DUST IN THE ATMOSPHERE OF MARS AND ITS IMPACT ON HUMAN EXPLORATION: A REVIEW OF EARLIER STUDIES. Joel S. Levine, Department of Applied Science, The College of William and Mary, P. O. Box 8795, Williamsburg, VA 23187-8795 and NASA Engineering and Safety Center (NESC) Robotic Spacecraft TDT, jslevine@wm.edu

Introduction: The impact of Mars atmospheric dust on human exploration has been a concern of engineers, medical researchers and mission planners for many years [1-3] (For example, the National Research Council (2002) [1] and the Mars Exploration Program Analysis Group (2005) [2,3]. The impact of dust 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 surface systems, e.g., space-suits, habitats, mobility systems, (3) The impact of Mars atmospheric dust on human surface operations, and the (4) The impact of Mars atmospheric dust on the near-surface electric field.

National Research Council: Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002) [1]: A Review

The NRC report discusses four problem areas of chemical interaction of Martian soil and airborne dust with astronauts and critical equipment, (chapter 4) which is summarized here.

(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 three reasons for being cautious 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, perhaps produced by photochemical reactions in the atmosphere, can be highly toxic to humans.

Mars Exploration Program Analysis Group: An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars (2005) [2]: A Review

The MEPAG (2005) 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 risk of the first human mission to Mars [2]. 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: 2015 (MEPAG, 2015) [3]. The following four highest priority investigations are of indistinguishable priority order [2]:

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. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

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.

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.

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 following remaining six investigations are listed in order of descending priority [2]:

2. Determine the possible toxic effects of Martian dust on humans.
3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.
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.
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.
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.
7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Of the ten investigations, four investigations (Priority 1, 2, 3, and 7) involve the impact of atmospheric dust on human exploration and are discussed here [2]:

<u>Priority1A. 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).</u>

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 [4], 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 [5] and terrestrial desert studies [6] 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 [7-12]. 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 [13]. 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 [14]. 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 [15]. 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 [1].

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. Consequences: mild illness to loss of crew. 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 [16].

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 [17, 18]. Observations indicate the dust is magnetic [19]. Direct measurements detected Si, Al, Fe, Mg, Ca, Ti, S, Cl and Br in the soil [20]. 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 [1]. 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.

To protect the crew from potential hazards of Martian dust, reactive, corrosive and irritant properties need to be understood [1]. To obtain the needed information requires assays for chemicals with known toxic effect on humans, e.g., oxidizing species such as CrVI; 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 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 INVESTIGATION AND MEASUREMENTS

1A. 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 airborne dust collected during a major dust storm.

d. Subsets of the complete analysis described in a), and measured at different locations on Mars (see Note #2). For individual measurements, priorities are:

i. Shape and size distribution and mineralogy ii. Electrical iii. Chemistry.

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

<u>Priority 2. Determine the possible toxic effects of Martian dust on humans.</u>

The Viking LR/GEX experiments indicate that some highly reactive agent is omni-present in the environment, possibly being of atmospheric origin.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

2. Determine the possible toxic effects of Martian dust on humans. Measurements:

1. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species such as CrVI. (May require 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. \

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 [4], 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 [21]. 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 (like that described in point 1 above) 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.

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

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 [22]. Further, the field strengths may approach the local breakdown field strength of the Martian atmosphere, leading to discharges [23]. 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 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.

<u>Priority 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.</u>

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)

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