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# Martian Dust Exposure Limits: Permissible Exposure Limits (PELs), toxicological risks, and health standards for Martian dust as discussed by the Mars dust working group (February 20 and 27, 2026)

*Compiled by:*

*Douglas Ebert, Office of the Chief Health and Medical Officer, KBR, Houston, Texas*

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## Table of Contents

# Panel Members

- **David Damby**: Research Chemist, U.S. Geological Survey Volcano Hazards Program, California Volcano Observatory
- **Claire Horwell**: Professor of Geohealth, Department of Earth Sciences, Durham University, UK; founder/director of the International Volcanic Health Hazard Network
- **Brian Hynek**: Professor, Department of Geological Sciences & Research Associate at the Laboratory for Atmospheric and Space Physics, University of Colorado Boulder
- **Shaunna Morrison**: Professor, Department of Earth and Planetary Sciences Rutgers University
- **Joyce Tsuji**: Principal Scientist/Toxicologist, Health Sciences Practice, Exponent, Inc.

# NASA Presenters

- **Katie Borremans**: Moon2Mars Program Mars architecture team
- **Elizabeth Rampe**: Astromaterials Research and Exploration Science (ARES) Division
- **Torin McCoy**: Moon2Mars Program Associate Chief Health and Performance Officer and Lunar and Martian Dust Risk Custodian

# Moderators (all from the NASA Office of the Chief Medical Officer – OCHMO)

- **Doug Ebert**: Standards Integrator and Multidisciplinary Scientist
- **Dave Francisco**: Technical Fellow for Health, Medical & Performance Standards; OCHMO Standards Team Lead
- **Kim Lowe**: OCHMO Standards and Moonbase Requirements Integrator, OCHMO Standards website curator

# Executive Summary

Human exploration of Mars will expose crews to a persistent, fine particulate environment whose physicochemical properties and health implications remain only partly understood. Because no samples of authentic Martian airborne dust have been returned to Earth, NASA must rely on lunar dust toxicology, Martian regolith simulants, and extensive rover/lander geochemical and mineralogical datasets to develop an initial, risk-informed Permissible Exposure Limit (PEL).

Across two working sessions, panel members reviewed mission architecture drivers, the current scientific understanding of Martian dust composition and behavior, and the toxicological evidence base supporting the establishment of a Mars dust PEL. Discussions emphasized the critical interplay between dust standards and Mars mission design elements including Extravehicular Activity (EVA) cadence, dust ingress characteristics, and the performance of habitat environmental control systems; these features highlight the need for a limit that is conservative, verifiable, and adaptable as the Mars architecture evolves.

The Martian Dust Limit Working Group addressed four primary goals:

1) **Evaluate NASA's proposed derivation of this initial standard**

The panel concluded that NASA's approach to deriving a 30-day continuous PEL of 0.1 $mg/m^3$ is reasonable and appropriately conservative for early short-stay missions. This value originates from the established lunar 30-day PEL (0.4 $mg/m^3$), reduced by a 3x database uncertainty factor to account for knowledge gaps in Martian dust toxicity, higher iron content, amorphous constituents, and differences between simulants and actual dust. Members supported this framework, noting that a continuous limit applied using measured time-weighted averages is more practical than making assumptions tied to fixed dust clearance rates given the diversity of spacecraft designs. They also acknowledged that near-term exposures will be peak-driven (e.g., post-EVA suit ingress) and therefore recommended that the standard explicitly address the need to manage short-duration spikes.

2) **Identify chemical constituents requiring further scrutiny**

The panel affirmed that overall dust mass remains the primary near-term engineering concern, but several chemical constituents warrant attention. Chromium $6^{+}$, manganese, and perchlorate were all considered low-risk in the context of inhaled Martian dust, provided the overall dust PEL is applied (see below). However, perchlorate was recommended for broader agency-level exposure management across multiple intake routes (e.g., ingestion due to in situ crop growth). Iron was discussed in detail due to its high abundance in Martian regolith and its potential to generate Reactive Oxygen Species (ROS), though current toxicology shows no clear link between iron-driven ROS and pulmonary harm; still, knowledge gaps led the panel to prioritize iron for further study and potential Spacecraft Maximum Allowable Concentration (SMAC) development. Arsenic was judged unlikely to pose meaningful risk at present.

3) **Weigh the merits of an overall dust limit versus separate SMACs**

Chemical constituents embedded within Martian dust were evaluated with respect to whether independent SMACs are warranted. Based on rover observations indicating predominantly trivalent chromium, low airborne perchlorate, and manganese concentrations well below conservative SMAC thresholds at the proposed PEL, the group agreed that the overall dust limit is likely sufficiently protective for expected 30-day missions. However, panel members advised that SMACs be maintained for select constituents such as perchlorate and manganese for mission-planning crosschecks. From the requirement perspective, an overall Martian dust PEL approach was favored for practicality and clarity, with constituent-specific SMACs retained or developed only where they add tangible operational value.

**4) Refine the standard's technical language for operational use**

The working group also refined the standard language to ensure clarity and consistency in implementation. Members recommended that the limit apply to a specified time-weighted average measurement period but also making it explicit that the requirement is for protectiveness over continuous exposure. They encouraged incorporation of peak-exposure management within the rationale, and highlighted uncertainties related to iron content, nanophase iron, and oxidative potential so that future revisions can incorporate emerging scientific insight.

***Martian Dust Contamination***

*[V2 6253] The system shall limit the concentrations of Martian dust particles less than 10 μm in size in the habitable atmosphere below a 24-hour time-weighted average of 0.1 mg/m$^3$ during exposure scenarios lasting up to 30 days in duration.*

Taken together, the working group's deliberations reinforce that an initial Martian dust standard must balance conservatism with operational feasibility while accommodating architectural and scientific uncertainty. The proposed requirement provides a defensible, evidence-informed foundation for design, verification, and risk communication. As additional Martian data and toxicological research become available, this standard should be periodically revisited to ensure continued protection of crew health during human exploration of Mars.

# Background

Extensive lunar dust research and preliminary Martian regolith simulant studies have identified key physicochemical properties—such as fine particle size, crystalline silica content, surface reactivity, and biopersistence—that can potentially contribute to the toxicological health risks of Martian dust exposure for future human explorers. Establishment of a PEL for Martian dust will be necessary to protect crews and inform planning for vehicle design and operations. Unlike lunar dust, there is unlikely to be sample return of Martian dust that can enable direct studies of toxicity (i.e., similar to studies that were conducted under the Lunar Airborne Dust Toxicity Assessment Group, LADTAG). Thus, there is a need to leverage existing knowledge in order to appropriately inform a Mars PEL, while conservatively accounting for inherent uncertainties. It is understood that this PEL for Martian dust is subject to emerging data from Mars, advancements in terms of understanding of particulate toxicity, and crew exposure assumptions relevant to a future Mars mission.

There is a moderate knowledge base for lunar dust that can be leveraged in setting a Mars PEL, including similarities and differences between Martian and lunar dust that can affect extrapolation of lunar dust findings to Mars applications. Other sources of data are Mars simulant studies (e.g., Lam et al., 2002), which offer both strengths and limitations in terms of contributions to setting a Mars dust PEL. Finally, there are extensive data sets from Mars rovers that provide tremendous amounts of insight in certain contexts. It is important to note that these are all credible, but imperfect, sources of data on Mars dust toxicity, but must be leveraged to the extent practical given the lack of full chemical analysis and direct toxicity measurements.

Risk assessment for Martian dust is generally more complex than for lunar dust, due to the potential presence of inorganics such as perchlorates and specific heavy metals (e.g., chromium, manganese). Fortunately, Mars rover missions mentioned above provide a wealth of chemical data on these constituents from in situ analysis, such that an overall risk assessment can be performed with reasonable fidelity despite not having samples that have been returned to Earth.

NASA has conducted an initial risk assessment on Martian dust and associated chemical constituents and identified chromium, manganese, and perchlorate as potentially needing separate risk consideration and SMAC development. A SMAC for manganese has been developed, and a risk assessment approach for how it could be integrated with a future Mars PEL was proposed (Romoser et al., 2019). Chromium was shown to primarily be in a trivalent valence state, which has relatively low toxicity potential and may not necessitate specific evaluation as a risk priority. While crew inhalation is believed to be the most sensitive exposure route for Martian dust itself, certain constituents present within that matrix may necessitate consideration of other relevant exposure routes. As a primary example, NASA recognized perchlorate as a potential multi-exposure concern that warranted consideration from an integrated air, water, and crop uptake perspective.

In the initial assessment, NASA noted that, at least with chromium, manganese, and perchlorate, it seemed likely that protection of crew from pulmonary hazards of Martian dust would also protect against associated chemical-specific toxicity. Following this approach, SMAC development for chemical constituents is kept as an important but separate technical endeavor. If appropriate, this is a simplifying approach and may allow greater efficiency in terms of monitoring. An example of this approach and application is provided in the manganese SMAC (Romoser et al., 2019).

# Goals of the Review

(1) Assess NASA's proposed approach to developing an initial PEL for Martian dust, based on leveraging LADTAG findings, Mars simulant studies, and other data.

(2) Identify other chemical constituents in Martian dust that NASA may need to evaluate in more depth while developing SMACs for a Martian mission.

(3) Provide feedback to NASA on the pros/cons of developing separate SMACs for constituents of concern, as compared to accounting for them directly through adjustments in the Mars dust PEL.

(4) Evaluate the proposed standard language in the context of these considerations.

# Methods

Prior to the meetings, the background and goals (above) were distributed to panel members and participants. Two meetings of approximately 4 hours each were conducted one week apart, during which NASA subject matter experts presented technical content that outlined the current state of knowledge regarding Martian dust and its potential health effects (see the agenda in Appendix A, including presenters and presentation titles). Interactive discussion was encouraged, with ample time for additional discussion during the second session.

The panel was not asked to form a consensus recommendation, rather expression of all opinions and alternate interpretations or approaches was encouraged. The intent was to gather all viewpoints and uncover new perspectives that may not have been considered in the proposed NASA approach.

Meetings were held via Teams and were recorded. Summaries were distributed to participants after each day. Panel members were asked to provide any additional inputs within two weeks of the meetings, but all members felt that the in-person discussions were sufficient, and no additional input was received.

Presentations and discussions were summarized into this report which also includes the proposed Martian dust standard. This standard represents a reasonably conservative position based on the current state of knowledge, but like all standards, is subject to review as new data and experience are available.

# Presentations and Discussion (Day 1)

## Presentation #1: NASA's Moon to Mars Architecture (Katie Borremans)

NASA's Moon to Mars Architecture was introduced as a systems-engineering blueprint that evolves through annual Architecture Concept Reviews (ACR) as opposed to a single mission or manifest approach. The architecture decomposes agency objectives into capabilities and elements spanning transportation, habitation, infrastructure, operations, and science, with explicit traceability from "why we explore" to executable plans. For the panel, this framing clarifies the interface points where health and performance standards (including dust exposure limits) must be integrated and later verified in provider designs.

### Segments, Sub Architectures, and Decision Framework

The roadmap organizes work into staged segments: Human Lunar Return, Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars. Each integrates sub architectures (e.g., Habitation Systems, Mobility, Power, In Situ Resource Utilization (ISRU), Autonomy & Robotics, and Communications and Positioning, Navigation, and Timing Systems (C&PNT)) that must be codesigned and validated together. The ACR process sequences priority decisions, exposes dependencies, and identifies knowledge gaps that need maturation before downstream choices can be made.

### Operating on Mars: Time, Latency, Weather, and Terrain

There are operational realities unique to Mars: the sol is ~24 hours 39 minutes, and roundtrip communications delays may reach 44 minutes, necessitating greater crew autonomy and onboard decision making than in Low Earth Orbit (LEO) or lunar missions. The atmosphere is ~100 times thinner than Earth's and is approximately 96% $CO_2$ but supports global dust storms (planet encircling events which are infrequent but operationally significant). The terrain is extreme with topography such as Olympus Mons

(72,000 ft; 21.9 km) and Valles Marineris (more than 3,000 km long, up to 600 km across, and 98 km deep). Combined, these features create challenges for landing accuracy, navigation, and communications.

## Transportation and Entry–Descent–Landing (EDL): Precision and Energy Trades

Architecture work spans multiple in-space propulsion options, lander types, and surface systems, noting that crewed EDL must achieve unprecedented landing accuracy and accommodate greater landed mass than prior robotic missions. Transit energy varies substantially by departure window, with some years requiring 20–60% more energy. This reality couples propellant availability, aggregation, and generation decisions to downstream mass margins for health systems and environmental controls.

## ACR Decision: Surface Power for Initial Human Mars Missions

A key recent ACR outcome is NASA's selection of nuclear fission as the primary surface power generation technology for initial crewed Mars missions. The decision logic weighed robustness to dust storms, scalability, and operational reliability; compared to photovoltaic systems with energy storage, fission provides power that is not dependent on solar flux, season, or day/night, simplifying environmental control continuity during high opacity events.

## Crew Complement and Roles

The architecture targets no fewer than four crew to the surface for the initial Humans to Mars segment, with consideration for up to six to enhance mission capability and risk reduction. Decisions on skill mix and role training are tied to mission objectives, vehicle maintenance, and contingency response under a Mars mission's latency, distance, and environmental constraints.

## Living and Working on the Surface

Habitation systems must account for terrain hazards, planetary protection, communications latency/blackouts, and dust storms (visibility, solar energy disruption, material abrasion). The architecture process emphasizes decision sequencing, for example how choices about habitation form factor, mobility, and ISRU affect dust ingress pathways and Environmental Control and Life Support System (ECLSS) sizing such that health standards can be traced to design impacts and pragmatically validated.

## Panel Discussion Highlights: Architecture Driven Exposure Scenarios

Discussion reinforced why dust standards must be framed within evolving Mars mission architecture rather than a single vehicle concept. NASA's architecture still has approximately 50 remaining decisions, reflecting active trade space across architecture level choices and not simply implementation level decisions. This uncertainty means crews may either live only in the lander, primarily in a pressurized rover, or alternate across multiple vehicles (lander, separate ascent vehicle, and rover) during a short surface stay. Each scenario changes dust ingress pathways (e.g., suit handling, airlocks, tracked in regolith) and the verification needs for environmental control.

Seasonal dust storm predictability was brought up as an operational context driver, with the group deferring the topic to the geoscience segment (presentation #2, Rampe).

The discussion also addressed ISRU and construction analogs (e.g., Crew Health and Performance Exploration Analog (CHAPEA) and regolith processing), which would increase airborne dust generation and therefore heighten housekeeping and filtration demands. In parallel, architecture choices about surface power (e.g., fission) directly enable such processing, further underscoring that dust limits must ultimately be paired with procedural controls and verification of removal rates in habitats and vehicles.

Finally, surface duration remains an open decision; however, orbital dynamics make "short stay" segments (~30 days) a pragmatic choice for near term missions. The panel noted that a 30-day PEL provides a realistic design target, while leaving room to revisit limits and verification approaches for longer stays as architecture decisions converge.

## Presentation #2: Martian Dust: Observations from Landers and Orbiters (Elizabeth Rampe)

The presentation summarized what is known about Martian dust from orbital and in situ measurements, covering how dust is detected and characterized, where it resides, how "storms" behave, and the chemical and mineralogical composition of dust.

Orbital datasets (e.g., Mars Global Surveyor Thermal Emission Spectrometer (MGS TES), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), Mars Color Imager (MARCI), Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité," which translates to "Observatory for Mineralogy, Water, Ice, and Activity" (OMEGA)) provide long baseline tracking of dust optical depth and storm evolution, while surface instruments capture grain size/shape, elemental composition, and mineral phases within dust-rich soils and dust coatings. This dual approach confirms that airborne dust is present from the surface to approximately 80 km altitude and that atmospheric dust content varies strongly with season and geography.

Instruments cited include UV/visible/IR spectrometers (for optical depth, storm tracking, and spectral fingerprints), and rover/lander payloads such as the Alpha Particle X-ray Spectrometer (APXS), ChemCam/SuperCam Laser-Induced Breakdown Spectroscopy (LIBS) instrument, Planetary Instrument for X-ray Lithochemistry (PIXL), CheMin X-ray Diffractometer (XRD), Sample Analysis at Mars (SAM) evolved gas analysis (EGA) instrument, microscopic imagers, and Atomic Force Microscope (AFM). Together these techniques describe particle sizes, spatial/temporal variability, bulk chemistry, and phase assemblages relevant to crew health and environmental control.

## Atmospheric Dust and "Storms": Seasonality, Scale, and Variability

"Dust storm" on Mars is a misnomer: events are not characterized by strong winds at the storm location. Primary dust storm activity occurs between solar longitudes (Ls) 140–250° (northern hemisphere, summer/fall) with a secondary season between Ls 300–360° (northern hemisphere, winter); local events ($<1.6\times10^6$ km$^2$, <3 sols), regional events ($>1.6\times10^6$ km$^2$, >3 sols), and planet encircling (global) storms (multiregional sequences spanning most longitudes) are observed. Planet encircling events typically build over 10–40 sols and decay over up to 150 sols. Since 1971 there have been 12 planet encircling storms, and an activity database (~15,000 events) supports quantitative analyses of paths, durations, and sizes.

Limb measurements (planetary atmospheric edge) from the Thermal Emission Spectrometer (TES) indicate ~1.5–2 μm particles at 30–60 km during high loading seasons and ~0.5–1 μm during lower loading; lower atmosphere particles are commonly ~1.5–2 μm. These ranges shape deposition and filtration expectations for habitats.

## Deposition Rates and Grain Scale Observations

At the Mars Pathfinder site, calibration targets accumulated ~5–10 μm of dust over the mission, corresponding to ~20–45 μm per Earth year, consistent with regional deposition estimates. Curiosity Mars Hand Lens Imager (MAHLI) images at Gale crater show dust coatings on larger grains within regolith, and the Phoenix Mars lander AFM at resolved particles in the ~2–4 μm size range, providing context for settling behavior and surface adherence on suits and in habitats.

## Chemical Composition: Homogeneity, Volatile Enrichment, and Elemental Trends

Across Mars Exploration Rover (MER)/Mars Science Laboratory (MSL)/Mars 2020 (M2020) datasets, dust is compositionally homogeneous at the planetary scale and distinct from local dark soils and rocks. Dust is enriched in S, Cl, Ni, Zn, P, and Fe relative to rock and sand substrates. APXS measurements on Curiosity's Ti observation tray show $SO_3$ at 8.3 weight % and Cl at 1.1 weight %, with a molar S/Cl ratio of 3.35 ± 0.34, consistent with prior dust studies. Elevated Fe relative to average Mars soils is also observed. The presentation noted that S and Cl enrichments likely reflect adsorbed ions, coordination with lighter species (e.g., perchlorate), and/or mixtures of multiple salt phases (Mg/Ca sulfates, halite).

## Mineralogical Phases and Amorphous Components

XRD (CheMin) and complementary datasets show basaltic igneous minerals (plagioclase, olivine, pyroxene) dominate dust-bearing soils, with trace secondary phases including hematite ($Fe_2O_3$) and anhydrite ($CaSO_4$). A substantial X-ray amorphous component (~35 weight %) is Fe- and volatile-rich, consistent with chemical weathering and aqueous alteration pathways. Mössbauer data identified nanophase ferric oxides (npOx; poorly crystalline iron-rich phases responsible for the reddish color), including ferrihydrite-like materials. LIBS and PIXL reinforce that dust coatings are basaltic and volatile-enriched, with electrostatic effects influencing grain size sorting on calibration surfaces.

## Chromium and Perchlorate: Specific Notes from Rover/Lander Data

Dust and soils at MER landing sites and Gale crater show Cr primarily tied to magnetite/olivine, with no $Fe^{6+}$ detected by Mössbauer (detection limit of 1-2%). Assuming similar detection limits for $Cr^{6+}$, there is negligible $Cr^{6+}$ relative to total Cr (typical dust values ~0.22–0.40 wt% $Cr_2O_3$, with local variability in active sands). This supports a low-$Cr^{6+}$ context in planetary dust. It was also noted that $Fe^{6+}$ and $Cr^{6+}$are not stable in the presence of strong reducing agents such as $Fe^{2+}$.

Evolved gas analysis (SAM) indicates ~0.3–0.5 weight % perchlorate in dust-bearing Rocknest soils. Perchlorate may contribute to the observed S/Cl enrichment patterns in dust coatings and amorphous fractions; however, direct quantification in airborne dust remains to be established.

The presentation summarized physical abrasion by wind-blown sediment, explosive volcanism, and impact fragmentation as primary dust sources, with chemical alteration contributing npOx and volatile enrichment. The Medusa Fossae Formation (MFF) was highlighted as a major candidate source of dust, given its high S/Cl signatures and erosional volume consistent with substantial dust contributions to the planet.

Laboratory and in situ observations indicate 1) charge segregation with smaller grains tending to be negatively charged and larger grains to be positive and 2) electrostatic discharge at low Mars pressures, generating free radicals and driving salt oxidation (including chloride systems). PIXL calibration targets demonstrated preferential dust accumulation (~10× higher) on PTFE versus glass, consistent with charge-dependent adhesion and suggesting electrostatic sorting on exposed surfaces.

## Panel Discussion Highlights: Martian Dust Physical Properties

Early questions highlighted a perceived paradox: if winds tend to be weak during Martian dust storms, what keeps dust lofted and why does lifting occur in the first place? Participants suggested extreme atmospheric dryness as a key factor in sustaining suspension, with electrostatic effects likely contributing, and proposed that persistent, steady winds rather than brief gusts could be the relevant driver. Dr. Rampe noted that the detailed mechanisms of dust lifting remain insufficiently understood and offered to consult atmospheric specialists; she also confirmed that, while seasons of elevated dust activity can be anticipated, the onset and evolution of individual storms cannot yet be reliably predicted. Dr. Rampe followed up with Dr. Scott Guzewich, a Martian atmospheric scientist at the Goddard Space Flight Center who explained that "dust lifting: mostly occurs due to strong winds at the surface which start sand saltation and those saltating sand grains “splash” dust into the atmosphere. Those strong winds can either be “straight-line” winds associated with larger scale dust storms or rotating strong winds associated with dust devils. There could be other effects which help lift dust like electrostatic forces, but those are totally speculative at this point. What keeps dust lofted: that’s a balance between gravity and the upward directed vertical wind. Dust can (probably) also be removed by being used as a nucleus for water ice or $CO_2$ ice condensation and then those particles may fall out of the atmosphere. This paper by Melinda Kahre contains some estimates of expected fall velocities of dust particles https://www.sciencedirect.com/science/article/abs/pii/S0019103508000614?via%3Dihu.

The difference between “dust” and “regolith” was queried and Dr. Rampe answered that the distinction is primarily by particle size, with “dust” often treated as the fine fraction at the few micron scale (noting thresholds on the order of several micrometers in the Mars literature), whereas “regolith” denotes loose soil or sand that commonly contains some dust mixed in. This distinction may be useful for standardizing risk communication and test protocols.

Microscopy imagery from the Phoenix mission prompted debate about particle angularity. One reviewer observed that grains appear highly weathered with limited angular components, suggesting rounding from extended wind-blown transport. Dr. Rampe agreed the available imagery makes angularity hard to judge and acknowledged gaps in the published record on shape metrics for the finest fractions; at the same time, the visual impression of rounded "blobs" is consistent with long residence or long-distance movement on the surface.

Several exchanges examined magnetic and nanophase iron components and their potential health implications. Panelists asked how much dust resides in magnetic fractions (e.g., magnetite) and whether nanophase iron oxides could pose neurological or broader toxicity concerns. Dr. Rampe explained that rover magnets naturally accumulate magnetic particles and that "clearing" of those magnets occurred through ambient conditions rather than instrumented removal, an operational detail relevant to interpreting those samples. She noted that magnetic dust captured on rover magnets is enriched in iron phases, but explained that Mössbauer spectra of bright soils show only small contributions of magnetite, while most airborne and surface dust appears dominated by basaltic silicates with a substantial amorphous component; the exact proportion of nanophase iron in the total dust remains uncertain and is an active topic of analysis. Questions also revisited a past concern about hexavalent chromium; the discussion reflected confidence that $Cr^{6+}$ is unlikely to be significant in Martian dust under observed conditions.

The group weighed how much crystalline silica should be expected and how to treat it in standards and hazard communication. Reviewers reiterated the working expectation of very low crystalline silica content (on the order of one percent or less in the fine fraction) and pointed out that regulatory frameworks typically address quartz, cristobalite, and tridymite under the same umbrella, even though high quantity exposures to the latter two polymorphs are relatively uncommon. Others cautioned against assuming uniform toxicity across silica forms, underscoring the so called "silica enigma": cristobalite can be less hazardous than quartz depending on physicochemical attributes (including surface coatings), and toxicity can be modulated by environmental context. Participants emphasized that Mars lacks high silica volcanism and plate tectonics, reducing the likelihood of widespread crystalline silica production compared with Earth's rhyolitic systems. Dr. Rampe agreed the measured quartz fraction in bulk fine material is very low and, when questioned about secondary silica phases, confirmed detections of cristobalite and tridymite in particular sedimentary samples but these are rare and context specific findings that prompted further discussion of plausible origins.

Attendees asked which terrestrial materials are most informative as analogs and simulants. The group noted common practice of using Arizona volcanic ash as a lunar analog and Hawaiian basaltic ash as a Martian analog, while acknowledging that Martian alteration processes and amorphous components complicate one-to-one comparisons. Attention was drawn to sulfur; Martian materials often exhibit higher sulfur content than many terrestrial volcanic ashes, underscoring that composition and the resultant reactive chemistry may differ materially from familiar Earth dusts. The information captured in Table 1, Key Physical and Chemical Characteristics of Lunar and Martian Dust, provides a review of known celestial dust properties.

**Table 1. Key Physical and Chemical Characteristics of Lunar and Martian Dusts (<20 μm)**

| Characteristics | Lunar Dust | Martian Dust |
|---|---|---|
| Particle Size | Peak size distribution in soil samples between 0.1 and 1 μm; respirable fraction present | Atmospheric seasonal average ~1.5 μm, >4 μm during dust events (5–6x larger than in lunar dust fraction); respirable fraction present |
| Morphology | Primarily jagged edges due to fracturing; amorphous glass agglutinates; only micrometeorite and solar wind weathering | Limited imaging; less characterized than lunar dust; chemical and physical weathering expected |
| Distribution | Comprises ~20 wt% of regolith; ubiquitous, but composition varies (mare vs highlands) | Relatively uniform due to global and seasonal dust storms, up to 80 km altitude |
| Composition | Basaltic (mare) to feldspathic (highlands) minerals; pervasive nanophase metallic iron; solar-wind–implanted volatiles; largely anhydrous; <1-2% crystalline silica | Basaltic igneous minerals; enrichments in S, Cl, Fe, nanophase oxides, Ca-sulfate; <1-2% crystalline silica |
| Perchlorates | None identified | 0.2–0.4 wt% in dusty soils |

## Presentation #3: Risk Assessment Context on Setting of a Martian Dust Exposure Limit (Torin McCoy)

### Agency Risk Posture and Principles

NASA's approach to human-system risks is shaped by mission context: isolation and confinement, distance from Earth, radiation, altered gravity, and the closed environment of spacecraft and habitats. Celestial dust exposure is one of the key closed-environment hazards within this framework. Accordingly, the agency's guiding principle is to set exposure limits that are protective of crew health yet mission risk-informed, balancing operational feasibility with credible health protection. To anchor dust decisions within accepted mission risk tolerance, the agency has used loss of crew thresholds as reference points: approximately 1 in 75 for cislunar missions, about 1 in 30 for lunar surface landings, and preliminary Mars studies indicating thresholds could be as high as 1 in 3. These values do not minimize health risk; rather, they contextualize dust related decisions within broader mission risk acceptance so that environmental controls and standards are aligned with overall mission posture.

### Mars Dust Context and Exposure Cadence

Mars' thin, arid atmosphere fosters long residence times for smoke-like suspended particles, with typical suspended dust sizes near 1–5 μm (average ~3.2 μm). In a Mars habitat particles will settle more quickly than on the Moon but less than on Earth due to differences in gravity and moisture. Dust storms are seasonal, with local and regional events occurring more frequently and planet encircling storms episodically lasting up to several months. These environmental realities set the stage for conservative planning around ingress, egress, and routine operations.

Operational cadence. Dust will be introduced through repeated EVAs and tracked into habitat volumes. A short stay (~30 day) mission therefore requires that exposure limits inform ECLSS design, cleaning strategies, and monitoring plans, enabling crews and providers to maintain compliance throughout daily operational rhythms.

### Leveraging Lunar Dust Evidence (LADTAG)

Both lunar and Martian dusts are silicate rich with minimal crystalline silica (typically <1–2%), a feature that distinguishes them from high silica terrestrial materials (e.g., quartz) which are often associated with pneumoconiosis. In controlled comparisons, lunar dust exhibited lower toxicity than quartz and greater toxicity than $TiO_2$, establishing a relative ranking useful for conservative extrapolation. Notably, surface reactivity (e.g., particle generated oxidants) did not correlate with pulmonary toxicity outcomes, suggesting that intrinsic mineral properties are stronger drivers of effect than short lived ROS effects. The LADTAG deliberations ultimately resulted in standard language published in NASA-STD-3001 Vol. 2, which limits lunar dust exposure to 0.3 mg/m$^3$ ($\leqslant$10 μm) as a time-weighted average for intermittent daily exposures up to 6 months. Based on Haber's rule which allows risk translation across exposure scenarios (risk = concentration x duration), this standard has been tailored into Artemis Program requirements of 1.6 mg/m$^3$ for 7-day continuous exposures and 0.4 mg/m$^3$ for 30-day continuous exposures. Values are derived from the 30-day rat inhalation point of departure (6.8 mg/m$^3$; No Observed Adverse Effect Level (NOAEL)) using species/time adjustments. These PELs reflect adoption of continuous exposure limits rather than intermittent or pre credited dust removal assumptions. The 0.4 mg/m$^3$ for 30-day continuous exposures requirement is considered most relevant to Martian dust exposure.

***LUNAR SURFACE REQUIREMENTS***

***7-day PEL: 1.6 mg/m$^3$***

*6.8 mg/m$^3$ (point of departure from 30 day rat inhalation study) ÷ 3 (species extrapolation) x (120 hrs study/168 hrs lunar exposure)*

***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)*

## Derivation of the Proposed 30-Day Mars Dust PEL: 0.1 mg/m$^3$ (continuous)

The lunar 30-day PEL of 0.4 mg/m$^3$ was used as a starting point. A Database Uncertainty Factor (DUF) of 3x was applied to address unknowns in actual Martian dust (since there has been no sample return), simulant differences, and potential Mars-specific hazards (e.g., higher iron content, other compounds). The rounded result (0.13 → 0.1 mg/m$^3$) yields a conservative continuous limit for a 30-day mission.

A larger DUF (e.g., 10x) would produce 0.04 mg/m$^3$, which is more stringent than the OSHA crystalline silica PEL (0.05 mg/m$^3$).[1] Given the consistently lower relative toxicity of

[1] Although the OSHA PEL is for 8 hours rather than a continuous 24-hour exposure duration, which would decrease the OSHA PEL to 0.0166 mg/m$^3$). Nevertheless, it is unlikely that dust on Mars is only 2.4 times less toxic than crystalline silica.

lunar/Mars dust versus quartz in controlled studies, the 3x factor strikes a pragmatic balance between conservatism and operational feasibility.

## Specific Chemical Considerations

Rover/lander data indicate total chromium content is approximately 0.3% (observed as $Cr_2O_3$), comparable to basaltic soils; presence of a significant quantity of $Cr^{6+}$ is not supported by current speciation analyses on Mars. At a dust PEL of 0.1 mg/m$^3$, the implied $Cr^{3+}$ exposure is ~0.0003 mg/m$^3$/day, preserving roughly an 80x margin to the interim $Cr^{3+}$ 180-day SMAC of 0.025 mg/m$^3$.

Phoenix and Curiosity soil measurements indicated 0.4–0.5 weight % perchlorate ($ClO_4^-$). Using the proposed dust exposure limit of 0.1 mg/m$^3$ and assuming 20 m$^3$/day inhalation, the inhaled perchlorate dose would be ~0.01 mg/day, which is ~0.3% of a 3 mg/day allowable intake for healthy, screened astronauts with adequate iodine. 3 mg/day is an interim SMAC derived from controlled human studies and risk-informed NASA practice. Comprehensive mission risk management should apportion intake across air, water, and crops (for example: dust 1%, water ~10%, crops ~89%) to ensure cumulative exposures remain within limits.

Manganese (Mn) is a potential neurotoxicity concern and has been measured in Mars soils by Spirit, Opportunity, and Curiosity rovers. Assuming an average Mn concentration of 0.38% in Mars dust, daily dust exposure at 0.1 mg/m$^3$ would result in 0.0004 mg/m$^3$ of Mn exposure, providing an approximate 20 x margin to the 180/1000-day Mn neurotoxicity SMAC (0.0078 mg/m$^3$) and far below the 30-day irritation threshold (0.3 mg/m$^3$). These margins reflect screening against conservative benchmarks while acknowledging uncertainties in bioaccessibility.

## Implementation & Monitoring Strategy

Two complementary approaches were considered for managing constituents in the dust matrix:

Option 1: “Constituent-informed” dust limit: use the dust PEL (0.1 mg/m$^3$) together with known constituent percentages to determine whether any inorganics would exceed health-based limits, assuming dust is controlled. If screening shows adequate margins, individual SMACs may be unnecessary for routine compliance. The benefits of this approach are 1) it is implementable with dust monitoring alone, and 2) it aligns risk communication with the actual dust context. The drawbacks of this approach are 1) it can be a communication challenge, and 2) it is best positioned as a screening approach, not full validation.

Option 2: Traditional approach with individual SMACs: establish and compare modeled constituent concentrations against constituent specific SMACs. The benefit of this approach is that it provides straightforward comparisons for modeling and design reviews. The drawbacks of this approach are 1) it is harder to implement in flight given limited constituent monitoring capability, and 2) chemicals with multiple potential exposure routes (e.g., perchlorate) still require intake-based limits.

## Panel Discussion Highlights: Martian Dust Health Effects

The panel questioned whether animal studies adequately addressed cancer endpoints in addition to inflammatory and fibrotic outcomes. Several participants emphasized that, in short duration rodent experiments, early indicators such as hyperplasia largely arise under lung overload conditions to which rats are susceptible, as well as being uniquely prone; to developing lung tumors with chronic exposure (Driscoll 2022). These mechanisms are not considered human relevant for setting limits in the mission durations under consideration. The group judged cancer risk to be an unlikely driver for initial Mars exposures. Fibrosis was recognized as requiring higher exposures over longer periods than planned for early missions, therefore the near-term focus should remain on preventing acute and subacute inflammatory responses associated with dust inhalation.

Participants then probed the perchlorate evidence base, asking whether the widely cited concentrations reflect scooped soils rather than the airborne dust fraction that would actually be tracked into a habitat. The strongest measurements to date derive from soil samples, with dust specific concentrations still uncertain, and noted that active aeolian sands show patterns suggesting lower perchlorate loading relative to dusty soils in some localities. Given the proposed mechanism of perchlorate formation on Mars (dust that is high in chloride being irradiated with ultraviolet light), it is logical to expect higher perchlorate in dust as opposed to soil. The group agreed that the dust fraction warrants targeted verification and that any limits should distinguish between soil versus dust as they pertain to different exposure routes.

A detailed exchange examined the role of particle size in clearance and toxicity for Mars versus lunar dust. The discussion reaffirmed that Mars dust particles are, on average, larger than the respirable fraction observed in lunar data, which can lengthen residence times and challenge macrophage clearance in some scenarios; however, it was also noted that smaller is not always more toxic, because ultrafine particles may clear more rapidly and behave differently physiologically. From a regulatory standpoint, the panel underscored that current occupational controls target crystalline silica polymorphs (e.g., quartz, cristobalite, tridymite), whereas amorphous silica is treated differently; consequently, near term Mars risk management should prioritize the poorly soluble particle behavior of the dust over assumptions drawn from terrestrial crystalline silica paradigms.

Finally, the panel revisited calcium sulfate phases and their behavior upon inhalation, asking whether hygroscopic sulfates like gypsum could harden in the lung environment. The response highlighted that in dust rich soils, the predominant phase is anhydrite (anhydrous $CaSO_4$) which is far less hygroscopic than gypsum. Moreover, dissolution tests indicate that calcium sulfate particles dissolve rapidly in lung fluid, shifting concern away from the intact mineral toward the released ionic species, which would then be evaluated under standard toxicological frameworks.

The panel then explored bioaccessibility of manganese embedded in amorphous components of dust (e.g., glass network modifiers). It was suggested that the slow dissolution kinetics of these amorphous phases likely mitigate immediate bioavailability; Mr. McCoy acknowledged this as a legitimate moderating factor that is not always integrated into analyses.

A portion of the discussion focused on exposure limit implementation, contrasting an 8-hour, work shift style assumption with a continuous exposure limit approach. While the existing lunar dust standard specifies intermittent exposures (derived from an 8 hour per day exposure assumption), NASA's implementation for operational environments favors a continuous limit and then averages measured exposure over the actual removal and cleanup time observed in the vehicle or habitat. The panel clarified numerical implications of this difference and discussed mission scenarios, noting that dust loading would be most intense early in the surface phase of the mission (during repeated surface activity) and then diminish as environmental control measures reduce airborne particulates during the transit home. This concept reinforces that continuous limit implementation can simplify verification across varying designs and mission timelines.

On engineering controls, the panel agreed that High-Efficiency Particulate Air (HEPA) filtration is a highly effective solution for fine particulates; the uncertainty lies not in efficacy but in provider-specific implementation (filter bed sizing, changeout frequency, and habitat volume). Mr. McCoy clarified that verification would require providers to demonstrate clearance performance relative to the selected exposure limit, and the panel noted that adding an explicit 8-hour removal assumption into the standard can create avoidable complexity (e.g., design-dependent alternative limits) compared with a continuous limit framework that decouples the standard from specific removal times while still enabling robust verification.

The panel discussed whether countermeasures or treatments should factor into deriving exposure limits and affirmed that the hierarchy of controls applies: preventive controls and design requirements take precedence, and clinical countermeasures are not built into the derivation of limits. An operational example highlighted that commonly used spacecraft biocides (such as iodine in water systems) can interact with certain dust constituents (e.g., perchlorate), illustrating why standards should avoid reliance on downstream treatment and instead aim for primary prevention backed by clear verification pathways for environmental controls.

Turning to overall dust versus constituent specific hazards, the panel endorsed an overall dust limit that envelopes the risks from currently recognized hazardous constituents, while explicitly keeping the door open to separate SMACs for specific elements if future data demonstrate they are not adequately screened by the dust limit. Participants highlighted the planetwide variability in dust composition and the practical challenges of comprehensive inflight monitoring for many individual species; in that context, an overall dust limit is a feasible default, with the option to lower the dust limit or add constituent specific requirements where modeling or evidence indicates a gap.

Regarding measurement capability, the panel confirmed that particulate monitoring will be required on future missions and that optical techniques are available through commercial off-the-shelf devices that have been proven in terrestrial industries; these can be supplemented with spaceflight-specific tools as needed. The panel agreed that there are no monitoring feasibility issues, but key constraints are mass, volume, power, and verification resources. Further, effective implementation hinges on risk communication, credibility, and disciplined selection of critical instrumentation within mission resource envelopes.

Finally, the panel emphasized that standards are part of an iterative process: they are established to anchor dialogue, guide engineering, and identify data gaps. This Martian dust standard is being established well ahead of crewed Mars missions, and as additional evidence accumulates, limits and rationales can be revised toward less or more conservative values.

# Summary of Day 2 Panel Discussions (Feb 27, 2026)

## Goal 1 — Assess NASA's proposed approach to an initial Martian dust PEL

The panel concluded that NASA's methodology is appropriate for early Mars missions, which must advance despite the limited toxicological data available for airborne Martian dust. This approach relies on the LADTAG lunar dust evidence base, findings from simulant and toxicology studies, and observations obtained from rover and lander operations.

Applying a database-uncertainty factor of three to this body of evidence yields a 30-day continuous PEL of 0.1 $mg/m^3$, a value the panel determined to be a justified and prudent starting point under current knowledge constraints. Members emphasized that the method is risk-informed and appropriately conservative given uncertainties in particle size distributions, surface reactivity, and speciation in the amorphous fraction. The group agreed that this framing allows programs to design to a clear mission health constraint while the evidence base matures.

During discussion, participants highlighted practical aspects of mission exposure: dust ingress is expected to occur in pulses associated with EVA suit returns and housekeeping events, followed by removal via habitat ECLSS/HEPA filtration. Because actual removal time is design dependent, several members preferred NASA's choice to express the PEL as a continuous limit and evaluate compliance using measured time-weighted averages, rather than assuming that dust would be cleared below the PEL within 8 hours. This avoids setting different effective limits across providers and keeps the standard verifiable.

## Goal 2 — Identify other chemical constituents requiring SMACs or special treatment

For near-term missions, the panel concurred that dust mass is the primary engineering and monitoring driver; however, selected constituents warrant parallel attention.

### Chromium (Cr)

Based on Mars in-situ data and iron valence arguments, the group deemed hexavalent chromium an unlikely driver of risk. Trivalent $Cr^{3+}$ is the predominant form of chromium with no immediate need for a $Cr^{6+}$ SMAC in the Mars dust context.

### Perchlorate ($ClO_4^-$)

The panel noted that because of the long duration of exploration activities, there are likely multiple exposure routes (air, water, crops) and recommended that perchlorate be handled through agency exposure management (analogous to iodine practice) rather than only controlling the inhalation exposure route. Any future perchlorate SMAC and monitoring plan should be crafted to account for intake apportionment across all exposure routes.

### Manganese (Mn)

With a provisional SMAC already in place, members supported keeping Mn in the background toolkit for modeling and verification, while acknowledging bio-accessibility depends on phase (e.g., glass vs. oxide) and may merit targeted follow-on assessment.

## Additional Chemical Constituents Considered by the Panel

In addition to chromium, perchlorate, and manganese, the panel engaged in substantive discussion regarding iron and its oxidative potential as a constituent of Martian dust. The conversation focused on the high iron content observed in Martian regolith, often exceeding 20% (by mass) iron oxide, which is significantly higher than terrestrial volcanic ash or lunar dust. Panelists noted that this elevated iron fraction, particularly in nanophase and amorphous forms, could be relevant to both surface reactivity and potential pulmonary toxicity. The group acknowledged that iron's ability to generate ROS via Fenton chemistry is well established, and that iron in the $Fe^{2+}$ state is especially important for hydroxyl radical production. However, the panel also recognized that $Fe^{3+}$ can be reduced in vivo, allowing for ROS generation even from ferric iron phases, albeit at a slower rate.

The panel reviewed available toxicological evidence including studies of Martian meteorites and lunar dust but found no clear correlation between iron-driven ROS and pulmonary toxicity in animal models. Studies have shown that ROS species can be derived from lunar dust simulants using an iron-mediated pathway (Turci et al. 2015 and Pavan et al. 2025). Harrington et al. (2017) indicated that while orders-of-magnitude differences in ROS generation could be demonstrated in meteorite samples, these did not translate to increased lung toxicity in mice. Nevertheless, the panel emphasized that uncertainty remains, particularly given the unique mineralogy and nanophase iron content of Martian dust, and recommended further investigation into iron's role, including its bio-accessibility and fractionation among mineral phases (e.g., glass vs. olivine). The group agreed that iron should be ranked above manganese in terms of relative risk, given its abundance and immediate surface reactivity, and recommended that iron be prioritized for further study and potential SMAC development, especially as new toxicological data become available.

Arsenic was briefly mentioned as a compound sometimes raised in the literature, but panelists generally dismissed it as a high-profile element unlikely to pose significant risk in the Martian context, based on current evidence. No panelist advocated for immediate SMAC development for arsenic, though the group remained open to revisiting this if new data emerged.

Overall, panelists recommended using the dust PEL as a screening backbone, and maintaining constituent-specific SMACs only where practical monitoring and mission sensitivities justify it (e.g., perchlorate for ISRU/crop pathways). A summary of specific toxicological considerations is presented in Table 2, Toxicology Insights and Concerns.

**Table 2. Toxicology Insights and Concerns**

| Category | Findings |
|---|---|
| Overall Toxicity | Mars dust simulants show slightly higher toxicity than lunar dust |
| Iron-driven Reactive Oxygen Species (ROS) | Relationship unclear, requires further study |
| Perchlorate Risk | Potential thyroid effects; multiple exposure routes |
| Manganese | Neurotoxicant; limits appear protective |
| Chromium | Trivalent form is more prevalent; hexavalent has much higher toxicity but likely low prevalence therefore low risk |
| Nanophase Materials | Bioaccessibility and toxicity uncertain; more research needed |

## Goal 3 — Consider pros/cons of separate SMACs vs. overall dust PEL

Panelists broadly accepted the use of an overall dust PEL standard as the principal means of health protection during missions, primarily because dust can be measured and controlled, whereas comprehensive inflight monitoring of all potential constituents is impractical. Controlling cabin dust was also seen as a way to cap particle-carried constituent exposures.

Several participants suggested maintaining or developing SMACs for selected high-concern constituents (examples discussed: perchlorate and manganese) as a second-tier protection tool. The intent is two-fold: 1) enable rapid evaluation if local variability produces unusually high constituent levels, and 2) demonstrate that the adopted dust limit remains protective when cross-checked against constituent-specific limits.

Regarding risk communication and implementation, participants found it clearer to separate the roles of a dust PEL and individual SMACs: use the dust PEL for particulate burden and use SMACs for specific chemicals of concern, keeping constituent standards independent of the dust standard to reduce confusion in monitoring and verification. They cautioned against embedding complex “dust-as-carrier” math inside the PEL language; instead, where deemed necessary, manage SMACs in parallel and audit against them as needed.

The measurement and control of dust peaks following suit ingress and cabin cleanup activities was highlighted; while the peak-control topic is also part of the standard-language discussion (Goal 4), it reinforces why the PEL-first approach is operationally workable, with SMACs available for spot checks and contingencies as onboard technology allows.

The group again underscored uncertainty surrounding iron, ROS, and oxidative potential (including nanophase iron and mineral phase differences). While prior work has not shown a consistent link between surface reactivity and pulmonary toxicity, panelists recommended tempering definitive statements and reviewing recent literature as the rationale is finalized.

## Goal 4 — Evaluate and refine the proposed standard language

The panel recommended making the continuous nature of the limit explicit in the requirement clause (not only in the rationale), to avoid misinterpretation and assumption of any particular dust clearance rate. Suggested edit: "…*below a continuous 24-hour time-weighted average of 0.1 mg/m$^3$ during exposure scenarios lasting up to 30 days.*" This preserves uniformity and allows each program to verify removal rates empirically.

Recognizing that exposures will be peak-driven (e.g., post-EVA), members advised explicitly addressing peaks either a) in the standard/rationale (e.g., a nuisance dust ceiling reference), or b) by specifying a shorter averaging window that bounds peak magnitudes (e.g., compliance evaluated over rolling 8–24 hour TWAs within the 30-day period). Several panelists suggested referencing a nuisance dust ceiling ($\approx$ 5 mg/m$^3$) to manage irritation and operational impacts; others preferred defining an averaging window to prevent bolus dust loading events from being diluted by a long 30-day average. The group agreed this is generally a program-level verification topic but asked that the standard acknowledge peak management explicitly.

Multiple experts asked that the uncertainty statement in the rationale reflect: a) higher bulk Fe typical of many Mars sites (often reported around ~20 weight % Fe-oxide at landing sites), b) the importance of Fe coordination (glass vs. olivine/magnetite) to surface reactivity, and c) the weak empirical linkage observed to date between lab ROS assays and pulmonary toxicity outcomes. The panel did not conclude that iron is a primary risk driver at the adopted PEL but recommended that iron/ROS uncertainty be explicitly flagged and that ongoing literature (meteorite/simulant studies, phase-specific bio-accessibility) be tracked as the standard evolves.

The panel discussed the need for crew-facing guidance distinguishing short-term irritation exceedances (nuisance dust) from longer-term health protection criteria, so crews and flight controllers do not over-react to brief spikes or under-react to accumulating exposure. It was also noted that standards are human-focused, whereas engineering requirements will translate the limit into dust load reduction performance (e.g., "reduce airborne concentration to $\leqslant$ X within Y hours post-ingress"), with verification aligned to actual monitoring data.

Moderators reminded the panel that NASA standards are implemented by programs with verification statements, where peak management, averaging windows, and monitoring modality are more fully defined. The panel appreciated this flow-down and requested that the rationale text make implementation guidance explicit such that the programs' plans to measure, average, and control peaks are consistent with the standard's intent.

## Cross-cutting technical topics discussed on Day 2

Members reiterated that the Mars dust size range includes respirable fractions; however, HEPA performs least efficiently near ~0.3 μm, and Mars dust often exceeds that size, implying effective removal once air is processed through HEPA filters. The panel agreed that actual removal times must be verified in each vehicle or habitat (volume, airflow, filter layout) rather than assumed.

For returning EVAs, the working Artemis value of 100 grams of dust per EVA per crewmember (all sizes) was noted; with typical respirable fractions of approximately 1%, the starting respirable mass per EVA is on the order of 1 g, underscoring the operational importance of pre-entry suit cleaning, airflow control, and prompt filtration to keep 24-hour averages within limits. Table 3, Engineering Controls and Exposure Drivers, presents a synopsis of operational engineering controls and exposure drivers.

**Table 3. Engineering Controls and Exposure Drivers**

| Factor | Summary |
|---|---|
| HEPA Filtration | Effective for Martian dust, minimum efficiency at ~0.3 μm |
| Air Turnover | Critical for post-EVA dust load management |
| Operational Exposure | Episodic exposure spikes expected, ~100 g/crew/EVA |
| Peak Exposures | A means to limit peaks is needed in the standard |

# Conclusions

The Martian Dust Working Group successfully compiled a comprehensive set of expert perspectives regarding Martian dust toxicology, exposure pathways, and mitigation strategies. The group endorsed the proposed NASA-STD-3001 technical requirement defining crew exposure limits for Martian dust (with recommendations for edits) as part of NASA's broader human health standards framework. A summary of the standards framework is in Table 4, Proposed Exposure Standard Framework, and the full standard text is included in the following section in its near-final form (the panel's recommendations have been incorporated; any additional edits will likely be limited to editorial).

**Table 4. Proposed Exposure Standard Framework**

| Component | Recommendation |
|---|---|
| Draft Limit | 0.1 mg/m$^3$ continuous exposure |
| Exposure Averaging | Continuous basis preferred |
| Individual SMACs | Not required, but recommended for key chemicals (e.g., Mn, perchlorates) especially when multiple exposure routes are likely |
| Monitoring Strategy | Dust-based monitoring recommended |

# Proposed NASA-STD-3001 Martian Dust Technical Requirement *(includes post-discussion modifications)*

Minor updates to the rationale for *[V2 6153] Celestial Dust Monitoring and Alerting* are proposed to account for the addition of the new Martian dust standard:

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

> *[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. Celestial dust monitoring frequency and particle size fraction are 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 and [V2 6253] Martian Dust Contamination. There may be other specific mission scenarios (e.g., surface launch vehicle docking to orbital vehicle) where dust monitoring may be required.]*

The draft Martian dust exposure standard that was proposed to the panel was:

**[V2 6253] Martian Dust Contamination**
The system shall limit the concentrations of Martian dust particles less than 10 µm in size in the habitable atmosphere below a time-weighted average of 0.1 mg/m$^3$ during exposure scenarios lasting up to 30 days in duration.

*[Rationale: This exposure limit leverages toxicological knowledge from lunar dust as detailed in peer-reviewed studies completed by the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) (Lam et al., 2013). While there are differences between lunar and Martian dust, there are toxicological and geological similarities that are relevant in the context of inhalation toxicological risk assessment. For example, both lunar and Martian dusts are characterized by having similarly low levels of crystalline silica (Morrison et al, 2024), which is an important factor in hazard assessment. Comparative inhalation toxicity studies on lunar and Martian simulants suggest that Martian dust toxicity is similar, but perhaps slightly higher in toxicity as compared to lunar dust (Lam et al., 2002). Conversely, the average particle size of Martian dust is likely larger than lunar dust (e.g., Park et al., 2008, Lam et al, 2002), which may result in fewer particles that become deeply entrained within the respiratory tract, and consequently more favorable health outcomes. Although Martian dust has higher average iron content than lunar dust, this is expected to have a negligible effect on its inherent toxicity (Lam et al. 2022).*

*Translation of [V2 6053] Lunar Dust Contamination into a 30-day continuous exposure limit results in a value of 0.4 mg/m$^3$. For Martian dust, the exposure limit was lowered by an additional safety factor of 3 to account for database uncertainty (lack of data for authentic Martian dust) in risk extrapolation. A 30-day exposure limit was established because this is the approximate duration of a surface stay for an opposition-class (short stay) Mars mission. It assumes that further exposure to Mars dust will be effectively mitigated by the return vehicle ELCSS during the longer transit phase. This limit will need to be reevaluated if longer surface mission stays are anticipated and is subject to ongoing reassessment as more data regarding Martian dust become available. The ability to meet this exposure standard will depend upon factors such as the amount and frequency of dust introduction, mitigation best practices, and ECLSS removal rates.*

*It is noteworthy that there are extensive geologic and chemical data available from Mars rover missions and other observational endeavors. These data indicate the presence of certain toxic substances in dust (e.g., perchlorate, manganese) that can exert their own separate chemical-specific toxic effects. The individual chemical exposures should be compared with applicable spacecraft maximum exposure limits (e.g., Romoser et al,* *2019), although it is possible that they will be shown to be adequately protected through implementation of this Martian dust limit. This potential for other contributing chemicals of health concern is a key distinction for Mars that is generally not relevant with lunar dust exposures. Finally, this requirement does not account for non-airborne sources of potential Martian dust chemical constituent exposure that may be applicable to a mission design, such as in-situ resource utilization (e.g., perchlorate dissolution from Mars regolith into water and subsequent uptake by food crops).]*

After review and modification by the panel and NASA subject matter experts, the proposed Martian dust standard is:

**[V2 6253] Martian Dust Contamination**
The system shall limit the concentrations of Martian dust particles less than 10 µm in size in the habitable atmosphere below a 24-hour time-weighted average of 0.1 $mg/m^3$ during exposure scenarios lasting up to 30 days in duration.

*[Rationale: This exposure limit leverages toxicological knowledge from lunar dust as detailed in peer-reviewed studies completed by the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) (Lam et al., 2013). While there are differences between lunar and Martian dust, there are toxicological and geological similarities that are relevant in the context of inhalation toxicological risk assessment. For example, both lunar and Martian dust are characterized by having similarly low levels of crystalline silica (Papike et al., 1991, McCoy, 2025, Morrison et al., 2024), which is an important factor in hazard assessment. Comparative inhalation toxicity studies on lunar and Martian simulants suggest that Martian dust toxicity is similar, but perhaps slightly higher in toxicity, as compared to lunar dust (Lam et al., 2002). Conversely, the average particle size of Martian dust is likely larger than lunar dust (e.g., Park et al., 2008, Lam et al., 2002), which may result in fewer particles that become deeply entrained within the respiratory tract, and consequently more favorable health outcomes. Martian dust has higher average iron content than lunar dust; inherent toxicity has been shown to be low (Lam et al. 2022), however there are significant unknowns regarding oxidative potential.*

*Translation of [V2 6053] Lunar Dust Contamination into a 30-day continuous exposure limit results in a value of 0.4 $mg/m^3$. For Martian dust, the exposure limit was lowered by an additional safety factor of 3 to account for database uncertainty (lack of data for authentic Martian dust) in risk extrapolation. A 30-day exposure limit was established because this is the approximate duration of a surface stay for* *an opposition-class (short stay) Mars mission. It assumes that further exposure to Martian dust will be effectively mitigated by the return vehicle ELCSS during the longer transit phase. This limit will need to be reevaluated if longer surface mission stays are anticipated and is subject to ongoing reassessment as more data regarding Martian dust become available. 24-hour time-weighted average is included in the standard to provide a reasonable operational band that can accommodate periods of higher dust exposure while still providing protection. Peak dust exposure levels should be limited to 10 mg/m$^3$ (100-fold the 30-day permissible exposure limit (PEL)) to minimize the risk of acute health effects and to increase the likelihood of maintaining the 24-hour time-weighted average. While this recommended peak value is above the OSHA limit of 5 mg/m$^3$ for respirable nuisance dust, the Occupational Safety and Health Administration (OSHA) limit is applied over an 8-hour time-weighted average (OSHA, 2026); the recommended Martian dust peak exposure of 10 mg/m$^3$ is to be applied as an instantaneous peak value with the intention of limiting bolus exposures during habitat ingress following surface activities. The ability to meet this exposure standard will depend upon factors such as the amount and frequency of dust introduction, mitigation best practices, and ECLSS removal rates.*

*Data from Mars rover missions indicate the presence of certain toxic substances in dust (e.g., perchlorate, manganese) that can exert their own separate chemical-specific toxic effects. The individual chemical exposures should be compared with applicable spacecraft maximum exposure limits (e.g., Romoser et al., 2019) although based on available data, implementation of this Martian dust limit will also protect from these compounds. The potential for other contributing chemicals of health concern is a key distinction for Mars that is generally not relevant with lunar dust exposures. Finally, this requirement does not account for non-airborne sources of potential Martian dust chemical constituent exposure that may be applicable to a mission design, such as in-situ resource utilization (e.g., perchlorate dissolution from Mars regolith into water and subsequent uptake by food crops).]*

# References


Achilles, C. N., Downs, R. T., Ming, D. W., Rampe, E. B., Morris, R. V., Treiman, A. H., ... & Morookian, J. M. (2017). Mineralogy of an active eolian sediment from the Namib dune, Gale crater, Mars. Journal of Geophysical Research: Planets, 122(11), 2344-2361.

Arvidson, R. E., Gooding, J. L., & Moore, H. J. (1989). The Martian surface as imaged, sampled, and analyzed by the Viking landers. Reviews of Geophysics, 27(1), 39-60.

Bandfield, J. L., & Smith, M. D. (2003). Multiple emission angle surface–atmosphere separations of Thermal Emission Spectrometer data. Icarus, 161(1), 47-65.

Bandfield, J. L., Glotch, T. D., & Christensen, P. R. (2003). Spectroscopic identification of carbonate minerals in the Martian dust. Science, 301(5636), 1084-1087.

Battalio, M., & Wang, H. (2021). The Mars Dust Activity Database (MDAD): A comprehensive statistical study of dust storm sequences. Icarus, 354, 114059.

Berger, J. A., Schmidt, M. E., Gellert, R., Campbell, J. L., King, P. L., Flemming, R. L., ... & Desouza, E. (2016). A global Mars dust composition refined by the Alpha-Particle X-ray Spectrometer in Gale Crater. Geophysical Research Letters, 43(1), 67- 75.

Berger, J. A., Gellert, R., Boyd, N. I., King, P. L., McCraig, M. A., O'Connell-Cooper, C. D., ... & Yen, A. S. (2020). Elemental composition and chemical evolution of geologic materials in Gale Crater, Mars: APXS results from Bradbury landing to the Vera Rubin ridge. Journal of Geophysical Research: Planets, 125(12), e2020JE006536.

Bickel, V. T., Almeida, M., Read, M., Schriever, A., Tirsch, D., Hauber, E., ... & Roatsch, T. (2025). Dust devil migration patterns reveal strong near-surface winds across Mars. Science advances, 11(41), eadw5170

Bishop, J. L., Murchie, S. L., Pieters, C. M., & Zent, A. P. (2002). A model for formation of dust, soil, and rock coatings on Mars: Physical and chemical processes on the Martian surface. Journal of Geophysical Research: Planets, 107(E11), 7-1.

Blake, D. F., Morris, R. V., Kocurek, G., Morrison, S. M., Downs, R. T., Bish, D., ... & Feldman, S. (2013). Curiosity at Gale crater, Mars: Characterization and analysis of the Rocknest sand shadow. Science, 341(6153), 1239505.

Braverman LE, Pearce EN, He X, Pino S, Seeley M, Beck B, Magnani B, Blount BC, Firek A. Effects of six months of daily low-dose perchlorate exposure on thyroid function in healthy volunteers. J Clin Endocrinol Metab. 2006 Jul;91(7):2721-4. doi: 10.1210/jc.2006-0184. Epub 2006 Apr 24. PMID: 16636123.

Clancy, R. T., Wolff, M. J., Whitney, B. A., Cantor, B. A., Smith, M. D., & McConnochie, T. H. (2010). Extension of atmospheric dust loading to high altitudes during the 2001 Mars dust storm: MGS TES limb observations. Icarus, 207(1), 98-109.

Davila AF, Willson D, Coates JD, McKay CP. Perchlorate on Mars: a chemical hazard and a resource for humans. *International Journal of Astrobiology*. 2013;12(4):321-325. doi:10.1017/S1473550413000189

Driscoll KE. Review of Lung Particle Overload, Rat Lung Cancer, and the Conclusions of the Edinburgh Expert Panel-It's Time to Revisit Cancer Hazard Classifications for Titanium Dioxide and Carbon Black. Front Public Health. 2022 Jul 28;10:907318. doi: 10.3389/fpubh.2022.907318. PMID: 35968415; PMCID: PMC9366718.

Forget, F., & Montabone, L. (2017, July). Atmospheric dust on Mars: A review. 47th International Conference on Environmental Systems.

Forward, K. M., Lacks, D. J., & Sankaran, R. M. (2009). Charge segregation depends on particle size in triboelectrically charged granular materials. Physical review letters, 102(2), 028001.

Glavin, D. P., et al. (2013), Evidence for perchlorates and the origin of chlorinated hydrocarbons detected by SAM at the Rocknest aeolian deposit in Gale Crater, J. Geophys. Res. Planets, 118, 1955–1973, doi:10.1002/jgre.20144

Hamilton, V. E., H. Y. McSween Jr., and B. Hapke (2005), Mineralogy of Martian atmospheric dust inferred from thermal infrared spectra of aerosols, J. Geophys. Res., 110, E12006, doi:10.1029/2005JE002501.

Harrington, A.D., McCubbin, F.M., Kaur, J., Smirnov, A., Galdanes, K., Schoonen, M.A., Chen, L., Tsirka, S.E., & Gordon, T. (2017). Acute Meteorite Dust Exposure and Pulmonary Inflammation - Implications for Human Space Exploration.

Horwell, C.J., Fenoglio, I., & Fubini, B. (2007). Iron-induced hydroxyl radical generation from basaltic volcanic ash. Earth and Planetary Science Letters, 261, 662-669.

Johnson, J. R., Grundy, W. M., & Lemmon, M. T. (2003). Dust deposition at the Mars Pathfinder landing site: Observations and modeling of visible/near-infrared spectra. Icarus, 163(2), 330-346.

JSC 20854 Spacecraft Maximum Allowable Concentrations for Airborne Contaminants (SMACs). Human Health and Performance Directorate. NASA. 02/11/2026. https://www.nasa.gov/wp-content/uploads/2026/02/jsc-20584-smacs-rev-d.pdf

Knight, A. L., VanBommel, S. J., Ganly, B., Yingst, R. A., Schmidt, M. E., Martínez, G. M., ... & Hurowitz, J. A. (2024). Dust Accumulation on the PIXL Calibration Target: Phosphorus Enrichment and Role of Electrostatic Effects. LPI Contributions, 3007, 3393.

Krauss, C. E., Horanyi, M., & Robertson, S. (2003). Experimental evidence for electrostatic discharging of dust near the surface ofMars. New Journal of Physics, 5(1), 70.

Lam CW, James JT, McCluskey R, Cowper S, Balis J, Muro-Cacho C. Pulmonary toxicity of simulated lunar and Martian dusts in mice: I. Histopathology 7 and 90 days after intratracheal instillation. *Inhal Toxicol.* 2002 Sep;14(9):901-16. doi: 10.1080/08958370290084683. PMID: 12396402.

Lam CW, Scully RR, Zhang Y, Renne RA, Hunter RL, McCluskey RA, Chen BT, Castranova V, Driscoll KE, Gardner DE, McClellan RO, Cooper BL, McKay DS, Marshall L, James JT. Toxicity of lunar dust assessed in inhalation-exposed rats. *Inhal Toxicol.* 2013 Oct;25(12):661-78. doi: 10.3109/08958378.2013.833660. PMID: 24102467.

Lam CW, Castranova V, Zeidler-Erdely PC, Renne R, Hunter R, McCluskey R, Scully RR, Wallace WT, Zhang Y, Ryder VE, Cooper B, McKay D, McClellan RO, Driscoll KE, Gardner DE, Barger M, Meighan T, James JT. Comparative pulmonary toxicities of lunar dusts and terrestrial dusts ($TiO_2$ & $SiO_2$) in rats and an assessment of the impact of particle-generated oxidants on the dusts' toxicities. *Inhal Toxicol*. 2022;34(3-4):51-67. doi: 10.1080/08958378.2022.2038736. Epub 2022 Mar 16. PMID: 35294311.

Lasue, J., Cousin, A., Meslin, P.-Y., Mangold, N., Wiens, R. C., Berger, G., et al. (2018). Martian eolian dust probed by ChemCam. Geophysical Research Letters, 45, 10,968–10,977. https://doi.org/10.1029/2018GL079210

Lasue, J., Meslin, P. Y., Cousin, A., Forni, O., Anderson, R., Beck, P., ... & Supercam Team. (2023, March). Supercam first shots: dust composition and variability. In 54th Lunar and Planetary Science Conference 2023 (Vol. 54, p. 2244).

Lemmon, M. T., Guzewich, S. D., McConnochie, T., de Vicente-Retortillo, A., Martínez, G., Smith, M. D., et al. (2019). Large dust aerosol sizes seen during the 2018 Martian global dust event by the Curiosity rover. Geophysical Research Letters, 46, 9448–9456. https://doi.org/10.1029/2019GL084407

Leshin, L. A., Mahaffy, P. R., Webster, C. R., Cabane, M., Coll, P., Conrad, P. G., ... & Fabre, C. (2013). Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity rover. science, 341(6153), 1238937.

Madsen, M. B., Goetz, W., Bertelsen, P., Binau, C. S., Folkmann, F., Gunnlaugsson, H. P., ... & Yen, A. S. (2009). Overview of the magnetic properties experiments on the Mars Exploration Rovers. Journal of Geophysical Research: Planets, 114(E6).

McCoy JT. Addressing the Myths: Human Health Risk Assessment Context for Lunar Dust. 54th International Conference on Environmental Systems (ICES-2025-17), 13–17 July 2025, Prague, Czech Republic. NASA Johnson Space Center.

Ming, D. W., & Morris, R. V. (2017, June). Chemical, mineralogical, and physical properties of Martian dust and soil. In Dust in the atmosphere of Mars and its impact on human exploration workshop (No. JSC-CN-39581).

Morris, R. V., Agresti, D. G., Lauer Jr, H. V., Newcomb, J. A., Shelfer, T. D., & Murali, A. V. (1989). Evidence for pigmentary hematite on Mars based on optical, magnetic, and Mossbauer studies of superparamagnetic (nanocrystalline) hematite. Journal of Geophysical Research: Solid Earth, 94(B3), 2760-2778.

Morris, R. V., Klingelhoefer, G., Schröder, C., Rodionov, D. S., Yen, A., Ming, D. W., ... & Arvidson, R. E. (2006a). Mössbauer mineralogy of rock, soil, and dust at Meridiani Planum, Mars: Opportunity's journey across sulfate-rich outcrop, basaltic sand and dust, and hematite lag deposits. Journal of Geophysical Research: Planets, 111(E12).

Morris, R. V., Klingelhoefer, G., Schröder, C., Rodionov, D. S., Yen, A., Ming, D. W., ... & Arvidson, R. E. (2006b). Mössbauer mineralogy of rock, soil, and dust at Gusev crater, Mars: Spirit's journey through weakly altered olivine basalt on the plains and pervasively altered basalt in the Columbia Hills. Journal of Geophysical Research: Planets, 111(E2).

Morrison SM, Blake DF, Bristow TF, Castle N, Chipera SJ, Craig PI, Downs RT, Eleish A, Hazen RM, Meusburger JM, et al. Expanded Insights into Martian Mineralogy: Updated Analysis of Gale Crater's Mineral Composition via CheMin Crystal Chemical Investigations. *Minerals*. 2024, 14, 773. https://doi.org/10.3390/min14080773

National Research Council. 2005. Health Implications of Perchlorate Ingestion. Washington, DC: The National Academies Press.

Occupational Safety and Health Administration. (2026). Air contaminants (29 C.F.R. § 1910.1000, Table Z-1). U.S. Department of Labor. https://www.ecfr.gov/current/title-29/subtitle-B/chapter-XVII/part-1910/section-1910.1000

Ojha, L., Lewis, K., Karunatillake, S., & Schmidt, M. (2018). The Medusae Fossae Formation as the single largest source of dust on Mars. Nature communications, 9(1), 2867.

Park J, Liu Y, Kihm KD, Taylor LA. Characterization of lunar dust for toxicological studies. I: Particle size distribution. *J Aerosp Eng.* 2008 Oct;21(4):266–71. doi: 10.1061/(ASCE)0893-1321(2008)21:4(266).

Papike J, Taylor L, Simon S (1991) Lunar Minerals. In: Heiken GH, Vaniman DT, French BM (eds) Lunar Sourcebook: A User's Guide to the Moon, Chapter 5. Cambridge University Press, New York, pp. 121–181.

Pavan, C., Bianco, P., Tammaro, O., Castellino, M., Marocco, A., Petriglieri, J. R., Tomatis, M., Pansini, M., Esposito, S., Turci, F. (2025). Atmospheric environment shapes surface reactivity of Fe(0)-doped lunar dust simulant: Potential toxicological implications.

Journal of Hazardous Materials, 492, 138096. https://doi.org/10.1016/j.jhazmat.2025.138096

Pike, W. T., Staufer, U., Hecht, M. H., Goetz, W., Parrat, D., Sykulska-Lawrence, H., ... & Madsen, M. B. (2011). Quantification of the dry history of the Martian soil inferred from in situ microscopy. Geophysical Research Letters, 38(24).

Romoser AA, Ryder VE, McCoy JT. Spacecraft maximum allowable concentrations for manganese compounds in Mars dust. *Aerosp Med Hum Perform*. 2019; 90(8):709–719. https://doi.org/10.3357/AMHP.5264.2019

Turci, F., Corazzari, I., Alberto, G., Martra, G., & Fubini, B. (2015). Free-radical chemistry as a means to evaluate lunar dust health hazard in view of future missions to the Moon. Astrobiology, 15(5), 371–380. https://doi.org/10.1089/ast.2014.1216

Valantinas, A., Mustard, J. F., Chevrier, V., Mangold, N., Bishop, J. L., Pommerol, A., ... & Thomas, N. (2025). Detection of ferrihydrite in Martian red dust records ancient cold and wet conditions on Mars. Nature Communications, 16(1), 1712.

VanBommel, S., Berger, J., Knight, A., King, P., Dietrich, W., Lo, D., & Gellert, R. (2025). Beyond Bulk Chemistry: Enhancing the Science Return of Landed In Situ X-ray Spectrometers (No. EPSC-DPS2025-717). Presented at the EPSC-DPS2025, Copernicus Meetings. https://doi.org/10.5194/epsc-dps2025-717

Wang, A., Yan, Y., Jolliff, B. L., McLennan, S. M., Wang, K., Shi, E., & Farrell, W. M. (2020). Chlorine release from common chlorides by Martian dust activity. Journal of Geophysical Research: Planets, 125, e2019JE006283. https://doi.org/10.1029/2019JE006283.

Wang, A., Yan, Y., Houghton, J., Jolliff, B., &Wang, K. (2019). Iron Phase Transformations Induced by Plasma Chemistry During Martian Dust Events, abstract #2036 for 50th Lunar and Planetary Science Conference.

Wang JL, Rosenbaum JJ, Prasad AN, Raad RR, Putman EJ, Harrington AD, Aintablian H, Hynek BM. (2025). Potential health impacts, treatments, and countermeasures of Martian dust on future human space exploration. *GeoHealth*. 9, e2024GH001213. https://doi.org/10.1029/2024GH001213

Yen, A. S., Gellert, R., Schröder, C., Morris, R. V., Bell III, J. F., Knudson, A. T., ... & Zipfel, J. (2005). An integrated view of the chemistry and mineralogy of Martian soils. Nature, 436(7047), 49-54.

# Appendix A – Acronym List

| Acronym | Definition |
|---|---|
| ACR | Architecture Concept Review |
| AFM | Atomic Force Microscope |
| APXS | Alpha Particle X-ray Spectrometer |
| C&PNT | Communications and Positioning, Navigation, and Timing Systems |
| Ca | Calcium |
| $CaSO_4$ | Calcium Sulfate |
| CHAPEA | Crew Health and Performance Exploration Analog |
| Cl | Chlorine |
| $ClO_4^-$ | Perchlorate |
| $CO_2$ | Carbon Dioxide |
| Cr | Chromium |
| CRISM | Compact Reconnaissance Imaging Spectrometer for Mars |
| DUF | Database Uncertainty Factor |
| ECLSS | Environmental Control and Life Support System |
| EDL | Entry–Descent–Landing |
| EGA | Evolved Gas Analysis |
| EVA | Extravehicular Activity |
| Fe | Iron |
| $Fe_2O_3$ | Ferric Oxide |
| HEPA | High-Efficiency Particulate Air (filter) |
| ISRU | In Situ Resource Utilization |
| LADTAG | Lunar Airborne Dust Toxicity Assessment Group |
| LEO | Low Earth Orbit |

| | |
|---|---|
| LIBS | Laser-Induced Breakdown Spectroscopy |
| M2020 | Mars 2020 |
| MAHLI | Mars Hand Lens Imager |
| MARCI | Mars Color Imager |
| MFF | Medusa Fossae Formation |
| Mg | Magnesium |
| Mn | Manganese |
| MGS TES | Mars Global Surveyor Thermal Emission Spectrometer |
| MSL | Mars Science Laboratory |
| NOAEL | No Observed Adverse Effect Level |
| OMEGA | Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (Observatory for Mineralogy, Water, Ice, and Activity) |
| PEL | Permissible Exposure Limit |
| PIXL | Planetary Instrument for X-ray Lithochemistry |
| ROS | Reactive Oxygen Species |
| SAM | Sample Analysis at Mars |
| $SiO_2$ | Silicon Dioxide |
| SMAC | Spacecraft Maximum Allowable Concentration |
| S | Sulfur |
| $TiO_2$ | Titanium Dioxide |
| UV | Ultraviolet |
| Zn | Zinc |

# Appendix B – Agenda

**AGENDA – Day 1**

**Day 1 of Working Group:** Friday 2/20/2026, 9:00AM – 1:00PM CST
**Location:** Virtual

| | |
|---|---|
| **9:00AM–9:15AM** | **Introductions and Overview of the Goals**<br>Presenters: Dave Francisco (NASA) and Doug Ebert (KBR) |
| **9:15AM–9:45AM** | **Moon to Mars Architecture** (mission overview and challenges)<br>Presenter: Katie Borremans – NASA |
| **9:45AM–11:15AM** | **Martian Dust: Observations from Landers and Orbiters** (geological & mineralogical considerations)<br>Presenter: Liz Rampe – NASA |
| **11:15AM–11:25AM** | **Break** |
| **11:25AM–12:50PM** | **Risk Assessment Context on Setting of a Martian Dust PEL** (human health considerations & proposed methodology)<br>Presenter: Torin McCoy – NASA |
| **12:50PM–1:00PM** | **Closeout Instructions/Summary** |

**AGENDA – Day 2**

**Day 2 of Working Group**: Friday, 2/27/2026, 9:00AM – 12:30PM CST
**Location:** Virtual

| | |
|---|---|
| **9:00AM–9:30AM** | **Review of Day 1** |
| **9:30AM–11:00AM** | **Discussion on Issues and Forward Plans** |
| **11:00AM–11:15AM** | **Break** |
| **11:15AM–12:30PM** | **Finalize Recommendations and Closeout** |