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An Assessment of Dust Effects on Planetary Surface Systems to Support Exploration Requirements

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Acronyms

AIM	Advanced Integration Matrix
EVA	Extravehicular Activity
GN&C	guidance, navigation and control
IVA	inner-vehicular activity
PLSS	Portable Life Support System
QD	quick disconnects

Abstract

Apollo astronauts learned, first hand, how problems with dust impact lunar surface missions. After three days, lunar dust contamination on Extravehicular Activity (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. During the return trip to Earth, when microgravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes. Some mechanical systems aboard the spacecraft were damaged due to dust contamination. Study results obtained by Robotic Martian missions indicate that Martian surface soil is oxidative and reactive. Exposures to the reactive Martian dust will pose an even greater concern to the crew health and the 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.

The Advanced Integration Matrix (AIM) Dust Assessment Team was tasked to identify systems that will be affected by the respective dust, how they will be affected, associated risks of dust exposure, requirements that will need to be developed, identify knowledge gaps, and recommend scientific measurements to obtain information needed to develop requirements, and to design and manufacture the surface systems that will support crew habitation in the lunar and Martian outposts.

1.0 Introduction

Planetary dust leads to major system and mission failure risks. To mitigate the risks associated with dust, Life Support and Habitation initiated a study to determine direction to better understand lunar and Martian dusts.

Engineering requirements are required to bound measurable quantities within the functional limits of people or technologies. Good requirements are generated through a process that involves reviewing lessons learned, identifying systems impacted by dust and other contaminates. Once requirements are written, feasibility studies need to be performed to identify technologies to meet the requirements.

The scope of this assessment was to identify applicable documents relevant to lunar and Martian dust, identify Lunar and Martian human support systems that will be affected by the dusts, determine the requirements that will need to be written, perform a gap analysis to determine what information is still needed to write the requirements, and recommend experiments and measurement on the Earth, moon, and Mars to obtain needed information. See figure 1 for a graphical representation of the boundaries of the assessment.

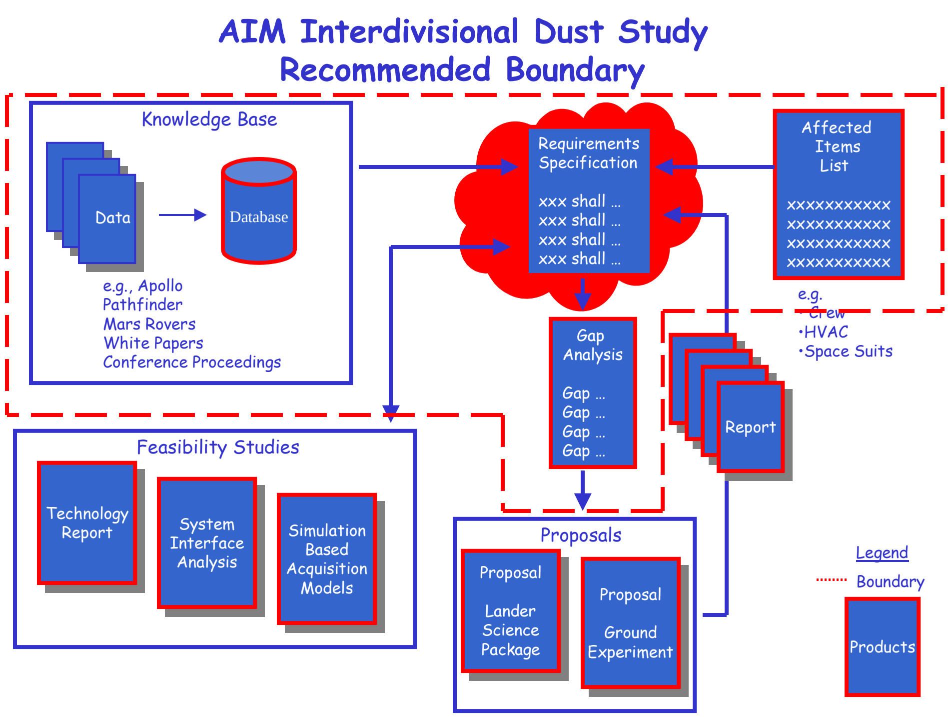

Figure 1

This report contains descriptions of the problem, document collection, the assessment, the team's recommendations, and recommendations for forward work.

1.1 Problem Statement

We know from our Apollo surface mission experience that planetary dust presents major risks to the success of surface missions on the moon and Mars.

We know that on Earth, dust causes equipment failure. For example, after the WWII North African campaign, the military left almost all of their equipment because the sand made it useless. They found that dust-covered equipment needs great care in cleaning because the cleaning can cause even more damage.

To mitigate these risks, we need to have an in-depth understanding of dust that crews will encounter. This assessment was performed to formulate questions that need to be answered in order to create feasible requirements, leading to mission success. This assessment asks the questions that, when answered, will lead to definition of the problem.

1.2 Document Collection

Team members collected documents discussing dust on planetary surfaces. The documents include: scientific data obtained on the Earth, moon and Mars; lessons learned from lunar and Martian missions; theoretical discussions of lunar and Martian dust behavior and chemistry; and, potential technical solutions to the problems we expect to encounter on the moon and Mars on future exploration missions.

A document database was created to house data about the documents that were collected by team members and contributing inputs from source experts. The database contains information including title, author(s), date, location, and abstract.

The documents are housed in the Dust Abatement folder on the AIM server. The documents have been named according to the unique identifier in the database.

2.0 Assessment

2.1 Systems Affected by Dust

The team began by identifying planetary human support systems that would be affected by dust. Systems were divided into Advanced Life Support Systems, Advanced Extravehicular Activity (EVA) Systems, and Advanced Food Systems. When the team identified other systems, they were placed into an Other Systems category.

2.1.1 Advance Life Support Systems

Advanced Life Support Systems included air revitalization, water recovery, solid waste processing, thermal control, and other. Then, each subsystem was further broken into subsystems and components. The effects of dust on these follow.

2.2 Air Revitalization System

The Air Revitalization System includes the ventilation system, trace contaminant control, carbon dioxide (CO_2) removal, CO_2 reduction, oxygen (O_2) generation, CO_2 compressor, and the particulate control system.

The effects of dust on air subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Ventilation System	Mechanical components of vents, fans, intakes, louvers, may be compromised. Certain failures in these systems have the potential to become active dust spreaders rather than dust eliminators.
Trace Contaminant Control	Impaired system would decrease the capacity to scrub contaminants.
CO_2 Removal	Desiccant and sorbent beds may become fouled with dust, reducing performance.
CO_2 Reduction	Catalytic beds may become fouled with dust, reducing performance.
O_2 Generation	May become fouled with dust, reducing performance.
CO_2 Compressor	May become fouled with dust, reducing performance.
Particulate Control System	Possible system overload and/or drastic increase in mass due to high use of expendables.

2.3 Water Recovery System

The water recovery system may include a biological water processor and/or physical chemical water processor and water quality monitor.

The effects of dust on water subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Biological Water Processor	Bacterial organisms may be poisoned by chemicals in dust.
Water Quality Monitor	Clogging or blocking of chemically reactive sites or physical pathways of instrument resulting in performance degradation.

2.4 Solid Waste

The solid waste system includes waste collectors, waste transporter, mineralization system, waste containment, waste compactor, waste resource recovery, particle size reducer, waste disposal, and general solid waste impacts.

The effects of dust on solid waste subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Waste Collectors	If salts and metals from the dust are present, biological processes may not be able to remove said materials from the system and, if trying to use recycled materials contaminated with dust constituents, time dependent buildup to unacceptable levels could occur. Affects crops and water.
Waste Compactor	Compactor tubes may be scratched, scored, damaged.
Particle Size Reducer	Dulled cutting blades.
Waste Disposal	Filters and other components will be frequently replaced, placing a burden on waste disposal processes and storage.

2.5 Thermal

The thermal systems include radiators and humidity control.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Radiators	Deposits on the radiator surface may degrade performance.
Humidity Control	Clogging of pitot tubes, small orifices in rotary separators, and porous media used to separate condensate from the air stream.

2.6 Other Systems

Other Advanced Life Support subsystems and components affected by dust are crop growth, crop harvesting, valves, pumps, membranes, filters, seals, tanks, heat exchangers, flow tubes, fluid connectors, data connectors, and power connectors.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Crop Growth	If dust is used in the root substrates, when it dries, circulating air around the plants may stir up dust. Chemicals in dust may poison plant organisms.
Crop Harvesting	Harvesting of dry crops may produce organic dust.
Valves	Compromise sealing surfaces, corroding or scoring turning shafts.
Pumps	Plugging, eroding bearings, moving parts.
Membranes	Chemical attack, fouling, puncturing, plugging.
Filters	Plugging.
Seals	Plugging or compromising sealing surfaces.
Heat Exchangers	Internal clogging, covering of external heat exchanging surfaces.
Flow Tubes	Clogged, scratched, scored, damaged.
Fluid Connectors	Sliding seals can get scratched and lead to leakage.

2.6.1 Advanced EVA Systems

Advanced EVA Systems affected by dust are airlock, suit assembly, helmet, Portable Life Support System (PLSS) power and communications, PLSS Cooling, PLSS O_2, PLSS Vent, ancillary equipment, structures, tools and hardware, rovers, displays, solar cells, windows, lights, sensors, and cameras.

2.7 Airlock

Airlock subsystems and components affected by dust are quick disconnects (QD)/connecters and Hatch Seals.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
QDs/Connectors	Seal degradation, leaks, higher spares/maintenance.
Hatch Seals	Seal degradation, leaks, higher gas makeup, spares/maintenance, dust transfers into habitat/vehicle.

2.8 Spacesuit Assembly

Spacesuit Assembly subsystems and components affected by dust are outer garment, bearings, visor coatings, lighting.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Outer Garment	Dust accumulation/transfer to airlock-habitat; degradation of materials.
Bearings	Seal degradation, leaks, higher spares/maintenance.
Visor Coatings	Scratches/severe abrasion; loss of coatings.
Lighting	Reduced illumination due to dust coating illumination source.

2.8.1 Portable Life Support System Power and Communications

PLSS Power and Communications subsystems and components affected by dust are electric circuits, batteries, and fuel cells.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Electrical Circuits	Charged dust particles could result in static shock to electronics
Battery/Fuel cell	Dust in battery contacts cause power drain and potential short circuit.

2.8.2 PLSS Cooling

PLSS Cooling subsystems and components affected by dust are evaporative membrane, QDs and connectors, and radiator surface.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Evaporative Membrane	Contamination of membrane surface; transport blockage.
QDs and Connectors	Seal degradation, leaks, higher spares/maintenance.
Radiator Surface	Thermal coating degradation/loss of cooling efficiency.

2.8.3 PLSS O_2

PLSS O_2 subsystems and components affected by dust are QDs, connectors, and regulators.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
QDs/connectors	Seal degradation, leaks, higher spares/maintenance.
Regulators	Contamination of orifices; transport blockage.

2.8.4 PLSS Vent

PLSS Vent subsystems and components affected by dust are QDs, connectors, and venting membranes.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
QDs/connectors	Seal degradation, leaks, higher spares/maintenance.
Venting Membranes	Contamination of membrane surface; transport blockage.

2.8.5 Ancillary Equipment

Ancillary Equipment subsystems and components affected by dust are power tools, wrenches, sockets, drills, joints on translation aids, structures, and tools and hardware.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Power Tools	Dust in battery contacts cause power drain & potential short circuit.
Wrenches	Buildup and restriction of working parts.
Sockets	Buildup and restriction of working parts.
Drills	Buildup and restriction of working parts.
Joints on Translation Aids	Buildup and restriction of working parts.
Structures	Buildup and restriction of working parts. Corrosive constituents in dust may lead to degradation of structures if water used in EVA operations contacts dust on surfaces.
Tools/Hardware	Buildup and restriction of working parts.

2.9 Unpressurized/Pressurized Rover

Rover subsystems and components affected by dust are chassis, wheels, crew station, and airlock.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Chassis (suspension)	Dust accumulation.
Wheels (tires, brakes)	Abrasion/dust accumulation.
Crew Station (seats, controls, displays, restraints)	Dust accumulation.
Airlock (hatch/seals)	Seal degradation, leaks.

2.10 Other Systems

Other subsystems and components affected by dust are displays, solar cells, windows, lights, sensors, and cameras.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Displays (wrist)	Obscure view.
Solar cells	Obscure/reduce output.
Windows	Occlude or scratch windows.
Lights	Reduce light level.
Sensors	Loss of sensitivity.
Cameras	Occlude or scratch camera lens coatings.

2.10.1 Advance Food Systems

Advanced Food Systems included food storage, food processing, and food preparation. The effects of dust on these follow.

2.11 Food Systems

The effects of dust on food storage subsystems were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Food Storage System	Contamination.
Processing Equipment	Contamination.
Food preparation equipment	Contamination.

2.11.1 Associated Systems

Other Systems affected by dust are guidance, navigation and control (GN&C), structures, inner-vehicular activity (IVA), fire detection and suppression, environmental monitoring, power, electrical and electronics, and communications.

2.12 Guidance, Navigation and Control

Dust effects on GN&C were identified.

Subsystem/Component	Effect due to Dust Exposure
GN&C	Mechanical and electrical components may fail or degrade.

2.13 Structures

Other subsystems and components affected by dust are habitat structure, water pipes, water tanks, and filtration.

Dust effects on subsystems and components were identified.

Subsystem/Component	Effect due to Dust Exposure
Habitat Structure	If Martian dust is reactive, the structure may degrade over time due to exposure.
Water Pipes	Dust getting into water pipes may contaminate drinking water.
Water Tanks	Dust getting into water tanks may contaminate drinking water.
Filtration	Excessive dust handled by filtration will require frequent change out leading to additional waste generation and weight lifted to the moon and Mars.

2.14 Inner-Vehicular Activity

IVA subsystems and components affected by dust are laundry, food preparation, medical implements, hygiene, filters, vacuum cleaners, seals, hoses, connectors, computer displays, crew time, cameras, windows, lights, and clothing.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Laundry	Additional water needed to wash dust contaminated clothing and discard of waste water and sediment.
Food Preparation	Food handling and meal preparation will require analysis to determine dust impact.
Medical Implements (syringes, gauze, etc.)	Dust contamination of medical implements will lead to crew exposure.
Hygiene	Crew will need to wash off dust and flush eyes.
All Filters	Cleaning and unclogging filters will release dust into the environment .
Vacuum Cleaners	Reduce efficiency.
Seals	Degradation of seals on all systems (airlock, oxygen masks/bottles, etc.).
Hoses	Abrasion.
Connectors	Abrasion.
Computer Displays	Reduce contrast of fine lines and edges.
Cameras (interior)	Occlude or scratch camera lens coatings.
Windows (interior)	Occlude or scratch windows.
Lights	Reduce light level and increase maintenance.
Clothing	Reduce/remove dust from clothing so it does not act as an abrasive to the skin.
Crew Time	Increase in maintenance/housekeeping activities. Increase in monitoring of system degradation.

2.15 Fire Detection and Suppression

Dust effects on Fire Detection and Suppression were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Fires Detection and Suppression Systems	Dust contamination could result in detectors failing to detect smoke and/or suppression system actuators failing. May render system unreliable.

2.16 Environmental Monitoring

Dust effects on Environmental Monitoring were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Environmental Monitoring	Dust contamination could result in failure of environmental monitoring systems/windows and camera lenses coated with dust, obscuring view.

2.17 Power

Power subsystems and components affected by dust are heat rejection and radiators, solar arrays and PV cells, solar cells, and solar sensors.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Heat Rejection/Radiators	Radiator performance degraded. Lowers efficiency/system overheat.
Solar Arrays/PV Cells	Lowers efficiency.
Solar Panels	Dust collecting on solar panels will degrade power generation systems.
Solar Cells	Occludes light to solar cells.
Solar Sensors	Underestimate intensity.

2.18 Electrical/Electronics

Electrical and electronic subsystems and components affected by dust are avionics, keyboards, buttons, switches, circuits, electrical connectors, and data connections.

Dust effects on subsystems and components were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Avionics	Dust contamination will cause degraded performance and may cause failure of critical systems.
Keyboards	Keyboard failure.
Buttons	Button failure.
Switches	Switch failure.
Circuits	Dust contamination will cause degraded performance and may cause failure of critical systems.
Electrical Connectors	Dust in battery contacts cause power drain and potential short circuit.
Data Connectors	Dust in data connectors may cause degraded performance or failure.

2.19 Communications

Dust effects on communication systems were identified.

Subsystem/Component	**Effect due to Dust Exposure**
Communications	Communications systems may be degraded with exposure to dust. Optics performance degrades with dust buildup.

2.20 Risks

Risk identification and preliminary consequence assessment is a valuable tool in risk mitigation decisions during the early phases of projects. The team performed a high-level risk assessment based on the effects of dust on each system. Identified risks fall into three categories: safety, crew health, and mission success. Cost and schedule risks are also assessed.

The following tables define the risk identifications for likelihood and consequence as used in this study:

LIKELIHOOD — *What is the likelihood the situation or circumstance will happen ?*

Level	*Probability*	*. . . Or the current process . . .*
5	Very High	cannot prevent this event, no alternative approaches or processes are available.
4	High	cannot prevent this event, but a different approach or process might
3	Moderate	may prevent this event, but additional actions will be required.
2	Low	is usually sufficient to prevent this type of event.
1	Very Low	is sufficient to prevent this event.

CONSEQUENCE — *What is the Consequence (Cost, Schedule, Technical, or Safety) of this OSP risk?*

Level	1	2	3	4	5
Cost	Minimal or no impact	Budget Increase < 5%	Budget Increase >5%	Budget Increase >10%	Budget Increase >15%
Schedule	Minimal or no impact	Additional activities required. Able to Meet date.	Key Program milestone slip <= 1 month	Key Program milestone slip > 1 month, or Program critical path impacted	Cannot achieve Major Program milestone
Technical	Minimal or no impact	Moderate Reduction, Same Approach Retained	Moderate Reduction, But Alternatives Available	Major Reduction, But Alternatives Available	Unacceptable, No Alternatives Exist
Safety	• No Safety and Health Plan Violation • No adverse hazard or reliability change • Full regulatory compliance	• Documented CIL • Change in hazard controls but no increase in PRA • Minor violation of Federal or State regulation • <10% decrease in reliability	• CIL without acceptance rationale • Change in hazard controls with increase in PRA • Violation of Federal or State regulation • 10-20% decrease in reliability	• Major but temporary injury • Potential damage to assets • Multiple violations of Federal or State regulation • >20% decrease in reliability	• Potential for permanent injury or death • Loss of critical assets • Willful or major violations of Federal or State regulation

2.21 Safety

Risk Statement: If critical life-safety systems fail due to dust buildup on systems, injury or loss of crew member(s) will result.

Consequences: 4 to 5, severe injury or loss of crew.

Likelihood: 5, critical life-safety systems do not yet exist to function in the Martian and lunar dusty environments.

Context: This risk was identified in Advanced Life Support, Advanced EVA, and Other Systems. The affected subsystems and components include ventilation, electronics, CO_2 removal, fire detection and suppression, EVA suits, rovers, windows, visors, optics, crops, and power systems. If critical life support systems completely fail, rescue is not feasible because a rescue mission, even if it were ready to launch immediately, would take 3 days for a crew visiting the moon and months for a crew visiting Mars.

2.22 Crew Health

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

Consequences: 2 to 5, mild illness to loss of crew.

Likelihood: 5, health protection systems do not yet exist to function in the Martian and lunar dusty environments.

Context: This risk was identified in Advanced Life Support, Advanced Food Systems, and Other Systems. Dust could be transported into the habitat via a dust-contaminated airlock and dust-laden EVA suits. The presence of dust in the habitable area will decrease effectiveness of air, water, and food management systems, and it will pose an inhalation hazard to the crew. Inhalation of sufficient amounts of lunar dust could impair lung function. Exposures to Martian dust, which is oxidative and reactive and have a greater potential to produce lung pathology, will pose a greater health risk to crew. In the context of human presence, the single largest concerns are the respiratory effects associated with fine dust of respirable sizes.

2.23 Mission Success

Risk Statement: If dust causes early degradation of mission critical components, crew will be diverted from science and mission may terminate prematurely.

Consequences: 3 to 4, loss of science and/or premature mission termination.

Likelihood: 5, mission critical systems do not yet exist to function in the Martian and lunar dusty environments.

Context: This risk was identified in Advanced Life Support, Advanced Food Systems, and Other Systems. Affected subsystems and components include water processing, waste management, ventilation, humidity control, thermal management, electrical, food supply, computer, computers and avionics, EVA Systems, windows, cameras, and scientific collection and analysis systems. To control dust, crew will be diverted from science activities to perform cleaning, replacement, and maintenance activities. If mission critical systems fail, mission will have to be terminated prematurely.

2.24 Cost

Risk Statement: If new technology is not developed and systems designed to minimize the effects of Martian and lunar dust on Human Support Systems, cost of mission will be prohibitive.

Consequences: 5, program cancellation.

Likelihood: 5, dust control systems do not yet exist to manage dust in the Martian and lunar environments

Context: This risk applies to every system, subsystem, and component analyzed. Transporting replacement parts to the moon and Mars add to mission cost. The lower the reliability of surface human support systems, the more replacement parts must be transported and the greater the expense of supplying replacement parts.

2.25 Schedule

Risk Statement: If new information about lunar and Martian dust is learned after systems have been designed reveals that surface human support systems designs are insufficient, design changes will lead to significant schedule slips.

Consequences: 5, greater than 20 percent schedule slip.

Likelihood: 5, dust is not well understood.

Context: This risk applies to every system, subsystem, and component analyzed.

3.0 Knowledge Gaps

Definition of knowledge gap: Identification of areas of study where information is not available to address critical questions. To mitigate the above risks, the team identified knowledge gaps for lunar and Martian soil. The recommendations section suggested tests, sampling, and analysis to fill the knowledge gaps. Armed with more complete knowledge, designers will be equipped to design systems for reliability in the dusty environments.

The physical and chemical properties of lunar dust are well understood for Apollo Surface Mission locations. Dust was returned from the moon and complete characterization has been performed. Other locations, such the far side, have not been sampled and analyzed. Simulants have been developed to approximate lunar dust and have been used to test various components. Actual moon dust has not been used for this purpose. Differences between lunar dust and the simulant may result in additional studies and redesign. The toxicological properties of simulated lunar soil have been characterized; however, the toxicity of the real moon dust has not been tested.

Martian dust is not as well understood because samples have not been analyzed at the same level of detail. Information needed to mitigate risks include pH, complete chemical characterization including trace and toxic constituents, particle size, electrostatic properties, magnetic susceptibility, corrosion, reactivity, mineral content, velocity and particle size of sand in dust storm cores, aggregation, in-situ thermal conductivity, morphology, photoreactions, optical properties in the optical and thermal infrared region, thermal cycling, in-situ dust adherence, and rate of accumulation.

The table below provides dust parameters and identifies the associated risk.

Dust Parameter	Associated Risk(s)
pH	Safety/Crew Health/Mission Success
Complete chemical characterization including trace and toxic constituents	Crew Health/Mission Success
Particle size	Safety/Crew Health/Mission Success
Electrostatic properties/Magnetic susceptibility	Safety/Mission Success
Corrosion	Safety/Crew Health/Mission Success
Reactivity	Safety/Crew Health/Mission Success
Mineral content	Crew Health
Velocity and particle size of sand in dust storm cores and agglomeration	Mission Success
In-situ Thermal Conductivity	Safety/Mission Assurance
Morphology	Safety/Mission Assurance
Photoreactions	Safety/Mission Assurance
Optical Properties in the optical and thermal infrared region	Safety/Mission Assurance
Thermal Cycling	Safety/Mission Assurance
In-situ Dust Adherence	Safety/Mission Assurance
Rate of natural accumulation	Safety/Mission Assurance
Aggregation	Safety/Mission Assurance

4.0 Recommendations

Recommendations included measurements of lunar and Martian dust, and test and demonstration of systems and components using dust simulants.

The recommendations for sampling and analysis that can only be made on the Martian surface will be forwarded to the Mars Human Precursor Science Steering Group's Dust, Soil and Toxicology Team for their use in developing requirements for future robotic missions to Mars.

Recommendations for sampling and analysis that can only be made on the lunar surface will be forwarded to the Lunar Human Precursor Team for their use in developing requirements for future robotic missions to the moon.

5.0 Forward Work

Forward work was broken down into activities that should be performed on Earth, the moon, and Mars. The team's recommendations follow.

5.1 Earth

The recommendations for Earth-based forward work are divided into three parts. Part 1 describes overall forward work. Part 2 considers work that should be done to develop and validate requirements. Part 3 considers toxicology forward work.

5.1.1 Part 1: Overall Earth-based Forward Work

Review all relevant lunar surface data (Apollo experience, laboratory testing of samples) to develop a standard set of lunar dust properties that future designers can use.

Review all relevant Mars surface data (remote sensing, lander experience) to develop a standard set of Martian dust properties that future designers can use.

Develop and fully characterize new lunar and Martian soil simulants that can be used in a wide variety of test programs.

Develop lunar and Martian test chamber that closely approximates the vacuum, thermal, and electrical properties of the lunar and Martian surfaces to support test programs.

Develop a test program, equivalent to the "shake and bake" testing performed on spacecraft prior to launch, to demonstrate that systems can function in the lunar and Martian dust environments.

Work with the Lunar Curator to obtain small quantities of actual lunar dust for critical test programs (i.e., toxicology).

Compile information (such as symptoms) on Apollo crew's experience with the lunar dust.

Implement complete medical monitoring for astronauts exposed to lunar and Martian dust.

Survey technology investments currently being performed by industry, academia, and the Department of Defense in the areas of dust removal systems (electrostatic, mechanical); new materials and surface treatments; materials to ensure integrity of seals and joints, as well as novel, time-saving operational approaches toward dust mitigation. Identification of advanced materials, systems, and components with potential to mitigate problems arising from adherence and entry of lunar and Martian dust during EVA may assist with future design considerations for the EVA suit.

5.1.2 Part 2: Requirements Development and Forward Work

Developing requirements will require the identification of interactions between systems and subsystems. Higher level requirements will result from element and part level requirements. As subsystems are joined together, global limits are established and become the “working requirement,” the global limiting case. Each subsystem/assembly will have its own accumulation or concentration limits; thus, each subsystem will have to identify the impact of dust independently and in union with total system.

When requirements are generated, care must be made to account for the total accumulated contaminate level and the recognition of accumulation rate. Instantaneous measures that verify “safe” operating limits are subject to change, especially when coupled with moving boundary components like egresses. The instantaneous dust limit may be defined in terms of human occupancy but possibly to some stricter limit that reduces maintenance time and reduces weight of cleaning systems to be launched. Instantaneous limits cannot be pinned down until the individual subsystems define their operational limits. Recommendations to explore these subjects are provided:

1. Conduct studies of a) dust characterization (size, density, etc.) in the vicinity of the habitat, b) potential for dust to enter pressurized cabin (weight or volume per minute, thru airlock primarily), and c) dust concentration in cabin due to intrusion.
2. Identify maximum dust concentration allowed in cabin (probably the NASA-STD-3000 value).
3. Each major system needs to identify their maximum allowable dust accumulation (weight or volume per unit of time) and maximum dust concentration, and compare these to the potential dust accumulation rate from 1b, and to the maximum concentration allowed (from 2) to determine if additional filtering equipment is needed either at the system level or the airlock/cabin level.
4. Redefine the maximum dust concentration allowed in (2) if warranted, and iterate on steps 1 to 3.

5.1.3 Part 3: Toxicology Forward Work

Crew members will require adequate protection from the toxicological effects of dust present on the lunar or Martian surfaces. The level of that protection will depend on a number of the physical and chemical properties of these dusts. Requirements need to be created to determine the following parameters:

1. Diversity of the types of dust that could be present in the area of the outpost. Based on brief discussions, one would expect that Martian dust is well mixed on a planetary basis and does not differ from one location to another. Lunar dust may differ depending on the nature of the impacts that created the dust in the vicinity of the outpost. If the launch platform is not far from the outpost, then one must consider the added effect of propellant byproducts on the surface of the dust.
2. Particle size and shape distribution of the dust fraction below 20 microns. Particles below 10 microns can be respired into the lower respiratory tract where injury can occur. Crystalline particles will be more toxic than amorphous particles of the same composition.

3. Reactivity of the particle surface may be a major factor in determining the potential hazard to crew health. Based on the data obtained by NASA from the Apollo manned missions and Martian robotic missions, Martian surface soil is oxidizing and reactive, whereas lunar dust is relatively inert. The results of our study with simulated Martian and lunar dusts supported this speculation that the former would be more toxic than the latter. However, how toxic are lunar and Martian dusts would require further investigations with the lunar dust and simulated Martian dusts (Hawaii volcanic ash) doped with appropriated oxidative chemicals.
4. If in-situ resources are to be used, then the dust generated in association with that process must be assessed for hazard to the crew. For example, if water is to be recovered from in-situ resources, then the dust that accompanies that water must be removed to a safe level for consumption by the crew.
5. Larger, non-respirable particles could present a hazard to the eyes of the crew.

Ambient exposure limits of dusts in the habitable environments in the lunar and Martian outposts need to be set.

Prolonged exposures to dusts may result in fibrosis and other lung diseases. The toxicity of dusts in the lungs will depend on particle sizes, chemical composition, surface chemistry, and geometry. Based on the data obtained by NASA from the Apollo manned missions and Martian robotic missions, Martian surface dust is oxidizing and reactive, whereas lunar dust is relatively inert. Our toxicity study with simulated Martian and lunar dusts supported the speculation that the former would be more toxic than the latter. However, how toxic are the lunar and Martian dusts would require further investigations with the lunar dust and activated simulated Martian dusts (Hawaii volcanic ash doped with appropriated oxidative chemicals) in animals.

To substantiate experimental results obtained from animal toxicity studies with the lunar dust and activated simulated Martian dust, results should be gathered from epidemiology studies of human exposures to volcanic ashes, and information on crew experience with the lunar dusts in the lunar commending modules should be collected.

<u>Moon (things that can only be done on the lunar surface)</u>

For lunar missions, the team recommended that samples be collected and analyzed in regions where dust may be different than the samples collected in the Apollo surface missions. For example, this information would be valuable for missions that include in-situ resource utilization on the polar regions that may contain water, or for science missions that require low interference from Earth radio sources such as observation using telescopes.

Other measurements include fully characterizing electrostatic levitation, the only known mechanism for mobilizing significant quantities of lunar dust. Dust can also be moved by mechanical means, such as a sweeper, brush, rovers, and crew moving across the surface, or if the particles are magnetic by magnets. Magnetic properties of the dust should be determined, as well.

The team also recommended demonstrating the operation of airborne dust monitors and filters in the lunar environment prior to committing human crews.

Mars (things that can only be done on the Martian surface)

For Mars missions, the team recommended rovers and Mars Sample Return to characterize soil for the parameters identified in the risk section of this report.

Further recommendations were:

- Measure dust loading in the Martian atmosphere under a variety of environmental conditions
- Fully characterize the electrostatic properties of the Martian surface
- Return Martian dust samples to Earth for full analysis well before committing humans to a Mars mission

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13. ABSTRACT *(Maximum 200 words)*

Apollo astronauts learned, first hand, how problems with dust impact lunar surface missions. After three days, lunar dust contamination on Extravehicular Activity (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. During the return trip to Earth, when microgravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes. Some mechanical systems aboard the spacecraft were damaged due to dust contamination. Study results obtained by Robotic Martian missions indicate that Martian surface soil is oxidative and reactive. Exposures to the reactive Martian dust will pose an even greater concern to the crew health and the integrity of the mechanical systems.

The Advanced Integration Matrix Dust Assessment Team was tasked to identify systems that will be affected by the respective dust, how they will be affected, associated risks of dust exposure, requirements that will need to be developed, identify knowledge gaps, and recommend scientific measurements to obtain information needed to develop requirements, and to design and manufacture the surface systems that will support crew habitation in the lunar and Martian outposts.

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