Dust in the Atmosphere of Mars and its Impact on Human Exploration

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Edited by

Joel S. Levine, Daniel Winterhalter and Russell L. Kerschmann

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PREFACE TO THE BOOK

Dust in the Atmosphere of Mars and Its Impact on Human Exploration

Over the last decade as NASA's plans for the human exploration of Mars have developed and matured, a major concern has surfaced about the possible negative impacts of Mars surface and atmospheric dust on human health and on the human surface systems and surface operations on the Red Planet. To address these concerns, the NASA Engineering and Safety Center (NESC) Robotic Spacecraft Technical Discipline Team (TDT) organized a workshop, "Dust in the Atmosphere of Mars and Its Impact on Human Exploration" at the Lunar and Planetary Institute (LPI), adjacent to the NASA Johnson Space Center in Houston TX, June 13-15, 2017.

Approximately 100 participants, including Mars scientists, space engineers, mission architects, mission planners, medical researchers, physicians and undergraduate and graduate students attended the workshop. In a series of invited plenary papers, specialists in these areas of research reviewed our understanding and our knowledge gaps in the following areas: the chemical, physical and electrical properties of Mars atmospheric dust, the evolution and occurrence of localized, regional and planetary-scale dust storms, the human health effects of Mars atmospheric dust, including inhalation of and potential toxicity of dust particles and the impact of Mars atmospheric dust on surface systems and on surface operations. Abstracts of the invited plenary papers and contributed papers are available on line at: https://www.hou.usra.edu/meetings/marsdust2017/pdf/program.pdf

Workshop participants identified a number of gaps in our knowledge of dust on the surface and in the atmosphere of Mars and its impact on human health and on human surface operations. Some of these knowledge gaps include:

1. The particle size distribution and density of atmospheric dust in "clear" and dust storm conditions.
2. The chemical composition of atmospheric dust, including the identification of possible toxic compounds.

3. The electrical nature of Mars atmospheric dust particles and how potential electrical charges on dust particles may be dissipated.
4. How to better predict the occurrence, location severity and duration of dust storms on Mars.
5. To more accurately understand the impact of Mars dust in human respiration in a reduced gravity environment over the extended periods (500 days) of time that the astronauts will spend on the surface of Mars
6. To better understand the role of the omnipresent atmospheric dust in the potential transport of Earth microorganisms around Mars (forward contamination) and the role of atmospheric dust in transporting possible Mars microorganisms back to Earth by the astronauts and their onboard equipment (back contamination).

In the report to the NESC, the workshop organizers recommended how these gaps in our understanding may be addressed prior to humans setting foot on Mars using future robotic missions presently being planned and by laboratory experimentation and computer modeling simulations.

On the first day of the workshop, after the initial plenary session and the presentation of the invited plenary papers, workshop attendees participated in one of three breakout panels of their choice. The three breakout panels covered the following subject areas:

1. The nature, structure, composition, distribution, electrical properties and the forward and backward contamination of Mars surface and atmospheric dust. The moderators of this panel were Joel S. Levine and David W. Beaty. The panel recorder was Brandi L. Carrier. The panel recorder for the invited plenary papers was Jason Nykorczuk.
2. The impact of Mars surface and atmospheric dust on human health. The moderator of this panel was Russell L. Kerschmann. The panel recorder was Pamela Sparks.
3. The impact of Mars surface and atmospheric dust on surface systems (e.g., space suits, habitats, mobility systems, etc.) and surface operations. The moderator of this panel was Daniel Winterhalter. The panel recorder was James W. Ashley.

On days two and three of the workshop, workshop attendees participated in morning and early afternoon panel sessions and late afternoon plenary sessions. This volume includes the invited plenary papers and some of the contributed papers presented and discussed at the workshop.

The book consists of 17 chapters organized into the three sections. Section 1 contains 8 chapters covering the nature, structure, composition, distribution, electrical properties and the forward and backward contamination of Mars surface and atmospheric dust. Section 2 contains 3 chapters covering the impact of Mars surface and atmospheric dust on human health. Section 3 contains 6 chapters covering the impact of Mars surface and atmospheric dust on surface systems (e.g., space suits, habitats, mobility systems, etc.) and surface operations.

The NASA Engineering and Safety Center (NESC)

The mission of the NASA Engineering and Safety Center (NESC) is to perform value-added independent testing, analysis, and assessments of NASA's high-risk projects to ensure safety and mission success. The NESC engages proactively to help NASA avoid future problems.

NESC is dedicated to promoting safety through engineering excellence, unaffected and unbiased by the programs it is evaluating. It is a resource meant to benefit the programs and organizations within the Agency, the NASA Centers, and the people who work there.

At the core of the NESC is an established knowledge base of technical specialists. This ready group of engineering experts is organized into 15 disciplines areas called Technical Discipline Teams (TDT), formally known as Super Problem Resolution Teams (SPRT). TDT members are from the NASA Centers, industry, academia, and other government agencies. By drawing on the recognized expertise of leading engineers from across the country, the NESC consistently optimizes its processes, deepens its knowledge base, strengthens its technical capabilities, and broadens its perspectives, thereby further executing its commitment to engineering excellence.

NESC's technical evaluation and consultation products are delivered in the form of written reports that include solution-driven, preventative, and corrective recommendations. The NESC strives to set the example for the Agency by providing full and appropriate documentation of every activity its teams perform. Along with each report, lessons learned are communicated to Agency leadership and to engineers through avenues such as the NASA Lessons Learned system.

Another important function of the NESC is to engage its proactive investigations to identify and address potential concerns before they become major problems. To further this goal, the NESC is currently leading NASA's efforts for independent data mining and trend analysis. The NESC has established a Data Mining and Trending Group that includes representatives from all NASA Centers, as well as external experts. This group ensures that results are maximized and that the NESC comprehensively learns from previous efforts.

Joel S. Levine
Daniel Winterhalter
Russell L. Kerschmann
Workshop Organizers and Editors

CHAPTER ONE

DUST IN THE ATMOSPHERE OF MARS AND ITS IMPACT ON HUMAN EXPLORATION: DEFINING THE PROBLEMS

JOEL S. LEVINE

Introduction

The United States is planning an historic journey—sending humans to the surface of Mars and returning them safely to Earth (For example, see: Drake, 2009, Levine and Schild, 2010, Aldrin, 2015, David, 2016). There are several reasons for the human exploration of Mars, including human scientific exploration, national prestige, national security, economic vitality, the human urge to explore new frontiers, to excite and stimulate the next generation of our nation's scientists, engineers, technologists and mathematicians, and to make the human species a two-planet species by establishing a human presence on another planet.

The impact of dust on the surface and in the atmosphere of Mars on human exploration is a multi-faceted problem, including (1) The impact of Mars atmospheric dust on human health, (2) The impact of Mars atmospheric dust on human surface systems, e.g., spacesuits, habitats, mobility systems, etc. (3) The impact of Mars atmospheric dust on human surface operations, (4) The impact of Mars atmospheric dust on the near-surface atmospheric electric field, and, (5) The impact of Mars atmospheric dust on the potential transport of Earth microorganisms around Mars (forward contamination) and the role of atmospheric dust in the inadvertent transfer of possible Mars microorganisms back to Earth with the astronauts and their equipment (back contamination).

Clearly, there are many concerns about human health and safety on a mission to Mars. The impact of Mars atmospheric dust on human exploration has been a concern of scientists, engineers, medical researchers and mission planners (National Research Council, 2002, the Mars Exploration Program Analysis Group (MEPAG), 2005 and Beaty et al., 2005). NASA's Human Exploration and Operations Mission Directorate (HEOMD) has identified Mars atmospheric dust as a "Long Pole" in the human exploration of Mars (HEOMD, 2017). A "Long Pole" is defined as an engineering or capability challenge that has a major bearing on any mission due to the significant effort it takes 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. Discussions of problems associated with Mars atmospheric dust on human health and surface operations on Mars have appeared in the general literature (Jaggard, 2015, Bushnell and Moses, 2016, Levine et al., 2018).

Dust on the Moon: The Apollo Experience

A major surprise of the Apollo Moon missions was the deleterious impact of lunar dust on the astronauts, their spacesuits and other equipment and even inside the Command/Service Module during their return to Earth. Lunar dust permeated everything and impacted mechanical systems! The dust on the Moon's surface was disturbed and became airborne by the routine actions of the astronauts as they walked and performed their exploration of the lunar surface. The dust permeated everything and impacted all mechanical systems. Apollo 17 astronaut, Gene Cernan, who along with Harrison Schmitt, were the last humans to walk on the Moon, had some very illuminating observations about lunar dust during his post-flight technical debrief (NASA, 1969a, 1969b, 1971a, 1971b, 1972 and 1973, Connors et al., 1994, Kennedy and Harris, 1992):

> *"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."*

> *"One of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and its restrictive friction-like action to everything it gets on."*

Dust on Mars

On Mars, surface and atmospheric dust may be even more detrimental to the human health and exploration than on the Moon if only because of much longer expected exposures. The Apollo 17 astronauts spent a total of 75 hours on the Moon with their three extravehicular activities (EVAs) lasting a total of 22 hours and 4 minutes days; whereas the Mars astronauts may spend up to 500 days on the surface of the Red Planet with EVAs of much greater duration than the Apollo astronauts, thus greatly extending their exposure time to atmospheric dust on Mars. In addition, the atmosphere of Mars includes a myriad of chemically active trace atmospheric gases that may lead to the production of toxic species that may be deposited onto the surface of Mars and on wind-blown dust particles.

A major finding of the Viking mission was the discovery of a persistent atmospheric background of dust ranging in diameter from <1 to >10 micrometers resulting in an atmospheric dust opacity (tau) ranging from a few tenths to more than 1.0 at visible wavelengths. This persistent background of fine atmospheric dust is responsible for the pinkish-reddish color of the atmosphere of Mars. During dust storms, the opacity of atmospheric dust can increase to a tau of more than 3.

The surface of Mars is very dusty, covered with unconsolidated soil and dust that is readily transported into the atmosphere by horizontal and vertical winds. Mars is well known for its localized, regional and planetary-scale dust storms. Figure 1 shows two photographs of Mars taken by the Hubble Space Telescope: the left photograph taken on June 26, 2001 shows a “clear” Mars and the right photograph taken on September 4, 2001 shows Mars almost obscured by airborne dust .

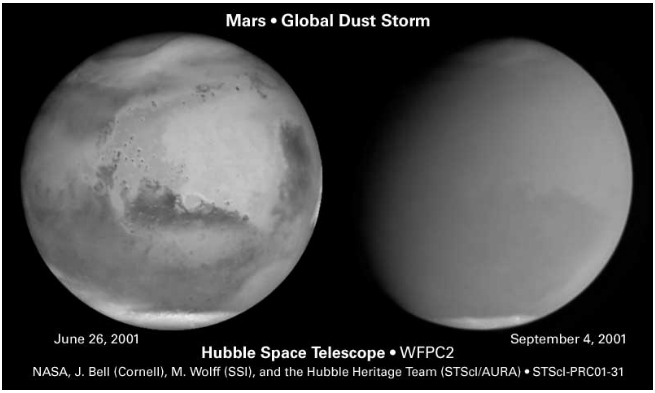

Fig. 1. Hubble Space Telescope images of Mars: Left photograph shows a “clear” Mars on June 26, 2001 and the right photograph shows Mars covered by a planetary-scale dust storm on September 4, 2001.

Localized, small-scale dust devils are also a regular feature of the Mars atmosphere (Figure 2).

Tracks of multiple dust devils on surface of Mars are photographed from orbit (Figure 3).

Measurements of a regional dust storm obtained by the Viking Orbiters in 1977 led to an estimate of the mass of atmospheric dust associated with this regional dust storm of about 430 million metric tons of dust (Martin, 1995). Viking Orbiter measurements were also used to deduce the mass of atmospheric dust associated with a localized dust storm near Solis Planum as about 13 million metric tons of dust lofted into the atmosphere (Martin, 1995).

Fig. 2. Dust devil on surface of Mars and it's shadow photographed from Mars orbit.

Mars atmospheric and surface dust must be investigated for their impact on human health, the operation of Mars surface systems (e.g., space suits, habitats, mobility systems, ascent rockets, etc.) and on surface operations and exploration (e.g., reduced atmospheric visibility, limited extra vehicle activities (EVAs), hampering of regular habitat maintenance, etc.). Earlier studies have considered the impact of Mars atmospheric dust on human exploration: *Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface* published by the National Research Council (NRC) in 2002 and *An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars* published by the Mars Exploration Program Analysis Group (MEPAG) in 2005. NASA's Human Exploration and Operations Mission Directorate (HEOMD) has identified Mars atmospheric dust as an engineering "long pole" for the human exploration of Mars (HEOMD, 2017).

The NRC and MEPAG reports and the HEOMD study, which is still ongoing, considered the impact of Mars atmospheric dust on human health, surface equipment and on human surface operations, including astronauts inhaling airborne particulate matter, toxic metals (e.g., hexavalent chromium (Cr^{6+}), a highly toxic form of chromium in Mars soil and airborne dust), and potentially toxic atmospheric gases. In 2008, after

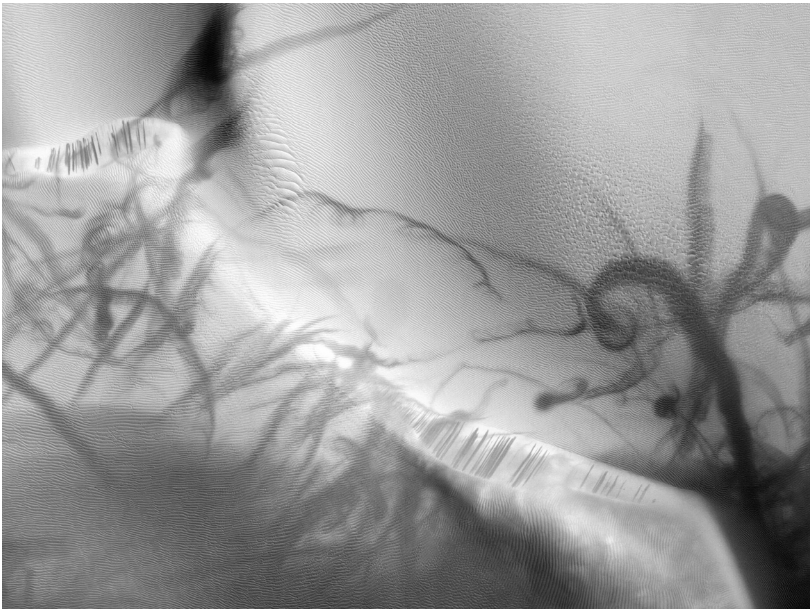

Fig. 3. Tracks of multiple dust devils on surface of Mars photographed from orbit.

the publication of the NRC and MEPAG humans on Mars reports, the Phoenix Mars lander discovered compounds of perchlorate (ClO_4^-) in the soil of Mars. The presence of perchlorate in the soil of Mars has now also been confirmed by soil measurements obtained by the Mars Science Laboratory Curiosity. Perchlorate has been shown to interfere with the normal iodide uptake by the thyroid gland. Hence, perchlorate has been added to the list of potential toxic compounds in the soil of Mars. The next three sections summarize the key points in the NRC and MEPAG reports and the HEOMD study that will lead to a better understanding of the impact of Mars atmospheric dust on human health, human surface equipment and on human surface operations.

Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (National Research Council, 2002)

The NRC report, *Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface* discusses four areas of concern of the interactions of Martian soil and atmospheric dust with astronauts and astronaut equipment, including:

(1) Toxic Metals: Hexavalent Chromium

Airborne dust and soil on Mars could contain trace amounts of hazardous chemicals, including compounds of toxic metals that are known to cause cancer over the long term if inhaled in sufficient quantities. For example, Mars Pathfinder measurements established that chromium is present in Mars soil. Chromium contained in naturally occurring geologic materials is primarily in a trivalent state (a +3 ion), which is a stable form of chromium and minimally toxic to humans. However, hexavalent chromium (Cr VI, a +6 ion), a highly toxic form of chromium, is rarely encountered in natural geologic materials. If even a modest fraction of the chromium present in the Martian soil and airborne dust is hexavalent chromium (more than 150 parts per million), it would pose a serious health threat to astronauts operating on the surface of Mars. The NRC report outlines reasons for being concerned about the presence of hexavalent chromium on Mars.

(2) Astronaut Exposure to Inhaling Airborne Particulate Matter

(3) Biological Degradation and Equipment Corrosion

There are high concentrations of sulfur and chlorine in Martian soil. This implies that both the soil and airborne dust might be acidic, which could pose a hazard if they are introduced into an astronaut habitat. When inhaled by astronauts, acidic soil and dust could degrade their lung tissue and, if humidified and allowed to penetrate control units inside the habitat, could corrode sensitive critical equipment, such as control circuits.

(4) Hazardous Organic Compounds and Atmospheric Gases

Certain organic compounds and atmospheric gases potentially produced by photochemical reactions in the atmosphere, can be highly toxic to humans.

An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars (Mars Exploration Program Analysis Group (MEPAG), Beaty et al., 2005)

The MEPAG report, *An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars* lists ten prioritized investigations to reduce the health and safety risks of the first human mission to Mars (Beaty et al., 2005). (Five contributors to this MEPAG report are also contributors to this book: William Farrell, Michael Hecht, Steve Hoffman, Joel Levine and Daniel Winterhalter). The prioritized investigations in this report are based on Goal IV: Preparation for Human Exploration of the MEPAG *Mars Science Goals, Objectives, Investigations, and Priorities: 2005* (MEPAG, 2005). The following four highest priority investigations are of indistinguishable priority order and hence are listed as Priority 1A, 1B, 1C and 1D:

MEPAG Priority 1A. Characterize the particulates that could be transported to mission surfaces through the atmosphere (including both natural aeolian dust and particulates that could be raised from the Martian regolith by ground operations), and that could affect hardware's engineering properties. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

MEPAG Priority 1B. Determine the variations of atmospheric dynamical parameters from ground to >90 km that affect entry, descent and landing (EDL) and take-off, ascent and orbit insertion (TAO) including both ambient conditions and dust storms.

MEPAG Priority 1C. Determine if each Martian site to be visited by humans is free, to within acceptable risk standards, of replicating biohazards, which may have adverse effects on humans and other terrestrial species. Sampling into the subsurface for this investigation must extend to the maximum depth to which the human mission may come into contact with uncontained Martian material.

MEPAG Priority 1D. Characterize potential sources of water to support ISRU (In Situ Resource Utilization) for eventual human missions. At this time it is not known where human exploration of Mars may occur. However, if ISRU is determined to be required for reasons of mission affordability and/or safety, then, therefore the following measurements for water with respect to ISRU usage on a future human mission may become necessary (these options cannot be prioritized without applying constraints from mission system engineering, ISRU process engineering, and geological potential):

The remaining six investigations are listed in order of descending priority are listed here:

MEPAG Priority 2. Determine the possible toxic effects of Martian dust on humans.

MEPAG Priority 3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.

MEPAG Priority 4. Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.

MEPAG Priority 5. Characterize in detail the ionizing radiation environment at the Martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.

MEPAG Priority 6. Determine traction/cohesion in Martian soil/regolith (with emphasis on trafficability hazards, such as dust pockets and dunes) throughout planned landing sites; where possible, feed findings into surface asset design requirements.

MEPAG Priority 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Of the ten investigations, four of them (Priorities 1, 2, 3, and 7) of the MEPAG report (Beaty et al., 2005) are related to the impact of atmospheric dust on human health, human exploration and surface operations on Mars and are reproduced here almost verbatim due to their importance and relevance to this subject (Beaty et al., 2005):

MEPAG Priority 1A. Characterize the particulates that could be transported to mission surfaces 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 hardware's engineering properties (This investigation is one of four investigations assessed as highest priority).

Characterization of the Martian dust (including particulates raised from the regolith during surface operations) is a relatively high priority item. Such investigations are important for mission hardware design to mitigate the effects of abrasion, adhesion, corrosion, and damage from potential electrical discharge, or arcing, as well as to mitigate potential adverse effects on human health from dust inhalation, and exposure).

The Martian atmosphere is the origin of many possible hazards to both humans and equipment. The unknown thermodynamic properties of the bulk gas fluid, including unexpected turbulence in the near-surface boundary layer (Zurek et al., 1992), represent risks during vehicle entry, descent and landing (EDL). Major dust storms may also affect EDL and adversely affect a human explorer's ability to perform extravehicular activities (EVAs). More recent laboratory (Eden and Vonnegut, 1973) and terrestrial desert studies (Renno et al., 2004) indicate that triboelectric effects within dust storms can give rise to large electric fields which might prove hazardous to both explorers and equipment.

Apollo astronauts learned first hand how problems with dust impact lunar surface missions (NASA, 1969a, 1969b, 1971a, 1971b, 1972, 1973, Connors et al., 1994, Kennedy and Harris, 1992). After three days, lunar dust contamination on EVA suit bearings led to such great difficulty in movement that another EVA would not have been possible. Dust clinging to EVA suits was transported into the Lunar Module Connors et al., 1994). During the return trip to Earth, when micro gravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes (Kennedy and Harris, 1992). Some mechanical systems aboard the spacecraft were damaged due to dust contamination. Study results obtained by robotic Martian missions indicate that Martian surface soil may be oxidative and reactive (Zent and McKay, 1994). Exposures to the reactive Martian dust may pose an even greater concern to crew health and integrity of the mechanical systems. As NASA embarks on planetary surface missions to support its Exploration Vision, the effects of these extraterrestrial dusts must be well understood and systems must be designed to operate reliably and protect the crew in the dusty environments of the Moon and Mars.

Abrasive properties of dust accumulating on surfaces and penetrating systems could lead to failure of air generation and delivery, carbon dioxide removal, fire detection (causing false alarms) and suppression, EVA suits, rovers, windows, visors, and optics. If critical life support systems completely fail, rescue or mission termination is not feasible due to the laws of orbital mechanics.

Dust Inhalation and Ingestion

Dust Toxicity to Crew:

Risk Statement: If the crew inhales or ingests dust, adverse health effects may result.

Dust in the human environment resulting from human interactions of the Martian surface may be inevitable, and dust mitigation strategies for the human habitation modules are currently not developed.

Context: Dust transported into the habitat via leakage or EVA suits may decrease effectiveness of air, water and food management systems and lead to inhalation and ingestion of dust particles. The properties of soils, which can produce medical impact to humans on planetary surfaces, include both physical and chemical reactions with skin, eyes and mucous membranes.

Sub-micron particles could lead to effects similar to black lung disease. Peroxide is chemically reactive. Martian dust may also contain toxic materials and trace contaminants. Very small particles, especially in low gravity, stay in the atmosphere longer and increase chances of inhalation. Electrostatically charged particles adhere to tissue and create bronchial deposits. Possible toxicity (acute pulmonary distress and systemic effects) caused by nanoparticles, if present in the Martian atmosphere, should be considered as an added risk.

Since the site specific lung deposition of inhaled medical aerosol particles depends, among other factors, upon the aerodynamic size and electrostatic charge distributions and the gravitational forces, respiratory drug delivery may be compromised due to reduced and zero gravity conditions.

Subset Risk: Inhalation or ingestion of the dust may cause irritation or disease that can compromise an astronaut's health and their ability to carry out mission objectives. Transport of these species to the humid atmosphere of the habitation module may cause the generation of additional toxic and corrosive species.

Current State of Knowledge

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 (Matijevic, 1997).

Models indicate particle size is 0.1 to 2000 µm, particle hardness is 1 to 7 on Moh's hardness scale, dust particles are tabular, angular and rounded, particle density is 2.6 to 3.0 g/cm3, friction angle is 18 to 40 degrees, dielectric characteristics are K' = 1.9d, cohesion is 0 to 20 kPa, and adhesion is 0.9 to 79 Pa (Greeley and Haberle, 1991, Shorthill et al., 1976). Observations indicate the dust is magnetic (Hvidd et al., 1997). Direct measurements detected Si, Al, Fe, Mg, Ca, Ti, S, Cl and Br in the soil (Rieder, et al., 1997). The soil, probably slightly acidic, is generally oxidized but may be reactive.

Desired Future State of Knowledge

To reduce risk for the first human Mars mission, Earth-based laboratory and computer simulations and toxicological studies need to be performed to ensure that human systems operate properly and crew health is protected. Physical property parameters predicted by models should be verified in situ by direct measurement to ensure that Earth-based simulations and studies are valid.

In order to design human systems that would properly function in the dusty Martian environment specific knowledge should be obtained to provide simulation and study designers with detailed chemical and physical properties of Martian dust and sand to understand adhesive, electrostatic, and abrasive properties (National Research Council, 2002). These properties include shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, chemistry of relevance to predicting corrosion effects, polarity and magnitude of charge on individual dust particles and concentration of free atmospheric ions with positive and negative polarities (Burose et al., 2002).

To protect the crew from potential hazards of Martian dust, reactive, corrosive and irritant properties need to be understood (National Research Council, 2002). To obtain the needed information requires assays for chemicals with known toxic effect on humans, e.g., oxidizing species such as Cr-VI; characterization of soluble ion distributions; understanding of reactions that occur upon humidification and released volatiles; knowledge of shapes of Martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs), and determination of toxic response in animals should be performed.

Investigations, Measurements, and Priorities to Reduce Risk(s) and/or Cost

The MEPAG Report Dust/Soil Focus Team evaluated each risk and recommended investigations that would be needed to provide data to mitigate the risk. It also prioritized measurements based on the probability and consequence of risks, evaluating if investigations must be performed in situ or if the mitigation could be performed on Earth using existing data to create simulated Martian environments or computer software, and considering cost of performing in-situ measurement versus the value of the data that would be obtained.

The need for Martian dust/regolith simulant(s)

An important strategy for reducing the risks related to the effects of granular materials on both engineering and biological systems is to establish one or more Martian dust/regolith simulants. Widely accepted standard materials make it possible to compare technology performances from different laboratories and to generate empirical rather than theoretical data. For risks associated with MEPAG Goal IV Investigation 1A, we recommend using the simulants to test dust accumulation on various types of materials; dust repellant, removal and cleaning technologies; various types of decontamination procedures; flight hardware designs; reliability, maintainability and waste minimization technologies; and operational procedures. For risks associated with MEPAG Goal IV Investigation 2, we recommend using simulants to perform in-vitro and in-vivo laboratory exposure testing, laboratory animal tests, establishment of respiratory and inhalation limits, and the development of operational procedures, mitigation methods, and exposure levels.

Finding: Proposed Investigations and Measurements

Characterize 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.

Measurements

a. A complete analysis, consisting of 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 as large as might be affected by human surface operations. Note #1: 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. Note #2: Obtaining a broad range of measurements on the same sample is considerably more valuable than a few measurements on each of several samples (this naturally lends itself to sample return). Note #3: There is not consensus on adding magnetic properties to this list.

b. Polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities. Measurement should be taken during the day in calm conditions representative of nominal EVA excursions. Note #4: This is a transient effect, and can only be measured in situ.

c. The same measurements as in a) on a sample of air-borne dust collected during a major dust storm.

d. Subsets of the complete analysis described in a), and measured at different locations on Mars. For individual measurements, priorities are:

1. Shape and size distribution and mineralogy of atmospheric dust.
2. Electrical properties of atmospheric dust.
3. Chemistry of atmospheric dust.

The following MEPAG investigations involving surface and atmospheric dust and human exploration are listed in descending priority order:

MEPAG Priority 2. Determine the possible toxic effects of Martian dust on humans.

The Viking Labeled Release/Gas Exchange Experiment (LR/GEX) experiments indicate that some highly reactive agent is omnipresent in the environment, possibly being of atmospheric origin.

Finding: Proposed Investigation and Measurements

1. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species such as chromium-VI (Cr-VI). (May require Mars Sample Return (MSR)).
2. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith from a depth as large as might be affected by human surface operations.
3. Analyze the shapes of Martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).
4. Determine if Martian regolith elicits a toxic response in an animal species, which is a surrogate for humans.

During crew occupation and EVA, dust storms may affect visibility, restrict departure times, limit EVAs, and hamper regular habitat maintenance. 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 (Zurek et al., 1992), 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 (MGS/TES), but regional and local storms appear quasi-random (Cantor, 2003). To assess the risk, lander meteorological packages (like those suggested in point 1 above) 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 baseline, and act to alert surface-stationed astronauts of impending storm activity.

MEPAG Priority 3. Derive the basic measurements of atmospheric electricity that affects Take-off, Ascent and Orbit insertion (TAO) and human occupation.

Electric fields in convective dust storm may exceed breakdown, leading to discharge, arcing, RF contamination. Discharge to ascending vehicle is potentially serious issue during take- off (e.g., Apollo 12). High levels of atmospheric electricity may limit EVAs.

Dust storm electrification may cause arcing, affecting TAO. 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 (Farrell et al., 2004). Further, the field strengths may approach the local breakdown field strength of the Martian atmosphere, leading to discharges (Melnick and Parrott, 1998). 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 MEPAG Atmosphere Focus Team suggests placing an atmospheric electricity (direct current (DC) and alternating current (AC electric fields, conductivity) package on at least one future landed missions to assess the risk.

MEPAG Priority 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Local, regional and even global dust storms are likely to occur for 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 external maintenance of habitat. (e.g., Gulf War II dust storm)

During crew occupation and EVA, dust storms may affect visibility, restrict departure times, limit EVAs, and hamper regular habitat maintenance. 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 (Zurek et al., 1992), 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 MGS/TES, but regional and local storms appear quasi-random (Cantor, 2003). To assess the risk, lander meteorological packages (like those suggested in point 1 above) 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 baseline, and act to alert surface-stationed astronauts of impending storm activity.

Study on Engineering Long Poles for Getting Humans to the Surface of Mars (NASA Human Exploration and Operations Mission Directorate (HEOMD), 2017)

NASA's Human Exploration and Operations Mission Directorate (HEOMD) has identified Engineering Long Poles for Getting Humans to the Surface of Mars (HEOMD, 2017). Two Mars atmospheric dust-related Long Poles are summarized below:

Long Pole 6: "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:

1. The potential for the transport of organisms through globally circulating dust, which can influence planetary protection polices

2. The toxicological properties of dust, which are a crew health concern
3. 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?

1. To conform to planetary protection policies for mitigating forward and backward contamination.
2. To ensure crew health and safety and reliable systems operation.

Long Pole 9: "Surface Dust Filtration." 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 EVA or inflatable fabrics, hatch seals, or mechanisms, causing leakage and mechanical abrasion damage over time. Additionally, Martian dust is potentially toxic, causing deleterious physiological effects including, but no limited to, respiratory illness and eye/skin irritation. Martian dust contains fine-grained silicate minerals. If breathed in, 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 system.

Conclusion

The United States is embarked on a historic journey to send humans to Mars and return them safely to Earth. Humans will become a two planet species. To prepare for this historic journey, the United States is building new space vehicles and space systems, including a new, powerful heavy-lift launch system (the Space Launch System or SLS) to carry humans and cargo to Mars, the Orion Crew Exploration Vehicle (CEV) and Earth Return Vehicle, a trans-Mars module, a Mars Transit Habitat and developing new technologies for human entry, descent and landing (EDL) onto the surface of Mars and Mars in situ resource utilization techniques for "living off the land" on Mars. The Human Exploration of Mars Science Analysis Group (HEM-SAG) chartered by the NASA Mars

Exploration Program Analysis Group (MEPAG) has identified potential landing sites for the first human missions (Levine et al., 2010a, 2010b) and analysis of these sites has already begun (For example, see College of William and Mary, 2016).

The human journey to Mars and the human exploration of Mars are very challenging and very risky activities. The National Research Council, the Mars Exploration Program Analysis Group, the NASA Human Exploration and Mission Directorate and the contributors to this book have outlined some of the concerns of Mars surface and atmospheric dust on human health, surface equipment, surface operations and on planetary protection-both forward and backward contamination. These documents have identified a series of important questions and new information needed to reduce the risks of the human exploration of Mars. Over the next decade a new generation of Mars robotic missions will carry new instruments capable of making previously unobtainable measurements of Mars surface and atmospheric dust. These future measurements, coupled with laboratory experiments and computer simulations of Mars surface and atmospheric dust will provide new insights and information on techniques and protocols to mitigate and maybe even eliminate the detrimental impacts of Mars surface and atmospheric dust on human health and on the human exploration of Mars.

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