Lunar Dust: Risk, Balance, and Overview

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Key Take Home Messages

- Lunar dust is a real, but manageable, environmental challenge for NASA and its Artemis partners. Despite gaps, we have a significant technical knowledge base to lean on with lunar dust.

- Human health is only one aspect of lunar dust risk management. System compatibility and dust mitigation are equally as important, but are addressed elsewhere.

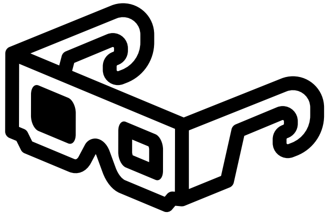
- NASA has established health-based exposure standards, based on carefully-designed studies and collaborations. These standards were informed by toxicity testing with actual Apollo lunar dust and were crafted in a way that makes them applicable to Artemis. Keeping exposures within these limits helps to ensure crew health protection and minimize mission impacts.

- Health risks with lunar dust are largely influenced by the length of crew exposures, particle size, and the mass of dust that is airborne. The small size of lunar dust particles is one unique aspect of lunar dust to anticipate. HEPA filtration is an excellent method for controlling lunar dust, and prevention and monitoring are essential to risk mitigation.

- The crew respiratory system is the primary concern with excessive lunar dust exposure. Irritation and lung inflammation are the types of health effects that are credible "worst-case" within an Artemis context. For reasons associated with both dust properties and our exposure conditions, outcomes like silicosis, lung cancer and other extremes are NOT relevant for Artemis.

- Controlling average exposures to lunar dust is most relevant to limiting our health concerns. Peak exposures may not always impact crew health, but can jeopardize the longer-term average and should still be managed carefully.

- Lunar dust monitoring serves several purposes, including assurance of crew health protection, validation of integrated operational design, and situational awareness in addressing crew observations and dust introduction/removal dynamics.



CRH HEALTH

SYSTEM COMPATIBILITY

MITIGATION

Credit. National Geographic, 2017

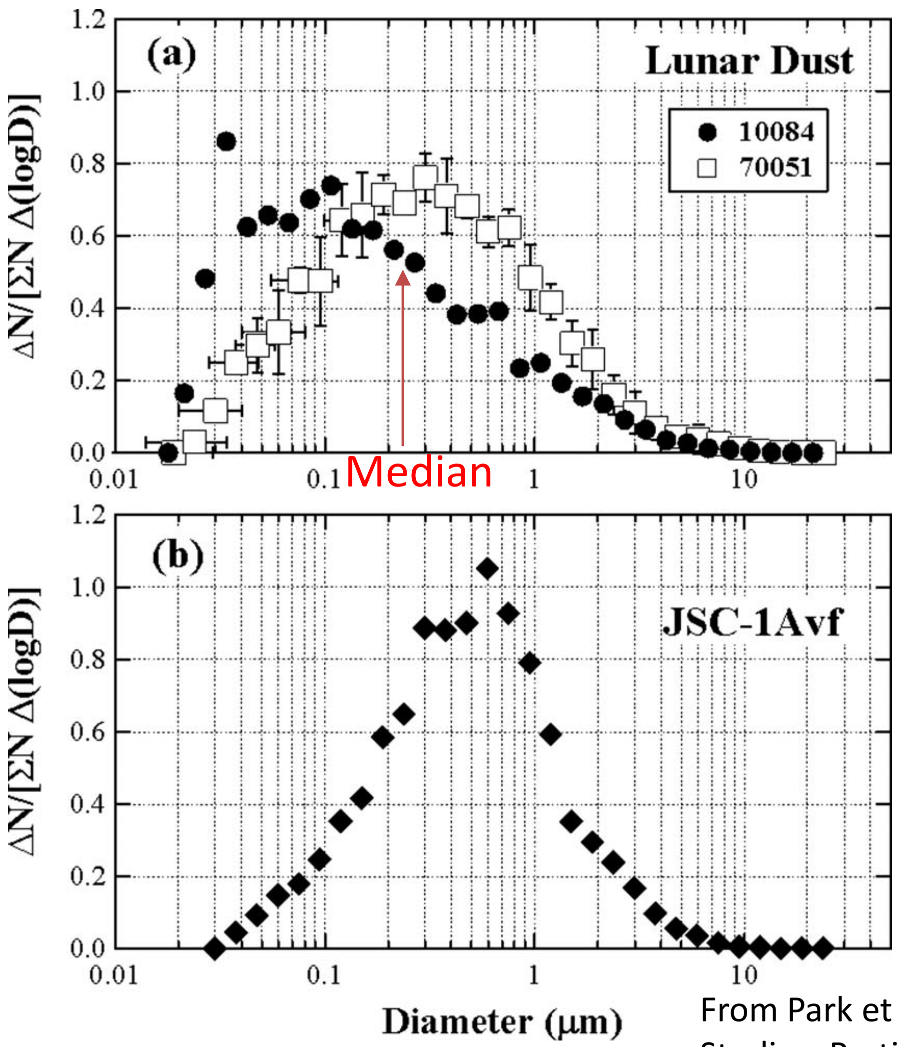
Where is Lunar Dust on the Spectrum of "Dust"?

- Health effect potential of "dust" varies greatly based on
  - Size of particles (influences where they go)
  - Shape (e.g., asbestos)
  - Reactivity (chemical constituents)
  - Dust mass (current risk metric)

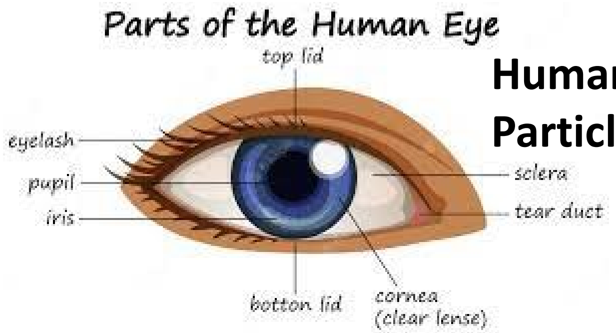
- Range of potential effects
  - No effect-(body clears by cough/swallowing)
  - Inflammation
  - Fibrosis (chronic exposure-affects pulmonary function)
  - Silicosis (scarring/fibrosis with potential complications such as lung cancer, tuberculosis)

-PM<10 microns are "inhalable", (perhaps trapped in nasal passages, etc)
-PM<2.5 microns are "respirable", (penetrate deeply in lungs, more health impact potential)
-Smaller nanoparticles (<0.1 microns) can have systemic effects, and research is ongoing)

State of Knowledge: Lunar Dust Particle Size Profiles (Apollo 11 and 17, <43 micron fraction)



General cabin particulate (10 - >100 micron)



Human eye can't see Particles smaller than 50-100 microns

NOTE: Although prevalent, lunar dust particles less than 1 micron in diameter only contribute ~1% of mass

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

Lines of Evidence Informing Lunar Dust Risk Assessment

- Apollo Experience
- Knowledge of the Inherent Toxicity of Lunar Dust Particles

LUNAR DUST AND THE VOICES OF APOLLO
Taken from Apollo Medical Operations Project (2007)

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

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

"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 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."

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

"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."

Lunar Dust and Apollo

Conclusion: Survivable, but mission-disruptive and not without health impacts/uncertainty

- **Strengths:**
  - It is the best Artemis analog we have for "uncontrolled" lunar dust exposures!
  - Artemis should be much better, so it is bounding

- **Apollo-era Dust Control:**
  - No High-efficiency particulate air filtration (HEPA). No cabin monitoring.
  - Wet towels and other mitigations were likely ineffective with inhalable dust (not-visible)

- **Limitations:**
  - 12 crew exposed over 6 surface missions. Individual variation and experience likely.
  - Mission specifics do not exactly match Artemis
    - Exposure durations
    - # of planned EVAs
    - Unrealized contingency events

Lines of Evidence Informing Lunar Dust Risk Assessment

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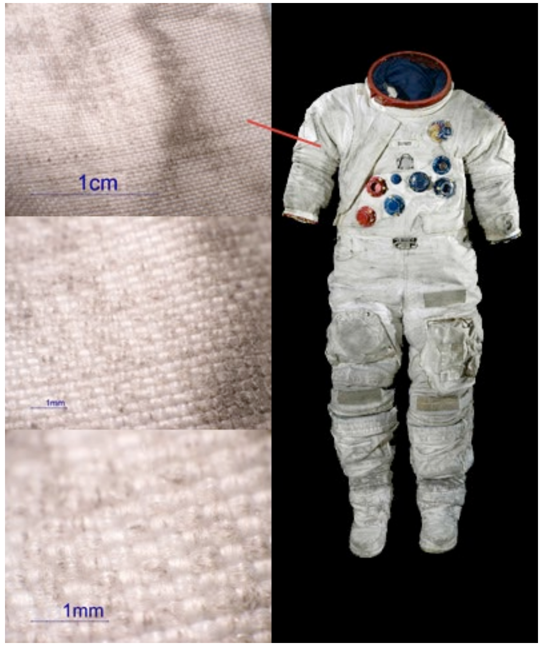
Lunar Dust Investigations



- 2005 formation of the "Lunar Airborne Dust Toxicity Assessment Group" (LADTAG)
- 2005-2013: Extensive Lunar Dust Investigations by Toxicologists/ Geologists
- Intratraecheal and inhalation exposures to actual lunar material with rats. Extensive attempts to restore and reflect native surface reactivity.

Toxicology

How will crew be exposed to lunar dust (risk assumptions)?
How toxic is lunar dust relative to well-studied reference dusts?
What is the toxicity of lunar dust in rats, and how would those findings relate to crew exposure standard?

Geology

- What is a "representative" lunar dust for LADTAG purposes"?
- What properties of lunar dust need to be characterized?
- How should lunar dust be prepared for toxicity testing?

RISK

Take Aways

(1) Relative Pulmonary Toxicity

Quartz > **Lunar Dust** > Titanium Dioxide

- Lung inflammation, septal thickening, and other signs of respiratory system toxic challenge were seen in rodents exposed to lunar dust, with negative outcomes increasing with exposed dose. **These are the same general types of effects that could occur in spaceflight crew if lunar dust were not properly controlled.**
- Risks of **eye abrasion and skin irritation** (e.g., EVA gloves, under fingernails) are additional considerations. While they may not be as health-sensitive as lung inhalation, these effects can still have health and operational mission impacts and are important to manage.
- **Averaging** of relevant exposure periods is most applicable to crew risk, and acute limits are not set at this time. Peak lunar dust levels aren’t expected to cause serious acute health impacts (e.g., ammonia).
- ***Lethality, silicosis, cancer are not credible concerns with our exposures.***
- No significant additional concerns with lunar dust **settling on food, water** in context of Artemis.

While lunar dust is high in silicate minerals, not all silica is created equal

Crystalline Silica (SiO_2)

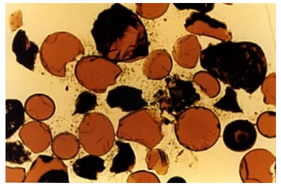
Quartz

Cristobalite

TOXICITY

Amorphous (non-crystalline)/Silicate Minerals

Diatomaceous Earth



Lunar Glass

Olivine (Mg Fe SiO_4)

Crystalline silica (SiO2) content of various materials[1,2,3]	
Sandstone	70-90%
Concrete/Mortar	25-75%
Granite	20-45%
Volcanic Ash	3-7%
Lunar Dust	**<1-2%**

[1]Unless noted, Y. Sultan, 2016
[2]Volcanic ash, Baxter, et al, 1981
[3]Lunar dust content only, J. Papike Lunar Minerals 1991. Table 5.1. (Some basalts have up to 5%)

Ocular Risk Considerations

Ocular Risk:

- Two-tier study. First tier used in vitro (EpiOcular™) procedure to expose cultured human keratinocytes. Results showed minimal chemical irritancy, so proceeded to second tier that involved application of particles to the eyes of 3 rabbits to determine mechanical irritancy. With a maximum possible score (Draize criteria) of 110 points, jet-milled lunar dust only produced a score of 4 points (slight redness and swelling of the conjunctiva after 1 hr, which resolved within 24 hours).

NASA Standard 3001 Volume 2 Requirements

6.2.8.3 Lunar Dust Contamination

[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.

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.

Tailoring of Permissible Exposure Limit (PEL) for future Artemis Missions

Haber's Rule: Allows us to translate risk across exposure scenarios based on Risk= Concentration x Duration

	180 day PEL	30 day PEL	
Lunar Dust PEL	0.3 mg/m^3	0.4 mg/m^3	

EXISTING STANDARD

HLS

LUNAR SURFACE REQUIREMENTs

30 day PEL: 0.4 mg/m^3

6.8 mg/m^3 (point of departure from 30 day rat inhalation study) ÷ 3 (species extrapolation) x (120 hrs study/720 hrs lunar exposure)

{TAILORED REQUIREMENTS}

Example Tailored Dust Requirements: Pressurized Rover

3.11.4[EHP-R-057] Lunar Dust Contamination
EHP systems shall limit the levels of lunar dust particles in habitable volumes to a 33-day time[1]weighted average of 0.4 mg/m3 <TBR-EHP-10012-009> and between 0.02 and 10 µm in size.

Rationale: This limit is based on a minimum currently expected permissible limit, as estimated by the Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG) in 2007. Although the standard 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. Reference NASA-STD-3001, V2 standard V2 6053.

This requirement is not meant to take the place of hardware operations and safety assessments with respect to lunar dust.

Why do we need a requirement to monitor lunar dust?

- **Health and Medical Technical Authority (HMTA) have consistently advocated for lunar dust monitoring.**
  - Monitoring helps ensure crew health protection (NASA standard crew exposure average that must be maintained)
  - Monitoring allows for medical experts to RULE OUT excessive dust as a cause if crew experience unknown health effects
  - Monitoring allows for a record of crew exposures to a known environmental hazard (due diligence)
  - Monitoring is the ONLY objective way to determine whether Artemis dust introduction controls, mitigation strategies, and ECLSS design are working as designed (no integrated system test is possible on the ground)
  - Monitoring buys down risk for future sustained Artemis and even future Mars missions, where dust management will be even more of a challenge

If we would have had dust monitoring data from Apollo, Artemis would be way ahead in preparation!

Conclusions on Dust Severity

- Controlling lunar dust exposure within established exposure limits is key to minimize crew health risks.

- **Severity for uncontrolled Artemis exposures should consider a "reasonable worst-case" informed by our Apollo experience and knowledge of lunar dust toxicity.**

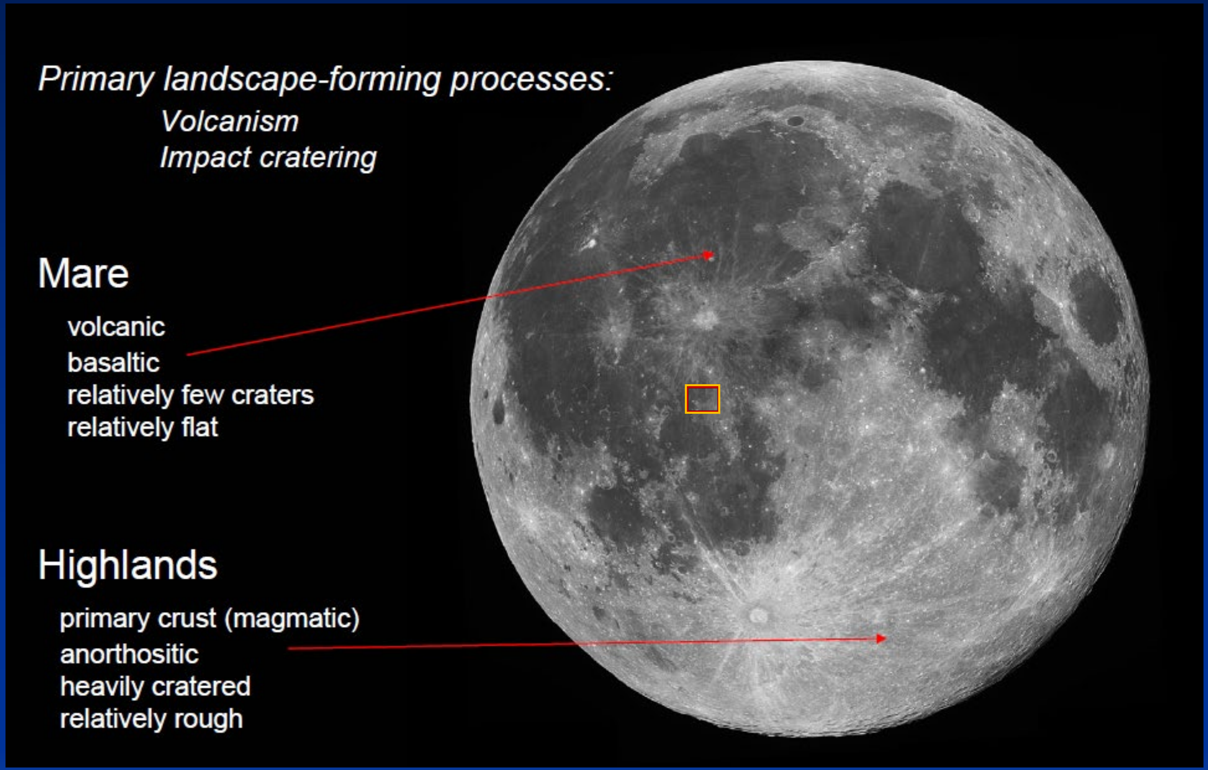
For missions up to 30 days:

	Reasonable Worst-case Artemis (Ineffective Control)	Examples
In Mission Health	Minor crew illness that can be dealt with by crew without ground support (Critical)	Disruptive coughing, nasal congestion, sore throat, irritation
Operations	Significant reduction in crew performance threatens loss of a mission objective	Inability to complete a key task/objective due to dust-related lost crew time, distraction, or impairment.
Long-term Health	Treatable career-related medical condition that may require hospitalization for management. (Critical)	Therapy to ensure restoration of nominal pulmonary function.

ARTEMIS

SPECIAL CONSIDERATIONS FOR LUNAR DUST RISK

Lunar Dust: Apollo 14 Mission



Mare Regions – dark areas, low lying planes composed of basalts.
Basalts are composed of relatively heavy elements such as iron, manganese and titanium.

Highlands Regions - light areas, hilly regions with many craters covered with anorthosite.
Anorthosites are rich in light weight elements such as aluminum and calcium.

Lunar Dust Collected Apollo 14 Mission

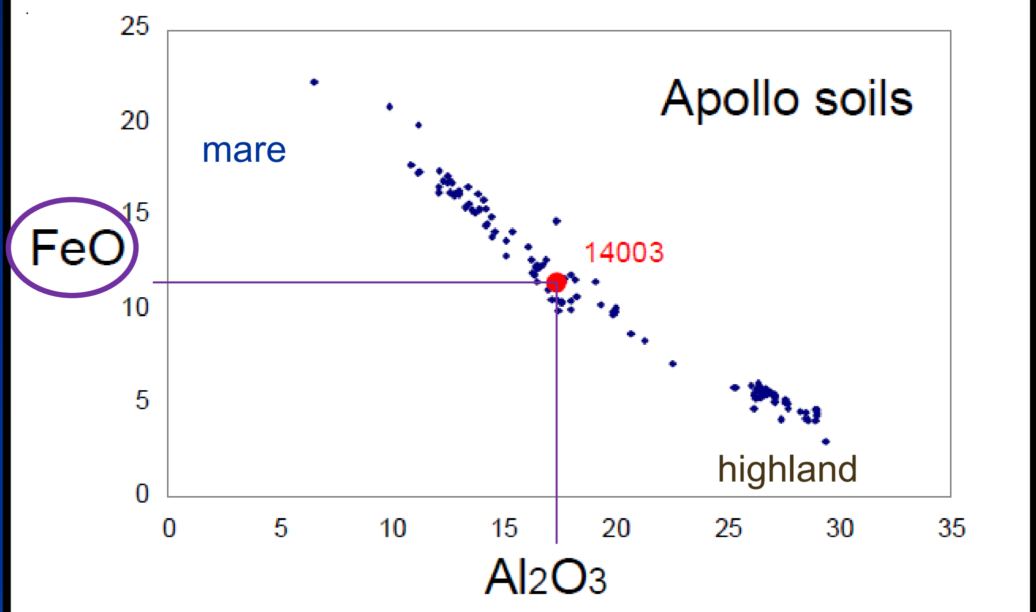
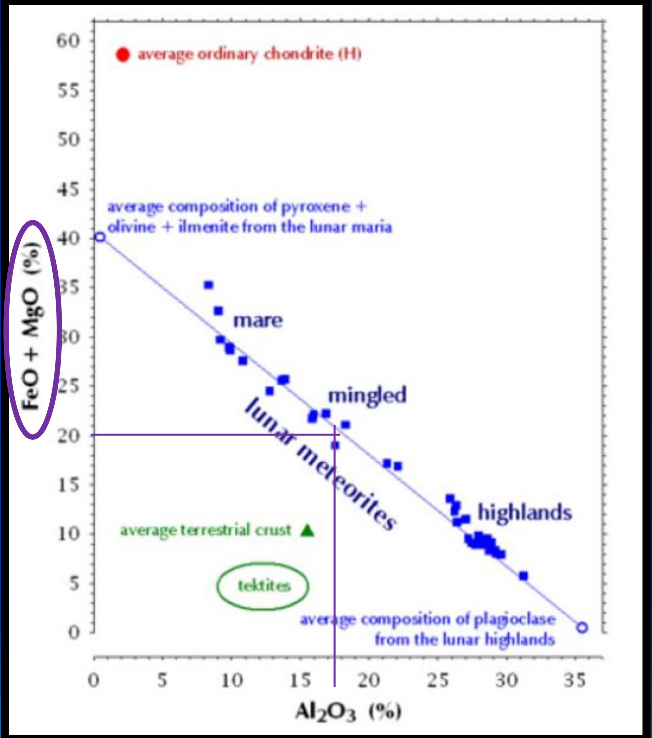


Figure 4: Composition of 14003 compared with that of other Apollo soil samples.



Meyer C. 2011. Lunar Sample Compendium.
14003 – 947.9 grams. Soil. Contingency Sample.

Korotev RL. 2012.

In risk assessment, you want to reflect a reasonable worst-case average over the likely area of exposure (temporally/spatially). Focusing on extremes often limits the applicability of risk conclusions.

Background: Lunar Dust and Immunological/Allergenic Concerns

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

> "Exposure to lunar dust from the suits caused a reaction that worsened with each of the 3 sampling periods. The first exposure caused a stuffy nose and watery 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 2023 HRP-funded study was conducted to attempt to inform this gap.
  - Apollo 16 dust was obtained (Highlands regolith), Human blood donors were evaluated for signs of response.

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, and a lack of previous sensitization to lunar dust.

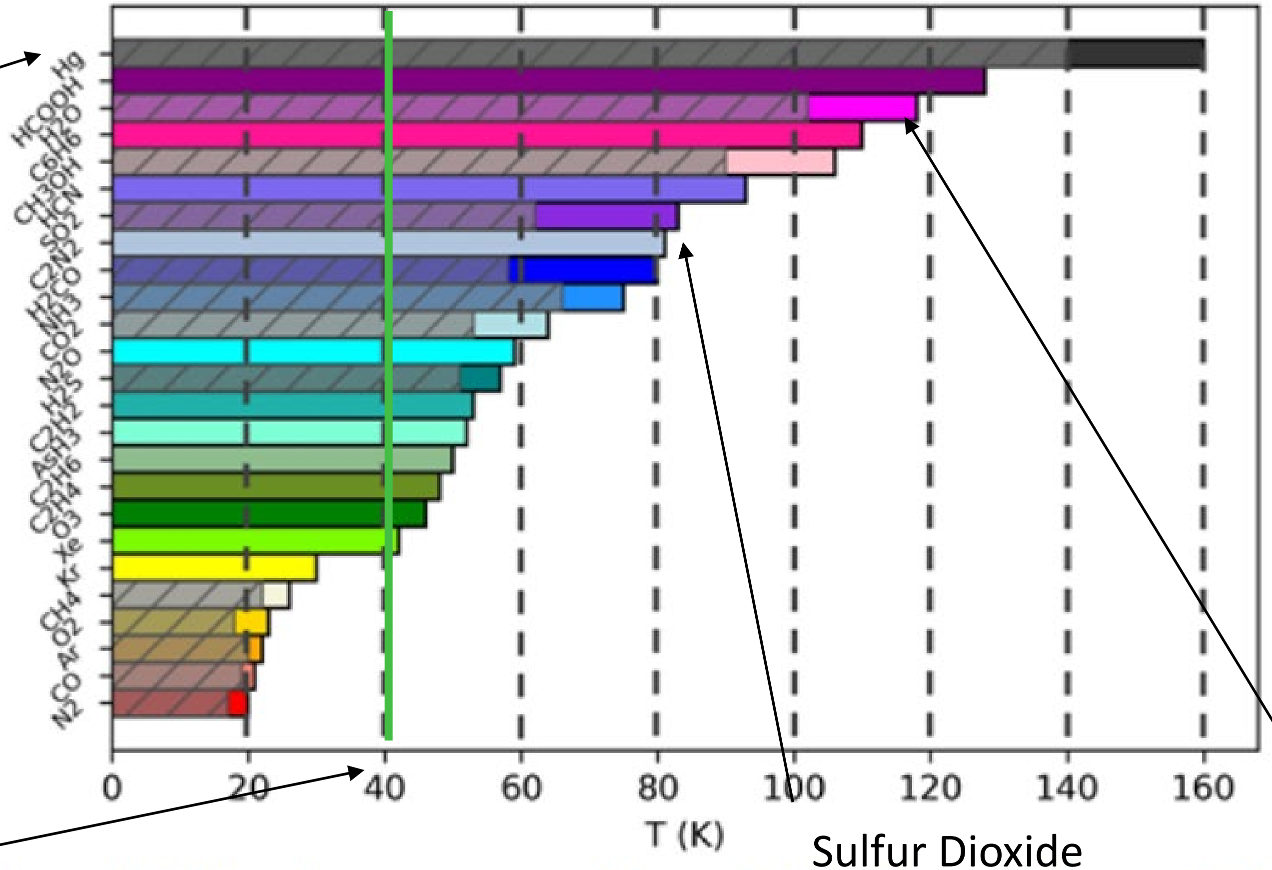
State of Knowledge: Potential for Polar Volatiles of Toxicological Concern

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, sulfur dioxide)
- The source for these volatiles includes endogenous lunar and solar wind.
- Given impact studies, estimates of concentration are very rough and can vary by several orders of magnitude. 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 be stored in the habitable volume. **Toxicological awareness and proper containment needs to be maintained in order to ensure crew protection**
- **NASA has made progress in characterizing this risk, and is informing design for sample containers, mapping volatiles.**

Cold Traps for Volatiles

Mercury



Sulfur Dioxide

Water

Large PSR

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.

These volatiles may still be present at 40 K, As it is too cold to sublimate

Large, old PSRs

- **SETTING:** PSR interiors with very low surface temperatures (40 K)
- **TRAP**: Very cold temperatures create thermodynamically stable areas for volatiles to condense and persist
- **SUPPLY**: Interior outgassing and exogenous supply from early in lunar history.
- **AGE**: Some craters formed early enough to have existed at the time of high supply
- **OBSERVED**: Condensed volatile species (e.g., ices) are observed in PSRs in areas that are old enough to have existed when supply was high. This is mostly the big, old craters (not accessible AIII or AIV targets).