airway sensitivity, ocular irritation).
- **Rationale for Risk Disposition:** Based on Apollo history, short-term exposure to lunar dust could result in minor eye and/or throat irritation and some performance challenges during a mission. However, these did not rise to a more significant consequence in Apollo, and they varied among crew.
- **DRM Specific Assumptions:** NASA Std 3001 Standards are in place and ECLSS design and operation are adequate

- **DRM Specific Evidence/Level of Evidence:** 1 (Strong)

Lunar Orbital + Surface (< 30 Days)
Long-Term Health

2x2	Accepted with Monitoring

- **LxC Drivers for Likelihood: Low probability** (estimated at 1-5%).
- **LxC Drivers for Consequence:** Long-term health consequences are not expected after short-duration missions.
- **Rationale for Risk Disposition:** Based on Apollo history and on focused animal research, long-term negative health outcomes (e.g., pulmonary impairment, fibrosis) are not expected to be associated with these short-term missions.
- **DRM Specific Assumptions:** Assuming that NASA Std 3001 Standards are in place and ECLSS design and operations are adequate.
- **DRM Specific Evidence/Level of Evidence:** 1 (Strong)

Lunar Orbital + Surface (< 30 d – 1 yr)
Operations

3x3	Requires Mitigation

- **LxC Drivers for Likelihood:** A **moderate probability** exists that crewmembers will experience health impacts or performance issues during a mission.
- **LxC Drivers for Consequence:** Characterized as a **significant impact** to performance and loss of some mission objectives due to acute effects (watery eyes, upper airway sensitivity, ocular irritation, and limited potential for allergen response due to sensitization). These impacts may increase as exposure to lunar dust is extended (>30 days). Certain lunar volatiles (present in specific samples) may pose a risk to the health of the crew if improperly contained.
- **Rationale for Risk Disposition:** Longer missions introduce a greater chance of anomalies or excessive lunar dust events. Observations of system performance during short-term lunar mission will inform this LxC.
- **DRM Specific Assumptions:** Assuming that NASA Std 3001 Standards are in place and ECLSS design and operations are adequate
- **DRM Specific Evidence/Level of Evidence:** 2 (Moderate)

Lunar Orbital + Surface (< 30 d – 1 yr)
Long-Term Health

3x4	Requires Mitigation

- **LxC Drivers for Likelihood:** A **low-moderate probability** exists that crewmembers will experience long-term health effects (estimated at 5–10%).

- **LxC Drivers for Consequence:** This duration is significantly beyond Apollo experience, and a potential for critical career-related medical conditions exists. Certain lunar volatiles (present in specific samples) may pose a chronic risk to the health of crewmembers if improperly contained.
- **Rationale for Risk Disposition:** The risk of long-term health outcomes (e.g., pulmonary impairment, fibrosis) are somewhat increased due to the longer duration of these missions. Although unlikely, allergen response cannot be definitely ruled out at this time. Observations of system performance during short-term lunar mission will inform this LxC.
- **DRM Specific Assumptions:** NASA Std 3001 Standards are in place and ECLSS design and operations are adequate
- **DRM Specific Evidence/Level of Evidence:** 2 (Moderate)

Mars Planetary (730-1224 d) Operations

4x4	Requires Characterization

- **LxC Drivers for Likelihood:** The likelihood is driven by the uncertainty surrounding the health risk from exposure to Martian dust given that Martian dust has not been fully characterized, and the fact that this risk level will likely be reduced with successful long-term habitation and dust management on the lunar surface.
- **LxC Drivers for Consequence:** This consequence is most likely overstated because it is driven by uncertainty surrounding the toxicity of Martian dust and a lack of firm understanding of what types of crew activities might be required during a Martian mission (e.g., In-situ resource utilization [ISRU] of Martian dust). The absence of significant issues during a prior long-term lunar mission would likely lower this rating.
- **Rationale for Risk Disposition:** Martian dust has similarities to lunar dust in terms of minerology, and thus, NASA's understanding of lunar dust (both through existing animal research and in upcoming long-term lunar missions) lay the framework for acceptance of risk of health effects from exposure to Martian dust. The chemical structure (e.g., perchlorates) of Martian dust is somewhat characterized, and is very different from lunar dust. A full toxicological characterization of Martian dust has not been conducted, although initial assessment of select chemical constituents (perchlorate, manganese, chromium) suggest that this risk can be managed. Risk assessment depends on ISRU plans and other clarifications.
- **DRM Specific Assumptions:**
- **DRM Specific Evidence/Level of Evidence:** 3 (Weak)

Mars Planetary (730-1224 d) Long-Term Health

4x4	Requires Characterization

- **LxC Drivers for Likelihood:** The likelihood is driven by the uncertainty surrounding the health risk from exposure to Martian dust given that Martian dust has not been fully characterized, and the fact that the risk level will likely be reduced with successful long-term habitation and dust management on the lunar surface.

- **LxC Drivers for Consequence:** This consequence is most likely over-stated because it is driven by uncertainty surrounding the toxicity of Martian dust and the lack of a firm understanding of what types of crew activities are required during a Martian mission (e.g., ISRU of Martian dust). The absence of any significant long-term health observations during a prior long-term lunar mission would likely lower this rating.
- **Rationale for Risk Disposition:** Martian dust has similarities to lunar dust in terms of minerology, and thus, NASA's understanding of lunar dust (both through existing animal research and in upcoming long-term lunar missions) lay the framework for acceptance of the risk of health effects from exposure to Martian dust. The chemical structure (e.g., perchlorates) of Martian dust is somewhat characterized, and is very different from lunar dust. A full toxicological characterization of Martian dust has not been conducted, although initial assessment of select chemical constituents (perchlorate, manganese, chromium) suggest that this risk can be managed. Risk assessment depends on ISRU plans and other clarifications.
- **DRM Specific Assumptions:**
- **DRM Specific Evidence/Level of Evidence:** 3 (Weak)

10. Overall Assessment of the Evidence

Lunar:
The overall body of LTH and Ops evidence supporting short-term (i.e., < 30 days) lunar orbital and surface missions for LxC is **strong**. These missions are generally similar to the Apollo experience, conditions, and mission durations.

The body of evidence for longer duration (i.e., 30 days–1 year) is **moderate.** Although Apollo missions did not extend to these durations, some reports documented diminishment of (acute) crew health outcomes during the Apollo era. The Lunar Airborne Dust Toxicity Advisory Group (LADTAG) rodent studies clearly indicate an increased risk of adverse pulmonary outcomes with longer-duration exposure to lunar dust (which is mitigated by applying correspondingly more stringent limits of exposure to lunar dust). Lunar dust has very limited allergenic potential, as evidenced by a recent NASA study of Apollo 16 dust. However, it can be difficult to rule out the possibility of sensitization during long-term missions, therefore, it may be pragmatic to establish operational solutions and countermeasures that to address an individual spectrum of responses to dust inhalation.

Martian:
The body of evidence for Martian planetary missions is **weak**. Although Martian dust and regolith likely has many similar properties as lunar dust, some key chemical distinctions are worth noting (e.g., perchlorate). This evidence rating is driven by the uncertainty around 3 concerns: (1) the lack of specific testing of Martian dust toxicity; (2) the broader exposure routes affecting crewmembers during a Martian mission relative to a lunar mission (e.g., due to ISRU exposures such as recovery of Martian water); and (3) the current lack of well characterized and successful lunar missions of this duration that can inform capability to handle Martian dust (which may be even more challenging given global dust storms, etc.). The MSR campaign scheduled for the

early 2030s offers potential to address knowledge gaps, complement lunar rover data, and inform simulant development.

11. State of Knowledge
New Evidence

Background: Lunar Dust and Immunological and Allergenic Concerns

Post-flight account of crew surgeon who removed suites from capsule over several Apollo missions.

"Exposure to lunar dust from the suits caused a reaction that worsened with each of the3 sampling periods. The first exposure caused a stuffy nose and water eyes. Lab results showed about 5% eosinophilias and a couple basophilia. On the second exposure, there were more symptoms and eosinophilias went up to 9%. On the third exposure, it was impossible to stay inside the spacecraft long enough to get a sample due to watery eyes. In order to get the sample, it was necessary to get out, take a deep breath, then return. Again, there was 9% eosinophilia and 5% basophilia. Others performed the same function after the return of other missions and had no reaction."

Key Points:

- Exposures like this are difficult to attribute definitively to a specific cause.
- There is no anticipated biological basis for lunar dust to elicit an allergenic response (e.g., protein antigens).
- An immune gap in knowledge was retained for this risk, given the surrounding uncertainty.
- A recently completed Human Research Program (HRP)-funded study was conducted (Immune Lab Team) to attempt to inform this gap.
  - Apollo 16 dust was obtained (Highland regolith), which is the most "Artemis-relevant" Apollo material
  - Desire HSRB feedback on these study findings and implication for the LxC and remaining gaps.

Can Lunar Dust Act as an Allergen?

Colorado, A. A., Gutierrez, C. L., Nelman-Gonzalez, M., Marshall, G. D., Mccoy, J. T., & Crucian, B. E. (2025). Hazards of lunar surface exploration: determining the immunogenicity/allergenicity of lunar dust. *Frontiers in immunology*, *16*, 1539163. https://doi.org/10.3389/fimmu.2025.1539163

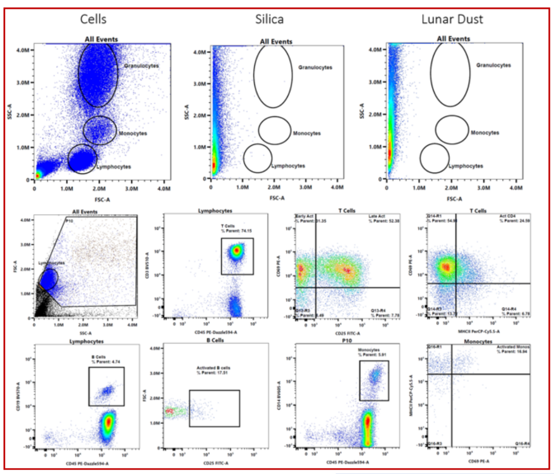
Aims: This HRP-funded study investigated if lunar dust (LD) (actual Apollo 16 lunar dust was obtained and studied) exposure elicits anIgE mediated allergic response either to the LD itself or concomitant antigen exposure during spaceflight.

Summary of methods: Healthy donor blood immune cells were co-cultured with cellular mitogens, common recall antigens (Der p1), fine ground silica quartz, or LD, to study whether LD exposure could alter the generation of selective immune responses associated with clinical allergic reactions. Measured outputs include supernatant-derived IgE, leukotriene, histamine, and selected cytokines levels. Cellular activation was monitored by assessing activation markers via flow cytometry. EM/x-ray analysis was used to determine cellular interactions with dust particles.

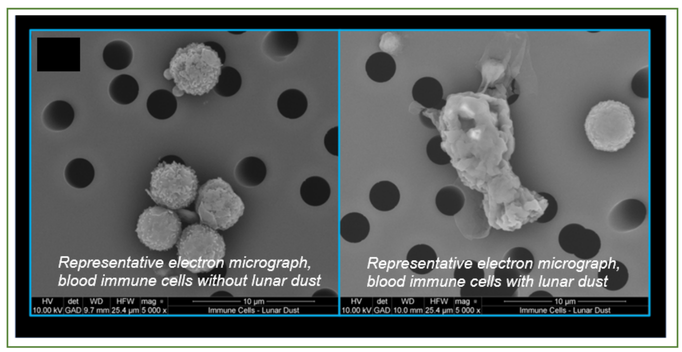
Conclusions: In short, assessments in primary human subject blood immune cells indicated no evidence for cellular responsiveness, nor 'allergy' to LD. Possible caveats include the limited number of subjects used, the wide range of atopy seen in generally healthy individuals (the subjects were not known to be atopic), a lack of previous sensitization (we do not believe any of the subjects had visited the lunar surface), or the possible use of antihistamines.

Assessments using purified 'allergic' cell lines, did yield some unique but mild responsiveness to LD. At least for monitoring activation for the Eosinophil cell line, responsiveness was observed to BOTH LD and silica. For leukotriene and histamine, responses were seen that seem to be LD specific. The Eo responsiveness to silica could indicate a manifestation of some sort of particulate response, however the Lt and histamine responses were more specific.

Can Lunar Dust be an 'Allergen'? Representative data.

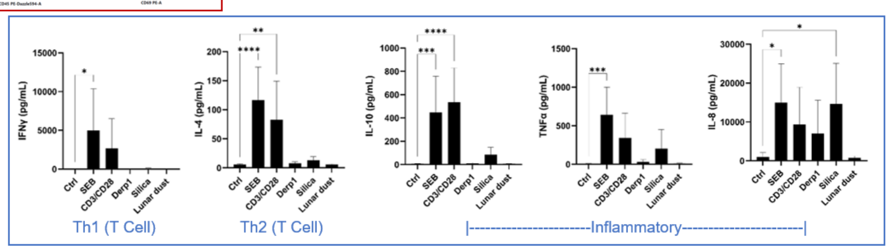


Cytometry evaluation strategy for whole blood cells with lunar dust



Immune cell co-cultured with lunar dust contains a detectable high energy particle when imaged with a back scatter detector allowing for higher energy particles to be detected.

Supernatant cytokine concentration (pg/mL) in whole blood cultures after 48 hour stimulation



Images: Colorado et al. (2025)Front Immunol © 2025 the authors.

Monitoring Development of Lunar Dust 'Reactivity' in Artemis Astronauts

The risk custodial team believes that the findings of Colorado et al. (2025) suggest that lunar dust is not likely to illicit allergenic response during short-term missions. However, a gap remains in the assessment of lunar dust "allergenic sensitization" potential (i.e., as occurs by repeated exposures) that is worth further assessment and possible mitigation. Comments are specifically being requested from the HSRB on this approach.

The team will consider options for how this potential might be assessed. One example approach is to augment the Standard Measures Studies that will be conducted on future Artemis crewmembers.

- Current Standard Measures Cellular Profile includes assessment of:
  - Complete blood count and eosinophils and basophils counts
  - Basic leukocyte subsets
  - Generalized (T/innate) immunocyte function (to polyclonal stimuli)
  - Latent virus reactivation (generalized biomarker of immune compromise)

- Immune system reactivity (either induced and sensitized, or suppressed and compromised) to any specific antigen is *not* included in the standard measures study (specific recall antigens, allergens, lunar dust, virus, and fungi, etc.)

- The lunar dust allergen ground study (Colorado et al., 2025) could only assess 'existing' sensitivity to lunar dust. It could not assess 'inducible' sensitivity (i.e., as occurs by repeated exposures). By nature of the missions, Artemis crews represent a unique opportunity to assess 'induced' sensitivity via a continued (weeks to months) operational exposure to actual lunar dust.

Risk custodian teams for the Lunar Dust Risk and the Immune Risk propose adding monitoring of *immune reactivity to lunar dust* to the current standard measures cellular profile. Currently, 6.0 ml of blood is collected in a blood tube containing acid citrate dextrose for this cellular profile assessment. The team does not anticipate a need for an additional sample. The proposal simply adds one additional cell culture (lunar dust) to the current standard measures cell culture array (generalized mitogenic stimuli). Measured outputs for the lunar dust component will include surface activation antigens, leukotrienes, histamine, etc.

***Immune Standard Measures* - Assay Categories**

Peripheral leukocyte distribution: Bulk leukocyte and lymphocyte subsets, T cell subsets, activated T cells, etc.
Constitutive cytokine profiles*: Plasma - 48 cytokine array; spans Th1/Th2/Th17, Inflammatory, chemokines, growth factors
T cell function/early blastogenesis: Expression of T cell activation antigens following +24hr mitogenic stimulation
Mitogen stimualted cytokine profiles: (13 plex) +48hr culture in presence of antibodies to CD3/CD28 (T cells); PMA+ionomycin (all leukocytes); LPS (innate cells) **
Latent Herpesvirus reactivation: Quanitative PCR DNA analysis of saliva for EBV, VZV, HSV1

**Plasma cytokine levels may be obtained via the new Biochemical Profile activity onboard*

***Propose to add cell culture assessing reactivity to LD. Can be ran in parallel to these existing cell cultures that assess 'general' immune function. No additional astronaut samples required.*

New Evidence: NASA Standard 3001 Vol. 2: Dust Monitoring

- A new Dust Monitoring and Alerting Standard was added into Rev. C as no current lunar/planetary dust monitoring standard existed in NASA Standard 3001 Vol 2. This standard will allow for tracing and will improve defensibility.

- 6.2.7.5 Celestial Dust Monitoring and Alerting

  [V2 6153] The vehicle shall monitor celestial dust and alert the crew locally and remotely when they are approaching defined limits.

  [Rationale: Celestial dust includes, but is not limited to, lunar, Martian and other extraterrestrial bodies. In-flight monitoring of habitable environments is required to characterize concentrations of celestial dust which enables any necessary crew action to maintain health and safety, tracking of average exposure, while also informing necessary treatment options after the mission, and providing a record of crew exposures. Lunar dust monitoring frequency and particle size fraction is dependent on mission characteristics and whether crew health concerns are based on chronic or acute exposure considerations as noted in [V2 6053] Lunar Dust Contamination. There may be other specific mission scenarios (e.g., surface launch vehicle docking to orbital vehicle) where dust monitoring may be required.]

Lunar Dust Monitoring: Encouraging Signs

Progress	Impact on Risk
❖ Both HLS providers have expressed intent to provide lunar dust monitoring ❖ HLS CrewCo Monitoring Trade Study (FY24) • Informs GFE/Contractor Furnished options ❖ ECLSS-SCLT Roadmaps detail both and options for a monitoring device. ❖ Development and acceptance of NASA 3001 Vol 2 Standard was a big step forward.	❖ Prior LxC (2021) assumed lack of lunar dust monitoring. ❖ Given broader community acceptance, the "C" of LxC was reduced for several relevant DRMs, reflecting the reduced potential for more health-significant chronic exposures to persist.

Human Landing System Commercial Orbital Transportation Services Dust Monitor Trade Study

Dust Monitors:

- GRIMM 11-D
- GRIMM EDM-264
- Kanomax Dust Monitor 3443
- Kanomax Piezobalance 3521
- Lighthouse 3016IAQ
- TSI DustTrak DRX 8534

Recommended Forward Work: Acute Effects Risk Communication and Approach

- ❖ Acute exposures has been an understood gap with celestial dust risk. Exposure limits are based on time weighted averages (e.g., 7, 30 or 180 days). Lack of clear basis for shorter-term limits on peak dust exposures.

- ❖ The focus on averages is an implementation and risk communication challenge (Message received is that there are NO acute health effects associated with celestial dust, which is inaccurate). Acute concerns are not necessarily reflected in our LxC, but represented valid and practical areas of emphasis to ensure both crew health and performance.

- ❖ As is true for most dust, acute effects (e.g., eye or throat irritation, congestion) can be driven by short-term exposures (e.g., household dust in attic example). Having crew experience these effects may have operational impacts and may raise questions about the adequacy of long-term health protection.

- ❖ These practical realities suggest that NASA consider developing supplemental guidance, countermeasures, and/or requirements to improve our approach with celestial dust.

Examples could include:

- Requiring crew wear dust masks and/or goggles when dusty conditions are expected in mission (e.g., ISS visiting vehicle experience).
- Benchmarking with short-term limits from other mineral dusts used to protect workers on Earth.
- Application of long-term averages as "peak" limits to simplify implementation in decision making.
- Deployment of key medications/responses to mitigate physiological responses to any dusty environment (e.g, nasal irrigation, steroidal sprays).

State of Knowledge: (New Evidence for Awareness)

2023 Dust Mechanisms Paper

Lam, C. W., Castranova, V., Driscoll, K., Warheit, D., Ryder, V., Zhang, Y., Zeidler-Erdely, P., Hunter, R., Scully, R., Wallace, W., James, J., Crucian, B., Nelman, M., McCluskey, R., Gardner, D., Renne, R., & McClellan, R. (2023). A review of pulmonary neutrophilia and insights into the key role of neutrophils in particle-induced pathogenesis in the lung from animal studies of lunar dusts and other poorly soluble dust particles. *Critical reviews in toxicology*, *53*(8), 441–479. https://doi.org/10.1080/10408444.2023.2258925


CRITICAL REVIEWS IN TOXICOLOGY

Taylor & Francis

REVIEW ARTICLE

OPEN ACCESS

A review of pulmonary neutrophilia and insights into the key role of neutrophils in particle-induced pathogenesis in the lung from animal studies of lunar dusts and other poorly soluble dust particles

Chiu-wing Lam, Vincent Castranova, Kevin Driscoll, David Warheit, Valerie Ryder, Ye Zhang, Patti Zeidler-Erdely, Robert Hunter, Robert Scully, William Wallace, John James, Brian Crucian, Mayra Nelman, Richard McCluskey, Donald Gardner, Roger Renne and Roger McClellan

ABSTRACT

ARTICLE HISTORY

KEYWORDS

- ❖ Lam *et al.* 2023 paper leverages NASA lunar dust findings to propose new pulmonary toxicity mechanism for a class of poorly soluble mineral dusts.

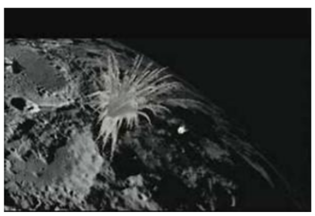
- ❖ Focus placed on the role of oxidants from alveolar neutrophils, rather than particle surface reactive oxygen species (psROS). Citing evidence from Apollo 14 rat exposures from LADTAG (where 14 fold increases in psROS had no toxicity correlations)

- ❖ This mechanism theory doesn't specifically reduce uncertainty in this approach or affect LxC.

- ❖ While not definitive, this adds to a wealth of other research efforts in the scientific literature debating general particulate toxicity and mechanism of action.

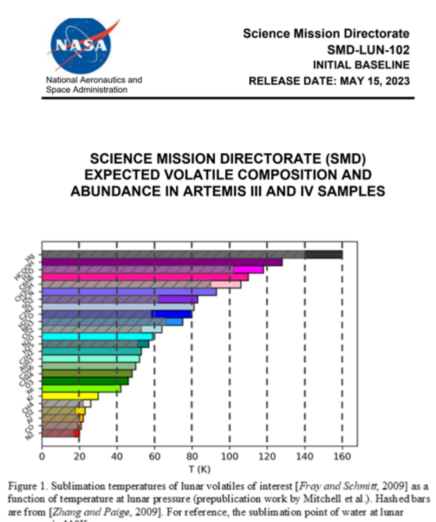
State of Knowledge: Potential for Polar Volatiles of Toxicological Concern

2009 NASA Lunar Crater Observation and Sensing Satellite (LCROSS), and LAMP spectrograph on Lunar Reconnaissance Orbiter (LRO)



- Lunar observations have provided credible evidence that permanently shaded regions/subsurface of the lunar poles may serve as cold traps for volatiles (Permanently Shadowed Regions, PSR), including those with potential health concern (e.g., ammonia, mercury, hydrogen sulfide)
- The exact source for these volatiles is debated, and may include endogenous lunar geological sources or contributions from solar wind.
- Given impact studies, estimates of concentration are very rough and can vary by several orders of magnitude. **VIPER study on lunar surface will provide more data on volatiles to inform risk (~2025)**
- Not viewed as a nominal concern for retention on surface lunar dust particles on suits, tools due to their volatility and effect of vacuum.
- The main concern is that the polar ice/subsurface regolith samples will likely be stored in the habitable volume. **Toxicological awareness and proper containment needs to be maintained in order to ensure crew protection, while minimizing overconservatism.**
- **NASA has made progress in characterizing this risk, and is informing design for sample containers, mapping volatiles.**

SMD/Artemis Internal Science Team Clarification



National Aeronautics and Space Administration

Science Mission Directorate
SMD-LUN-102
INITIAL BASELINE
RELEASE DATE: MAY 15, 2023

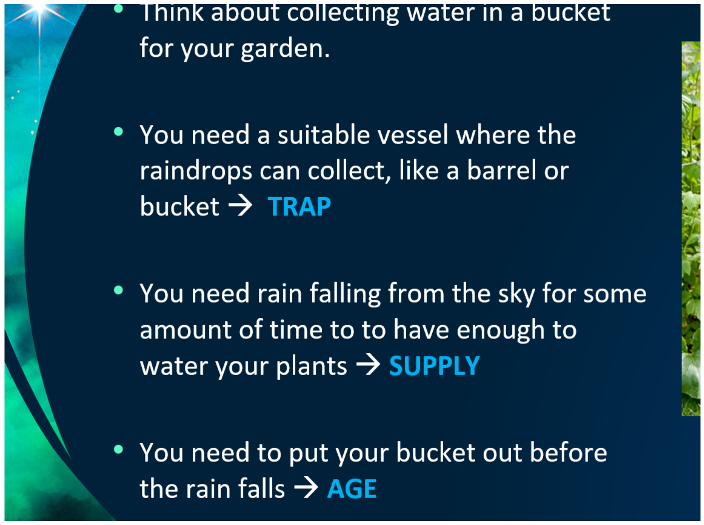
SCIENCE MISSION DIRECTORATE (SMD)
EXPECTED VOLATILE COMPOSITION AND
ABUNDANCE IN ARTEMIS III AND IV SAMPLES

Figure 1. Sublimation temperatures of lunar volatiles of interest [*Fray and Schmitt*, 2009] as a function of temperature at lunar pressure (prepublication work by Mitchell et al.). Hashed bars are from [*Zhang and Paige*, 2009]. For reference, the sublimation point of water at lunar pressures is 110K.

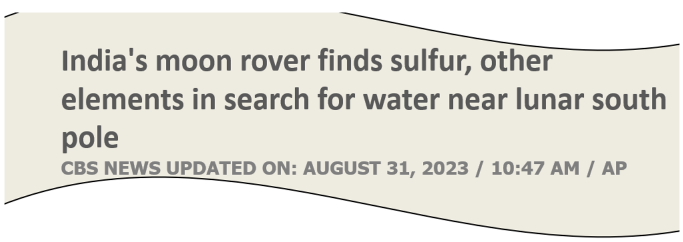
- 5/11/23 assessment by AIST geologists concluded that volatiles of health concern are predicable and will not be encountered during Artemis III and Artemis IV).
- While small PSRs will be explored in a limited extent in these missions, the temperatures/depths/age of the PSR is not conducive to toxic volatile liberation.
- Ultimately, this informs mission-specific risk planning, but doesn't directly affect lunar surface DRMs for the Celestial Dust Risk (i.e, DRM is not built around site or mission science)

"Samples collected in Artemis III and IV are most likely to contain volatile compounds in similar composition and abundance as Apollo samples"

Where will we find lunar volatiles?



Indian Space Agency: Chandrayaan-3 Rover Sulfur Findings


India's moon rover finds sulfur, other elements in search for water near lunar south pole

CBS NEWS UPDATED ON: AUGUST 31, 2023 / 10:47 AM / AP

https://www.cbsnews.com/news/india-moon-rover-sulfur-hunt-for-water-lunar-south-pole/

Lunar Dust and The Voices Of Apollo: Taken from Apollo Medical Operations Project (NASA/TM-2007-214755)

"It smelled like gunpowder, however, you would get desensitized to it"

"There was dust in the mucous membranes of one crewmember that caused stuffiness and a changed voice, but it didn't seem like dust produced an inherent problem"

"We had bigger problems with fiberglass insulation."

"There will obviously be individual variation in the response and we may have to do susceptibility testing before flight."

"Nothing significant, did get some in eyes but more of a nuisance"

"Although it doesn't seem to have had an effect on the crewmembers, we had very limited exposure. Chronic exposure is very different than short-term exposure"

"There are reasons why you don't want lunar dust in your equipment or anywhere else. Consider it from an engineering context, rather than the impact on humans. Take the angle of prevention"

"As far as prolonged exposure to lunar dust, experimentation on Earth will not resemble the in situ properties of lunar dust, so we have to be careful about the conclusions we draw."

"Studies are being conducted on silicosis and this is important work."

Example Sulfur-Containing Minerals in Lunar Samples

- Troilite- FeS
- Chalcopyrite- $CuFeS_2$
- Cubanite- $CuFe_2S_3$
- Bornite- Cu_3FeS_4

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USES OF LUNAR SULFUR

D. Vaniman, D. Pettit*, and G. Heiken

*EES-1 (*M-9)*
Los Alamos National Laboratory
Los Alamos NM 87545

Sulfur and sulfur compounds have a wide range of applications for their fluid, electrical, chemical, and biochemical properties. Although known abundances on the Moon are limited (~0.1% in mare soils), sulfur is relatively extractable by heating. Coproduction of sulfur during oxygen extraction from ilmenite-rich mare soils could yield sulfur in masses up to 10% of the mass of oxygen produced. Sulfur deserves serious consideration as a lunar resource.

INTRODUCTION

Volatile constituents such as molecular oxygen, nitrogen, water, and hydrocarbons are rare on the Moon. The absence of such molecules is one of the problems that confronts prolonged lunar exploration or permanent lunar bases. The lightweight compounds of the elements from hydrogen to oxygen are vital for life, and many of these elements play important roles as fuels, solvents, and industrial chemicals in processes that have become the necessities of industrialized life on Earth. The scarcity of these elements on the Moon thus raises two barriers against easy expansion into space: one against the simple need to stay alive and the other against easy transplantation of Earthbound industrial processes.

With imagination this assessment need not be so bleak. Living in space will require adaptation, but it also opens opportunities to reassess the ways in which we live and use available resources. Sulfur on the Moon may well prove a satisfactory replacement for lighter volatile elements and their compounds in some applications. It may even open new possibilities and uses that surpass a mere duplication of what is already done on Earth.

Our present knowledge of lunar samples suggests that the best place to collect sulfur on the Moon is from mare soils and rocks. Although sulfur is not so abundant that it is available without effort, it does rank eleventh in weight abundance among the elements in average lunar mare rocks. *Gibson and Moore* (1974) found that the high-Ti mare basalts, in particular, have high sulfur contents, in the range of 0.16% to 0.27% by weight. These authors also make the important point that lunar basalts actually have more sulfur than terrestrial basalts, which seldom have more than 0.15%.

Although terrestrial basalts are relatively low in dispersed sulfur content, this sulfur is extracted and concentrated by circulation of heated water. This process results in the remarkable sulfur-rich environments at midocean spreading ridges, where base-metal sulfides are deposited in great abundance and "unearthly" sulfur-metabolizing organisms proliferate. Clearly, we cannot expect heated water to have concentrated sulfur on the Moon. The relatively high sulfur content of lunar mare basalt 12036, however, led *Gibson et al.* (1977) to speculate on the possibility of Fe-FeS liquid segregation and accumulation in some mare magmas. Discovery of sulfur-rich ore bodies on the Moon would be a major find that could accelerate exploitation immensely, but until their existence is actually proven, it would be unwise to plan on their use.

Another possible means for natural concentration of lunar sulfur may be vapor transport and deposition; the abundance of sulfur in volatile coatings on lunar pyroclastic glass droplets strongly suggests that sulfur was involved as a propellant gas in fire-fountain types of eruptions (*Butler and Meyer*, 1976). However, the analyses of volatile coatings on glass droplets suggest that significant amounts of sulfur are lost rather than trapped on droplet surfaces as a result of pyroclastic eruption. For example, the sulfur contents of the famous pyroclastic "orange glass" deposit of Shorty crater at Apollo 17 contains only 0.06–0.08% sulfur (*Gibson and Moore*, 1974), whereas comparable chilled Apollo 17 lavas retain more than 0.16% sulfur. Unless geologic traps for volatile sulfur are found on the Moon (perhaps in vesicle pipes or lava tubes?), there is reason to believe that lunar volcanic gases have acted more effectively in the dispersal of sulfur than in its concentration. The formation of soil on top of sulfur-rich lava flows also results in decreased sulfur content, through the combined processes of sulfur volatilization by small meteoritic impacts and of dilution by addition of sulfur-poor highland materials (*Gibson and Moore*, 1973, 1974). For practical purposes, the ranking of sulfur contents presently known in lunar samples is about as shown in Table 1.

TABLE 1. Sulfur in lunar samples.

Rock or Soil Type	Sulfur Content (wt%)
High-Ti mare basalts (A-17)	0.16-0.27 (avg 0.21)
Low-Ti mare basalts (A-12)	0.06-0.15 (avg 0.11)
High-Ti mare soils (A-17)	0.06-0.13 (avg 0.10)
Low-Ti mare soils (A-15)	0.05-0.06 (avg 0.05)
Highland rocks (A-16)	0.01-0.14 (avg 0.07)
Highland soils (A-16)	0.03-0.09 (avg 0.06)

Data from *Gibson and Moore* (1973, 1974), *Gibson et al.* (1977), *Kerridge et al.* (1975), and *LSPET* (1972). Note that the ranges and averages cited are for specific Apollo sites (12, 15, 16, and 17); the data include possible analytical differences between laboratories.

Although the richest known sources of sulfur are the high-Ti mare basalts, extraction of this sulfur would require energy-intensive crushing of hard rock. Most of the sulfur in the basalts occurs as sulfide in the mineral troilite (FeS). The easiest source of sulfur is high-Ti mare soils, which need not be crushed prior to processing. In addition to the sulfur in troilite, some surface-correlated sulfur can be found in soil samples. In pyroclastic soils, surface-correlated metal sulfides probably occur (*Butler and*

- Several mineral forms of sulfur are relevant to the moon. Lunar/Mars mineral form of sulfur "troilite", rare on earth, but found in meteorites,etc. Mild sulfur odor is reported with many of these minerals.
- Apollo findings show ~0.1-0.2% sulfur in mare regolith. Highlands (A16, which is reflective of lunar south pole) contained half as much sulfur.
- Gibson and Moore (1973) experiments with Apollo regolith suggested sulfur ISRU possibility following heating to 750°C, (up to 30% of sulfur liberated as H_2S/SO^2). Pettit (1992) advocated for ISRU leverage of the lunar sulfur content (electrical/fluid properties/sealant/propulsion)
- As these are toxic constituents, Risk Team reached out to our ISRU to understand if there were plans to exploit lunar sulfur
  - ISRU had not been working on liberation of sulfur as a resource, but appreciated the info on health context and knew it was a contaminant they have to manage.

CONCLUSION: Sulfur is not expected to nominally be present in a toxic form in typical lunar regolith, but ISRU activities should be aware of liberation potential. Characteristic mild odor of dust may be attributable to the presence of non-toxic sulfur mineralogy.

Mars Sample Return (MSR)

Quick Facts

- **Aim:** Deliver samples collected by the Mars Perseverance rover to Earth
- **Launch:** Planned launches in 2027 (orbiter) and 2028 (lander)
- **Landing Location** Jezero Crater
- **Return of Samples :** Expected to arrive on Earth in 2033–2035
- **43 sample tubes brought to Mars, 38 for sampling and 5 as "Witness Tubes". As of October 2023, 22 have been collected**
- Atmo Mtn/Crosswind Lake (Samples 17/18) are regolith samples that have been cached. Almost all others are rock samples. Sample report states…*"in addition will be useful for questions related to human health and in situ resource utilization".*
- Forward work: -Engagement opportunity -Assess what gaps exist, or how HHP/HSRB risk team can work with MSR team to share information and leverage needs/info/testing

12. Risk Mitigation Framework—Color Changes

❖ How do we know when we go from **red** → yellow?

– Successful completion of lunar sustaining surface missions with monitoring and analysis that demonstrates dust control and crew health protection.

– Development of a Martian dust permissible exposure limit to be shared with ECLSS and other stakeholders

❖ How do we know when we go from yellow → **green**?

- Allergens sensitization potential is fully addressed
- Successful completion of initial lunar surface missions with monitoring and analysis that demonstrates dust control and crew health protection

13. High Value Risk Mitigation Targets (Forward Work)

❖ **"Mars Leaning" Lunar Surface Mission Experience** ← Human Landing System (HLS) Program and Stakeholders (SA, ECLSS, Safety, Dust Mitigation Teams)*

- ECLSS performance
- Dust mitigation strategies
- Crew health observations

❖ **Incorporating/Encouraging Lunar Dust Monitoring** ← HMTA, Crew Health and Performance (CHP), HLS Program*

- ~~Add NASA Standard 3001 Vol.2 standard for celestial dust monitoring~~ Completed!
- Continue to advocate for acceptance of celestial dust monitoring requirem[ent] ... mitigation strategy for future lunar and Martian missions.
- Enables assessment of ALL of the above elements on the moon.

❖ **XI Assessment of Lunar Volatiles** ← XI, VIPER, SK (Tox)*

- Chemical reactivity and behavior
- Containment strategies
- Volatile mapping and further exposure characterization

❖ **Complete Planned Allergen Assessment of Lunar Dust** ← SK (Immune), Initial research funded by HRP completed and addresses short-term DRM, Followon sensitization study is recommended.

❖ Further development of practical measures to address acute health concerns ← HMTA, CHP

*Potential collaborators and/or stakeholders

14. Risk → Standard → Requirements Flow

Adverse Health and Performance Effects Due to Celestial Dust

Risk of Adverse Health and Performance Effects Due to Celestial Dust

Standard

NASA-STD-3001: NASA Space Flight Human-System Standard Vol. 1, Crew Health, Revision C – September 2023

- [V1 3003] In-Mission Preventive Health Care
- [V1 3004] In-Mission Medical Care

NASA-STD-3001: NASA Space Flight Human System Standard Vol. 2, Human Factors, Habitability, and Environmental Health, Revision D – September 2023

- [V2 6001] Trend Analysis of Environmental and Suit Data
- [V2 6153] Celestial Dust Monitoring and Alerting
- [V2 6053] Lunar Dust Contamination
- [V2 6109] Water Quantity
- [V2 7010] Food Contamination Control
- [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

Requirements

ISS	MPCV	CCP	HLS	Gateway	EHP	CLDP
N/A	MPCV 70024 Human System Integration Requirements	CCP-REQ-1130 JSC-65993 CHSIR	HLS-HMTA-001 (Initial) HLS-HMTA-006 (Sustained)	GP 10004 Subsystem Specification for ECLSS GP 10015 Subsystem Specification for Crew systems GP 10016 Subsystem Specification for CHP GP 10017 Subsystem Specification for HSR	xEVAS-SRD-001	N/A

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15. Conclusions

- Assessments using primary human blood immune cells indicated no evidence for allergenic effects of lunar dust. Although allergenic response to lunar dust appears unlikely, it cannot be definitively ruled out for all design reference missions (DRMs). Further study is necessary to fully assess sensitization potential.

- The Space Mission Directorate (SMD) geology team released a position paper that clarified the mission conditions that would lead to an encounter with hazardous volatiles from samples collected from the permanently shadowed region (PSR) of the Moon. This has no impact on DRM risk posture, it informs sample containment and mission-specific risk decisions.

- The recent successful landing of the Indian Space Agency Rover (Chandrayaan-3) at the lunar south pole has resulted in reports of sulfur in lunar regolith samples, which is consistent with the body of historical evidence.

- New evidence includes a recently released manuscript describing the toxicity mechanism of lunar dust, which adds to a broader debate regarding the toxicity mechanism induced by particulate matter. This paper has no direct impact to the LxC for the dust risk.

- Acute exposures to celestial dust may warrant more thorough assessment. Additional research and development in this area is probably justified to better inform operational response and planning to support crew health and performance (CHP).

- Reductions in LxC scores were proposed for several lunar DRMs, resulting in some colors changing from yellow to green. These changes were justified by the risk custodial team based on the negative allergen findings and the new celestial dust monitoring requirement in NASA Standard (Std) 3001.

- Martian DRM was retained as an LxC of 4x4 (Red). The Mars Sample Return (MSR) campaign slated for 2030s will include at least one sample of Martian regolith. This is a unique opportunity to gain insight into the toxicity of Martian dust and to work with the MSR team to address gaps in knowledge.

16. Recommendations

- Work with the MSR community to leverage knowledge and communicate data needs
- Assess ways to improve communication regarding risk from acute exposure to lunar dust, including consideration of any future requirements, research, and countermeasure development
- Evaluate ways to further assess allergenic sensitization potential

17. Acronyms and Abbreviations

Acronym	Definition
CHP	Crew Health and Performance
CR	Change Request
CrewCo	Crew Compartment
DAG	Directed Acyclic Graph
DRM	Design Reference Mission
ECLSS	Environmental Control and Life Support Systems
EIHSO	Earth Independent Human Systems Operations
EVA	Extravehicular Activity
HLS	Human Landing System
HRP	Human Research Project
ISRU	In Situ Resource Utilization
LADTAG	Lunar Airborne Dust Toxicity Assessment Group
LO	Lunar Orbit
LOS	Lunar Orbit + Surface
LTH	Long-Term Health
LxC	Likelihood x Consequence
MSR	Mars Sample Return
Ops	Operations
PEL	Permissible Exposure Limit
PPE	Personal Protective Equipment
PSR	Permanently Shadowed Region
SCLT	Strategic Capability Leadership Team
SMD	Space Mission Directorate
Std	Standard
VIPER	Volatiles Investigation Polar Exploration Rover

18. Reference Materials

- LADTAG (Lunar Airborne Dust Advisory Group) Final Report 2014