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The Dust in the Atmosphere of Mars and Its Impact on the Human Exploration of Mars: A NESC Workshop

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August 2018

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Acknowledgments

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Special thanks to the final report peer reviewers:

- Michael Aguilar
- Steve Gentz
- Jon Haas
- Dexter Johnson
- Joseph Minow
- Cynthia Null

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NASA Engineering and Safety Center
Technical Assessment Report

The Dust in the Atmosphere of Mars and Its Impact on the Human Exploration of Mars: A NESC Workshop

July 12, 2018

Report Approval and Revision History

NOTE: This document was approved at the July 12, 2018, NRB. This document was submitted to the NESC Director on August 8, 2018, for configuration control.

Approved:	*Original Signature on File*	8/9/18
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Daniel Winterhalter, NESC Chief Scientist, JPL	07/12/18

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Technical Assessment Report

Technical Support Report

1.0 Notification and Authorization

The NASA Engineering and Safety Center (NESC) Chief Scientist provided support to produce an NESC final report on the "Dust in the Atmosphere of Mars and Its Impact on Human Exploration" workshop held June 13–15, 2017, in Houston, TX. This report follows the standard NESC report format to describe the findings, observations, and NESC recommendations developed by the workshop participants.

The key stakeholders for the final report are the Mars mission designers and engineers for the precursor missions and the crewed mission, and the NESC. Further stakeholders are the mission planners deciding on the payload selections for the Mars missions.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 8/16/18

Dr. Daniel Winterhalter Date

Significant Contributors:

Dr. Joel S. Levine Date

Dr. Russell Kerschmann Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Daniel Winterhalter	NESC Lead	JPL
Joel Levine	Technical Lead	LaRC (ret)
Russell Kerschmann	Medical and Life Science	ARC (ret)
Business Management		
Linda Moore	Program Analyst	LaRC/MTSO
Assessment Support		
Pamela Sparks	Project Coordinator	LaRC/AMA
Dee Bullock	Technical Editor	LaRC/AMA

3.1 Acknowledgements

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4.0 Executive Summary

With the increasing focus on a crewed mission to Mars in the 2039 time frame, many Mars-specific environmental factors are now being considered by NASA and other engineering teams. Learning from NASA's Apollo Missions to the Moon, where lunar dust turned out to be a significant challenge to mission and crew safety, attention is now turning to the dust in Mars' atmosphere and regolith. To start the process of identifying possible dust-caused challenges to human presence on Mars, and thus aid early engineering and mission design efforts, the NASA Engineering and Safety Center (NESC) Robotic Spacecraft Technical Discipline Team (TDT) conducted a Workshop entitled "Dust in the Atmosphere of Mars and Its Impact on Human Exploration" that was held at the Lunar and Planetary Institute (LPI), Houston, TX, June 13–15, 2017. For the purpose of the workshop, "Dust" was defined to mean regolith particulates light enough to be lifted into the atmosphere by naturally occurring processes such as weather, electrostatic characteristics, or saltation, as well as by anticipated human activities. Unless specifically mentioned, the context should clarify which form of dust is discussed.

The workshop addressed the following general questions:

1. What is known about Mars' dust in terms of its physical and chemical properties, its local and global abundance and composition, and its variability (Panel 1)?
2. What is the impact of Mars atmospheric dust on human health (Panel 2)?
3. What is the impact of Mars atmospheric dust on surface mechanical systems (e.g., spacesuits, habitats, mobility systems, etc.) (Panel 3)?

The approximately 70 participants from NASA centers, universities, and industry were divided into three panels according to their expertise and interest to discuss the above three questions (see Appendix A). With many presentations and much debate, each panel agreed to a number of findings and recommendations, but the three identified as having the highest priorities (one from each panel) are the following.

Highest priority finding from Panel 1 (addressing dust structure, composition, and chemistry): There is insufficient knowledge on the possibility of extant life on Mars. It is especially important to know if there are microbes present in the globally circulating dust for the purposes of planetary protection for a returned human mission. It is inevitable that this material will interact with humans and systems on Mars and some will be returned to Earth by the return mission. **Recommendation:** The question of life in the atmospheric dust can and should be addressed via Mars Sample Return. Because the atmospheric dust is globally mixed, the return and analysis of a single dust sample would be sufficient for this purpose. Life detection measurements (e.g., the lab on a chip, etc.) should also be included on a future Mars rover to search for extant life in near-surface materials that would be disturbed by human activities causing potential contamination.

Highest priority finding from Panel 2 (addressing dust impact on human health): There is currently insufficient information on the toxicological features of Mars dust to set standards for any duration of crew exposure. The prioritization of these investigations should be: 1. complete chemical speciation, 2. particle size distribution, 3. charge state, 4. component solubility, 5. porosity/surface to volume ratio, 6. hygroscopic properties, 7. bioavailability of grain components. **Recommendation:** Future Mars missions should include instrumentation to obtain missing toxicologically relevant in-situ measurements, preferably at multiple locations, and especially for respirable dust <10 microns for both regolith-based and wind-borne dust if possible. Similarly, any Mars sample return materials should be examined to provide this information, either by direct studies on the native material or indirectly through use of validated, authentic simulants.

Highest priority finding from Panel 3 (addressing dust impact to systems): There is insufficient knowledge of the dust particle size and frequency distribution and flux below 10μm down to a few nm, especially in the lower atmosphere and on the surface. Should the flux be appreciable, the small particles will enter the astronauts' environments (suit, habitat, etc.) in significant quantity, unless the habitats are engineered with impractical and expensive constraints. Also, other mechanical and electrical/electronic systems, as well as Concepts of Operations (CONOPS) and In-situ Resource Utilization (ISRU), will be affected. All environments and systems will experience the potentially detrimental effects of the dust. Knowledge of the dust distribution would help the program on many levels. The knowledge gap can be closed by appropriate instrument(s) on the Martian surface. Laboratory tests (e.g., with simulants) will be necessary, but are not sufficient. **Recommendation:** Conduct measurements on the Martian surface for an extended period of time (multiple seasons), preferably on multiple platforms if possible, and targeting the size range of 5nm–10μm. The measurements could be taken with a filtration system designed to capture the particles from the ambient air (preferred), in conjunction with a measurement technique (e.g., a micro-imager) to determine the desired dust characteristics. Mars exploration infrastructure designers could make conservative assumptions and engineer against them, but this adds to the cost of a human mission. These measurements should be collected early (well before cutting metal). For system designs, consider Mars 2020 mission environmental requirements. See Committee on Space Research (COSPAR) guidelines for planetary protection, especially for ≈10 nm (https://cosparhq.cnes.fr/).

In summary, the assembled experts concluded that dust in the atmosphere of Mars is an issue to be addressed well before spacecraft are built to carry humans to the red planet. In particular, measurements and experiments need to be taken and conducted on the surface of Mars by precursor landers to ascertain dust characteristics that will influence hardware design as well as provide toxicology data to safeguard crew health. In addition, dust samples need to be collected and examined for possible extant life, perhaps via a Mars Sample Return mission. Recent findings by the Curiosity rover team regarding the presence of complex organics and seasonal methane are important steps in this direction [1].

5.0 Workshop Motivation and Description

The impact of Mars atmospheric dust on human exploration has been a concern of engineers, medical researchers, and mission planners for many years. This is evidenced by a considerable body of work and publications such as the National Research Council Report [2] (and references therein), Mars Exploration Program Analysis Group Reports [3, 4] (and references therein), and many others. Mars' dust poses a multi-faceted problem, raising concerns about human health, impact on surface systems, e.g., spacesuits, habitats, mobility systems, and on crewed surface operations.

With the renewed focus by NASA and other space agencies on a crewed mission to Mars in the 2039 time frame, many Mars-specific environmental factors are now starting to be considered again by NASA and other engineering teams. Learning from NASA's Apollo Missions to the Moon, where lunar dust turned out to be a significant challenge to mission and crew safety, attention is turning again to the dust in Mars' atmosphere and regolith. Even though four NASA rovers have traversed Mars' landscape successfully for years now, and landers have made measurements of their landing environments, and orbiters provided excellent data on planetary and synoptic scales, even on mesoscales, detailed knowledge of the dust's characteristics, and how it might affect mechanical/electrical and human systems, is still sparse.

To start the process of revitalizing research into possible dust-caused challenges to the human presence on Mars, and thus aid early engineering and mission design efforts, the NESC Robotic Spacecraft TDT organized and conducted a Workshop on the "Dust in Mars' Atmosphere and Its Impact on the Human Exploration of Mars", held at the LPI, Houston, TX, June 13–15, 2017. The workshop addressed the following general questions:

1. What is known about Mars' dust in terms of its physical and chemical properties, its local and global abundance and composition, and its variability?
2. What is the impact of Mars atmospheric dust on human health?
3. What is the impact of Mars atmospheric dust on surface mechanical systems (e.g., spacesuits, habitats, mobility systems, etc.)?

For each of these three questions, workshop participants addressed the following:

- The identification of the status of current knowledge in each in each of these areas.
- The identification of gaps in our knowledge in each of these areas.
- Needed measurements and experiments to fill in the gaps of knowledge prior to the first human landing on Mars.

Workshop participants included Mars scientists and engineers, mission architects, mission planners and medical researchers, including physicians and toxicologists (67 researchers registered for the workshop. In addition, approximately 30 college students and LPI and NASA Johnson Space Center summer students and interns attended the workshop). The workshop attendees participated in one of three panels:

1. Mars Dust: Structure, Composition, Chemistry (Panel 1)
2. The Impact of Mars Dust on Human Health (Panel 2)
3. The Impact of Mars Dust on Surface Mechanical Systems and Surface Operations (Panel 3)

The list of workshop participants and their panel participation is contained in Appendix A. Each of the three panels had one or two moderators and a recorder. The moderators and recorders are also identified in Appendix A. Prior to forming panels, the entire workshop heard a series of eight invited plenary review papers (30 minutes each) by experts reviewing the subject areas to be discussed at the workshop. The plenary speakers are also listed in Appendix A.

Independent of (but concurrently with) the NESC workshop, NASA's Human Exploration and Operations Mission Directorate (HEOMD) has identified Engineering Long Poles for Getting Humans to the Surface of Mars (HEOMD, 2017). A "Long Pole" is an engineering or capability challenge that has major bearings on any mission due to the significant effort it takes to develop over a long period of time. A Long Pole, if left unresolved, could significantly delay or have a serious adverse impact on a particular mission. Two Mars atmospheric dust-related Long Poles are summarized below:

1. Long Pole 6 is to "Evaluate the Hazard Potential of Mars Regolith and Atmospheric Dust on Crew Health and Mars Surface Operations." The biological, toxicological and mechanical properties of the Martian regolith and atmospheric dust environment need to be characterized in order to evaluate their potential in impacting crew health, system reliability and forward and backward planetary protection policies. Specific properties that need to be better characterized include:

- The potential for the transport of organisms through globally circulating dust, which can influence planetary protection polices
- The mechanical properties of dust, which influence requirements for engineering systems, and their approach to system maintenance.

Why does this Long Pole need to be solved?

- To conform to planetary protection policies for mitigating forward (from Earth to Mars) and backward (from Mars to Earth) contamination.
- To ensure crew health and safety and reliable systems operation.

2. Long Pole 9 is "Surface Dust Filtration" (or more generally, "Surface Dust Mitigation"). Living on the Martian surface requires the development of substantially capable habitation systems. Habitats must keep crew members healthy and happy for the duration of the surface missions. Dealing with the dusty environment on Mars and keeping the dust below permissible limits (currently being determined) within the surface habitats will drive habitat design decisions.

Dust may affect material and mechanism selection, operating protocols and risk. The dust on Mars can embed in extravehicular activities, (EVAs) or inflatable fabrics, hatch seals, or mechanisms, causing leakage and mechanical abrasion damage over time. Very little is known about any charge that may be carried by dust, or, for that matter, what the background electric field is near the surface. Possible germane mechanisms for charge build-up and data from precursor landers need to be examined to ensure the safety of crew, structure, and avionics. Additionally, Martian dust is potentially toxic, causing deleterious physiological effects including, but not limited to, respiratory illness and eye/skin irritation. Martian dust contains fine-grained silicate minerals. If inhaled, the silicate dust would react with water in the lungs to create damaging chemicals. The dust also contains perchlorates, which are known to damage the thyroid gland.

The NESC workshop has addressed the Long-Pole concerns, and the publication of the NESC document as well as the workshop proceedings will be of benefit to HEOMD's efforts.

Because the scope of problems that dust presents to a crewed mission is large, the workshop discussed in this report is the first of probably several to focus on Dust in the Atmosphere of Mars. Possible solutions to the many problems cannot be enumerated in one 3-day workshop, nor even the question be asked in a well-focused manner for many anticipated problems. Rather, this workshop was a starting point for problem identification activities that will continue for years, with future workshops providing increasingly focused advice usable for engineering solutions.

6.0 Panel Discussion-Point Summaries

6.1 Mars Dust: Structure, Composition, Chemistry (PANEL 1)

Martian dust physical properties, such as particle size distribution, particle hardness, particle shape, clod size, clod hardness, particle density, friction angle, cohesion, adhesion, dielectric characteristics, magnetic effects, elemental composition, and reactivity have been modeled based on observations from surface rovers and orbital spacecraft [5].

6.1.1 Current State of Knowledge

Models indicate the following dust particle properties (see Table 6.1-1).

Table 6.1-1. Dust Particle Properties

Particle Size	0.1 to 2000 μm
Particle Hardness	1 to 7 on Moh's hardness scale
Dust Particles	tabular, angular, and rounded
Particle Density	2.6 to 3.0 g/cm3
Friction Angle	18 to 40 degrees
Dipole Moment	K' = 1.9d
Cohesion	0 to 20 kPa
Adhesion	0.9 to 79 Pa [6,7]

Observations indicate the dust is magnetic [8]. Direct measurements detected Si, Al, Fe, Mg, Ca, Ti, S, Cl, and Br in the soil [9]. The soil, probably slightly acidic, is generally oxidized but may be reactive. Electrical properties of the regolith are found in [10], [11], and [12],

6.1.2 Desired Future State of Knowledge

A characterization is necessary of the particulates that could be transported to hardware and infrastructure through the air (including both natural aeolian dust and particulates that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and *in situ* lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

The necessary measurements are of the particle shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of soil from a depth that might be affected by human surface operations. For individual measurements, priorities are: 1) Shape and size distribution and mineralogy, 2) Electrical, and 3) Chemistry. The panel reached no consensus on adding magnetic properties to this list.

For sites where air-borne dust naturally settles, a bulk regolith sample is sufficient—analysis of a separate sample of dust filtered from the atmosphere is desirable, but not required.

Obtaining a broad range of measurements on the same sample is considerably more valuable than a few measurements on each of several samples (this supports sample return).

Polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities should be studied. Measurement should be taken during the day in calm conditions representative of nominal EVA excursions. This is a transient effect and can only be measured *in situ*.

6.1.3 Dust Storms

Local, regional, and even global dust storms are likely to occur during a long-stay mission. Storms can last for months. Storm opacity in the cores may be large enough to reduce EVA times, delay departure times, and affect external maintenance of habitats. (e.g., Gulf War II dust storm [13,14])

Operations in a major dust storm can be stalled due to obscured visibility and adhering dust. On Mars, global dust storms can last for 3 months [15], with possible crew internment for long periods (especially if there is a passage of high opacity core regions). Mitigation strategies include designing low-maintenance habitats and EVA systems, and/or avoiding human occupation at times when storms are expected. The ability to predict the large seasonal storms has greatly improved with Mars Global Surveyor/Thermal Emission Spectrometer, but regional and local storms appear quasi-random [16]. To assess the risk, lander meteorological packages should also have the capability to assess dust density/opacity. A remote-sensing orbital weather station would have the capability to monitor dust storm frequency, size, occurrence, and thermodynamic characteristics over a long-term baseline, and act to alert surface-stationed astronauts of impending storm activity.

Electric fields in convective dust storms may exceed breakdown conditions/limits, leading to discharge, arcing, or radio frequency contamination. Discharge to an ascending vehicle is a potentially serious issue during takeoff (e.g., Apollo 12). High levels of atmospheric electricity may limit EVAs.

Dust storm electrification may cause arcing, affecting takeoff, ascent, and orbit insertion. An emission of non-thermal microwave radiation by a Martian dust storm was interpreted as stemming from lightning [17]. On the other hand, an attempt was made to detect lightning from orbit by Mars Express, which was, however, not successful [18]. Based on laboratory studies and terrestrial desert tests, there is a growing body of evidence that dust devils and storms may develop dipole-like electric field structures similar in nature to terrestrial thunderstorms [19]. Further, the field strengths may approach the local breakdown field strength of the Martian atmosphere, leading to discharges [20]. A hazard during the vulnerable human return launch from Mars would be a lightning strike to the ascending vehicle. Apollo 12 suffered a lightning strike at launch, upsetting the navigation and electrical system. During human occupation of Mars, dust storm discharges and induced electrostatic effects may also force human explorers to seek shelter, reducing EVA time, habitat maintenance, etc.

Mitigation strategies include avoidance of aeolian dust clouds both at launch and during human EVA periods. However, to date, there are no measurements of Martian atmospheric electricity to evaluate the consequences of the proposed risk. The panel’s Atmosphere Focus Team suggests placing an atmospheric electricity (DC and AC E-fields, conductivity) package on at least one future landed missions to assess the risk.

6.2 The Impact of Mars Dust on Human Health (PANEL 2)

6.2.1 Health Effects of Mars Dust: Human Health Effects Breakout Panel Summary

Panel 2 organized the Human Health Effects (HHE) breakout panel. This subpanel recommends that a research program be created to assess the toxic potential of Mars dust and to set crew dust exposure standards, as detailed later in this report. The pervasiveness of dust on the surface of Mars and in its atmosphere, lack of key data about its chemical and physical properties, and the required length of manned missions to the surface of Mars are factors that were considered by the panel in arriving at this recommendation.

For lunar dust, NASA scientists have the benefit of being able to study substantial quantities of native material (actual lunar soil/dust) carefully collected on the Moon and returned to Earth during the Apollo era. This is not currently the situation for Mars dust since no samples have ever been returned to Earth.

To address toxicity issues, further *in situ* examination of Mars dust by robotic instruments or examination of returned samples will be necessary. *In situ* analysis by robotic methods, however, is inherently limited compared to direct study with ground-based instruments. At the same time, given the complexity and expense of a proposed Mars sample return mission, there likely will not be enough returned Mars dust for full direct toxicology studies (studies using actual Mars dust). Development of toxicity standards will then depend on the use of Mars dust simulants. To qualify these simulants, mission planners will need to obtain more data on the relevant features of Mars dust, ultimately with the goal of producing requirements for environmental control systems, dust decontamination methods, medical capabilities, and other critical systems to prepare for Mars missions.

The primary finding of the HHE was that currently there is insufficient knowledge of the physical and chemical properties of Mars dust to set exposure standards for any duration of exposure to the dust. Correspondingly, for this highest priority finding, it was the recommendation of the panel that missing toxicologically relevant information be obtained by performing *in situ* analysis of Mars dust, or by performing analysis of actual Mars dust samples obtained from a sample return mission. It is noted that both approaches have limitations. In the case of *in situ* studies by robotic instruments, there will naturally be restrictions on the scope of what can be performed, including the fact that no live-animal studies could be carried out. Performing a full panel of toxicological studies on returned Mars samples would be similarly constrained due the small amount of material available. Consequently, extensive toxicological studies will ultimately depend on simulants that are well validated against native material.

The HHE determined that further missions directly examining Mars dust should focus primarily on the following, currently poorly characterized features of Mars dust (in order of importance):

1. complete chemical speciation
2. particle size distribution
3. charge state
4. component solubility
5. porosity/surface to volume ratio
6. hygroscopic properties

7. dust grain micro-morphology influencing bioavailability of toxic components
8. presence and nature of organic compounds in regolith dusts

These data should be collected at an early opportunity and analyzed so that high-fidelity simulants can be produced followed by short- and long-term toxicology studies, which are essential to assure crew health on Mars. The health standards developed by these studies should be established prior to setting requirements for the design of critical environmental control and other engineered systems.

6.2.2 Toxicological Aspects of Crew Dust Exposure

Human exposure to toxic dusts can result in a range of pathologic responses in multiple organ systems. The range and severity of pathological responses to these dusts are not known.

Some pathological effects of toxic dust exposure may be reversible and some may be irreversible. Pathologically irreversible responses to Mars dust may include pulmonary fibrosis, allergic sensitization as a result of pulmonary exposure or skin exposure, organ damage/failure, or neoplasia. Reversible effects may include inflammatory conditions, thyroid gland impairment, blood cell effects, and renal insufficiency. It was the shared opinion of the HHE that robotic sample return would not yield enough Mars dust to perform adequate direct (using actual Mars dust) long-term toxicity studies to exclude irreversible conditions. Instead, sample return material could be used to authenticate a range of simulants designed to bracket the toxicity of Mars dust.

The HHE regards the pulmonary toxicity of sub-10 micron particles as are common in airborne dust as among the most important consequences of Mars dust exposure, but all size particles can enter the gastrointestinal tract, and come in contact with eyes and skin, possibly causing significant pathology. Some members of the HHE pointed out that there are Mars dust contains heavy metals (e.g. manganese [21]), which may gain access to the central nervous system via the olfactory pathway. Therefore, all possible exposure modes should be considered. Without data from further *in situ* or sample return missions, these toxicity pathways cannot be evaluated. Unanticipated toxicity reactions could affect crew health and performance and jeopardize mission success.

The HHE recommends that the NASA Office of the Chief Health and Medical Officer (OCHMO) work with NASA toxicologists to set short- and long-term limits for crew exposure to various types of Mars dust for all routes of exposure. These exposure limits should consider both reversible and irreversible reactions to Mars dust.

Furthermore, environmental factors such as reduced gravity, space radiation, habitat gas pressure and oxygen content, and other special environmental conditions (on Mars or in space) may have a synergistic and exacerbating effect on the toxicity of dusts. The HHE finds that partial or microgravity can alter the delivery of aerosolized dust particles into the most sensitive parts of the lung [22], and that the high ultraviolet radiation on Mars can enhance the known toxicity of certain compounds in atmospheric or surface dust [23].

6.2.3 EVA Suits and Dust Effects on Human Health

It is known from work on the International Space Station that pressure interfaces between EVA suits and the human body can be sites of skin and nail damage. Some evidence of the abrasive effects of Mars dust may be deduced from known damage to rovers; however, future studies will need to be conducted about the interaction of skin and nails with fabrics and other materials inside proposed Mars EVA suits. Skin and nail breakdown at EVA suit pressure points may increase risk of infection and compromise the water barrier functions of skin [24] resulting in uncontemplated evaporative loss into the EVA environmental control systems.

Mars robotic precursor mission planners should develop and deploy appropriate instruments to the surface of Mars or in Mars sample return laboratories to directly measure the mechanical properties of Mars dust, including strength, abrasiveness, etc., including on models of human skin, nails, cornea, teeth, and respiratory mucosa if feasible. This item is heavily dependent on availability of *in situ* instruments, suitable returned samples, simulants, and yet-to-be designed suit materials.

6.2.4 Diagnostic and Treatment Considerations of Crew Dust Exposure

There are a variety of technologies already available for diagnosing and monitoring human physiological responses to toxic dusts. However, it was the opinion of the HHE that a complete menu of point-of-care medical technologies for following crew responses to Mars dust exposure is not available and its development is dependent on a full characterization of the properties of the dust. This would include, for example, methods for monitoring toxic reactions to chlorine oxyanions and metals known to be present in Mars Dust.

The HHE recommends that OCHMO, in coordination with the NASA Human Research Program and relevant medical operations groups, develop and flight qualify a menu of point-of-care tests for Mars missions, at least of the specificity and sensitivity sufficient to detect and monitor the known and likely effects of Mars dust exposure through multiple anatomic routes as indicated by toxicology studies. This item should be completed with enough time remaining to develop medical countermeasures prior to manned missions to the surface of Mars.

If a dust-related condition were to be diagnosed in a crew member, appropriate therapeutic measures must be undertaken to reverse or mitigate toxic reactions. Medical treatments specific for Mars dust exposure-induced disorders are not currently established and are dependent on the outcome of toxicology studies and development of a mission diagnostic test menu, to which mission medical personnel can refer to develop crew treatments according to their clinical practice guidelines

The HHE thus further recommends that OCHMO, the Human Research Program, and relevant medical operations groups develop and flight qualify medical countermeasures for treatment of exposure to Mars dust, especially for short-term and contingent high-dose bolus exposures, with completion prior to first manned mission to the Mars surface.

6.2.5 Structuring Toxicological Studies

While a solution will need to be devised for studying the toxicology of Mars dust in the absence of sufficient native material, control and suitable analog or simulant materials are also a necessary part of dust toxicology studies.

However, barring discovery of a Mars biohazard or a unique property of Mars dust never seen on Earth, it is the finding of the HHE that development of new or novel methods do not appear required to determine the most likely toxicological effects of Mars dust through known routes of exposure.

Standard terrestrial particulate controls are available, but large quantities (~kilograms) of toxicologically high-fidelity Mars dust simulants will also be required for toxicology studies. As has been specified by the HHE, more data on Mars dust properties will be needed from improved *in situ* measurements or directly from sample return material, with a goal of establishing Toxicity Equivalency Factors for the simulants. Suitable simulants may require that sophisticated manufacturing processes be developed, since existing terrestrial volcanic Mars dust simulants may not be sufficiently authentic at the microscopic level for human toxicology studies.

The HHE recommends that a NASA toxicology laboratory construct a complete plan of toxicology studies directed to set exposure standards for Mars dust based on current standard toxicological methods, including the use of multiple candidate Mars dust simulants, standard nuisance dusts, and highly toxic standards like freshly ground quartz and suitable organic materials in a variety of toxicology models, with the goal to bracket the likely physiological response to Mars dusts.

Regarding safe handling of sample return Mars dust, simulants, and standards and controls, procedures must be employed for handling potentially toxic dust samples in analytical laboratories. Mars sample return soil and dust, and high-fidelity simulants are unique laboratory materials for which no safety data sheets and safe processing protocols currently exist. For terrestrial processing and study of Mars sample return dust it is the opinion of the Panel that standard engineering and hazard controls and existing Personal Protective Equipment would be adequate for handling Mars dust; but this is assuming that no uncharacterized extraterrestrial life forms are present.

OCHMO should direct the development of a policy and procedure for laboratory containment and safe handling of Mars sample return material and Mars dust simulants. If evidence of a unique Mars biohazard exists, NASA should form contacts with the Centers for Disease Control to determine the type of containment required. Assuming no such evidence emerges, these policies and procedures can be formulated in the near-term, prior to any receipt of return samples or creation of high-fidelity simulants.

6.2.6 Recommendation for the Appointment of an Expert Panel to Advise OCHMO

In order to maximize current knowledge and assist in formulating requirements for further data collection by robotic precursor instrumentation and from analysis of returned Mars samples, the HHE recommends that OCHMO appoint a panel of experts in toxicology, Mars mineralogy, and human health and performance to advise the OCHMO on Mars dust toxicity studies, patterned on the prior Lunar Airborne Dust Toxicity Assessment Group assembled by OCHMO to set the exposure limits for lunar dust and related standards.

6.3 The Impact of Mars Dust on Surface Mechanical Systems and Surface Operations (PANEL 3)

The purpose of the mechanical systems and surface operations panel was to determine the key issues associated with operating mechanical systems successfully in the Martian environment. The panel anticipated that any risks associated with the presence of dust could be managed within the context of sound engineering design and practice. The need for Martian dust-like material for testing the mechanical systems will be extensive and can only realistically be managed by the use of appropriate simulants. This creates a need for an early characterization of simulants that are appropriate for mechanical testing and a categorization of the required mechanical systems and their dust-related issues. In addition, it will be crucial to establish standards for testing and qualification of mechanical systems.

6.3.1 How much more do we need to know about dust?

For development and testing of mechanical systems, the basic properties of the Martian dust and regolith, especially of that fraction smaller than 20 microns, must be well characterized. We need a good understanding of the dust properties and their effects before effective testing can be carried out. Information on a variety of properties, as a function of particle size, will be required including

- Particle morphology, including size distribution and particle shape distribution
- Chemical composition and mineralogical structure of the regolith
- Physical properties including hardness and abrasiveness
- Electrostatic properties, since electrostatic adhesion drives the accumulation of dust
- Thermal and optical properties
- Dust dynamics – How much and what size of particles will be lofted (electrostatically, tribomechanically) to become potential hazards to mechanisms and/or deposited on surfaces? At what altitude does the plume become an issue for the sensors?
- Chemical absorption composition
- Magnetic properties, since these may be used to develop a mitigation strategy

It is particularly important to determine the particle size distribution, as well as the particle flux. Should the flux be appreciable, small-sized particles will enter the astronauts' environments (suit, habitat, etc.) in significant quantity, unless the habitats are engineered with impractical and expensive constraints. Also, other mechanical and electrical/electronic systems, as well as CONOPS and ISRU, will be affected. Laboratory tests (e.g., with simulants) will be necessary, but are not sufficient. All environments and systems will experience the potentially detrimental effects of the dust. Knowledge of the dust distribution and flux would help the program on many levels.

Also important to know is the behavior of the electric field near the Martian surface, and the charge characteristics of the dust particles. Measurements of this type should be included in the design of one of the robotic missions.

The properties of the actual Martian dust can be used to develop a detailed specification of Martian dust simulants. These could be specified for individual mechanical components and environments. Work done at the Marshall Space Flight Center on simulants has resulted in the development of a method to evaluate the quality of any simulant of the regolith [25].

6.3.2 What types of mechanical systems and operational scenarios are envisioned in the Martian environment?

There is no doubt that technical systems will be critically affected by Martian dust during a mission timeline that may span years, or even decades. It is important to understand which systems and components are affected and how. It has been hypothesized that only a small number of crucial components will be affected by dust, in which case mitigation efforts can be concentrated on this subset.

Since testing will be an important part of developing dust-resistant mechanical systems, it will also be important to develop an appropriate simulant. The physical and chemical reactivity of the dust will be application and location specific, and the different chemical characteristics of the dust will have different effects on the mechanical systems. Some components of Martian dust could have long-term effects, which may necessitate the design of materials that are able to tolerate direct interaction with the Martian soil.

The design of the mechanical systems must take into account not only their operation in the Martian dust environment but also the fact that they will require maintenance and repair in the presence of dust. Dust accumulation on the surfaces of components will affect their properties, e.g. power generation and the thermal/optical properties necessary for heat retention/rejection. Dust will also affect exposed connectors, seals, and sealing surfaces of umbilicals. The suggestion of the panel is that systems should to be designed to be maintenance free. Designs should be modular for easy replacement of components and to allow for redundancy.

The mechanical components that require study are bearings, bushings, gears, ball-screws, seals, lubricants, rotating surfaces, and fasteners (latches, clamps, bolts etc.). In order to test these components there must first be a good understanding of the dust attributes. The different components must be designed to mitigate the extent to which the Martian dust environment impacts the performance and operation of the Martian mechanical systems. It was suggested that there could be a multitude of design mitigations. For example, there are many coatings that can be tailored for a particular application, but there is not one single coating appropriate for every application. Mitigation suggestions included:

- Surface coatings that repel the dust
- Removal of the dust
- Altering the local Martian surface environment
- Charged brushes
- Systems that are designed to be tolerant of the dust
- Redundant systems that use a combination of these approaches

The impact of the dust will depend on the basic operations concept, and therefore CONOPS needs to be developed with consideration of operations within a dusty environment. In particular, there is a need to be conscious of anthropogenic dust generation. There will be an additional set of requirements for components depending on where they are to be located.

Martian dust could also act as a means of transporting other contaminants. For example, radioactivity could be transported on dust from a nuclear reactor or radioisotope thermal generators. Berms can be built as barriers for nuclear systems, but over time, the beams will become radioactive.

6.3.3 What is the appropriate set of development and qualification tests necessary for the demonstration of successful mechanical systems operations in the Martian dust environment?

A methodology and approach for design and testing needs to be developed. There is a need to identify the effects of the dust on the functionality of the system components so that the testing can be done on the individual components. For example, what effect does the dust have on the function of electrical connection? How does rubbing by dust affect the components?

Based on testing that has been conducted thus far, this group hypothesized that once the sensitivities are understood, and mitigation strategies defined, a robust qualification test program can be developed to verify mechanical system performance in the Martian dust environment.

7.0 Findings, Observations, and NESC Recommendations (FOR)

Even though the three panels operated mostly independently, their FORs show a significant amount of overlap. This is not surprising, since all three depend significantly on the dust's basic properties and characteristics. Many of them are largely unknown and thus prompt similar investigation requirements in all Panels.

The FORs listed below have the overlap removed, but the information of which panel contributed to a particular Finding was maintained by including the *(Panel x)* indicator. The Observations represent the discussion points entertained by the respective panels and are useful here in supporting their Findings. Finally, the NESC Recommendations are given ordered by priority: Very High, High, Medium, and Low. Unless otherwise stated, the recommendations are directed towards future NASA Science Mission Directorate and HEOMD Mars mission offices.

7.1 Findings

F-1. There is insufficient knowledge on the possibility of extant life on Mars. It is especially important to know if there are microbes present in the globally circulating dust for the purposes of planetary protection for a returned human mission. It is inevitable that this material will interact with humans and systems on Mars and some will be returned to Earth by the return mission. ***(Panel 1)***

F-2. There is insufficient knowledge about the lethality of the Martian physical and chemical environment to terrestrial microbes. This information is critical for understanding the potential for forward contamination of Mars. ***(Panel 1, Panel 2)***

F-3. There is insufficient knowledge on the transport of potential viable organisms and its transport on atmospheric dust particles. ***(Panel 1, Panel 2)***

F-4. There is insufficient knowledge about how dust is lifted off the surface and how it moves through the lowest boundary layer of the atmosphere. This includes material mobilized by human activities. It will affect how far potentially contaminated material can spread from areas of human activities. ***(Panel 1, Panel 2*)**

F-5. Landing and crewed surface exploration and operations on Mars require improved and more accurate forecasting of Mars dust storms, a capability that needs to be developed. ***(Panel 1; Panel 3)***

F-6. Understanding the magnitude, duration, and characteristics of the most extreme dust storm event possible must be known prior to human exploration of Mars. ***(Panel 1, Panel 3)***

F-7. There is insufficient knowledge of the mineralogy and chemical composition of the Martian dust grains. ***(Panel 1, Panel 2, Panel 3)***

F-8. The mineralogy and chemical composition of dust grains would be important for understanding the performance of solar panels and related technologies. ***(Panel 1, Panel 3)***

F-9. Mars crew safety requires that toxicology-based limits on crew exposure to Mars dust be established prior to operations on the planetary surface. ***(Panel 2)***

F-10. Without toxicological exposure studies of all possible anatomic routes of exposure to Mars dust, the full range of medical, physiological and pathological responses resulting as a consequence of exposure and appropriate monitoring and countermeasures cannot be understood. ***(Panel 2)***

F-11. A complete menu of diagnostic testing technologies will need to be developed for manned Mars Missions; but to adequately address this requirement, full characterization of the toxicologically relevant features of Mars dust, and human pathological responses to it, must be available. ***(Panel 2)***

F-12. The treatments for any Mars dust-induced disease need to be determined. ***(Panel 2)***

F-13. An appropriate panel of mineral particulate control materials and authentic simulants to be used for research into the toxicity of Mars dust must be determined. ***(Panel 2)***

F-14. Mars gravity, radiation, and other special space environmental factors, including habitat reduced ppO_2 and other atmospheric alterations, may have an exacerbating/multiplicative health impact on any toxicological effects of Mars dust. ***(Panel 2)***

F-15. The effects of Mars dust in the interfaces between Mars EVA suits and the human body are not known. ***(Panel 2, Panel 3)***

F-16. It is the determination of the Panel that barring a unique Mars biohazard discovery, for ground studies no new or novel methods are required to determine any toxicological effects of Mars dust through any route of exposure. ***(Panel 2)***

F-17. For terrestrial processing and study of Mars sample return dust, it is the opinion of the Panel that standard engineering and hazard controls and existing Personal Protective Equipment would be adequate for handling Mars dust, but this is assuming that no uncharacterized extraterrestrial life-forms are present. ***(Panel 2, Panel 3)***

F-18. The dust particle size distribution (PSD) and the particle flux are not well known, especially for particles below 10 µm. Thus, there is insufficient knowledge to ascertain how and to what extent particles will interact with systems and subsystems (including crew) on the ground. ***(Panel 1, Panel 2, Panel 3)***

F-19. There is insufficient knowledge available to constrain the character of the electromagnetic environment, beyond what has been observed at existing rover locations. ***(Panel 3)***

F-20. There is insufficient knowledge available on the subject of electrical charge buildup within the upper or lower Martian atmosphere. While no lightning has ever been observed on Mars, questions of non-ionizing discharge, bleed-off, sparking, etc., are concerning. ***(Panel 3)***

F-21. It is unknown how long a charge on a dust particle will persist, and how it is dissipated. Also, there is insufficient knowledge about the charge/mass ratio of the dust particles in the Martian environment. Understanding of the dust charge characteristics may be useful to mitigate dust collection on structures and surfaces. ***(Panel 3)***

F-22. There are knowledge gaps in how the Martian dust adheres to natural and artificial surfaces. ***(Panel 3)***

7.2 Observations

O-1. It has been hypothesized that extant life may be present in the globally circulating atmospheric dust on Mars. However, no measurements on the surface of Mars have tested this hypothesis. ***(F-1)***

O-2. It is unknown how terrestrial microbes will interact with the physical and chemical environment of Mars. ***(F-2)***

O-3. No measurements on Mars have assessed the potential of forward contamination of Mars by viable organisms transported on atmospheric dust particles. ***(F-3)***

O-4. The atmospheric transport processes, the rate of transport and the transport distance of Mars atmospheric dust from contaminated sites of human activities is not known. ***(F-4)***

O-5. There is insufficient knowledge of the causes and modes of formation, propagation, integration, and duration of dust events to forecast their occurrence effectively. Dust storm forecasting on seasonal time scales seems to work fairly well, at least on global or synoptic scales. However, the capability for shorter-term forecasting on local scales in the lower atmosphere appears to be non-existent. Dust storm forecasting capabilities need to be improved to allow for advance notice on the order of days to weeks, depending on the application (e.g., for Entry, Descent, and Landing or Mars ascent it would be necessary to have at least short-term forecasting, longer-term forecasting would be needed for planning EVAs, especially if the rover were solar powered). Having advance warning of dust events may be critical to safeguarding systems, supplies, and resources at the habitation complex. ***(F-5)***

O-6. The severity range of the more extreme dust events is uncertain. In order to better constrain and understand Martian climate and weather, including the most extreme dust events, it is desired to have continued observations for as long as possible. The important parameters are: Wind strengths, optical depth, duration, deposition depths, electrical activity, vorticity. This dataset should be increased well in advance of human landing in order to better understand weather and climate and to constrain the most extreme dust storms in terms of wind speed, duration, atmospheric opacity, etc. ***(F-6)***

O-7. Measurements of the chemical and mineralogical composition of atmospheric and regolith dust grains are very few and very limited in geographical distribution. However, more detailed and geographical broader dust information is important to assess the dust’s toxicological effects on human health, the abrasive effects on surface structures, how the Martian dust adheres to natural and artificial surfaces (e.g., solar panels), and for ISRU purposes. ***(F-7, F-8, F-22)***

O-8. There is currently insufficient information on the toxicological features of Mars dust to set standards for any duration of crew exposure. The prioritization of these investigations should be: 1. complete chemical speciation, 2. particle size distribution, 3. charge state, 4. component solubility, 5. porosity/surface to volume ratio, 6. hygroscopic properties, and 7. bioavailability of grain components. ***(F-7)***

O-9. The panel determined that exposure to Mars dust through multiple anatomic routes of exposure could cause a pathological response, especially pulmonary entry of sub-10 µm particles, eye exposure of any size particles, and effect on bowel function and flora due to ingested dust. Toxic perchlorates and related chemicals present on Mars are highly soluble and could enter the circulatory system via multiple routes. ***(F-10)***

O-10. Some of the technologies for crew member clinical status evaluation in response to Mars dust exposure are already available, but some advanced technologies may need to be developed pending further information on Mars dust toxicity. ***(F-11)***

O-11. Developing medical therapies is beyond the scope of the panel. They will depend on outcome of toxicology studies and development of mission medical diagnostics. ***(F-12)***

O-12. Standard control materials for pulmonary and other toxicology studies are available from commercial and government sources. However, the authenticity of Mars dust simulants cannot be adequately validated without more data on Mars dust properties. Current Mars dust simulants created for ISRU applications and other macroscopic applications may not be suitable for human toxicology studies because pathological reactions in the lung and other organs may be dependent on microchemical and other unique features of native Mars dust. ***(F-13)***

O-13. Crew radiation exposure could lower the threshold for pulmonary and other organ system Mars dust toxicity. There is evidence from parabolic flight studies on humans that partial or microgravity can alter the delivery of aerosolized dust particles into the most sensitive parts of the lung. Environmental conditions on Mars may enhance the known toxicity of certain compounds in the atmosphere or regolith prior to crew exposure. ***(F-14)***

O-14. Skin abrasion or other pressure effects due to trapped dust at EVA suit pressure points can cause trauma or compromise the water barrier functions of human skin resulting in significant physiological water loss into environmental control systems, or increase the risk of skin infections even by the normal skin flora. Some knowledge of the abrasive effects of Mars dust can be deduced from damage to rovers; however, nothing is known about the interaction of Mars dust and the fabrics and other materials of conventional EVA suits. ***(F-15)***

O-15. Standard toxicology studies appear to be sufficient to define the potential medical/physiological impacts of Mars dust exposure. However, as-yet undiscovered unique properties of Mars dust would require the development of supplemental studies. ***(F-16)***

O-16. Safety procedures must be employed for handling Mars dust samples in analytical laboratories. Mars dust and high-fidelity simulants are laboratory materials for which no safety data sheets and safe processing protocols currently exist. ***(F-17)***

O-17. There is insufficient knowledge of the dust particle size-frequency distribution and flux below 10μm down to a few nm, especially in the lower atmosphere and on the surface. All environments and systems will experience the potentially detrimental effects of the dust. For example, how much dust will enter the crew cabin and other systems/instruments/facilities will probably depend on the particle size. Also, CONOPS scenarios and mechanisms to either mitigate or tolerate the dust environment will require the PSD information. These measurements should be collected very early. For system designs, consider Mars 2020 mission environmental requirements. See COSPAR guidelines for planetary protection, especially for ≈10 nm. Knowledge of the dust's size distribution and flux would help the program on many levels. ***(F-18)***

O-18. Mars' atmospheric electric field is unknown, and so is its interaction with dust. Local magnetic fields have been observed from orbit but necessarily only on large scales. Knowledge of the electric and magnetic environments will be needed for the designs of possible high-voltage power grids, avionics, power management systems, and electromagnetic interference. ***(F-19, F-20)***

O-19. The charge on the dust particles is unknown. The panel indicated concern about unknown charge separation and build-up potential. ISRU and some dust-mitigation systems can be affected by charged dust. Also, the charge density carried by dust particles is a consideration when building electrical infrastructure. ***(F-20, F-21)***

O-20. Martian dust has been observed to be relatively easily removed from surfaces where it has accumulated. It is this characteristic of the dust, through solar array removal during localized cleaning events, that has allowed both Spirit and Opportunity rovers to outlast their nominal mission duration. However, it is not known how and why the dust sticks to different materials, and in the absence of fortuitous cleaning events accumulation of dust will pose a danger to the mission. A comprehensive strategy to mitigate dust collection on structures and solar panels via design and/or dust physical properties must be developed. The amount of dust deposition is location dependent, and a comprehensive strategy must take that into account. ***(F-22)***

7.3 NESC Recommendations

The following recommendations are priority ordered with: Very High, High, Medium, Low.

R-1. **(priority: VERY HIGH)** The question of life in the atmospheric dust on Mars can and should be addressed via Mars Sample Return. Because the atmospheric dust is globally mixed, the return and analysis of a single dust sample would be sufficient for this purpose. Life detection measurements (e.g., the lab on a chip, etc.) should also be included on a future Mars rover to search for extant life in near-surface materials that would be disturbed by human activities causing potential contamination. ***(F-1; O-1)***

R-2. **(priority: VERY HIGH)** It is recommended that future Mars missions should include instrumentation to obtain missing toxicologically relevant in-situ measurements, preferably at multiple locations, and especially for respirable dust <10 microns for both regolith-based and wind-borne dust. ***(F-7, F-8)***

R-3. **(priority: VERY HIGH)** Mars sample return materials should be examined to provide information on the missing toxicology (R-2), either by direct studies on the native material or indirectly through use of returned samples to validate authentic simulants. ***(F-7; O-8)***

R-4. **(priority: VERY HIGH)** Measure the size distribution and flux of the dust particles on the Martian surface in the ambient air, continuously for an extended period of time (multiple seasons), preferably on multiple platforms. A wide size range should be measured, from millimeter size downwards. Particularly important is the size range of 5nm–10µm. ***(F-4, F-18; O-4, O-17)***

R-5. **(priority: VERY HIGH)** Laboratory experiments should be performed under simulated Mars conditions to better constrain how long terrestrial microbes can survive and remain viable under these conditions. ***(F-2, F-3, F-4; O-2, O-3, O-4)***

R-6. **(priority: HIGH)** It is recommended that continuous orbital observations of dust conditions and of climate and weather proceed for as long as possible. This would require an orbiter with climate and weather monitoring instruments with a low altitude polar orbit lasting as long as possible. A series of spacecraft may accomplish the same goal. ***(F-5, F-6; O-5, O-6)***

R-7. **(priority: HIGH)** A high-quality meteorological station on the surface is recommended, potentially at the actual human landing site. This should be in place >5 years before the human landing to allow for data collection and analysis. The lander should monitor the dust conditions near the surface, and be instrumented to make mineralogical and chemical measurements, including spectroscopic analysis, of atmospheric dust grains on the surface. An areostationary satellite for atmospheric monitoring would also be desirable for local weather prediction at the human landing site. ***(F-5, F-6; O-5, O-6)***

R-8. **(priority: HIGH)** It is recommended that a multi-systemic assessment of pathological responses to Mars dust exposure be undertaken with outputs setting requirements for environmental control and decontamination technologies, medical diagnostic technologies, and medical treatment technologies. ***(F-9, F10, F-12; O-8, O-9)***

R-9. **(priority: HIGH)** It is recommended that the NASA Chief Health and Medical Officer be advised to create a panel of experts in toxicology, medicine, Mars mineralogy, and human health and performance to set Mars dust Permissible Exposure Limit, Short-term Exposure Limit, and other standards. This group would be patterned after the Lunar Aerosol Dust Toxicology Advisory Group that was created by OCHMO and set permissible exposure limits and related standards for lunar dust. ***(F-9, F10, F-12; O-8, O-9)***

R-10. **(priority: HIGH)** Once toxicology standards are created, it is recommended that the NASA Office of the Chief Health and Medical Officer, the Human Research Program, and relevant medical operations authorities should direct the creation of a set of Point of Care tests to detect and monitor the effects of Mars dust exposure. Based on current knowledge, at least perchlorate/chlorate urine testing, exhaled nitric oxide monitoring, allergy testing, neurocognitive testing, and thyroid function, to be coordinated with life support system monitoring technology development. ***(F-11; O-10)***

R-11. **(priority: HIGH)** It is recommended that once crew exposure standards have been developed, the NASA Office of the Chief Health and Medical Officer, the Human Research Program, and relevant medical operations authorities will be responsible for establishing medical countermeasures for exposure to Mars dust. ***(F-12; O-11)***

R-12. **(priority: HIGH)** For an adequate panel of toxicology studies, multiple candidate Mars dust simulants, standard nuisance dusts, and highly toxic standards like freshly ground quartz should be tested in a variety of toxicology models, in an effort to bracket the likely physiological response to Mars dusts. ***(F-13, F-14; O-12, O-13)***

R-13. **(priority: HIGH)** Measure the electromagnetic environment on the ground. Include instruments on future landers to measure (continuously) in multiple location the DC **and** AC electric and magnetic field. ***(F19; O-18)***

R-14. **(priority: MEDIUM)** Mineralogical and chemical measurements on the surface of Mars are required including spectroscopic analysis of atmospheric dust grains. ***(F-7, F-8; O-7)***

R-15. **(priority: MEDIUM)** It is recommended that further investigation of the toxicological synergies between Mars dust and radiation, partial gravity, reduced atmospheres, and other factors should be performed, since these can be unique to the Mars environment and related long-term spaceflight. However, this item is dependent on the outcome of standard pulmonary and other toxicity studies with authentic Mars dust simulants. ***(F-14; O-13)***

R-16. **(priority: MEDIUM)** It is recommended that Mars mission planners gather data on the mechanical properties of Mars dust, including strength, abrasiveness, etc. ***(F-15; O-14)***

R-17. **(priority: MEDIUM)** Using Sample Return dust, ground researchers should conduct simple experiments with candidate EVA suit materials and undergarments to determine skin abrasiveness similarly to what was done previously with lunar dust. ***(F-15; O-14)***

R-18. **(priority: MEDIUM)** Include instrument on future landers to measure dust charge characteristics, e.g. the charge/mass ratio. ***(F-20, F-21; O-18, O-19)***

R-19. **(priority: MEDIUM)** Regarding how dust adheres to natural and artificial surfaces, test materials and mitigation techniques using an accurate simulant when it becomes available. ***(F-22; O-20)***

R-20. **(priority: LOW)** It is recommended that, assuming no unforeseen biohazard is discovered to exist on Mars in the interim, existing toxicological methods described in the current medical literature will be sufficient to set exposure standards for Mars Dust. ***(F-16; O-15)***

R-21. **(priority: LOW)** It is recommended that the NASA Chief Toxicologist should determine what standard toxicological methods should be applied to Mars dust samples or simulants. On the chance that a determination is made by NASA that Mars return samples will have to be analyzed off-Earth, such as on the International Space Station, then it is recommended that the Human Research Program and NASA Chief Toxicologist develop and apply new methods for testing these materials in microgravity**.** ***(F-17; O-16)***

8.0 Alternative Viewpoint(s)

There were no alternative viewpoints identified during the course of this support by the NESC team or the NESC Review Board quorum.

9.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this support.

10.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this support.

11.0 Acronyms and Nomenclature List

CONOPS	Concept of Operations
COSPAR	Committee on Space Research
EVA	Extravehicular Activity
FOR	Findings, Observations, and NESC Recommendations
HEOMD	Human Exploration and Operations Mission Directorate
HHE	Human Health Effects
ISRU	In-situ Resource Utilization
JPL	Jet Propulsion Laboratory
LPI	Lunar and Planetary Institute
NESC	NASA Engineering and Safety Center
OCHMO	Office of the Chief Health and Medical Officer
PSD	Particle Size Distribution
TDT	Technical Discipline Team

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Appendix A. Mars Dust Workshop Participants

Participant, Affiliation	Panel
Agui, Juan H., NASA Glenn Research Center	Panel 1
Araghi, Koorosh, NASA Johnson Space Center	Panel 3
Archer, Paul D., NASA Johnson Space Center, Jacobs	Panel 1
Ashley, James W., Jet Propulsion Laboratory (JPL)	Recorder Panel 3
Baker, Mariah MacQueen, Johns Hopkins University	Panel 3
Beaty, David W., JPL, Moderator	Panel 1
Carrier, Brandi L., JPL	Recorder Panel 1
Chamberlain, Matthew K., NASA Langley Research Center	Panel 3
Choban, Pete S., The Aerospace Corp.	Panel 3
Connolly, John, NASA Johnson Space Center	Panel 1
Cook, John Gregory, President, Cook & Chevalier Enterprises, Inc.	Panel 3
Darquenne, Chantal J. Univ. California, San Diego	Panel 2
Dudley, Ingrid, USRA	
Edgett, Kenneth S., Malin Space Science Systems	Panel 1
Erickson, Lisa, NASA Johnson Space Center	Panel 3
Farrell, William M. NASA Goddard Space Flight Center	Panel 1
Fenton, Lori, SETI Institute	Panel 3
Gordon, Terry, NYU School of Medicine	Panel 2
Graham, Tim, Space X	Panel 1
Guzewich, Scott D., NASA Goddard Space Flight Center	Panel 3
Harrington, Andrea Dawn, NASA Johnson Space Center	Panel 2
Hecht, Michael H., MIT	Panel 1
Henninger, Donald L., NASA Johnson Space Center	Panel 1
Ignaut, Brian, Space X	Panel 3
Jakupca, Ian, NASA Glenn Research Center	Panel 3
Karlsson, Lars, Karolinska Institute	Panel 3
Kass, David M., JPL	Panel 1
Kerschmann, Russell, ARC (ret), Moderator	Panel 2
Kuroda, Takeshi, Nat. Inst. of Information & Communications Tech., Japan	Panel 1
Lam, Chiu-wing, NASA Johnson Space Center, Wyle	Panel 3
Levine, Joel S., College of William & Mary, Moderator	Panel 1
Levine, Michael J, MD	Panel 2
Loftus, David, NASA Ames Research Center	Panel 2
Lovelace, Ronney S., NASA Johnson Space Center	Panel 1
McClean, John B., Imperial College London	Panel 3
McCoy, James Torin, NASA Johnson Space Center	Panel 2
Meyer, Marit E., NASA Glenn Research Center	Panel 2
Ming, Douglas W., NASA Johnson Space Center	Panel 1
Montabone, Luca, Space Science Institute, LMD-CNRS, France	Panel 1
Morris, Richard, NASA Johnson Space Center	Panel 2
Morse, Jon A., BoldlyGo Institute	Panel 1

Moussa, Albert, BlazeTech Corp.	Panel 1
Nykorczuk, Jason D., College of William & Mary	Recorder, Plenary Session
Ogohara, Kazunori, Univ. of Shiga Prefecture	Panel 1
O'Hara, William J., NASA Johnson Space Center	Panel 3
Peretyazhko, Tanya, NASA Johnson Space Center, Jacobs	Panel 2
Phillips, James R., NASA Kennedy Space Center	Panel 1
Piszczor, Michael F., NASA Glenn Research Center	Panel 1
Prisk, G. Kim, University of California, San Diego	Panel 2
Robertson, Brandan, NASA Johnson Space Center	Panel 3
Robertson, Edward A., NASA Johnson Space Center	Panel 2
Romoser, Amelia A., NASA Johnson Space Center, Wyle	Panel 2
Rotter, Henry, NASA Johnson Space Center	Panel 3
Rucker, Michelle A., NASA Johnson Space Center, Plenary Lecturer	Panel 3
Sanders, Gerald, NASA Johnson Space Center	Panel 3
Scully, Robert R., Wyle	Panel 2
Sim, Peter Alan, Riverside Regional Medical Center, Newport News, VA	Panel 2
Smith Peter H., Univ. of Arizona	Panel 1
Sparks, Pamela, Langley Research Center	Recorder, Panel 2
Spry, James A., SETI Institute	Panel 1
Studor, George, Johnson Space Center (ret)	Panel 3
Sutter, Brad, NASA Johnson Space Center, Jacobs	Panel 1
Wadhwa, Meenakshi, Arizona State University	Panel 1
Wang, Alian, Washington University, St. Louis	Panel 1
Whitley, Ryan, NASA Johnson Space Center	Panel 3
Winterhalter, Daniel, JPL, Moderator	Panel 3.
Yun, Paul M., El Camino College, NASA Solar System Ambassador	Panel 3
Zurek, Richard W., JPL	Panel 1

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The NASA Engineering and Safety Center (NESC) Chief Scientist provided support to produce an NESC final report on the "Dust in the Atmosphere of Mars and Its Impact on Human Exploration" workshop held June 13–15, 2017, in Houston, TX. This report follows the standard NESC report format to describe the findings, observations, and NESC recommendations developed by the workshop participants.

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