DUST MITIGATION GAP ASSESSMENT REPORT

Feb 9, 2016

International Agency Working Group

"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."

Gene Cernan, Apollo 17 Technical Debrief

"Dust is still a principal limiting factor in returning to the lunar surface for missions of any extended duration. However, viable technology solutions have been identified, but need maturation to be available to support both lunar and Mars missions."

Dust Mitigation Gap Assessment Team, Final Report

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DUST MITIGATION GAP ASSESSMENT REPORT

INTERNATIONAL AGENCY WORKING GROUP

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1. OBJECTIVES AND APPROACH

The International Space Exploration Coordination Group (ISECG) formed two Gap Assessment teams to evaluate topic discipline areas that had not been worked at an international level to date. Accordingly, the ISECG Technology Working Group (TWG) recommended two discipline areas based on Global Exploration Roadmap (GER) Critical Technology Needs reflected within the GER Technology Development Map (GTDM): Dust Mitigation and LOX/Methane Propulsion. The ISECG approved the recommended Gap Assessment teams, and tasked the TWG to formulate the new teams with subject matter experts (SMEs) from the participating agencies.

<u>ISECG Gap Assessment Teams</u>

- Dust Mitigation technologies
  Participating agencies: ASI, CSA, ESA, JAXA, NASA

- LOX/Methane Propulsion technologies
  Participating agencies: ASI, CNES, DLR, ESA, JAXA, NASA

1.1 TWG AND SME GAP OBJECTIVES FOR ASSESSMENT TEAM

The objectives of the Gap Assessment Team were as follows:

- **Identify and make a presentation on technology gaps** related to the GER2 mission scenario (including cislunar and lunar mission themes and long-lead items for human exploration of Mars) at the international level. This presentation should include opportunities for international coordination and cooperation in closing the identified gaps.
- **Produce a gap assessment** in the form of a summary report and presentation identifying those GER Critical Technology Needs. This also should include opportunities for international coordination and cooperation in closing the identified gaps.

Note: A small number of GER Critical Technology Needs will only be considered for the initial technology gap analysis. Additional GER portfolio analysis will be done at a later time, pending the lessons learned and direction of the ISECG.

1.2 GAP ASSESSMENT APPROACH (TASKS)

The gap assessment approach involved four tasks:

- **Identification of Key Tasks/Questions:** In coordination with the International Architecture Working Group (IAWG), the Gap Assessment Team reviewed the existing GTDM and portfolio entries for GER architecture details and performance metrics (in accordance with current elements/capabilities tied to the GER 2.0 architecture). We then identified what updates are needed, if any, to the current GTDM portfolio of technology development activities to reflect each respective agency's activities/interest related to the GER.

- **Gap Analysis:** The team identified gaps for the identified technologies and capabilities, initially focused on critical technologies.

- **Options for Gap Closure:** The team identified the key technology/engineering solutions for closing the identified gaps.
- **Identification of Partnership/Coordination Opportunities**

1.3 EXECUTIVE SUMMARY OF KEY FINDINGS

- Dust is still a principal limiting factor in returning to the lunar surface for missions of any extended duration.
- Viable technology solutions have been identified, but need maturation to be available to support missions.
- No single technology completely solves the challenges of dust, but rather a suite of technologies will be required to address them.
- Gaps in existing dust mitigation technologies have been identified and require strategies for closure before extended lunar missions are undertaken.
- Situational awareness of the dust mitigation challenges needs to be infused into all aspects of mission architecture and operations.
- Investment in dust mitigation solutions increases system longevity and performance (including human-system performance).
- Resources (power, mass, volume) may be required to implement some of the mitigation solutions, but are offset by reduced logistics costs for spares, redundancies, etc.
- Solutions that work in one environment may not necessarily be fully applicable to other environments or destinations (e.g., chemistry differences, atmospheres, particles, locations on previously explored bodies).
- Trapped volatile gases are an additional factor of potential concern, which may require unique mitigation solutions.
- International cooperation within the dust mitigation community has already proven beneficial. This is currently limited to sharing information, but further opportunities are expected as commitment to narrowing the technology gap continues.

2. DUST MITIGATION CHALLENGES

"Apollo astronauts learned firsthand how problems with dust impact lunar surface missions. 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. 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. 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."

Advanced Integration Matrix (AIM): An Assessment of Dust Effects on Planetary Surface Systems to Support Exploration Requirements

The Dust Mitigation team started by leveraging prior work by each of the participating agencies, particularly the more extensive NASA work done to date. In that regard, a toximetry system was used as a starting point for consolidating the diverse areas of dust mitigation challenges. In addition to building upon the list with specific entries, further descriptions of the specific challenges were identified and added to the challenges matrix that became the common reference table for the international team. The following major discipline areas related to dust mitigation challenges were included for study:

- Life support systems (LSS)
- Extravehicular activity (EVA) systems (including suits, airlocks, suitport, tools)
- Human health and human-system performance
- Robotics and mobility systems
- *In situ* resource utilization (ISRU)
- Ascent/descent vehicles
- Surface power systems
- Thermal control systems

The major discipline areas for dust mitigation challenges are addressed in the summary tables that follow. In addition to identifying the effects resulting from dust exposure, the team also did an initial identification of performance characteristics where available/applicable. The Performance Characteristic field was defined as those parameters/metrics that would assist in quantifying the advancements in technology, engineering, and operations from the state-of-the-art (SOA) that would be necessary to mitigate the associated challenge. The tables represent the international team's summary of the broad range of dust mitigation areas that need to be addressed, and the associated potential adverse effects on spaceflight systems. The tables should be considered preliminary reference material that future work in the area of dust mitigation strategies can build upon. Areas with missing data require further investigation, discussion, or collaboration.

2.1 LIFE SUPPORT SYSTEMS

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
1. Life Support Systems (LSS)	The advanced Life Support System includes atmosphere revitalization, water recovery, solid waste processing, thermal control, and other subsystems. Each subsystem within the LSS is further broken into functional elements and components. The effects of dust on these follow.	The LSS must handle the basic particulate load defined in NASA TP-1998-207978, p. 35 and refined by ICES-2014-199 within the concentration limits defined by NASA-STD-3001 for <3 mg/m^3 total dust for particles <100 µm in aerodynamic diameter and <1mg/m^3 for the respirable fraction of the total dust <2.5 µm. Permissible concentration levels of lunar dust in the habitable environment are limited to 0.3 mg/m^3 for particle sizes <10 µm. It is assumed that physical and functional barriers to surface dust intrusion into the habitable vehicle cabin are >95% effective.
1.1 Atmosphere Revitalization (AR) Subsystem	The Atmosphere Revitalization subsystem includes cabin ventilation, trace contaminant control, CO_2 removal, CO_2 reduction, O_2 generation, CO_2 conditioning, and the particulate removal functional elements.	The AR subsystem architecture interfaces intimately with the cabin ventilation architecture. Particulate control is an integral functional component of the cabin ventilation functional element. The core AR subsystem equipment interfaces with the cabin ventilation architecture downstream of the particulate control stages to prevent fouling from crew- and EVA-generated debris and dust. An AR subsystem architecture is described by AIAA-2015-4456. The architecture has core AR subsystem functional elements protected by particulate removal functional elements.
Cabin Ventilation	Mechanical components of vents, fans, intakes, and louvers may be compromised. Certain failures in these systems have the potential to become active dust spreaders rather than dust eliminators.	The cabin ventilation architecture contains a multistage debris and particulate filtration capability. This multistage capability is described by NASA/TM-2009-215821. Debris screens remove lint and larger debris >800 µm. An inertial separation stage removes particulates such as skin fragments and dust <800 µm/>20 µm, and a high-efficiency media filter removes fine and ultrafine particulate matter <20 µm.
Trace Contaminant Control	Impaired system would decrease the capacity to scrub contaminants.	Functional inlet is downstream of the cabin particulate control equipment. Adsorbent media could be susceptible to particle fouling.
CO_2 Removal	Desiccant and sorbent beds may become fouled with dust, reducing performance.	Functional inlet is downstream of the cabin particulate control equipment. Some of the sorbent media can undergo size attrition, therefore the process equipment must control internally-generated particulates >50 µm. External vents must be designed to prevent clogging by surface dust.
CO_2 Reduction	Catalytic beds may become fouled with dust, reducing performance.	Functional inlet is downstream of the CO_2 removal equipment and thus functionally isolated from the cabin particulate load. External vents must be designed to prevent clogging by surface dust.

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
O_2 Generation	May become fouled with dust, reducing performance.	Potable water feed is filtered and isolated from the cabin particulate load. External vents must be designed to prevent clogging by surface dust.
CO_2 Compressor	May become fouled with dust, reducing performance.	Functional inlet is downstream of the CO_2 removal equipment and thus functionally isolated from the cabin particulate load.
Particulate Control System	Possible system overload or drastic increase in mass resulting from high use of expendables.	Particulate control equipment design uses filtration media on an indexing scroll mechanism to continually advance the media to reduce excessive loading as well as reduce crew time for maintenance (AIAA-2013-3486) coupled with regenerable inertial impaction techniques (ICES-2015-206).
1.2 Water Recovery Subsystem	The water recovery system may include a biological water processor or physical chemical water processor and water quality monitor.	
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.	
1.3 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.	
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, or 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.	
1.4 Thermal	The thermal systems include radiators and humidity control.	
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.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
1.5 Other	Other Advanced Life Support subsystems and components affected by dust are those related to crop growth, crop harvesting, valves, pumps, membranes, filters, seals, tanks, heat exchangers, flow tubes, fluid connectors, data connectors, and power connectors.	
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 of sealing surfaces, corroding or scoring of turning shafts.	
Pumps	Plugging, eroding bearings, moving parts.	
Membranes	Chemical attack, fouling, puncturing, plugging.	
Filters	Plugging.	Increased pressure drop and an increase in ventilation power required.
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.	

2.2 EVA SYSTEMS

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
2. 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. Other Advanced EVA Systems affected by dust are those related to the suit assembly, including the Pressure Garment System (PGS), PLSS interface to the PGS, power and communications, PLSS cooling, PLSS O_2, PLSS ventilation, ancillary equipment, tools, displays, lights, sensors, and cameras. Airlock systems are also affected by dust as they are the primary method of ingressing/egressing the habitable volume.	Current EVA Systems do not account for dust. Future designs for planetary exploration space suits will incorporate lessons learned from Apollo suits (Lunar Dust Effects on Spacesuit Systems, TP-2009-214786). A “Layered Engineering Defense Plan” for dust mitigation including tools for dust removal and dust resistant interfaces for EVA suits, etc. that are integral with vehicle systems will be necessary. SOA airlock systems do not account for dust. Dust mitigation and resistance to impact and abrasion poses a significant technical challenge for most Design Reference Missions (DRMs), with the exception of microgravity-free space such as International Space Station (ISS) or Mars transit. Dust can damage suit components and may become a crew health hazard if introduced into the crew cabin in sufficient quantities. Dust is removed from the suits in a multiphase operation in order to limit the amount of dust being introduced into the exploration EVA suits and crew cabin. Certain ingress/egress methods

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
		provide dust mitigation techniques, e.g., keeping the exploration EVA suits on the opposite side of the bulkhead from the habitable environment. Cabin filtration would still be necessary to mitigate dust on the assets/habitation. Need definition of each destination's environmental hazards, including dust constituents. What is the chemical composition of the dust and what are its characteristics, including particle sizes and shapes? Do the properties change when the dust exposed to a habitable environment (pressure, humidity, etc.)? What type of hazards does the dust present to humans? Need programmatic requirement for levels of contaminate within the habitable volume. Based on the suit outer garment material, dust properties, and vehicle architecture, what type of pre-ingress cleaning methods and tools will be required to remove dust from the suit? Is the dust electrically conductive? Is the dust flammable? Based on dust characteristics, need to define and develop appropriate level of cleanliness for intravehicular activity (IVA) maintenance of the EVA system. (EVA Gaps for SMT, Dust Mitigation, rows 114 and 115)
2.1 Airlock	Airlock subsystems and components affected by dust are quick disconnects (QDs)/connecters and hatch seals. The amount of dust transferred through the system on EVA suits, tools, and equipment varies depending on the design of the ingress/egress method. Airlock subsystems and components affected by dust are filtration, air reclamation, QDs/connecters, switches, hatch seals, etc.	Suits must be brought inside a habitable volume for nominal suit maintenance. An airlock system is necessary to provide a way to ingress/egress the habitat. Need an EVA suit maintenance capability within the habitat for missions longer than 28 days (a pure suitport architecture alone will not suffice). Airlock methods can include airlocks similar to the ISS airlock or concepts such as the suitlock or suitport-airlock, which include donning/doffing the suit through a bulkhead to mitigate the amount of dust transferred into the habitat (volume around the suits can be pressurized so that the crewmembers wear shirtsleeves in the chamber). Determine what is needed for a suit maintenance area inside vehicles/habitats for long-duration spaceflight; determine which DRMs require a mudroom maintenance area; determine what suit maintenance can be done with the suit attached to ingress/egress equipment and what needs to be done in the maintenance area during more in-depth procedures. Determine services and level of cleanliness needed in each area; will cleanliness requirements drive dust mitigation tools? Maturation will occur as DRMs become more concrete, element/vehicle concepts mature, suit is designed, safety/failure analysis begins, limited

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
		life items are identified, dust requirements flow down, etc. (EVA Gaps for SMT, Long Duration EVA Maintenance (>28 days), rows 110 and 112)
2.1.1 QDs/Connectors	Seal degradation, leaks, higher spares/maintenance.	
2.1.2 Hatch Seals	Seal degradation, leaks, higher gas makeup, spares/maintenance, dust transfers into habitat/vehicle.	
2.2 Suitport Concept	Suitport subsystems and components affected by dust are QDs/connecters and hatch seals, etc., most of which are external to the vehicle.	A suitport includes two pressure sealing interfaces, one between the Suitport Interface Plate (SIP) on the exploration EVA suit and the outside of the bulkhead and another between the inner vestibule hatch and the inside of the bulkhead in the habitable volume of a host vehicle. The suit's SIP is a critical sealing interface to the suitport bulkhead. It must be durable enough to withstand dust and allow the suit to seal to the suitport over many cycles. Inclusion of an interface between the suit and the ingress/egress method (i.e., interface plate) needs to include all environmental effects, particularly those related to dust, long-duration life cycle, loads, high cycle life, and thermal environment. By nature of the concept, the options to insulate/protect the interface will be limited. (EVA Gaps for SMT, Frequent EVA with Rapid Ingress/Egress and low consumable loss, rows 53 and 120)
2.3 Space Suit Assembly	Space Suit Assembly subsystems and components affected by dust are outer garment, bearings, visor coatings, lighting.	
PGS	Dust accumulation/transfer to airlock-habitat; degradation of materials.	
Bearings, Valves	Seal degradation, leaks, greater need for spares/maintenance.	Need protection of bearings to preclude dust from entering bearing race over long-duration surface missions. After dust exposure, mechanism shall fail gracefully, not catastrophically. Need protection of relief valves, purge valves, disconnects, actuators, and other mechanisms to preclude dust from hampering motion/function. (EVA Gaps for SMT, From dust, bearings, From dust, mechanism valves, rows 34 and 35)
Visor Coatings	Scratches/severe abrasion; loss of coatings.	Need visor that can be maintained and repaired and replaced (R&R'ed) on orbit. Knowledge: Need properties of dust and dust storms at each destination to inform dust-resistance requirements for visor. Will one scratch-resistant solution work for all destinations? (EVA Gaps for SMT, From Abrasion and point impacts including abrasion from dust, row 47)
Lighting	Reduced illumination as a result of dust coating the illumination source.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
2.4 Portable Life Support System (PLSS)		Need a PLSS that is designed to function in the relevant environments (gravity, dust, radiation, thermal, etc.). Need a PLSS design that can be completely recharged without ground maintenance and that can operate on expected consumables on an exploration mission (i.e., water and high-pressure oxygen). Need protection of relief valves, purge valves, disconnects, actuators and other mechanisms to preclude dust from hampering motion/function. Need environmental protection of PLSS, PLSS-to-PGS interface, and exhaust ports to preclude dust from entering PLSS, preclude dust from impeding rate of exhaust (one-way filter with near-zero pressure drop) over long-duration surface missions. (EVA Gaps for SMT, Portable Life Support System (PLSS), row 67)
2.4.1 Portable Life Support System (PLSS) Power & Communications	PLSS Power and Communications subsystems and components affected by dust are electric circuits, batteries, and fuel cells.	
Electrical Circuits	Charged dust particles could result in static shock to electronics.	
Battery/Fuel Cell	Dust in battery contacts can cause a power drain and potential short circuit.	
2.4.2 PLSS Cooling	PLSS cooling subsystems and components affected by dust are evaporative membrane, QDs, connectors, and radiator surface.	Dust that is built up on the outer layer of the suit will change its thermal capabilities. (EVA Gaps for SMT, Environmental Protection, row 49)
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.	
2.4.3 PLSS O_2	PLSS O_2 subsystems and components affected by dust are QDs, connectors and regulators.	
QDs/Connectors	Seal degradation, leaks, higher spares/maintenance.	
Regulators	Contamination of orifices; transport blockage.	
2.4.4 PLSS Vent	PLSS vent subsystems and components affected by dust are QDs, connectors, and venting membranes.	
QDs/Connectors	Seal degradation, leaks, greater requirement for spares/maintenance.	
Venting Membranes	Contamination of membrane surface; transport blockage.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
2.5 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, etc.	Dust mitigation including tools for dust removal, dust-resistant interfaces for EVA suits, etc., that are integral with vehicle systems. (EVA Gaps for SMT, Dust Mitigation (other than suit), row 114)
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	Includes power tools, wrenches, sockets, drills, joints in translation aids, etc. Buildup and restriction of working parts. Dust in battery contacts causes a power drain and potential short circuit.	
Umbilical Connections		For the umbilical connections or any connections to consumables on the suit, will dust-tolerant umbilical connectors (to prevent electrical connector shorts, contamination of O_2 lines with dust, and mechanical failure of connector, i.e., inability to connect) Need to develop a dust cover/closure for umbilical mating connectors that can withstand a dusty environment, high cycle life, long-duration missions. Dust cover shall be cleanable and replaceable. May also drive need for pre-ingress suit cleaning tools. (EVA Gaps for SMT, From planetary hazards (dust, biologicals, etc.), row 116)

2.3 MOBILITY SYSTEMS

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
3. Mobility Systems	Rover and Robotic Mobility subsystems and components affected by dust are chassis, wheels, motors, bearings, hinges, solar panels, radiators, optical sensors, crew station, and airlock. Unclear if it can affect communication. Permanently shadowed regions may be significantly fluffy to unknown depth (based on revised terramechanics of regolith compaction on Moon is due to thermal cycling as opposed to asteroid impact inducing vibrations). Also may cover subterranean holes (hidden navigation hazard).	
3.1 Unpressurized/ Pressurized Manned Rover	Rover subsystems and components affected by dust are chassis, wheels, crew station, and airlock.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
Chassis (suspension)	Dust accumulation.	Thermal emission characteristics of chassis may be altered by dust layer. Exposed linear sliding seals (e.g., typical vehicle shock absorbers) should be avoided in design because of rapid wear/degradation/failure after exposure to adherent, abrasive dust. Currently limited to designs incorporating rotary seals only for articulation.
Wheels (tires, brakes)	Abrasion/dust accumulation. Should mechanical brakes (e.g., used in large, heavy manned rovers) be incorporated in new designs, dust abrasion may reduce braking effectiveness or jam the subsystem.	Minimize amount of dust transported by wheels; keep angular speeds low or deflect dust (e.g., fender). Wheel brake drag. Human-rated transport will require flexible wheels/treads for first-level shock absorbing at reasonable speeds. Dust abrasion and potential clogging within moving parts/wheels could prematurely degrade entire mobility system.
Crew Station (seats, controls, displays, restraints)	Dust accumulation.	Obscuring displays; control malfunction (mechanical interference).
Airlock (hatch/seals)	Seal degradation, leaks.	See Section 2.1.
3.2 Mobility Robots		
Chassis (suspension)	Dust accumulation; abrasion.	Important to understand mechanism of electrostatic dust attachment. Behavior of charged dust in the electro field generated by vehicle surface. Charge, mass, and impact velocity are parameters. Applying an electric field to remove dust attached electrostatically to the chassis is comparatively easier than using this technique on moving parts.
Wheels (tires, brakes)	Abrasion/dust accumulation; terramechanics effects not conclusive.	Seals are needed especially for rotating parts such as motor housings. In case dust enters, the abrasion inside should be suppressed as much as possible. If magnetic dust particles are present (e.g., elemental iron in lunar regolith), they may be attracted to motor housings or other actuators that have magnetic fields.
Motors, Bearings, Rotary Seals	Abrasion: Dust will attack outermost protection first, increasing damage with total number of rotations. As seal effectiveness diminishes, dust starts infiltrating deeper into the subsystem. Effect of lubrication method (dry, liquid, solid) is unclear. Current indications are that tortuous path and multistage seal seems effective against lunar simulant.	Important parameters are motor power (increase in required torque resulting from increased drag from dust penetration and damage) and number of rotations. Values are mission- and architecture-dependent.
Arms, Articulators, End-Effectors	Abrasion/dust accumulation; may prevent end-effectors from latching or rigidizing as well as connector matings.	Detachable parts as end-effectors or tools should be protected when exchanged.

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
Sensors	Can jam microswitches or prevent electrical contact; can block optical-based switches/sensors; the effect (if any) on magnetic-based sensors is unclear.	Important to understand mechanism of electrostatic dust attachment and behavior of charged dust in the electro field generated by vehicle surface. Charge, mass, and impact velocity are parameters. May be easier to remove dust electrostatically attached to a sensor lens or cover-glass by applying an electric field than doing this on a moving part.
3.3 Self-folding Robots	Self-folding and self-unfolding mechanisms can be affected by dust particles.	Important to make sure that no dust particles of any size penetrate a folded robot.

2.4 HUMAN HEALTH AND PERFORMANCE

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
4.0 Human Health	Potential for both acute and chronic health effects if exposure is not mitigated within the habitat. Primary acute health effects may include ocular and respiratory irritation. Studies conducted by the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) have characterized the inflammatory properties of the dust when people are chronically exposed to it. Adverse pulmonary effects may occur if exposures exceed established protective exposure limits.	Control of chronic exposure has been addressed through the development of a 6-month permissible exposure limit (PEL) for lunar dust of 0.3 mg/m3 (NASA Standard 3001, Vol. 2). Guidelines on acute exposure limits remain a research gap. Acute exposure limits will address the exposures that the crew are subject to before ECLSS mitigation of any introduced dust. Cardiovascular effects and potentially allergenic properties of lunar dust may warrant further investigation.
4.1 Advanced Food Systems	Advanced Food Systems include food storage, food processing, and food preparation.	
Food Storage System	Contamination, or failure of components.	Dust contamination is expected to increase risk of ingestion by crew and possibly result in failure of storage system components. The risk from dust contamination (to crew and to food acceptability/adequate ingestion) must be investigated or dust must be prevented from entering food storage space.
Processing Equipment	Contamination, or failure of components.	Dust contamination is expected to increase risk of ingestion by crew and possibly result in failure of processing components. The risk from dust contamination (to crew and to food acceptability/adequate ingestion) must be investigated or dust must be prevented from entering food processing space.
Food preparation equipment	Contamination, or failure of components.	Dust contamination is expected to increase risk of ingestion by crew and possibly result in failure of preparation components. The risk from dust contamination (to crew and to food acceptability/adequate ingestion) must be investigated or dust must be prevented from entering food preparation space.

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
4.2 Human Exposure	"The toxicological effects of lunar dusts have not been studied in sufficient depth to develop an exposure standard for operations on the lunar surface. Lunar dusts have a high content in the respirable size range, they have a high surface area that is chemically reactive, and elemental iron *nano-particles* are imbedded in the dust grains. These unusual properties may cause the respirable dusts to be at least moderately toxic to the respiratory system, and larger grains to be abrasive to the skin and eye." Human Research Program Requirements Document, HRP-47052, Rev. C, Jan 2009.	
4.3 Human-System Interface	Effect on human-system interface and interactions as well as task performance.	Dust will affect the habitat design and layout, the user interface design of all the systems (including EVA systems), and task performance. The risk from dust exposure (to the human-system interface design) needs to be investigated to ensure the most effective and efficient design solution, or dust exposure to these interfaces must be prevented.

2.5 SYSTEMS

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
5. Systems	Other systems affected by dust are guidance, navigation, and control (GN&C), structures, intravehicular activity (IVA), fire detection and suppression, environmental monitoring, power, electrical and electronics, and communications.	
5.1 GN&C		
GN&C	Mechanical and electrical components may fail or degrade.	
5.2 Structures and Mechanisms	Other subsystems and components affected by dust are habitat structure, water pipes, water tanks, and filtration.	
Habitat Structure	If Martian dust is reactive, the structure may degrade over time as a result of 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 changeout, leading to additional waste generation and weight lifted to the Moon and Mars.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
5.3 IVA	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.	
Laundry	Additional water needed to wash dust-contaminated clothing and discard wastewater and sediment.	
Food Preparation/ Consumption	Contamination.	It is expected that dust contamination will increase the risk of the crew ingesting dust and potentially decrease acceptability and ingestion of food, resulting in crew malnutrition. The risk from dust contamination (to crew and to food acceptability/adequate ingestion) must be investigated or dust must be prevented from entering food preparation/consumption space.
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	Reduced efficiency.	
Seals	Degradation of seals on all systems (airlock, oxygen masks/bottles, etc.).	
Hoses	Abrasion.	
Connectors	Abrasion.	
Computer Displays	Reduced contrast of fine lines and edges	
Cameras (interior)	Occluded or scratch camera lens coatings.	
Windows (interior)	Occluded or scratch windows.	
Lights	Reduced light level and increased maintenance.	
Clothing	Unless dust is reduced/removed from clothing, it can be abrasive to the skin.	
Crew Time	Increase in maintenance/housekeeping activities. Increase in monitoring of system degradation.	
5.4 Fire Detection and Suppression		
Fire Detection and Suppression Systems	Dust contamination could result in detectors failing to detect smoke or suppression system actuators failing. May render system unreliable.	
5.5 Environmental Monitoring		
Environmental Monitoring	Dust contamination could result in failure of environmental monitoring systems/windows and could coat camera lenses with dust, obscuring view.	

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
5.6 Power	Dust affects power subsystems and components such as heat rejection and radiators, solar arrays and PV cells, solar cells, and solar sensors.	
Heat Rejection/Radiators	Radiator performance degraded. Lowers efficiency/system overheat.	
PV Arrays, Cells, and Sensors	Modeling and ground-based analysis estimates show that the power output from PV cells is cut in half by a covering of less than 3 mg/cm^2 of lunar dust. Measurements from the Sojourner rover on Mars found that PV cells lost efficiency of 0.28%/day owing to dust deposition. However, intermittent dust devils cleared dust from the PV arrays of the Mars Exploration Rovers Spirit and Opportunity, which indicates that local weather conditions can lower the degradation rate appreciably.	
5.7 Electrical/Electronics	Electrical and electronic subsystems and components affected by dust are avionics, keyboards, buttons, switches, circuits, electrical connectors, and data connections.	
Avionics	Dust contamination will degrade performance and may cause critical systems to fail.	
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 causes power drain and potential short circuit (or prevents electrical contacts).	
Data Connectors	Dust in data connectors may cause degraded performance or failure.	
5.8 Communications		
Communications	Communications systems may be degraded with exposure to dust. Optics performance degrades with dust buildup. Laser communication possibly affected if there's suspended regolith in laser path.	
5.9 Thermal	Impact can vary based on thermal system: Radiator is performance affected (lunar regolith has high thermal resistivity) (effect of absorbtivity is still to be determined). If using some cooling cycle with a working fluid, fluid contamination with regolith could cause significant issues (gaseous phase may quickly erode internal pipes, especially venturi/restrictions).	Both Apollo experience and experimental simulations show that even a small amount of dust increases solar absorptance substantially. The degree of degradation depends both on the fractional coverage of the dust and the absorptance (α) of the dust, which varies from quite light areas in the lunar highlands ($\alpha < 0.5$) to dark areas in the lunar mare ($\alpha > 0.9$). Performance metrics will depend on application,

Dust Mitigation Challenges (Reqt Drivers)	Effect of Dust Exposure	Performance Characteristics
	Dust deposits on thermal control surfaces and radiators will increase solar absorptance, causing equipment to run hotter.	but must be defined in terms of minimum α/ε (where ε is emittance) at end of life. A maximum of 20 percent degradation in α/ε is typical in NASA Design Reference Missions.
5.10 Optical & Sensor Surfaces	Other subsystems and components affected by dust are displays, solar cells, windows, lights, sensors, and cameras.	Charged dust particles adhesion or intermolecular adhesion to optical and sensor surfaces may be reduced by piezo crystal ultrasonic vibration and negatively charged coating. The degree of contamination (measured in ppm) depends on the objective of the project.
Displays (wrist)	Obscured view.	
Windows	Occluded or scratched windows.	
Lights	Reduced light level.	
Sensors	Loss of sensitivity.	
Cameras	Occluded or scratched camera lens coatings.	

2.6 ASCENT/DESCENT VEHICLES

Dust Mitigation Challenges (Reqts Drivers)	Effect of Dust Exposure	Performance Characteristics
6.0 Ascent/Decent Vehicles		
6.1 Regolith Transport	Optical and sensor surfaces are contaminated by regolith. Solar cells, windows, lights, and cameras are partially or completely covered up by regolith.	Experimental data on regolith transport with different types of soil similar to those found on Mars or Moon surface can be useful for the design of the sensor surface location. The data has to cover various angles of impingements as well as heights above ground with different numbers of retrorockets. Minimizing the surface area covered by contaminants is the goal.
Plume-Induced Regolith Impingement on Surface Assets	Abrasion or occlusion of surface assets may damage optical windows and sensor surfaces.	
Plume-Induced Regolith Impingement on Lander	Can cause malfunction of engines. Abrasion or occlusion of surface assets may damage optical windows and sensor surfaces. The magnitude of this issue will depend on the lander design. In the case of a direct landing such as was done on Apollo, the exhaust pressure causes the regolith particles to be scattered nearly horizontally so the lunar landers are not damaged by the landing. But when the “sky crane” deposited Curiosity on the Martian surface, a substantial amount of regolith, including some cm-size rocks, was lofted onto the surface of the rover.	With respect to GN&C, it is expected to obscure sensors below an altitude (say something less than 100 m, but preferably lower), and so the GN&C should be designed to meet accuracy requirements while navigating only on inertial measurement unit (IMU)-propagated states for that last portion of the descent. Past studies have shown that this type of requirement can be met, since state error growth during final descent is minimal.

2.7 *IN SITU* RESOURCE UTILIZATION

Dust Mitigation Challenges (Reqts Drivers)	Effect of Dust Exposure	Performance Characteristics
7.0 *In Situ* Resource Utilization (ISRU)		
7.1 Prospecting	Identification of regolith and resource properties.	
Sample Acquisition	Includes augers, coring drills, arm-scoops, funnels. Dust can impact motors and rotating bearings. Magnetic and electrostatic properties can cause dust/material to adhere to surfaces and not transfer properly.	
Sample Processing	Includes sample transfer, sample heating, heating chambers, gas/sample separation. Dust can reduce effectiveness of sealing and contaminate subsequent samples.	
Sample Analysis	Includes gas/volatile measurements such as spectrometers, mass spec. (MS), gas chromatography (GC). Dust in gas samples can clog sampling lines, lower performance of MS/GC, can coat optical windows for spectrometers, lowering performance. Can overwhelm subsequent measurements of different minerals.	
In Situ Measurement	Includes cameras, lights, microscopes, and spectrometers. Dust can adhere to optical surfaces and lower performance. Can overwhelm subsequent measurements of different minerals.	Charged dust particles adhesion and/or intermolecular adhesion to optical and sensor surfaces may be reduced by piezo crystal ultrasonic vibration and negatively charged coating. The degree of contaminant in ppm depends on the objective of the project.
7.2 Extracting		
Drilling	Very high compaction coupled with irregular lunar regolith shape increases difficulty of penetration depths, and possibly techniques. Dust can affect motors and rotating bearings. Magnetic and electrostatic properties can cause dust/material to adhere to surfaces and not transfer properly.	
Excavating	Involves mechanisms, actuators, and rotating joints and motors. Dust can affect lubricants, seals, and rotating joints. Some indications are that lunar excavation forces may be significantly higher than otherwise anticipated. Excavation forces on Mars are virtually unknown.	

Dust Mitigation Challenges (Reqts Drivers)	Effect of Dust Exposure	Performance Characteristics
7.3 Regolith/ Soil Processing		
Water Extraction	Includes sample transfer, sample heating, heating chambers, gas/sample separation. Dust can reduce effectiveness of sealing and contaminate subsequent samples. Dust can also contaminate water extracted. Filtration of extracted water will be required before conversion.	
Transport (internal process)	Depends on method, e.g., pneumatic transport may lead to excessive abrasion (i.e., sandblasting).	
7.4 Gas Processing	From Mars atmosphere or volatiles released from heated regolith or trash/waste.	
Mars Atmosphere Collection	Involves blowers, compressors, adsorption beds, or cryogenic/freezing surfaces and chambers. Dust can impact rotating components in blowers and compressors. Dust can coat adsorption materials or freezing surfaces lowering performance.	For dust in the Mars atmosphere, current estimates are in the range of 3 particles per cubic centimeter with an average diameter of 3 microns. The density will increase in dust storms by something like a factor of 10. Saltated particles (wind-mobilized particles that travel horizontally near the ground) may also be a concern and would typically be larger than particles suspended in the atmosphere.
Gas Processing Systems	Includes valves, recirculation pumps, heat exchangers, gas/gas and gas/water separators, and gas dryers. Dust can compromise seals in valves, rotating parts in recirculation pumps, and coat/degrade membrane surfaces in separators and adsorption materials.	
Water Processing into O_2/H_2	Involves solid oxide or proton exchange membrane processes. Dust in the system could degrade catalytic surfaces, reducing performance. PEM electrolyzers require deionized water for long-term operation.	
Gas Processors	Involves thermal, catalytic, or electrical conversion of gases such as CO_2 and CO into intermediate or final products such as water and oxygen. Dust entrained in gases could coat or poison active surfaces and catalysts, degrading performance.	
7.5 Support Systems – Other		
Power Generation	Potential solar thermal conversion effects (heat absorption, focusing mirrors obscured). Reflective, heat rejecting, and other surfaces can be compromised by excessive dust. Solar arrays will produce less power.	Solar panel degradation measurements are available in the literature.

Dust Mitigation Challenges (Reqts Drivers)	Effect of Dust Exposure	Performance Characteristics
Sensors to Control Autonomous Systems	Optical sensors may be occluded, sampling sensors may be clogged, and surface sensors may be occluded or poisoned.	Charged dust particles adhesion or intermolecular adhesion to optical and sensor surfaces may be reduced by piezo crystal ultrasonic vibration and negatively charged coating. The degree of contaminant in ppm depends on the objective of the project.
Radiators and Heat Rejection	Deposits on radiator surfaces will degrade performance.	Both Apollo experience and experimental simulations show that even a small amount of dust increases solar absorptance substantially. The degree of degradation depends both on the fractional coverage of the dust and the absorptance (α) of the dust, which varies from quite light areas in the lunar highlands ($\alpha < 0.5$) to dark areas in the lunar mare ($\alpha > 0.9$). Performance metrics will depend on application.
QDs and Connectors	Used for transferring gases, liquids, power, and data from ISRU units to other elements. Dust will degrade seals and could cause issues with power/data transmission. Dust allowed to enter gas/liquid lines could cause performance and safety issues (e.g., dust added to O_2 lines).	
Avionics	Electrostatic and magnetic properties of dust may degrade performance or cause failures/shorts to occur.	
Mobility for Soil Excavation and Delivery	See Section 3.2, Mobility Robots.	

3. DUST MITIGATION SOLUTIONS

Mitigation technologies can be categorized into active and passive technologies. Active technologies are those that are used to clean a surface or to protect it from dust deposition through external forces. Fluidal, mechanical, and electrodynamic/electrostatic methods fall into this category. Fluidal methods refer to those in which liquids, gels, foams, and gases are applied to carry the particles away from the surfaces. Mechanical methods include brushing, blowing, vibrating, and ultrasonic-driven techniques. Electrodynamic/electrostatic methods for dust control are inspired by the solar-based electrostatic levitation mechanism, though control of uncharged or low-charge particles requires an inventive charging mechanism different from the natural charging that occurs through photoemission and electron impingement.

Passive technologies are those in which items are pretreated physically or chemically in laboratories in order to mitigate dust attraction without using external forces after the items are installed. In these passive dust mitigation technologies, surfaces are modified to reduce the adhesion between the dust layer and the surface to be protected. Shades and shields that are applied to intercept dust before it is deposited also fall into this category.

3.1 ACTIVE TECHNOLOGIES

Fluidal Methods

The feasibility of using fluidal methods to clean dust from extraterrestrial surfaces was initially tested for thermal control surfaces (TCSs). Northrop Space Company and NASA Marshall Space Flight Center (MSFC) collaborated to determine the degradation of TCSs and then to examine potential dust mitigation methods. Among the methods tested, an incompressible fluid (inhibisol methyl chloroform) jet was found to be the most promising method for removing dust from TCSs. Later, the idea of using gases (particularly CO_2), and using gels, foams, or liquids on the Moon for removal of fine dust from space optics was proposed by Peterson and Bowers, and Wood, respectively. With the gel and foam solutions, once the deposited fine dust is suspended with the foaming solution, a blower probe removes the mixture from the surface. Alternatively, by spraying liquid or blowing compressed CO_2, the thrust of the fluid may overcome the adhesion forces over the surface to be cleaned (similar to the standard method of removing dust from semiconductors in the electronic industry).

Mechanical Methods

A mechanical brush and a vibrational surface were the first mechanical approaches to be developed for removing dust from contaminated surfaces. However, neither of these methods was effective. Aliberti split the mitigation of lunar dust into two stages—loosening and removing—and reviewed a series of fluidal/mechanical methods using hybrid mitigation technologies to loosen the particles with one technique and remove them with another. The brush-blower device was found to have the best overall characteristics for planetary surface dust removal. Fernandez et al. suggested a robotic dust wiper primarily to protect UV sensors on Mars. Although the cleaning efficiency of the dust wiper was higher than 93%, the technology was not recommended to protect surface areas larger than 30 cm^2 per wiper from 5 μm particles, as the power requirement to rotate levers will be limiting.

Gaier et al. performed an extensive series of experiments on the effectiveness of lunar dust brushes for TCSs. Under ambient conditions, nylon bristles were effective from AZ-93 TCS, and an electrically conductive Thunderon bristle brush was effective at removing dust from aluminized FEP Teflon (Al-FEP) TCS. However, when the same tests were repeated under simulated lunar conditions, none of the brushes were effective on all TCSs. These results illustrate how important it is to test dust mitigation techniques under realistic environmental conditions. Further experiments under simulated lunar conditions showed that dust removal effectiveness was almost insensitive to the rotational speed and tip geometry of the brushes, and longer, more flexible brushes in both the round and fan brush bristle arrangement proved to be more effective than short-bristle strip brushes.

Protection of mechanical components such as gear boxes, motors, bearing housings, and seals is another important challenge for future space exploration because of the wearing effects of particles deposited on their seals. To address this issue, the effectiveness of a spring-loaded Teflon seal was evaluated by Delgado et al. Preliminary results indicated minimal seal and shaft wear after 1,000,000 rotating cycles with no lunar dust simulant (JSC-1A and LHT-2 M) passed through the seal-shaft interface.

Electrostatic/Electrodynamic Methods

Introduced by researchers at NASA Kennedy Space Center and University of Arkansas (Biris et al., Calle et al., Mazumder et al., Sims et al.), the Electrodynamic Dust Shield (EDS) is perhaps the best-known electric-based technique in dust removal technology (Figure 3–1). The electric curtain consists of a set of conducting electrodes separated from one another by an insulating material. Since the electric curtain is connected to an AC power supply, a nonuniform electric field with spatial periodicity is created around the electrodes. When charged particles approach the electrodes, they undergo periodic motions resulting from the normal forces (which form standing waves) and tangential forces (which form traveling waves) to be shifted away from the surface protected by the electrodes. Many investigations have since been conducted on development of the electric curtain technology mainly as a toner supplier in electrophotography.

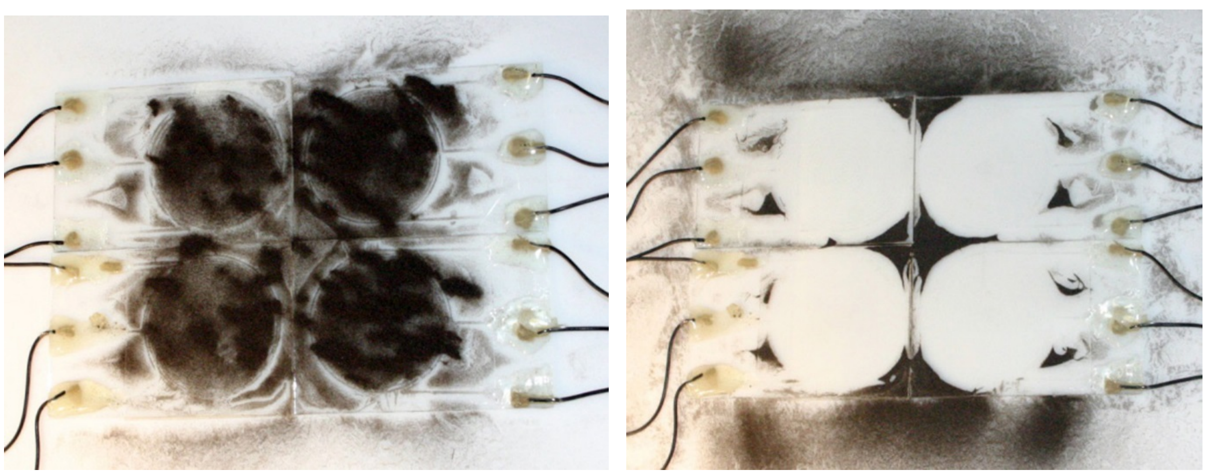

FIGURE 3–1. SIMULANT DUST REMOVAL WITH NASA KENNEDY SPACE CENTER'S EDS AT 10-6 KPA (CALLE ET AL. ACTA ASTRONAUT. 69, 2011: 1082-1088).

Experimental investigation on the EDS performance as an active self-cleaning method for removing deposited dust from both lunar and Martian surfaces has been conducted by various research groups (Figure 3–2). A linear relationship between the removal efficiency and the applied voltage was observed with 10 kV corresponding to 95% removal efficiency of the JSC Mars-1 simulants. The EDS removal efficiency was insensitive to the dust materials. The frequency determines how quickly the surface could be cleaned. Calle et al. investigated the relationship between the minimum required amplitude and frequency and determined that single-phase EDS, which only produces standing waves, was ineffective at removing dust.

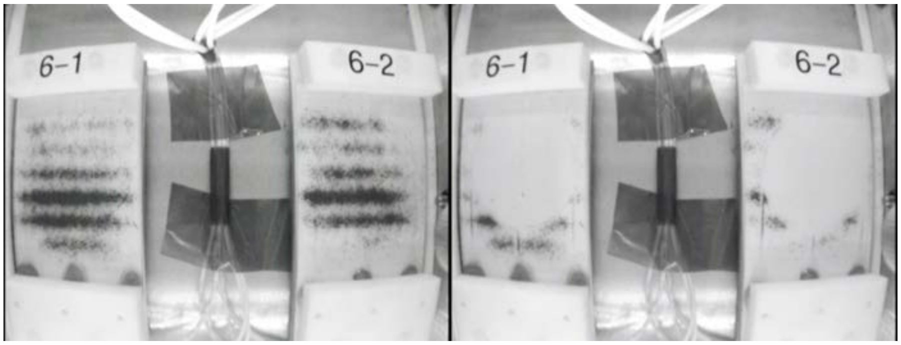

FIGURE 3–2. REMOVAL OF APOLLO 16 DUST WITH NASA KENNEDY SPACE CENTER'S EDS AT 10-6 KPA AND G/6 (CALLE ET AL., IEEE AEROSPACE CONF. PROC. 1510, 2010).

Kawamoto and Hara applied the EDS concept to remove particles trapped in fibers of the astronauts' suits (Figure 3–3). Experimental tests were conducted at ambient pressure on copper electrodes insulated in a thin layer of polyester film and stitched into the outer layer of a spacesuit contaminated with 10 mg FJS-1 lunar dust simulants (<53 Im). To improve the cleaning efficiency, they coupled the EDS with a mechanical vibrator. The hybrid technology increased the cleaning efficiency up to 90%. The majority of the particles remaining over the cloth surface were smaller than 10 μm. Removal of particles smaller than 20 μm with only EDS (without vibration) was not possible.

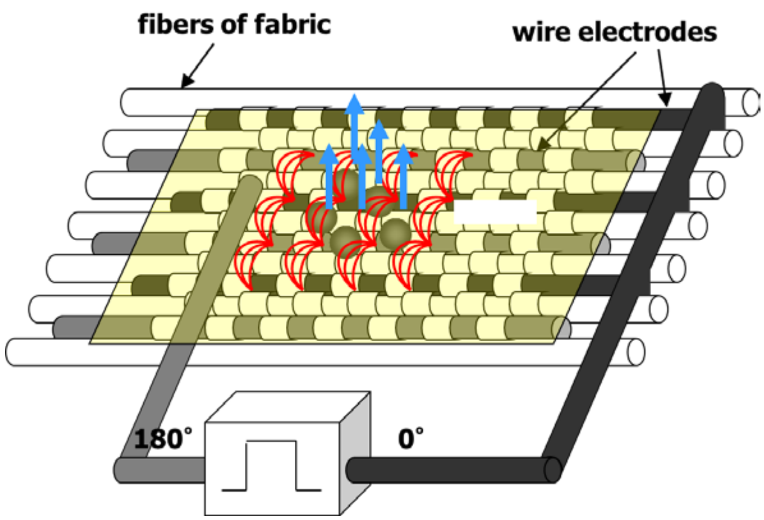

FIGURE 3–3. WASEDA UNIVERSITY'S ELECTROSTATIC CLEANING SYSTEM FOR REMOVING LUNAR DUST ADHERING TO SPACESUIT FABRIC (KAWAMOTO, H. AND N. HARA, J. AEROSP. ENG. 2012, 24: 442–444).

Alternatively, Kawamoto and Inoue developed a magnetic cleaning device that used magnetic force via a multipole magnetic roller to separate lunar dust from the spacesuits (Figure 3–4). Although the separation rate of this device was about 90%, the capture rate was low and the overall cleaning rate was about 40%. Hybrid application of the electrodynamic and magnetic forces for above-mentioned cleaning technologies led to 80% cleaning efficiency.

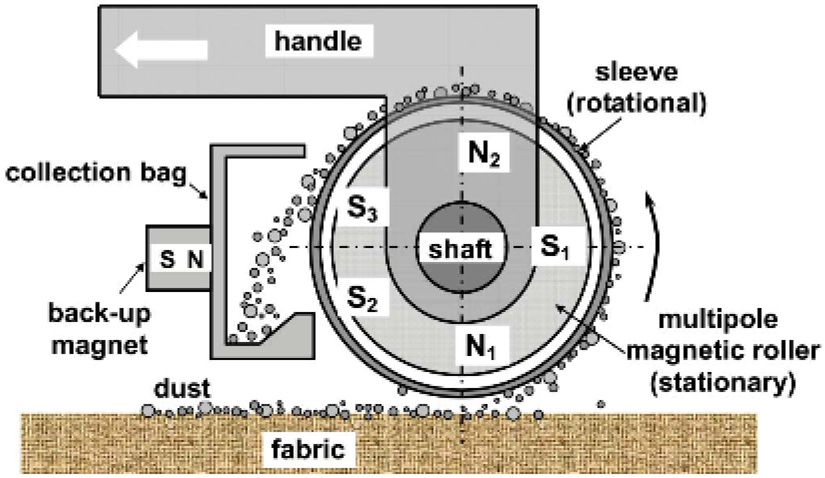

FIGURE 3–4. WASEDA UNIVERSITY'S MAGNETIC CLEANING DEVICE (KAWAMOTO, H. AND H. INOUE, J. AEROSP. ENG. 2012, 25: 139–142).

The lunar dust control technology proposed by Clark et al., the Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment (SPARCLE), involves charging the dust layer with beams of high-current electrons or ions emitting from a gun-shaped probe (Figure 3–5). The SPARCLE probe is connected to an automated robotic lever scanning the dust layer line by line to charge the deposited particles covering a surface with high energetic electrons/ions. The experimental results showed that the negative charge on initially neutral particles rapidly increased, causing adequate electrostatic repulsion to lift up the particles from the negatively charged surface to implant them in the surrounding positively charged chamber walls.

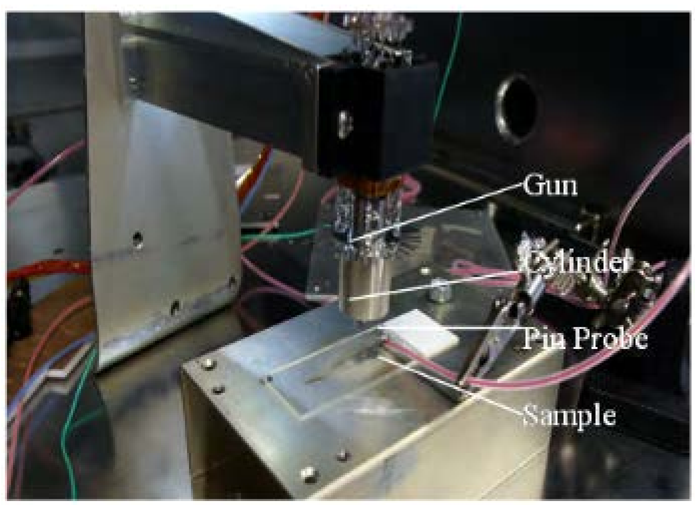

FIGURE 3–5. NASA GODDARD SPACE FLIGHT CENTER'S SPARCLE EXPERIMENTAL SETUP (CLARK ET AL., AIP CONFERENCE PROCEEDINGS, 1103, 2009: 608–614).

An Electrostatic Lunar Dust Collector (ELDC) proposed by Afshar-Mohajer et al. was a low voltage electrostatic collector for collecting naturally charged lunar dust before the deposition (Figure 3–6). Not only did the ELDC prevent charged lunar dust from being deposited, but it also required thousands of times smaller electric field strengths than the EDS, owing to the absence of surface forces. The electric power consumption of the ELDC was determined to be negligible compared to the produced electric power, and the cleaning frequency of the collection plates was estimated to be 3 times a month.

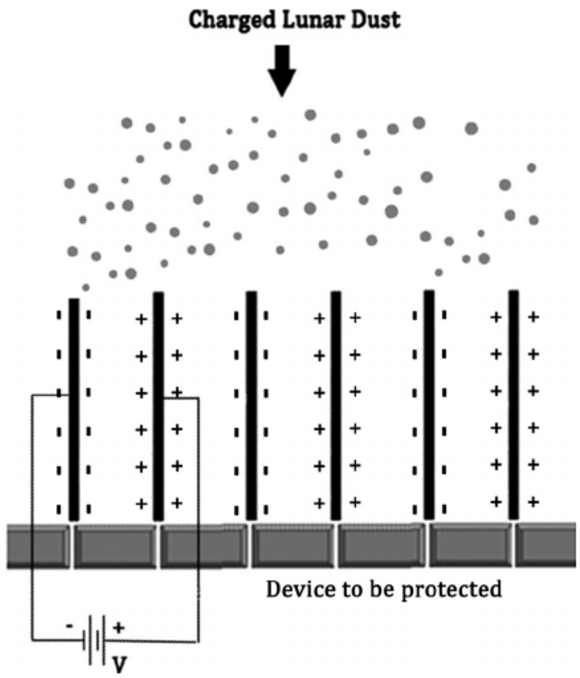

FIGURE 3–6. ELECTROSTATIC LUNAR DUST COLLECTOR (AFSHAR-MOHAJER ET AL., J. APPL. PHYS. 112, 2012).

An electrostatic-based system to remove dust from the ISRU atmospheric intakes on Mars missions is being developed at the Kennedy Space Center (Calle et al., Journal of Electrostatics 71 (2013) 254–256). The human exploration of Mars will require the utilization of the planet's resources for the production of consumables and for the construction, manufacturing, and repair of space utilities and power. The extraction of commodities such as oxygen, methane, and water from the Martian atmosphere will require the removal of atmospheric dust from the intakes of the processing chambers. Dust removal by electrostatic precipitation, an efficient and mature technology on Earth, can be adapted to the challenging Martian environment that limits the electrostatic potentials. Electrostatic precipitators do not require consumables, do not induce a pressure drop in the atmospheric intakes, and their maintenance can be automated. The system being developed at NASA Kennedy Space Center is an electrostatic precipitator in a flow-through that could be integrated into the ISRU demonstration unit planned for the future NASA Mars Sample Return Mission of 2024 (Figure 3–7). Initial results with the prototype in a no-flow configuration showed dust removal efficiencies of 99%. The flow-through configuration will match the planned flow rates for the Mars 2024 Sample Return Mission.

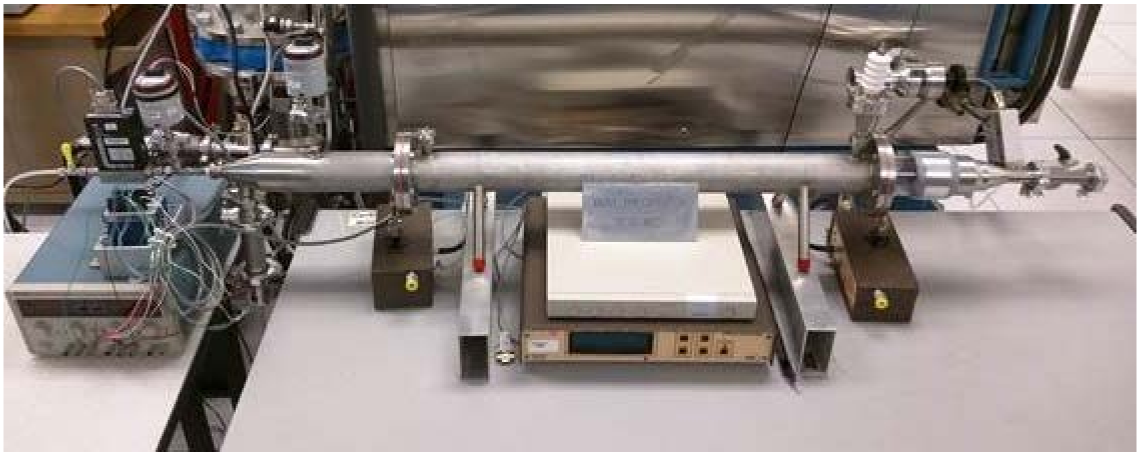

FIGURE 3–7. ELECTROSTATIC PRECIPITATOR (CALLE ET AL., JOURNAL OF ELECTROSTATICS 71 (2013) 254–256).

EVA Systems can include active technologies such as an electrostatic screen printed onto the outermost Thermal Micrometeoroid Garment layer of the space suit, magnetic bushes (lunar surface only), vacuum cleaners (after repress), and air or CO_2 showers.

3.2 PASSIVE TECHNOLOGIES

Passive Methods

The simplest passive method may be the fender design for lunar roving vehicle (LRV) wheels proposed by Mullis. His design consisted of a Lucite fender with flapped edges that enclosed the top, both sides, and front and rear of a full-sized LRV wheel. When the fenders were damaged during Apollo operations, the astronauts replaced sections with plastic maps, which proved highly effective.

Berkebile et al. and Gaier and Berkebile showed experimentally that electrostatic adhesion forces dominate over van der Waals forces under ultrahigh vacuum conditions such as those found on the lunar surface. Thus, passive methods should be based on minimizing electrostatic forces. This was borne out in tests where Gaier et al. successfully decreased the dust adhesion to metallized FEP TCSs by control of the work function of the surface. (See Figure 3–8.) Similar results were obtained using a proprietary ion beam coating developed by Ball Aerospace and Technology Inc., which combined a work function-matching coating with a textured surface. This contrasts with the same test carried out with metallized FEP samples that had been textured using a Hall oxygen ion beam that etched away part of the surfaces to leave conical structures (~1 µm in height) over the surfaces. The textured surfaces decrease the contact area between the surface and the dust particles, and hence would decrease van der Waals forces between the two, but have little effect on the electrostatic forces. Indeed, experiments showed that dust was not cleared from these surfaces.

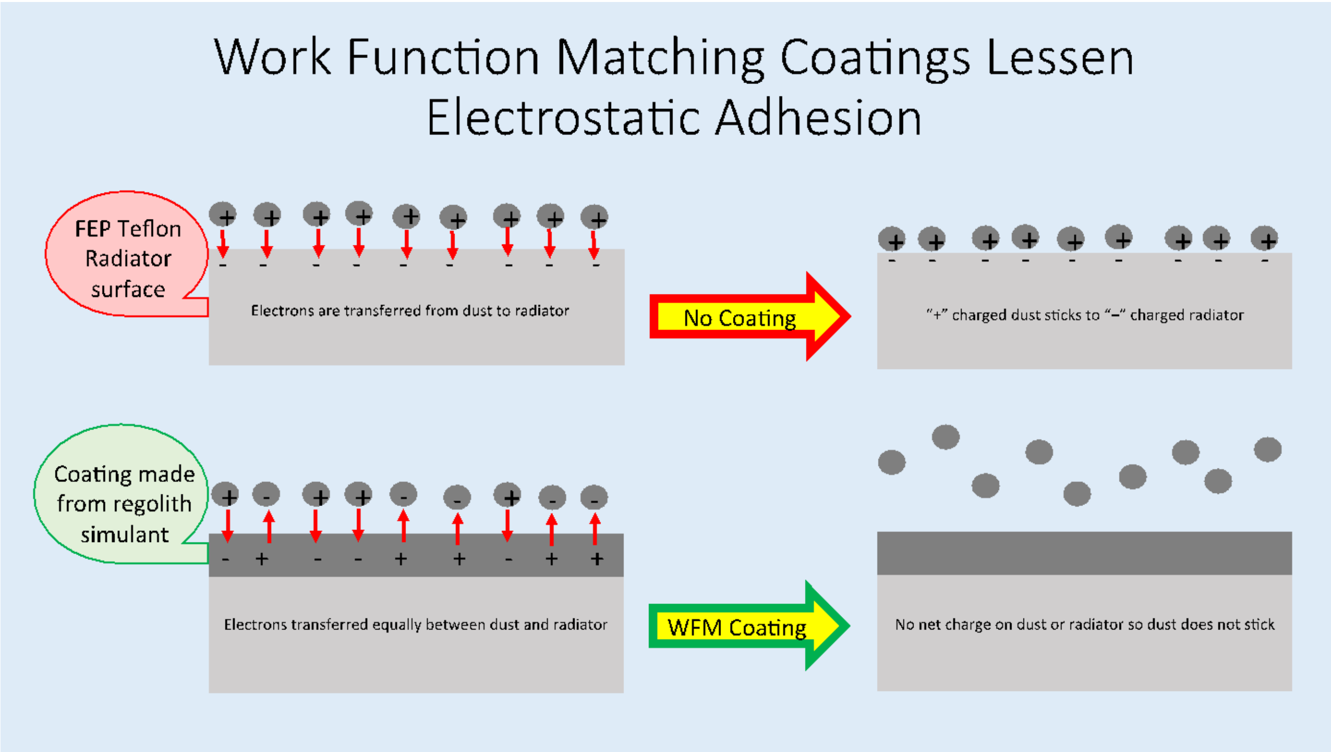

FIGURE 3–8. ELECTROSTATIC ADHESION COATING APPLICATION FOR THERMAL CONTROL SURFACES.

The idea of applying transparent adhesive tapes over the protected surfaces and then peeling them away after collecting an adequate amount of dust was also proposed by Tatom et al. and later by Wood. However, the tested arsenic trisulfate taping shield performed poorly, and because astronauts are involved in removing the contaminated tape and residue is likely to be left on the surface, this idea has not been investigated further.

<u>Filtration Methods</u>

Filtration was the technique used for collecting airborne fine lunar dust inside the Apollo command and lunar module pressurized cabins. Applications of high-efficiency particulate air (HEPA) filters with 99.97% particle collection efficiency for 0.3 μm particle size is the recommendation for future human explorations. *(NASA-STD-3001: The system shall limit the levels of lunar dust particles less than 10 μm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m^3 during intermittent daily exposure periods that may persist up to 6 months in duration.)* Lower efficiency media can be used in prefiltration stages to protect and prolong the life of the high-efficiency media. Several reviews on all aerosol filtration methods are available (e.g., Spurny). However, a caveat should be noted: extraterrestrial particles have jagged and irregular shapes that may damage the regular HEPA filters commonly used inside clean rooms.

The NASA GRC and Aerfil have developed prototypes of the indexing media filtration system (also known as the scroll filter system), which consists of three stages: an inertial impactor stage, an indexing (scoll) media stage, and a high-efficiency filter stage, packaged in a stacked modular cartridge configuration. Figure 3–9 shows pictures of the hardware and some of the internal components. Each stage targets a specific range of particle sizes that optimize the filtration and regeneration performance of the system. The inertial impactor filter stage was designed to capture the largest particles in order to reduce the loading on the next stages of filtration, nominally the scroll or high-efficiency stages. The scroll stage, which allows fresh media to be deployed in the flow volume when needed, captures intermediate particle sizes (typically a few microns). The high-efficiency stage, nominally a HEPA filter, is the backstop that captures the smallest (micron to submicron) particles and is usually a passive filter element. The filter system provides self-cleaning and regeneration technologies in the impactor and scroll filter stages that will significantly extend the life of these filter stages as well as any high-efficiency stage. This modular design also provides the flexibility to add more stages of filters in order to optimize performance, and to meet design and operational requirements of any space or sealed environment mission.

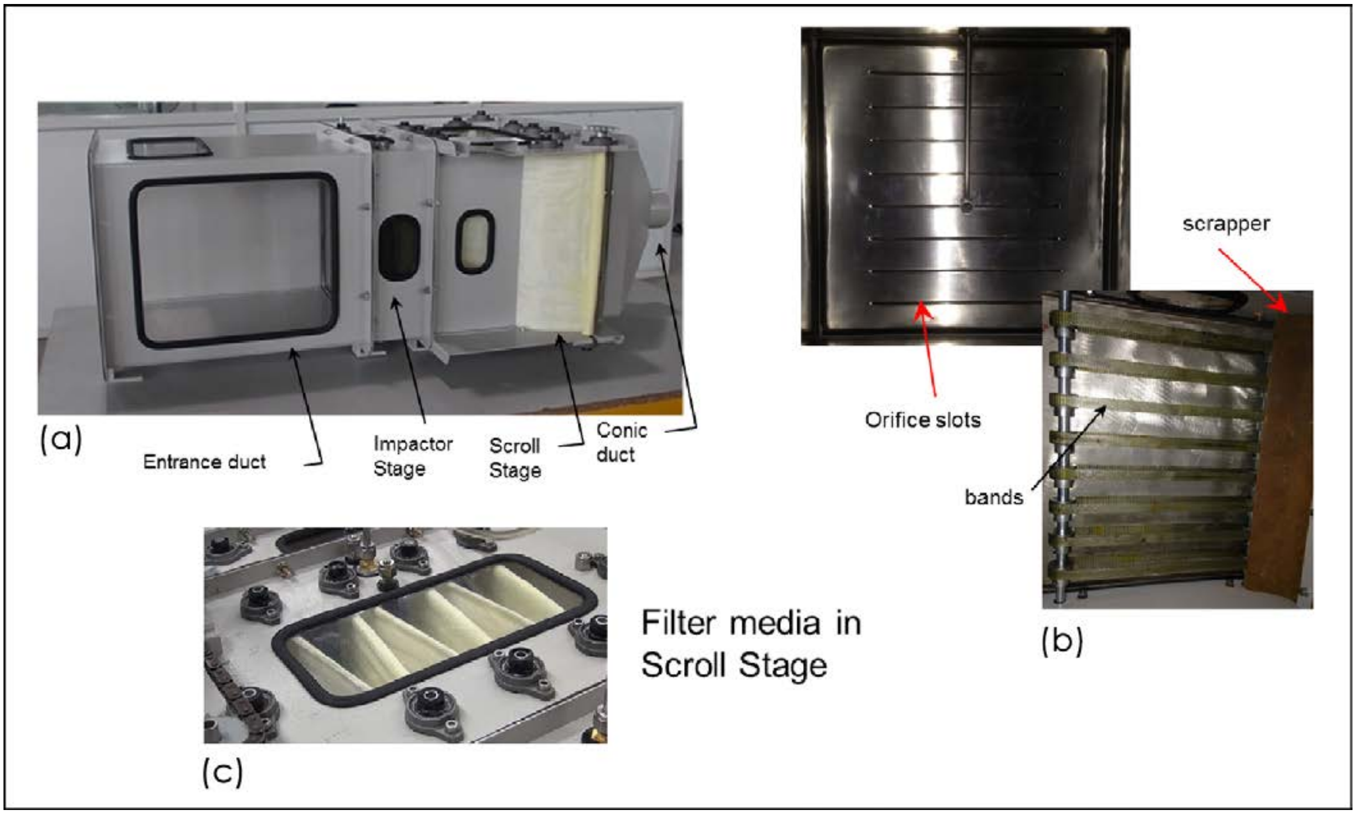

FIGURE 3–9. INDEXING MEDIA FILTRATION SYSTEM (SCROLL FILTER SYSTEM).

Note: (a) The scroll filter assembly consisting of the impactor filter and scroll filter stages (high-efficiency stage not included) and an entrance and conic duct to facilitate testing, (b) internal components of the impactor stages showing the slits, collection bands, and scrapper, and (c) the scroll filter stages showing the pleated media through a window in the stage.

Eimer and Taylor suggested an active lunar air filter with a permanent magnet system (LAF-PMS) that would use the magnetic properties of lunar dust for removing indoor particles. The LAF-PMS is a multistage filter made of a series of magnet plates that are arranged in rows at a certain distance. By placing opposite poles of two permanent magnets near each other, a large magnetic field is created to trap passing particles. Switching the magnetic polarity of the magnets is the suggested solution for cleaning the contaminated filters. The proposed filtration by this method is expected to remove particles larger than 20 nm.

Bango et al. reported on the feasibility of using electrospray technology as a way to capture fine particles from spacecraft atmospheres without producing the hazardous ozone that is generated in most high-voltage dust removal systems. The demonstrated electrospray techniques (which used safe materials with few consumables, operated at a few watts, and created a very small pressure drop) compared to traditional filters, effectively removed small particles from the air. This technique can remove even the smallest particles from the long-term habitation environment, but is less suitable for removing a heavy dust burden from areas such as an airlock. A complete flightlike unit was fabricated for testing in a simulated closed spacecraft environment, but has not yet been evaluated.

EVA systems can include passive technologies such as fabric coatings that rely on biomimicry to repel dust (e.g., lotus leaves and gecko feet), fabric coatings to attract and capture dust, scratch-resistant visor coatings, dust-tolerant connectors (impervious to dust and not fine alignment or that self-clean when disconnected), or peel-off visor layers.

3.3 ENGINEERING AND OPERATIONS SOLUTIONS

Other than those used in the Apollo Program, most state-of-the-art systems for human spaceflight (e.g., EVA systems) do not account for dust. The designs of space suits for future planetary exploration will incorporate lessons learned from Apollo suits (Lunar Dust Effects on Spacesuit Systems, TP-2009-214786). Engineering solutions can include active damage sensing (this is not really a "mitigation," but an indication that dust is negatively affecting the soft goods) and pressure garment bearings designed for easy changeout of saturated dust seals (see Figure 3–10).

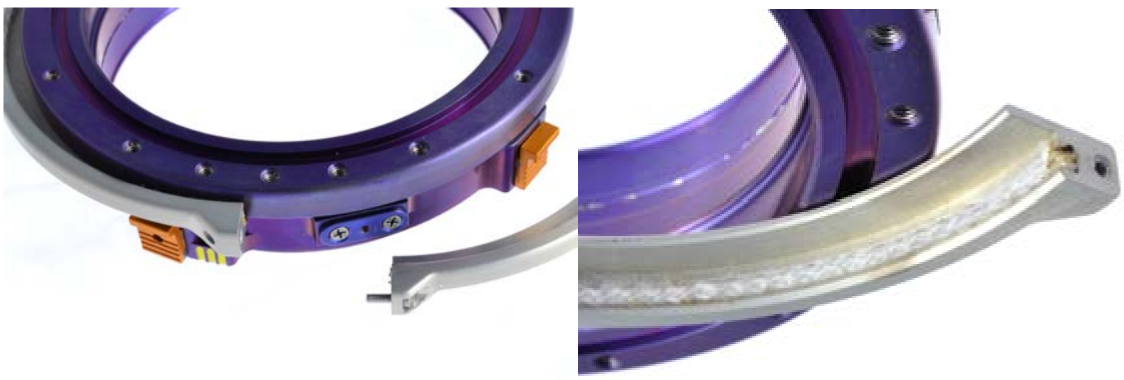

FIGURE 3–10. DUST-RESISTANT BEARINGS.

Certain ingress/egress methods provide for dust mitigation (such as those where EVA suits are stored on the side of the bulkhead that is opposite from the habitable environment), while others may amplify dust contamination. For instance, in a traditional airlock, crewmembers doff their presumably dusty suits on a don/doff stand and then translate through the dust that was just carried in on their suits. On a subsequent EVA, crewmembers must reverse this path and again translate through the dust in their undergarments/liquid cooling and ventilation garment (LCVG) before donning the suit. This architecture would fundamentally promote dust contamination issues.

To address this concern, one possible solution uses a "Layered Engineering Defense" plan (Wagner, S. 2014) in which "layers" help mitigate the effect of dust on the suit materials, control the transfer of dust on the suits, reduce or eliminate forward and backward contamination of the crew and their habitation, and minimize cleaning and protection (interior and exterior) and the use of air quality contamination zones. The space suits need to be brought inside a habitable volume for nominal and contingency maintenance, which will introduce some amount of dust into the habitable volume. However, because the removal of dust from the suits will be a multiphase operation, the amount of dust introduced into the suits and the crew cabin will be limited. Operational controls, air quality zones, and ingress/egress methods (such as air showers, mudrooms, rear-entry airlocks, suitport-airlocks, and suitports) will mitigate the transfer of dust into the cabin. An alternate ingress/egress method is needed to provide particulate mitigation and backward and forward planetary protection. In this method, crewmembers will don/doff the rear-entry EVA suit through a bulkhead, so that they do not have to walk through the dust while entering/exiting and donning/doffing the suit. Cabin filtration in the area where the suits are kept is necessary for dust mitigation and planetary protection. Alternate methods such as rear-entry airlocks/suitlocks and suitport-airlocks could include a chamber large enough for suit maintenance to be performed in a secondary chamber or mudroom. This would further contain contamination and increase air quality while the crewmember moves to the cleanest areas of the vehicles, such as habitats, pressurized rovers, and ascent vehicles.

With a suitport, suitport-airlock, or rear-entry suitlock, the majority of the dust remaining on the suit will be kept on the other side of the habitation zone. Depending on the design of the habitat, the ingress/egress method can add one or two zones to keep the contamination out of the crew quarters (refer to Figure 3–11). Below is an example of a layered engineering defense plan (tailored for EVA); other protocols can be followed. These details and operational concepts are in work.

<u>1st Layer – Mission Architecture Design</u>

- Avoiding special regions (defined as being within a specified radius of the lander/habitat)

<u>2nd Layer – Hardware Design</u>

- Acknowledging that EVA suits will leak/vent—engineering limits must be understood and intentionally accounted for
- Collection/containment of sampling tools

<u>3rd Layer – Operational Design</u>

- Reducing the amount of dust that reaches habitable volumes by having astronauts stomp off dust and brush down their suits on a porch before entering the habitat through an ingress/egress method designed to mitigate the transfer of dust (e.g., the astronauts could use rear-entry suits that they don/doff through a bulkhead)
- Using sampling protocols that limit inadvertent contamination
- Leaving EVA suits on surface prior to ascent to “break the chain” of contamination

<u>4th Layer – Contamination Control</u>

- Conducting verifiable decontamination of EVA hardware at regular intervals
- Conducting exterior and interior cleaning
- Using air quality contamination zones

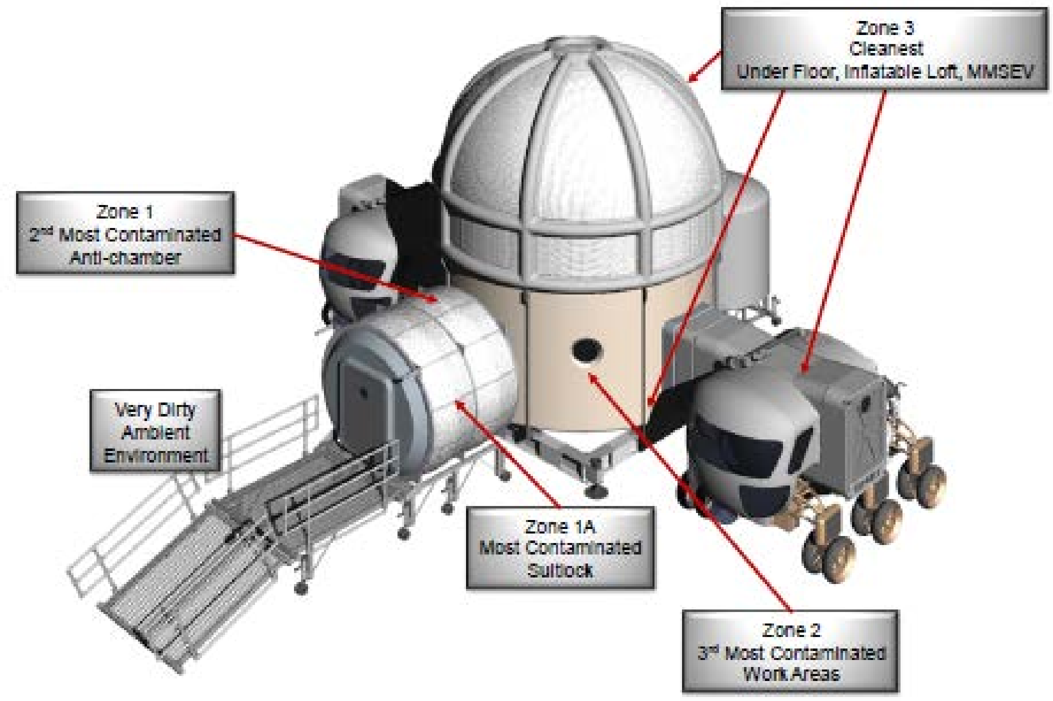

FIGURE 3–11. LAYERED ENGINEERING CONTAMINATION ZONES.

While suitports, suitport-airlocks, and rear-entry airlocks keep the suit outside the crew cabin, the PLSS is still inside the cabin vestibule door. For this reason, additional dust mitigation tools need to be investigated, such as brushes attached to the vestibule door, sealing mechanisms around the PLSS on the vestibule door to keep the dust inside that inner volume, and vacuum/filtration for the vestibule volume.

Alternate ingress/egress methods may be the best option for minimizing dust inside the cabin for the rover; however, on missions longer than 30 days, exploration EVA suits must be brought inside a pressurized volume for suit maintenance. Although the long-duration habitat is likely to have a rear-entry airlock or suitport-airlock, information is needed on how much this helps keep dust out of the habitable volume compared to the regular airlock (e.g., walking through the dust after every EVA). Dust modeling/testing should be performed to show the differences between using a concept that keeps suits on the opposite side of the bulkhead and heritage airlocks.

<u>Dust-Tolerant Connectors</u>

Standardized connectors that can be repetitively and reliably mated and demated during extravehicular activities will be required for structural integrity and commodities transfer between linked surface elements during exploration missions. The dusty environments of the Moon, Mars, and asteroids will clog and degrade the interface seals of these connectors, which could cause hazardous commodities to spill, contaminating the flow stream and degrading mechanisms. To mitigate this problem, NASA's Kennedy Space Center developed prototype dust-tolerant connectors (quick disconnects and umbilical systems) that can be repetitively and reliably mated and demated during extravehicular activities on the lunar surface (Figure 3–12) [Mueller, R.P. and I.I. Townsend, NASA Technical Reports Server, 2010]. Quick disconnect fittings are needed for the EVA spacesuit's Primary Life Support Systems as well as for liquid-cooled garment circulation and suit heat rejection. Umbilical electromechanical systems (connectors) are needed between discrete surface systems for transfer of air, power, fluid (water), and data. These connectors must be capable of being operated by crew members or robotic assistants.

FIGURE 3–12. DUST-TOLERANT CONNECTOR OPERATION.
(MUELLER, R.P., I.I. TOWNSEND, AND G.B. TAMASY, NASA TECHNICAL REPORTS SERVER, 2010).

Electrical connector concepts combining dust mitigation strategies and electrical cable diagnostic technologies have significant application for lunar and Martian surface systems, as well as for terrestrial applications in dusty environments. Circuit failures in wiring systems are a serious concern for the aerospace and aeronautic industries. Often, such circuit failures result from vibration that occurs during vehicle launch or operation. NASA'S Kennedy Space Center developed prototype connectors that combine dust mitigation and cable health monitoring with automatic circuit-routing capabilities [Lewis, M. et al., NASA Tech Briefs, February 2012].

3.4 FACILITIES, SIMULANTS, FIELD ANALOGS

The effectiveness of the proposed dust mitigating technology will be verified in a laboratory environment, where the artificial conditions can be locally controlled, and in the field, where longer tests with more realistic (sometimes, unpredictable) conditions can be run. These two types of investigations can be considered complementary: design verification can be performed in the laboratory under imposed and controlled conditions, while system validation can be done when operations are simulated in terrestrial analogs.

Extensive experimentation is needed to characterize and model the dusty environments themselves. Data acquired from or during missions will be used to increase our understanding of the presence and behavior of dust on different planetary surfaces and to create/correlate models describing the local dust cycle and interactions.

This basic knowledge will be used in constructing facilities and simulants for further experiments or in selecting representative terrestrial analogs.

3.4.1 FACILITIES

Simulation Facilities

Regolith simulants under terrestrial conditions will not necessarily mimic planetary regolith under its native conditions. Moreover, native regolith will not react the same under terrestrial conditions as it will under its native conditions. The environment of the Earth is humid, oxidizing, and relatively protected from high-energy radiation by the Earth's magnetic field and atmosphere. In contrast, the planetary environments are dry, tend to be chemically reducing (except for Mars, which is more oxidizing than Earth), and are constantly bombarded by high-energy electromagnetic and particle radiation. The surface chemistry of any material will be different in these two environments.

Airless planetary environments are expected to "activate" the surfaces of the regolith particles. Activation includes any processes that enhance the chemical reactivity of the surface. These processes include excitation of the electronic state of an atom, removal of electrons from the surface, or displacement of atoms from their equilibrium lattice positions. Bombardment of the planetary surface by solar wind and cosmic ray particles will act to activate regolith particles. Activated particles tend to stick together much more strongly that those that are not. Adhesive and cohesive forces may be increased by a factor of hundreds.

Passivation is the process of relaxation of atoms back to the ground state. These processes include collisions with foreign bodies, the emission of radiation, or radiationless relaxation processes. On airless planetary bodies, there are few opportunities for atomic collisions, which dominate passivation on the surface of the Earth. Hence, regolith dust particles will likely remain highly activated much longer on their native surfaces.

In order to accurately assess the adhesion and cohesion of fine regolith particles (dust), at the very least a simulation chamber must provide a slowed passivation rate. Thus, in most cases a vacuum chamber will be required at minimum. In the best case, the simulation chamber would also provide activation processes that are comparable to those occurring on the native surface. NASA undertook two separate facilities surveys between 2005 and 2007, one looking at chambers that could be used for dust mitigation and the other for chambers that could be used to test *in situ* resource utilization (ISRU) activities. Although the list (Appendix 4) is dated, it gives a flavor of the types of facilities that are available at the NASA centers. These range from small, very high-fidelity chambers like the Glenn Research Center Lunar Dust Adhesion Bell-Jar (LDAB) to large but lower fidelity chambers such as the Ames Research Center Martian Surface Wind Tunnel (MARSWIT) and the human-rated Johnson Space Center Chamber B. Many more chambers exist at other space agencies, universities, and private companies throughout the world.

3.4.2 REGOLITH SIMULANTS

High-fidelity lunar regolith simulants are required to verify the performance of structures, mechanisms, and processes to be used on the surfaces of the Moon, Mars, asteroids, and other planetary bodies. A crucial component of a high-fidelity planetary simulation is a regolith simulant that simulates a comprehensive set of properties. For example, lunar simulants have evolved from generic basaltic dusts used early in the Apollo Program to simulants that more closely mimic the bulk chemistry of the returned lunar samples. There has also been an increasing emphasis on volcanic glass content and better control over the size and shape distribution of simulant particles. But it is increasingly recognized that minor constituents will in some cases have major impacts. Small amounts of sulfur in the regolith can poison catalysts, and metallic iron on the surface of nano-sized dust particles may cause a dramatic increase in its toxicity.

Further complicating the picture is the fact that the definition of a high-fidelity simulant is application-dependent. For example, *in situ* resource utilization will require high fidelity in chemistry, meaning careful attention must be paid to minor components and phases; but some other applications, such as those concerned with abrasive effects on suit fabrics, might be relatively insensitive to minor component chemistry while abrasion of some metal components may be highly dependent on trace components. In some cases these minor constituents will introduce complications, but in others the minor constituents may prove to be beneficial.

There is also a growing awareness that the surface of the regolith particles may well be altered by solar and cosmic radiation, and the changes in surface chemistry may have implications for such surface-dependent properties as adhesion and biological activity. Research must be conducted to determine how sensitive the various mitigation and utilization technologies will be to minor components and environmental factors before those factors can be dismissed as unimportant.

See Table 3–1 for a list of regolith simulants used in past work on dust mitigation.

TABLE 3–1. A LIST OF REGOLITH SIMULANTS THAT HAVE BEEN USED TO EXPLORE DUST MITIGATION TECHNOLOGIES.

Chenobi	Lunar highlands (chemically enhanced OB1) (CSA/Deltion/EVC
NU-LHT	Lunar highlands (NASA/USGS)
NU-LHT-2M-700-1X	NU-LHT with agglutinates added (NASA)
MLS-1	Lunar mare (U. Minnesota)
MLS-1P	Plasma treated MLS-1 to add glass (U. Minnesota)
JSC-1	Lunar mare (NASA)
JSC-1A	Remake of JSC-1 (NASA)
JSC-1A-5000-2X	JSC-1A with agglutinates added
FJS-1	Lunar mare (JAXA)
GRC-1	Lunar geotechnical properties (NASA)
OB-1	Lunar highlands (CSA/Deltion/EVC) (discontinued for Chenobi)
BP-1	Black Point (Lunar geotechnical properties)
UW-1M	Lunar mare with nanophase Fe (CSA/U. Winnipeg)
UW-1H	Lunar highland with nanophase Fe (CSA/U. Winnipeg)
NAO-1	Lunar mare (Chinese Academy of Sciences)
Fullers Earth	Mars (commercially available)
JSC Mars-1	Mars optical properties (NASA)
Anorthosite	Most common lunar mineral
Chromite	Dark and abrasive lunar mineral
Harzburgite	Common lunar mineral
Ilmenite	Oxygen extraction mineral
Norite	Common lunar mineral

Note: Many simulant variations are derived by sieving these into different size fractions. For references and additional descriptions, see J.R. Gaier, S. Ellis, and N. Hanks, "Thermal Optical Properties of Lunar Dust Simulants," J. Thermophys & Heat Trans 26(4) (2012) 573–580.

Testing protocols should include direction for systems and subsystems to use simulants deemed most relevant for the intended environment. A definition of each destination's environmental hazards is needed, including dust constituents, chemical composition of the dust, and its characteristics, such as particle size and shapes. Other testing factors need to be considered:

- Do the properties (pressure, humidity, etc.) of the material change when exposed to a habitable environment?
- What type of hazards does the dust present to humans?
- Is the dust electrically conductive?
- Is the dust flammable?

3.4.3 FIELD ANALOGS

In addition to environmental simulation chambers, there are a number of planetary analog sites. These could be useful for verifying specific mitigation technologies in large scale (both spatial and temporal) and under unpredictable and controllable conditions, and are especially invaluable for refining operational strategies that minimize the impact of dust.

Considering the importance of these sites, their identification and selection was and is still performed in the frame of national and international scientific cooperation; several initiatives consolidated the effectiveness of field testing for robotic and human exploration programs.

Each site is usually more representative of specific aspects and local conditions (temperature/humidity, dust size and chemical properties, etc.). For example, the Sahara desert can be considered a good analog to Mars in terms of dust abundance and interaction. In fact, a dry, hot environment is necessary to create a condition in which dust is lifted from the surface (whereas cold deserts are too humid for large amounts of dust to be carried to the atmosphere). Hence, the Sahara desert is the arid area with the largest concentration of sand and dust, and it shows a complex aeolian circulation that intrudes and transports both sand and dust. (See Table 3–2.) Sand is basically transported near the sedimentary interface with saltation processes, while dust is present as a suspended load.

TABLE 3–2. MAXIMUM MEAN VALUES OF AEROSOL INDEX FOR MAJOR DESERTS DETERMINED BY TOMS (AFTER GOUDIE AND MIDDLETON, 2001).

Bodélé Depression of Central Sahara	>30
West Sahara, Mali and Mauritania	>24
Arabia, Southern Oman Saudi border	>21
Eastern Sahara, Libya	>15
Southwest Asia, Makran coast	>12
Taklamakan, Tarim basin	>11
Etosha Pan, Namibia	>11
Lake Eyre Basin	>11
Mkgadikgadi Basin, Botswana	>8
Salar de Uyni, Bolivia	>7
Great Basin of the USA	>5

Other atmospheric phenomena observed on the Martian surface that involve particle deposition are the "dust devils," which are low-pressure vortices formed from unstable near-surface warm air generated by insolation (Figure 3–13). Dust devils contribute to the background atmospheric opacity on Mars by their ability to lift fine particles even in higher atmospheric layers. The Italian DREAMS instrument on board the ESA ExoMars 2016 lander *Schiaparelli* will investigate this topic (including electrostatic effects in the Martian atmosphere) during the global dust storm season on Mars, but these natural phenomena and their effects on exposed materials and equipment can be also studied in analog environments on Earth, where they are expected to be observed.

FIGURE 3–13. "DUST DEVIL" OBSERVED IN SAHARA DESERT;
THIS PHENOMENA IS ALSO PRESENT IN MARS ATMOSPHERE, ESPECIALLY DURING A PARTICULAR SEASON.

Planetary Analog Sites

In addition to environmental simulation chambers, there are a number of planetary analog sites. These are less useful for verifying specific mitigation technologies, but are invaluable for refining operational strategies to minimize the effects of dust.

ISECG's Analogue Team (a part of the Exploration Roadmap Working Group/ERWG) surveyed member organizations for analogue sites found to be useful in preparation for planetary surface missions. The locations of the analogue sites collected during this survey are shown in Figure 3–14. For purposes of dust mitigation studies, not all of these sites are appropriate. The following subset of the ERWG Analogue Team sites could be considered for dust mitigation studies:

- **Blackpoint (Arizona), USA:** Location is within the San Francisco Volcanic Field. Recognized during the Apollo era as a highly suitable analog for lunar surface exploration activities. Dust at this location could have originated from erosion of the hard, crystalline basalt of the flow, from the underlying sediments, or from the soft, clay-rich Moenkopi Sandstone onto which the flow was deposited.

- **Eifel, Germany:** Location includes a barren field with volcanic tephra, with a reddish powdery dust covering the soil and a steep wall rising just in front of the site.

- **Haughton Crater, Canada:** Location is a polar desert with a prominent impact crater. Portions of the crater were previously filled by a lake which has now drained, leaving silt deposits. Dust is found throughout the location and could have been generated from impact breccia, lacustrine deposits, or freeze/thaw cycles.

- **La Reunion, France:** Location contains a diversity of volcanic mineral environments and structures, from sandy plains made by ashes and projections to a number of lava flows. Dust is generated primarily from volcanic ash. The geological characteristics of volcanic areas of Reunion Island are used for Moon and Mars analogs.

- **Mauna Kea (Hawai'i), USA:** Location is on the flanks of the Mauna Kea volcano. Sites at several different altitudes have been used. Sites could contain lava flows, tephra, or volcanic ash, which provide geologic terrain and composition similar to what scientists expect to find on the Moon, an asteroid, or Mars. Dust composition is made up from these volcanic sources.

- **Moroccan Desert (Ibn Battuta Centre), Morocco:** Location includes dry and arid desert environments with a number of sub-environments, including deflation surfaces, regoliths, sand seas, sand dunes, outcrops, evaporites, sabkha, etc. Dust is found throughout the site with composition dependent on the specific sub-environment.

- **Rio Tinto (Huelva), Spain**: Location is an old mining area with variable terrain (mountains, hills, sand plains). Dust at this site is abrasive, yellowish in color, and easily carried by light winds. Equipment will require protection.

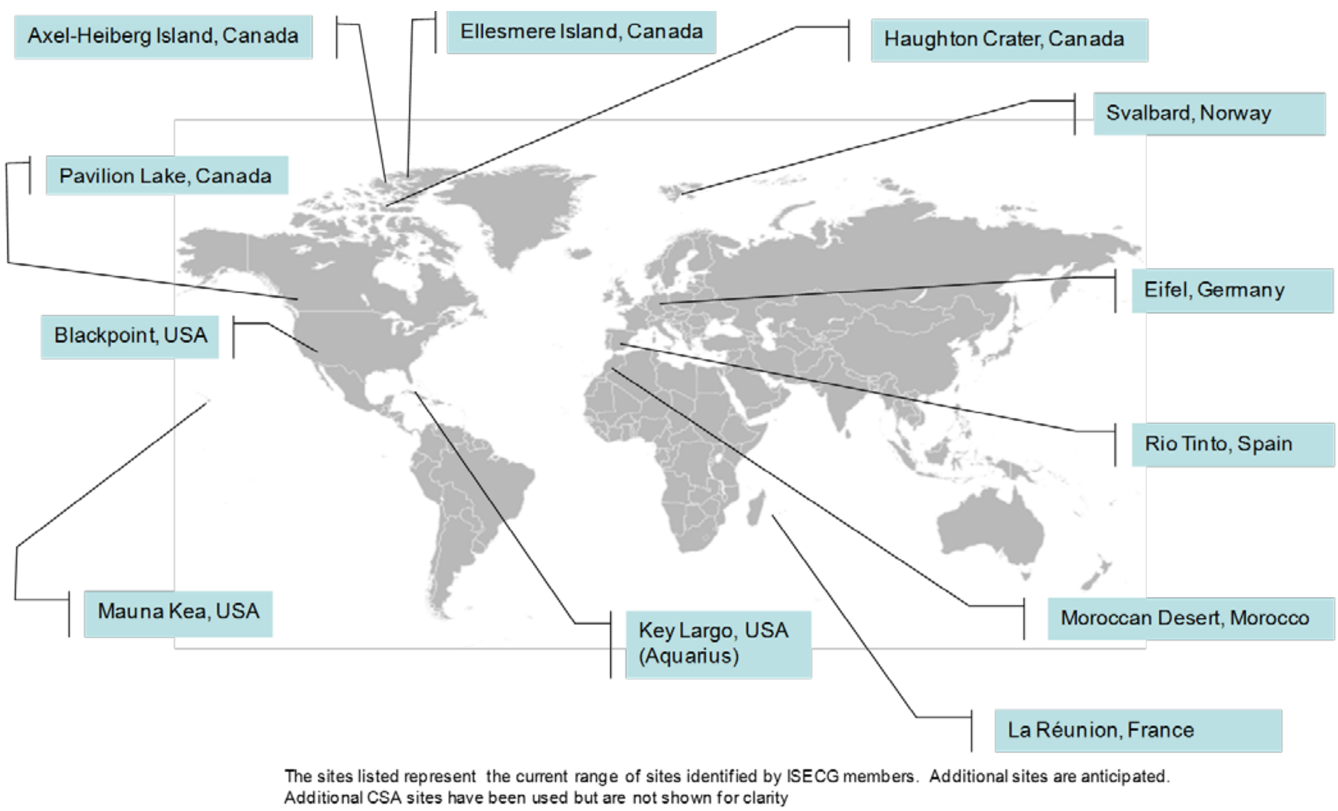

FIGURE 3–14. ISECG ANALOGUE TEAM FIELD SITE SUMMARY FOR PLANETARY SURFACE MISSIONS PREPARATION (NOTE: NOT ALL SITES ARE APPLICABLE TO DUST MITIGATION TESTING).

One such planetary analog site is the CSA Mars Emulation Terrain (120 m x 60 m) shown in Figure 3–15. The MET was built to support the development and testing of lunar and planetary rovers. Its terrain topography provides a variety of challenges to the mobility subsystems of exploration rovers as well as to their associated manipulators and instruments.

FIGURE 3–15. CSA MARS EMULATION TERRAIN.

Another example, shown in Figure 3–16, is the NASA JSC Planetary Analog Test Site (aka Rock Yard), which provides a large multi-acre test area that simulates general features of the lunar and Martian surface terrain environment and consists of various slopes, grades, simulated craters, and strewn-rock field conditions.

FIGURE 3–16. NASA JSC PLANETARY ANALOG TEST SITE (AKA ROCK YARD).

4. GAP ASSESSMENT SUMMARY

4.1 KEY TECHNICAL CHALLENGE AREAS

The following tables break down the systems areas into specific common components (key technical challenge areas) that are similar for each of the systems. Whereas systems engineers are interested in the effects of dust on the ECLSS system, EVA systems, or robotics systems, etc., it is inherently easier to break testing and mitigation technologies down to common subcomponents such as rotary seals for bearings. The seals themselves and the technologies to improve them are common across all the systems that we are interested in. For this reason, the following pivot tables were developed to cover the 13 basic Key Technical Challenge Areas:

1. Rotary Seals
2. Linear Motion Seals
3. Static Seals
4. Mating Connectors
5. Filters (Mechanical, Gas Scrubbers, and Other)
6. Human Health (Biological)
7. Thermal Control Surfaces
8. Optical Surfaces
9. Other Surfaces (Performance)
10. Flexible Materials
11. Chemical Contamination and Corrosion/Oxidation
12. Characterization of Dust and Regolith
13. High-Fidelity Simulation Chambers

TABLE 4–1. KEY TECHNICAL CHALLENGE AREAS.

	Key Technical Challenge Areas	ECLSS	EVA and Airlocks	Mobility and Robotics	ISRU	Ascent/Descent Vehicles	Systems
1	Rotary Seals	Fans, louvers, pumps	Articulation Joints – bearings	Wheel bearings, motor bearings, steering and suspension linkages, hinges	Drill and tool bearings, motor bearings, linkages, hinges	Landing gear, deployment ramps	Fans, wheels, antenna
2	Linear Motion Seals	Shafts	Sliding door seals – possibly airlock/ suitlock/ suitport seals	Controls, restraint systems, linear joints	Linear stages, restraint systems	Landing gear, cargo latches, deployment ramps	Docking and berthing, latches
3	Static Seals	Compartment covers, quick disconnects, hatch seals	Articulation joints – bearings, PLSS to PGS interface, hatch seals, quick disconnects, air reclamation, airlock/suitlock/ suitport seals	Compartment covers, quick disconnects, airlock	Sample encapsulation, handoffs (e.g., sample handling)	Planetary protection, docking and berthing.	Cables, hoses, quick-release connectors, planetary protection
4	Mating Connectors	Fluid and gas connectors	External and internal electrical, external gas and fluid connectors, EVA umbilicals	External and internal electrical, external gas and fluid connectors, tool mating, handoffs (e.g.: sample containers)	External and internal electrical, external gas and fluid connectors, tool mating, handoffs (e.g.: sample containers)	External and internal electrical, external gas and fluid connectors, docking and berthing	Cables, hoses, quick-release connectors, external and internal electrical, external gas and fluid connectors
5	Filters – Mechanical, Gas Scrubbers, and Other	Mechanical-electrostatic particulate filters, desiccant-sorbent-catalytic beds	Mechanical-electrostatic particulate filters, desiccant-sorbent-catalytic beds, PLSS trace contaminant control system, airlock air reclamation and filtration, CO_2 scrubbers	Depressurization vents	Volatile separators, depressurization vents, mechanical-electrostatic particulate filters, desiccant-sorbent-catalytic beds	Depressurization vents	Depressurization vents
6	Human Health (Biological)	Dermatitis, respiratory, carcinogen, chemo, gastrointestinal, cabin dust removal and control	Dermatitis, Respiratory, carcinogen, chemical contamination, gastro-intestinal	N/A	Tailings	N/A	Operational constraints

	Key Technical Challenge Areas	ECLSS	EVA and Airlocks	Mobility and Robotics	ISRU	Ascent/Descent Vehicles	Systems
7	Thermal Control Surfaces	Active radiator and other surfaces	Active radiator and other surfaces, PGS layup	Active radiator and other surfaces	Active radiator and other surfaces	Active radiator and other surfaces	Active radiator and other surfaces
8	Optical Surfaces		Displays, lights, camera lenses, visor, viewports, airlock/ suitport displays	Solar panels (reduced capacity), sensors, camera lenses, instrument calibration targets	Lenses, mirrors, lights, instruments, calibration targets, sensors, viewports,	Windows, camera lenses, instrument apertures, sensors, solar panels	Solar panels, laser communications and measuring, star trackers
9	Other Surfaces – Performance	Intakes, ducts, compressor blades, solid particle size reduction blades, pitot tube, porous media, membranes	Switches, relief valves, purge valves, actuators, regulators, evaporative membranes, regulators, ancillary equipment such as tools and translation aids. Static shock to electronics, battery drain—shorting	Crew stations (PLSS abrasion), wheels (abrasion) displays, lights, sensors, cameras, visor, viewports, ancillary equipment such as tools, switches, and sensors	Venturi tubing erosion in pneumatic transport, wheels (abrasion) displays, lights, sensors, cameras, viewports, ancillary equipment such as tools, switches and sensors	Pitting of surfaces due to blasting, mechanism and nozzle dust contamination due to plume rebound	Static shock to electronics, battery drain—shorting, antenna performance, anchoring (Philae)
10	Flexible Materials	Plastic tubing for water or gas, bellows, bladders	PGS, gloves, bladder, Liquid Cooling Ventilation Garment	External wiring and harness protection sheaths	External wiring and harness protection sheaths, bellows, bladders	External wiring and harness protection sheaths	External wiring and harness protection sheaths, mobility systems (“Tumble Weed” inflatable mobility ball)
11	Chemical Contamination and Corrosion/Oxidation	Bacterial (beneficial), reactive sites, instrumentation and sensor degradation	Chemical corrosion pitting on seals	Lubricant contamination	Lubricant contamination, sensor contamination and degradation, furnaces	Corrosion/oxidation	Corrosion/oxidation
12	Characterization of dust and regolith	Affected	Performance affected	Terramechanics of dust affects performance	Performance affected, berming, stabilizing, cement, thermal/MMOD shield	Performance affected	Affected: placement of sensors, experimental procedure, ground testing and validation
13	High-Fidelity Simulants and Environmental Chambers	All available chambers can be improved (higher fidelity simulants, dust delivery systems, ionization, radiation, volatiles) to provide more realistic environments. More robust ground support equipment (GSE).					

4.2 GAP DESCRIPTIONS AND ANALYSIS

This assessment looked at four categories of gaps: the Technology Gap, the Experience/Knowledge Gap, the Funding/Research Gap, and the Schedule Gap. The following sections describe each gap category, and then identify where these gaps are found. An exception is the table for schedule gap, which is a little more esoteric than the others. The schedule gap is an artificial one that is created by defining a mission schedule before defining a development schedule.

4.2.1 TECHNOLOGY GAP

The technology gap is the delta between the state of the art and the technology readiness level (TRL) required for extended human mission support. The durations currently required for most proposed missions are greater than 1 month for lunar missions or greater than1 year for missions to Mars.

TABLE 4–2. TECHNOLOGY GAP (GER EXTENDED HUMAN MISSIONS).

	Key Technical Challenge Areas	Technology Gap		
		Moon	Mars	NEOs*
1	Rotary Seals	NASA JAXA CSA	NASA CSA	
2	Linear Motion Seals			
3	Static Seals	NASA	NASA	
4	Mating Connectors	NASA	NASA	
5	Filters – Mechanical, Gas Scrubbers, and Other	NASA	NASA	
6	Human Health (Biological)	NASA ESA	NASA ESA	
7	Thermal Control Surfaces	NASA CSA	NASA CSA	
8	Optical Surfaces	NASA CSA	NASA CSA	
9	Other Surfaces – Performance	ESA	ESA	
10	Flexible Materials	NASA		
11	Chemical Contamination and Corrosion/Oxidation	NASA	NASA	
12	Characterization of dust and regolith	NASA JAXA CSA ESA	NASA ESA	NASA
13	High-Fidelity Simulation Chambers	NASA ESA	NASA	NASA
12	Characterization of dust and regolith	NASA CSA ESA	NASA ESA	NASA
13	High Fidelity Simulants and Environmental Chambers	NASA CSA ESA	NASA CSA	NASA

Legend for color coding:

Confident for extended human mission (1+ month Lunar/1+ year Mars)
Possible TRL 3 solutions for extended human mission
No TRL 3 solutions for extended human mission

Note: Agencies listed are either involved in ongoing research or have already developed solutions in that area.

* As we don't really know the composition and structure of NEO regolith, the only current work being done is some research into estimating material properties. No real work is being done on NEO dust mitigation. The assumption for NEO is that we can get some credit from the other two categories, whereas NEO regolith is assumed to be similar to lunar regolith yet certain deposition mechanics are obviously different owing to much lower gravity. The gap table reflects current solution levels, especially with respect to NEO.

4.2.2 EXPERIENCE/KNOWLEDGE GAP

The experience gap is the delta in the collective knowledge and experience of personnel required to bring a technology to (or back up to) the appropriate TRL. For example, many of the scientists and engineers who participated in the designs of lunar and Martian landers/rovers (circa 1960–1990) are now retired or unavailable. That being said, many agencies have extensive data repositories which the ISECG Dust Mitigation team is sourcing; and where available, we are providing links in a common repository. In cases where documentation is not already available online, it is being cataloged in the common repository, augmenting our collective knowledge in areas where actual and current experience may be lacking.

So to clarify, collective knowledge may be maintained through proper documentation and archiving, even while experience in practical work and actual flight missions may be lacking.

- Experience: people with history and practical work in actual flight missions
- Knowledge: available documentation and resources

Our collective knowledge, summarized in Table 4–3, serves as a way to mitigate the experience gap. For example, NASA personnel who have direct experience with rotary seals on the Moon or Mars may no longer be available to assist in future projects, but their knowledge of these techniques has been properly archived and is accessible.

It is important to note that the Experience/Knowledge gap in Table 4–3 specifically cites lunar human missions of 3 days. The GER is expecting to have both robotic and human missions that are an order of magnitude (10×) longer or more. Systems and subsystems that worked well during short lunar missions most likely will not last much beyond that without further research and improvement.

TABLE 4–3. EXPERIENCE/KNOWLEDGE GAP.

	Key Technical Challenge Areas	Experience/Knowledge Gap		
		Moon	Mars	NEOs*
1	Rotary Seals	NASA JAXA	NASA	
2	Linear Motion Seals			
3	Static Seals	NASA	NASA	
4	Mating Connectors	NASA	NASA	
5	Filters - Mechanical, Gas Scrubbers and Other	NASA	NASA	
6	Human Health (Biological)	NASA	NASA	
7	Thermal Control Surfaces	NASA JAXA		
8	Optical Surfaces	NASA	NASA	
9	Other Surfaces – Performance			
10	Flexible Materials –	NASA		
11	Chemical Contamination and Corrosion/Oxidation	NASA	NASA	
12	Characterization of dust and regolith	NASA	NASA	NASA
13	High-Fidelity Simulants and Environmental Chambers	NASA	NASA	NASA

Legend for color coding:

Systems that worked effectively (for NASA during Apollo (3 days) on the moon; Worked effectively on rovers on Mars (> 1 year))
Systems where there is no experience, but active research
Systems that did not work well (for NASA during Apollo (3 days) on the moon; Did not work effectively on Mars (> 1 year))
No comprehensive research past or present

Note: NASA is the main contributor to historical knowledge as other agencies do not have the flight background.

* As we don't really know the composition and structure of NEO regolith, the only current work being done is some research into estimating material properties. No real work is being done on NEO dust mitigation. The assumption for NEO is that we can get some credit from the other two categories, whereas NEO regolith is assumed to be similar to lunar regolith yet certain deposition mechanics are obviously different owing to much lower gravity. The gap table reflects current solution levels especially with respect to NEO.

4.2.3 FUNDING/RESEARCH GAP

In many areas of research, the current level of effort or funding is not enough to bring a dust mitigation technology to an appropriate TRL by the time it is needed. (This may also be considered a commitment gap.) One goal of the ISECG Dust Mitigation Team is to identify potential synergistic relationships between agencies and minimize duplication of effort. Identifying areas where agencies are currently working on, or anticipating research related to, dust mitigation is an initial step in understanding the level of investment among the ISECG partners (Table 4–4). Although agency-specific investment details are not within the scope of this report, some general funding/research gap analysis can be performed. Note: A green-colored field should not be interpreted to mean that there is sufficient funding/research, but only that multiple agencies are working in or anticipating research in that particular key technical challenge area.

TABLE 4–4. FUNDING/RESEARCH GAP.

	Key Technical Challenge Areas	Funding/Research Gap		
		Moon	Mars	NEOs*
1	Rotary Seals	NASA JAXA CSA	NASA CSA	
2	Linear Motion Seals	CSA	CSA	
3	Static Seals	NASA	NASA	
4	Mating Connectors	NASA CSA	NASA	
5	Filters – Mechanical, Gas Scrubbers, and Other	NASA	NASA	
6	Human Health (Biological)	NASA ESA	NASA ESA	
7	Thermal Control Surfaces	NASA CSA	NASA CSA	
8	Optical Surfaces	NASA JAXA CSA	NASA CSA	
9	Other Surfaces – Performance	ESA CSA	ESA	
10	Flexible Materials	NASA		
11	Chemical Contamination and Corrosion/Oxidation	NASA	NASA	
12	Characterization of Dust and Regolith	NASA JAXA ESA CSA	NASA ESA	NASA
13	High Fidelity Simulants and Environmental Chambers	NASA JAXA ESA CSA	NASA	NASA

Legend for color coding:

More than one agency involved in ongoing or anticipated research
One agency involved in ongoing or anticipated research
No agencies involved in research on this aspect

* As we don't really know the composition and structure of NEO regolith, the only current work being done is some research into estimating material properties. No real work is being done on NEO dust mitigation. The assumption for NEO is that we can get some credit from the other two categories, whereas NEO regolith is assumed to be similar to lunar regolith yet certain deposition mechanics are obviously different owing to much lower gravity. The gap table reflects current solution levels especially with respect to NEO.

4.2.4 SCHEDULE GAP

Currently there is a gap between when a dust mitigation technology is expected to become available (i.e., the appropriate TRL for that stage of design, which would typically be TRL 4 by program Critical Design Review [CDR] and TRL 6 by implementation) and when that technology is required for use in the concept/design of systems and components for future missions.

The first statement in the executive summary of the GER under Common Goals and Objectives is "Develop Exploration Technologies and Capabilities: Develop the knowledge, capabilities, and infrastructure required to live and work at destinations beyond low-Earth orbit through development and testing of advanced technologies, reliable systems, and efficient operations concepts in an off-Earth environment."

In order to realize this first statement of the GER's Common Goals and Objectives, immediate investment of both time and money is necessary so that these technologies and capabilities are available when mission objectives are planned.

A technology needs to be at TRL 4 by the time it is implemented into a design. Advancement to TRL 6 is required by the time the project reaches the build phase. It is unreasonable to assume that the development of supporting technologies will just happen in synch with program development. The foundation for programs will be the development, or rather, the predevelopment of supporting technologies.

According to the 2013 GER, the following are approximate mission dates:

Upcoming Robotic Missions and Dates

Lunar Lander
Luna 25 (2016–2017) Roscosmos
Chandrayaan-2 (2016–2019) ISRO
Selene 2 (2017–2019) JAXA
Luna 27 (2018–2019) Roscosmos
Luna 28 (2020–2021) Roscosmos
Luna 29 (2021–2023) Roscosmos
Selene 3 (2021–2023) JAXA

Mars Lander
ExoMars 2016 (2016–2018) ESA/Roscosmos
InSight (2016–2018) NASA
ExoMars 2018 (2018–2020) ESA/Roscosmos
Mars 2020 (2020–2023) NASA
Mars Precursor (2020–2023) JAXA
Post ExoMars (2024–2025) ESA

NEO
OSIRIS-Rex (2016–2023) NASA
Marco Polo-R (2022–2025) ESA

Upcoming Human/Human Support Missions and Dates

Lunar
Cargo (2026 and 2027)
Humans to Lunar Surface (2028 on)

Mars
Human-Assisted Sample Return (2024–2026)
Human-Scale EDL Test Mission Opportunities (2026 on)

Table 4–5 highlights the GER mission start dates, and from that, the assumed CDR dates (a year or two into the program/project). Based on the GER dates, the technology readiness levels and technology research start dates can be extrapolated.

TABLE 4–5. GER MISSION START DATES/CDR DATES (DUST MITIGATION@TRL 6)/ NEW DUST MITIGATION R&D ESTIMATED START DATES.

Technology Solutions/Programs	GER Mission Start Dates	CDR Need Dates (est.) (note 1)	R&D Start Dates (est.) (note 2)
Lunar Dust Mitigation (Robotics)	2020	2016	2012
Lunar Dust Mitigation (Human)	2026	2022	2016
Martian Dust Mitigation (Robotic)	2020	2016	2012
Martian Dust Mitigation (Human)	2030+	2022+	2018+
NEO Dust Mitigation (Robotic)	2022	2018	2014

Legend for color coding:

Time to start active research is in the future by at least one year taking into account the GER schedule
Time to start active research is this year (2016) taking into account the GER schedule
Time to start active research has passed, likely contributing to delays in the GER

Note 1: A typical space development program is estimated to run anywhere from 6 years to over a decade, and the Critical Design Review (CDR) is usually 1 to 2 years into that program. Dust mitigation technologies need to be at least well defined by PDR (TRL 4), and available by CDR (TRL 6). The CDR and R&D need dates were extrapolating using the shorter 6-year development cycle.

Note 2: Working backwards from that, we assume that the dust mitigation programs themselves take 4 years (even more aggressive than the 6-year minimum for other space programs) to develop viable solutions and techniques. In most, cases this 4-year estimated research program is assumed; however, where ESA has provided estimates for research programs, those dates were entered.

We also took into account the specific technologies and how they each would fit into the development process. For example, ECLSS, EVA, and airlocks will not be required for robotic missions to the Moon, ascent stages will only be required on sample-return missions or on human missions; but dust mitigation technologies supporting rotary seals will be needed for all missions and all systems.

The above can be elaborated for each specific Key Technical Challenge Area, further refining the R&D start dates based on the GER need dates for lunar, Martian, and NEO missions.

Based on a start date of 2020 for robotic missions, research to support these endeavors should have started in 2012. Since these early missions have most likely been though CDR, only post-2020 robotic missions are likely viable for new dust mitigation technologies infusion or pathfinder test demonstration opportunities.

But because of similarities in lunar and NEO mitigation techniques, we can deduct a couple of years between the start of NEO technology development and the start of lunar technology development. Unfortunately, despite this schedule compression, a dust mitigation program to support NEO should have begun around 2014.

For human missions to the Moon and Mars with mission start dates of 2026 and 2030+ respectively, these dust mitigation technology programs should start in 2016 (this year) and 2018.

Fortunately, many of the Key Technical Challenge Areas, rotary seals, mating connectors, optical surfaces, etc., are similar across systems, and some schedule benefits can be realized here. What should also be noted here is that durations are estimated for average development programs, whereas GER programs take 6 to 10 years and accelerated dust mitigation projects take 4 years to produce TRL 6+. Considering the usual project development timeframe, this is very aggressive. Unfortunately, as shown in Table 4–5, we are already well behind schedule to support the GER.

Although some limited funding and targeted research for dust mitigation technologies are currently underway, meeting the complex technical requirements and schedule identified within the GER necessitates more immediate and substantial effort and funding to be successful.

5. PARTNERSHIP OPPORTUNITIES

5.1 DATA SHARING

The data developed by the Dust Mitigation Gap Assessment Team is of value and consideration should be given to not only sharing this data within the network established by this initiative, but also outside the space agencies.

Data Products Developed

- Dust Mitigation Gap Assessment Report (this document)
- Dust Mitigation Challenges and Solutions Matrix.xls
- ISECG Dust Mitigation Gap Assessment reference material, including:
  - An archive of agency papers, conference proceedings, and reports
  - Mail distribution list containing all agency points of contact

Data Hosting/Archiving

The current platform for archiving the data is a CSA-hosted portal. This requires a username and password.

Portal Address: https://pie-isep.asc-csa.gc.ca/sfiler/Login.action
Administrators: taryn.tomlinson@canada.ca and mireille.bedirian@canada.ca

Forward Plan for Data Sharing

The assessment team may consider follow-on activities such as

- developing a joint paper to engage members of the community outside the space agencies,
- organizing seminars on dust and mitigation strategies,
- publishing lessons learned, and
- collecting new reference material for future work.

5.2 R&D OPPORTUNITIES

The scope of R&D opportunities include the following objectives:

1. Envision a technology roadmap related to dust mitigation
2. Minimize overlap of R&D work between participating agencies
3. Exchange technical information to enhance R&D
4. Fill missing technology gaps

Table 5–1 identifies the main R&D areas, according to the Gap Assessment Summary in Section 4, where each participating agency plans to participate in the near future (within 3 years). This has to be consistent with the each participating agency's own roadmap for dust mitigation work. Table 5–1 identifies teams who can work in particular research areas related to dust mitigation. Using this information, we can make cooperation between participating agencies more efficient and cost-effective, and streamline our R&D efforts.

TABLE 5–1. R&D PLANNED ACTIVITIES IN THE NEAR FUTURE.

	ESA	NASA	JAXA	ASI	CSA
Dust characterization	✓	✓	✓	✓	✓
Human health	✓	✓		✓	
Surface performance	✓	✓			
Chemical contamination		✓			
Simulation chambers		✓		✓	✓
Static seals		✓			
Flexible materials		✓			✓
Mating connectors		✓			✓
Filters		✓			
Rotary seals		✓	✓		✓
Thermal control surface		✓	✓		✓
Optical surfaces		✓			✓
Linear motor seals					✓

Several opportunities for cooperation between agencies were identified.

1. **Creating a R&D joint project**

   Table 5–1 shows an overlap in some R&D functions of the different agencies. These agencies could establish a joint project for some of these overlapping functions. A joint project can offer several benefits, such as

   - allowing agencies to share the same experience in R&D,
   - reducing the cost burden for each agency,
   - creating effective products that serve additional purposes,
   - improving the efficiency of technology transfer between different agencies.

2. **Exchanging R&D researchers**

   Various agencies, for example, ESA/JAXA and ESA/NASA, have already established fellowship exchange programs. However, these exchange programs are not specifically for dust mitigation research and they normally last for only a year or two. But it is feasible to create such an exchange program specifically for a common R&D project related to dust mitigation. The agencies involved would receive a number of mutual benefits, because it would

   - provide a better understanding of each other's capabilities in a specific area of R&D,
   - involve additional experts because of a better contact mechanism, and
   - encourage additional scientists and engineers to participate.

3. **Holding periodic joint seminars or conferences on R&D**

   Several international conferences take place annually, for example, American Institute of Aeronautics and Astronautics (AIAA) and American Society of Mechanical Engineers (ASME). Occasionally sessions are related to dust mitigation. Holding such a conference in the area of dust mitigation R&D, with the participating agencies attending, would offer a number of advantages. It would

   - acquaint scientists with the R&D work being done by other agencies,
   - improve communication between different agencies or institutes,
   - create opportunities to combine R/D knowledge, and
   - enhance interactions between experts.

4. **Visiting R&D sites**

   Visiting an R&D site is a key to understand and appreciate a new R&D product in an application that cannot be described fully on paper. In addition, this could serve a way to increase our trust and confidence in working with each other. As additional mutual benefits, visitation can

   - deepen the public relationship between different agencies,
   - promote cooperation, and
   - increase R&D product efficiency through the interactive exchange of ideas.

5.3 TEST, DEMONSTRATION, SIMULATION OPPORTUNITIES

Considering the wide range of possible environmental conditions and dust characteristics that can be encountered during space system operations (e.g., at different mission destinations), the availability of several test facilities with different characteristics is a powerful tool. The laboratory simulating chambers are usually developed by national efforts for a specific mission, and therefore have a targeted representativeness; also the terrestrial analog simulants, with their own features (particle size and abundance, humidity, etc.), are geographically distributed in different countries. International partnership is a great opportunity to overcome this limit.

The Working Group could create and maintain an updated "Dust Simulant Facilities Register," surveying and mapping the available facilities and their relative capabilities, and then highlighting their potential uses. The facilities, although funded by national agencies, are usually owned by research centers or private companies, so the participation of institutional agencies will promote and support cooperation in using the most suitable simulant tool.

International Space Station (ISS) is an existing international facility that could be involved in dust mitigation programs: The ISS environment offers the unique opportunity to analyze the interaction of dust with materials, parts, and systems under microgravity conditions and to verify the effectiveness of mitigating techniques under those same conditions. Proper chambers or compartments could be arranged or shipped from Earth in order to perform experiments and tests.

5.4 SUBSYSTEM AND SYSTEMS DEVELOPMENT (DDT&E)

Dust mitigation and resistance to impact and abrasion poses a significant technical challenge for the design, development, test, and evaluation (DDT&E) of subsystems and systems.

Each Key Technical Challenge Area (Table 4–1) could be assessed by the team to show the level of effort/interest for potential partnership areas in each phase of DDT&E. Phases of DDT&E could be tailored for each subsystem and system to highlight the optimal collaboration between partnerships. For instance, if a component or subsystem is being developed by an agency, but can be tested and evaluated using the facility of another, a potential partnership can be possible. It may be more cost-effective to work at the subsystem level on Key Technical Challenge Areas rather than the module level.

Dust, soil, and regolith have different characteristics/properties that influence landing site selections for destinations on the Moon, asteroids, and the surface of Mars. Once a destination is considered, it would be helpful to have a point of contact who can direct the collaborators to the most relevant simulants and facilities for testing and evaluation.

System and module-level interfaces should be tested with a relevant simulant as well. Discussion is needed on standards and goals concerning allowable levels of contaminate within habitable volumes/air quality zones.

6. KEY FINDINGS AND SUMMARY

The Dust Mitigation Gap Assessment Team was formed, under the direction of the International Space Exploration Coordinate Group (ISECG), to do a more detailed gap analysis on a particular critical technology need identified in support of the Global Exploration Roadmap (GER). Five participating member agencies of the ISECG (ASI, CSA, ESA, JAXA, and NASA) have supported the team's activity, and focused their respective agency's subject matter experts on the topic of dust mitigation for lunar, Mars, and NEO exploration. The approach taken by the team, with guidance from the ISECG Technology Working Group (TWG), is summarized below:

- Identification of Key Tasks/Questions
- Gap Analysis
- Options for Gap Closure
- Identification of Partnership/Coordination Opportunities

This report to the ISECG summarizes the results of the Dust Mitigation Gap Assessment team, with the team's key findings listed in the summary below.

Key Findings

- Dust is still a principal limiting factor in returning to the lunar surface for missions of any extended duration.
- Viable technology solutions have been identified, but need maturation to be available to support missions.
- No single technology completely solves the challenges of dust, but rather a suite of technologies will be required to address them.
- Gaps in existing dust mitigation technologies have been identified and require strategies for closure before extended lunar missions are undertaken.
- Situational awareness of the dust mitigation challenges needs to be infused into all aspects of mission architecture and operations.
- Investment in dust mitigation solutions increases system longevity and performance (including human-system performance).
- Resources (power, mass, volume) may be required to implement some of the mitigation solutions, but are offset by reduced logistics costs for spares, redundancies, etc.
- Solutions that work in one environment may not necessarily be fully applicable to other environments or destinations (e.g., chemistry differences, atmospheres, particles, locations on previously explored bodies).
- Trapped volatile gases are an additional factor of potential concern, which may require unique mitigation solutions.

- International cooperation within the dust mitigation community has already proved beneficial. This is currently limited to sharing information, but further opportunities are expected as commitment to narrowing the technology gap continues.

The Dust Mitigation Gap Assessment team would like to thank the ISECG for the opportunity to work this important study at an international level, and trusts that this report will have good distribution among the member agencies. We believe the subject matter material within the report will be helpful to the various organizations within respective agencies responsible for dust mitigation studies and solutions, including technology development program offices, systems engineering groups, exploration architecture teams, and program/project-level management. The prompt and proper attention, support, and work addressing dust mitigation challenges associated with exploration destinations are critical to the success of the GER scenario.

APPENDIX 1: DUST MITIGATION GAP ASSESSMENT TEAM ROSTER

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APPENDIX 2: AGENCY REFERENCE MATERIAL

ASI

#	ASI Document Title	Type	Doc #	Notes	Classification
A01	Thermal Vac Chamber for Mars Like Environment	Paper	CISAS-MARS-TV-TN		Shared
A02	Planetary Environment and Protection Solutions (PEPS) Technological Area @ Thales Alenia Space Turin	Facility Sheet	N/A		Shared
A03	Rational for the utilization od the Ibn Battuta Centra Field Facility for dust technical and scientific studies	Draft Memo	N/A		Shared
A04	Mars analougue activities: the Ibn Battuta Centre and the Sahara desert	EPSC Abstracts	Vol. 10, EPSC2015-780-2, 2015		Shared
A05	Ibn Battuta Centre Summary Brief	PPT Brief	N/A		Shared

CSA

#	CSA Document Title	Type	Doc #	Notes	Classification
C01	Project Moondust: Characterization and Mitigation of Lunar Dust	AIAA Paper	AIAA 2011-5184	CSA funded project	Proprietary, available (AIAA)
C02	MoonDust Lunar Dust Simulation and Mitigation	AIAA Paper	AIAA 2010-6023	CSA funded project	Proprietary, available (AIAA)
C03	Evaluation of the Resistance of Composite Materials to Lunar Dust Abrasion	IAC paper	IAC-10.C2.6.7	Internal research	Available through IAC
C04	Five Stage Defense Against Lunar Regolith	PPT & Abstract		PTMSS presentation	Abstract is public; presentation TBD
C05	Mars Emulation Terrain User Guide	User Guide	CSA-EXCO-MAN-0001	Analogue terrain	CSA, open use

ESA

#	ESA Document Title	Type	Doc #	Notes	Classification
E01	Contamination monitoring : WP 4240 Report : Safety assessment : Risk analysis	Report	189860	1989/Dornier System	public
E02	Amelioration des essais contamination plus irradiation : preetude no. 3, etude des procedures d'application de contaminants. Tome 1 : Essais et conclusions	Report	144606	1985/CERT	Available upon request ESRIN
E03	Etude des procedures d'application de contaminants. Tome 1: Essais et conclusions	Report	144514	1986/ONERA	Available upon request ESRIN
E04	Etude comparative de moteurs d'injection pour la mise a poste de satellites geostationnaires. Annexe 9 : Etude contamination	Report	145863	1976/ONERA	Available upon request ESRIN
E05	Degradation of the Meteosat radiometer primary mirror by contamination and radiation. Final report	Report	154824	1976/Aere Harwell	Available upon request ESRIN
E06	OSEAN / COMOVA 1.0 : Contamination modelling outgassing - Vent analysis tool : Final report	Report	159898	2000/HTS	public
E07	MIMOSA : Microbial contamination monitoring system for international space station	Report	162034	1998/ALENIA Aerospazio	public
E08	Surface effect data handbook : Contamination by droplets of bipropellant exhaust fumes. Progress report 1	Report	158084	1988/Technical U. Hamburg	Available upon request ESRIN
E09	Plume characterization testing : Plume testing technology transfer : WP 2.2 Exhaust plume analysis procedure (EPAP) DLR-version 1: Biopropellant thruster testing in the contamination chamber Goettingen (CCG)	Report	162086	2001/DLR	public
E10	Experimental investigation on plume contamination and surface effects. Final report, phase 2	Report	144184	1987/Technical U. Hamburg	Available upon request ESRIN
E11	Aerothermal studies and contamination assessment : Instrument sensitivity consultancy with Professor R	Report	159019	1991/FGE	public
E12	Plume characterization testing : Plume testing technology transfer : WP 2.4 Comparison of DASA,s first and second generation thruster plume characteristics and contamination potential	Report	162087	2001/DLR	public
E13	Cleaning VEX-Magnetometer data from spurious 32Hz contamination signals : Final report and software description	Report	179474	2009/Technical U. Braunsch	public
E14	Experimental study on the contamination degradation effects on the optical and thermooptical performances of optical parts of the Meteosat-radiometer in orbit : Degredation of a cold optical window by condensing gaseous matter : Interim report	Report	188168	1975/Deutsche Forschungs	public

JAXA

#	JAXA Document Title	Type	Doc #	Notes	Classification
J01	Effect of dust in vacuum on solid lubricants	Report	N/A	2007	public (In Japanese)
J02	Abrasive Wear of Ceramics by Lunar Regolith Simulant	Report	N/A	2007	public (In Japanese)
J03	Study on Dust Seal for Activity on the Moon – Evaluation of Properties in Air –	Report	N/A	2008	public (In Japanese)
J04	Abrasive Wear of Ceramics by Lunar Regolith Simulant (Section 2) – Wear Characteristics in Rolling Contacts –	Report	N/A	2008	public (In Japanese)
J05	Tribological Properties of Solid Lubricants in Moon Dust Environment	Report	N/A	2009	public
J06	Wear of materials in lunar dust environment	Report	N/A	2009	public
J07	Experimental study on a brush-type seal in air and in vacuum as a candidate for regolith seal applications	Report	N/A	2010	public (In Japanese)
J08	Development of a Laboratory Simulation System for Lunar Dust Charging and Levitation	Report	N/A	2010	public
J09	Wear of materials by lunar regolith simulant	Paper	N/A	2010	public (In Japanese)
J10	Performance of a small and compact brush-type seal in vacuum as a candidate for regolith seal applications	Report	N/A	2011	public (In Japanese)
J11	Long-term experiments in vacuum on a brush-type seal as a candidate for regolith seal applications	Report	N/A	2011	public (In Japanese)
J12	Tribological Properties of PTFE Composite in Lunar Extreme Environment	Report	N/A	2012	public
J13	Wear Properties of Polymer Materials in Vacuum Dust Environments	Report	N/A	2013	public (In Japanese)
J14	Electrostatic cleaning system for removal of sand from solar panels	Report	N/A	2015	public

NASA

#	NASA Document Title	Type	Doc #	Notes	Classification
N01	An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars - Dust / Soil Focus Team (June 2005)	Report	Report of the MHP SS#1F7571.doc	Chartered by MEPAG	Publicly available at mepag.jpl.nasa .gov
N02	An Assessment of Dust Effects on Planetary Surface Systems to Support Exploration Requirements (Aug 2006), Plus Appendix A& B	Report	CTSD-AIM-0029 JSC-62198	Includes Appendix A&B JSC Eng Dir	Publicly available at ntrs.nasa.gov
N03	The Apollo Experience Lessons Learned for Constellation Lunar Dust Management (Sept 2006)	NASA TP	TP-2006-21372 6		Unclassified (SF298)
N04	Agency Internal R&T Tasks (2008)	Spreadsheet	N/A	R&T summary	
N05	Constellation Program - Lunar Dust Smart Buyer Clinic Report (June 2007), plus Lab Notebook	Whitepaper	N/A	Includes Lab Notebook JSC CxP	
N06	Lunar Regolith Behavior Workshop Report (can only locate a draft) (Draft V1.0 Aug 2008), plus Lab Notebook; note: only draft available	Report	N/A	Includes Lab Notebook	
N07	Dust Management Project - External R&T Survey (draft / status presentation (May 2007)	PPT	N/A	TRL Matrix	
N08	Dust Mitigation Technology Focus Group Report (Aug 2007)	PPT	N/A	LRIFG debrief to ARDIG	
N09	Planetary Dust Mitigation Technology Focus Group Report (A Technology Integration Agent Report)	.doc	N/A		Proprietary (in title/pages)
N10	The Dust Management Project: Final Report (Dec 2011)	NASA TM Report	TM-2011-2170 37	Summary of Major Deliverables	Unclassified (SF298)
N11	Note: Several additional papers & documents on dust mitigation available at ntrs.nasa.gov (search on Dust Mitigation)	Papers, Studies, and Reports	Misc.		Publicly available at ntrs.nasa.gov

APPENDIX 3: AGENCY PROJECT SUMMARIES

ASI

Note: No dedicated technological projects to date.

CSA

Heritage Dust Mitigation Projects Summary – CSA

1. Project Moondust:
    a. Development of a more representative lunar simulant (UW-1M and UW-1H)
    b. Characterization of simulant
    c. Development of a small dusty vacuum chamber with dust charging
    d. Development of a carbon nanotube filter
    e. Development of a magneto-electrostatic carbon nanotube filter-based mitigation prototype
    f. Testing of prototype in atmosphere and in vacuum

2. Evaluation of the resistance of composite materials to lunar dust abrasion

3. Development of a planetary environmental test facility
    a. Capability includes: high vacuum, temperature control, dust deposition, dust charging, and proton injection

4. Dust Mitigation Technologies
    a. Perform baseline tests of various components while subjected to vacuum and dust
    b. Develop mitigation technologies
    c. Perform tests on baseline components using mitigation

5. Rover Drive Train Testing
    a. TVAC testing with Chenobi simulant
    b. Three weeks testing equivalent to 15 km of travel

Planned Dust Mitigation Projects Summary – CSA

1. Build a Dusty Thermal Vacuum Chamber (DTVAC)
    a. Larger capacity than current Canadian similar facilities
    b. Develop test rigs

ESA

Current Dust Mitigation Projects Summary – ESA

ESA is currently in a preparation phase to create three TRPs (Technology Research Programs) in the area of dust mitigation within the framework of ISECG. One of them is already approved and will start at the beginning of 2016. The other two are still pending. Following is a summary of the objectives of these TRPs.

1. **Effect of Regolith Liberated by a Rocket Plume Impingement:** The main objective for this TRP has three parts: (1) create a facility where a regolith liberated by a rocket plume can be simulated; (2) test it with different samples of soil to represent the characteristics of dust particles on Mars; and (3) study the distribution of dust particles spreading over the plume impingement surface.

2. **Dust Contamination of Spacecraft Components During Lift-off and Descent and Its Mitigation:** The dust atmosphere could be a result of regolith or wind blowing over the surface of the planet. The main objective is to study spacecraft components that could be sensitive to dust (such as optical surfaces) and pitting of surfaces due to blasting or mechanisms such as nozzles.

3. **Dust Contamination and Mitigation in EVA and Cabin Airlocks for Long-Duration Space Exploration:** The main objective is to study and test the influence of dust to the performance of EVA and cabin airlocks. In particular, suit assembly, portable life support system and ventilation are the most important areas in this TRP research. Active and passive solutions are the baseline products in this R&D.

JAXA

Dust Mitigation Study Summary – JAXA

Dust mitigation studies have been carried out at JAXA for Japan's future lunar exploration missions. The past/current efforts relevant to dust mitigation are listed below.

1. *A **lunar dustproof mechanism*** has been studied for application to robotic vehicles and construction systems. A brush-type seal has been developed as a passive solution for rotary joints. The effectiveness of the combination of brush and labyrinth seals was proved through durability tests conducted in vacuum. Detailed results are available in reference materials J10 and J11.

2. ***Wear properties of materials in lunar dust environment*** have been investigated. For the investigation, friction tests were conducted using a lunar regolith simulant and specimens made of several types of materials with various coatings. Material guidelines are being developed for lunar rovers and constructions on the Moon. Detailed results are available in reference materials J06, J09 and J13.

3. ***Abrasion/wear of mobile mechanisms (e.g., wheels or tracks) of a lunar rover*** has been studied and evaluated using a developed abrasion/wear test system, in which mobile mechanisms travel a long distance in a dusty environment.

4. An ***active technology*** for dust cleaning systems has been developed that uses electrostatic force to remove dust from the dielectric surfaces of spacecraft and rovers. A single-phase high voltage is applied to parallel wire electrodes embedded in the cover glass of a solar cell. It has been demonstrated that more than 90% of the adhering dust is repelled from the surface in atmospheric pressure. For further information, see reference material J14.

5. ***Two vacuum chambers*** are used for validating the above-mentioned studies. One is used for the component tests using a dust dispersion mechanism to clarify limit performance, and the other is used for the instrument and subsystem tests using a simulated lunar surface. Development of a method to simulate the lunar dust environment itself is an important research area.

NASA

Heritage Dust Mitigation Projects Summary – NASA

1. In the years leading up to the Apollo Program to explore the Moon, several dust mitigation studies were undertaken. Perhaps the most notable of these are recorded in a contractor report (NASA CR-61106) *Lunar Dust/Debris Hazards Associated with the Manned Flying* System undertaken by Northrup Space Laboratories (R.L. Stark, et al.) and delivered in October 1965, and a follow-on

report *Lunar Dust Degradation Effects and Removal/Prevention Concepts Final Report* by Northrop Corporation (TR-792-7-207B) delivered in June 1967.

2. During the Apollo Program, several instruments were delivered to the lunar surfaces to measure properties of the lunar dust. Apollo 11, 12, 14, and 15 carried the Lunar Dust Detector Experiment as part of their instrument packages. These consisted of calibrated solar cells whose output was monitored over time. The results of these experiments have been further interpreted over the past few years. Apollo 14 also carried the Thermal Degradation Sample (TDS) experiment, which examined the cohesion of lunar dust on several thermal control surfaces. In addition, the functionality of several experiments was degraded by the lunar dust, but this degradation yields information as well. The results are found among many papers in the open literature.

3. NASA Advanced Integration Matrix Study: *An Assessment of Dust Effects on Planetary Surface Systems to Support Exploration Requirements* (August 20, 2004). In this project, a NASA-wide dust assessment team identified systems that would be affected by dust, how the systems would be affected, associated risks, requirements that would need to be developed, and knowledge gaps. They recommended scientific measurements to obtain information needed to develop requirements, and design and manufacture the surface systems that will support humans. The focus of the study was lunar dust, but extensibility to Mars dust was considered as well. The study dealt almost exclusively with human EVA systems, rather than robotics or resource utilization.

4. BAA Dust Mitigation Effort: There was a Broad Area Announcement in 2005 that called for a wide variety of technology development efforts to support the return to the Moon (Constellation) effort. One of the projects selected for a four-year award, *Mitigation of Dust and Electrostatic Accumulation for Human and Robotic Systems for Lunar and Martian Missions,* led by the Colorado School of Mines (PI Masami Nakagawa), was to address dust mitigation. However, funding was withdrawn from all of projects within 6 months of award and no results were reported.

5. Advanced EVA out of NASA Johnson Space Center sponsored a series of workshops in 2005–2007 focusing on topics such as Biological Effects of Dust, Dust Mitigation Requirements, and a Technology Focus Group, and the establishment of a Dust Mitigation Community of Practice.

6. The NASA Lunar Airborne Dust Toxicology Assessment Group (LADTAG) was formed and responded to a request from the Office of the Chief Health and Medical Officer to "… develop recommendations for defining risk criteria for human lunar dust exposure and a plan for the subsequent development of a lunar dust permissible exposure limit." The LADTAG was composed of technical experts in lunar geology, inhalation toxicology, biomedicine, cellular chemistry, and biology from within NASA as well as leading U.S. experts in these fields.

7. The Dust Mitigation Project is the only NASA effort that went beyond paper studies to actually support technology development efforts in several targeted areas. These are summarized in *The Dust Management Project: Final Report,* NASA/TM-2011-217037 (M. Hyatt and S. Straka). The Dust Management Project (DMP) was tasked with the evaluation of lunar dust effects, assessment of the resulting risks, and development of mitigation and management strategies and technologies related to Exploration Systems architectures. To this end, the DMP supported the overall goal of the Exploration Technology Development Program (ETDP) of addressing the relevant high priority technology needs of multiple elements within the Constellation Program (CxP) and sister ETDP projects.

8. The Lunar Dust Experiment (PI – M. Horanyi, U. Colorado) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) robotic mission that orbited the Moon from 2013 to 2014 gathered

detailed information about dust in the lunar exosphere. The results are found among many papers in the open literature.

9. All of the landers and rovers that NASA has sent to the surface of Mars (Viking I and II, Pathfinder/Sojourner, Spirit and Opportunity, Phoenix, and Curiosity) have studied the composition of the Martian regolith and dust, and yielded valuable information about its composition and transport. The results are found among many papers in the open literature.

Current Dust Mitigation Projects Summary – NASA

NASA has a publicly available website called TechPort (https://techport.nasn.gov) that describes past and present technology efforts. These include not only efforts being carried out directly by NASA, but also those carried out through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Although records for past technology are incomplete, particularly for efforts more than 10 years old, the website does give some detail about present technology efforts, as well as the names of the leaders of the projects. The following is a list of current efforts related to that to dust mitigation.

1. Fabrication of Regolith-Derived Radiation Shield Project (Regolith Radiation Shield), NASA KSC, PI: James Mantovani, funded by Science Mission Directorate.
2. Electrodynamic Dust Shield for Lunar/ISS Experiment Project (EDS), NASA KSC, PI: Carlos Calle, funded by KSC IR&D.
3. Particle Flow Physics Modeling for Extreme Environments Project, CFD Research Corporation, PI: Peter Liever, funded by NASA SBIR Program.
4. Task-Specific Asteroid Simulants for Ground Testing Project, Deep Space Industries Inc., PI: John Lewis, funded by NASA SBIR Program.
5. Hydrogenous Polymer-Regolith Composites for Radiation-Shielding Materials Project, International Scientific Technologies, Inc., PI: Eugene Aquino, funded by NASA SBIR Program.
6. Cohesion of Asteroid Regolith Materials, NASA GRC, PI: James R. Gaier, funded by SMD Science Innovation Fund.

Dust Filtration for Atmospheric Gas Intakes on Mars, NASA KSC, PI: Carlos I. Calle, funded by NASA's Space Technology Mission Directorate/Game Changing Development Program.

APPENDIX 4: AGENCY FACILITIES

The following tables are the results of a survey of facilities related to planetary exploration that are capable of supporting dust mitigation testing.

ASI/Italy

Site	Facility	Size	Configuration	VAC	Cryo	Primary Use	Contact	Vol ft³	Vol m³
CISAS dept./ University of Padua (Padua)	TV chamber for Mars-like environment	1100 mm (diameter) x 4000 mm (length)	Surface and terrain simulant	10^{-6} mbar	93 K	Drilling testing	stefano.debei@ unipd.it		3,14
Thales Alenia Space Italy TAS-I (Turin)	Planetary environmental simulation chamber PESCha	1100 mm (diameter) x 1200 mm (length)	Planetary surface and atmosphere simulant	10^{-6} mbar		Thermal vacuum test in presence of lunar or martian soil	roberto.destefanis@ thalesaleniaspace.com		0,94
Morocco desert (Morocco)	Ibn Battuta Centre of International Research School of Planetary Sciences (IRSPS)		Planetary surface and atmosphere simulant			Analogue science and tests of rovers, landing systems, instruments and operations related to the exploration of Mars and Moon.	gg.ori@irsps.unich.it		

CSA

Site	Facility	Size	Configuration	Vac	Cryo	Primary Use	Contact	Vol ft³	Vol m³
CSA	Mars emulation terrain	120 m x 60 m	Surface terrain	N/A	Canadian winter	Rover analog testing	CSA Erick Dupuis	N/A	N/A
CSA	Planetary DTVAC	3 ft x 2 ft (estimated)	Horizontal cylinder	1.E -07 (vacuum); 1.E-4 (dust)	YES LN2	Under development	CSA Daniel Lefebvre		0.7
CSA/ITL	Planetary environmental simulator/test facility	less than 1 ft x 1 ft	Cubic chamber in horizontal vacuum chamber	1.E-04	LN2	Small component including dust activation	ITL INC (CSA Daniel Lefebvre)	less than 1 cu ft	
CSA/ITL	Lunar dust simulation facility	0.43 m diameter x 0.61 m height	Vertical bell jar	1E-04	LN2 cold plate	Small component, unit under test can be rotated using external motor	ITL/CSA Daniel Lefebvre	3 cu ft	0.088
CSA	Dusty chamber	8 ft x 4 ft	Horizontal box	NO	NO	Long-duration dust resistance	CSA Erick Dupuis	128 cu ft	

ESA

Site	Facility	Size	Configuration	Vac	Cryo	Primary use	Contact	Vol ft^3	Vol m^3
ESTEC	Large Space Simulator (LSS)	10 m diameter x 15 m height	Vertical cylinder	1.E-4 PA	Yes LN_2	Environment simulation	ESTEC Test Centre	N/A	2300
ESTEC	Phenix thermal vacuum	4.5 m diameter x 11.8 m length	Horizontal cylinder	1.E-4 PA	yes LN_2	Environment and thermal	ESTEC Test Centre	N/A	250
ESTEC	Physical properties machines	5 m x 3 m x 2 m	Horizontal lever	N/A	N/A	Dynamic balancing	ESTEC Test Centre	N/A	30
ESTEC/U. Glasglow	Regolith plume facilities	5 m x 5 m x 5 m (estimate, under development)	Vertical box	N/A	N/A	Regolith contamination assessment generated by rocket plumes	ESTEC Test Centre/U. Glasglow	N/A	150
ESTEC	Electromagnetic compatibility	6 m x 11 m x 6 m	Vertical box	N/A	N/A	Electrical and magnetic compatibility	ESTEC Test Centre	N/A	400

JAXA

Site	Facility	Size	Configuration	Vac	Cryo	Primary use	Contact	Vol	Vol m^3
JAXA	VC with dust dispersion mechanism	0.2 m diameter x 0.1 m	Horizontal cylinder	1e-05 Pa (vacuum); 1e-03 Pa (dust)	No	Dust dispersion mechanism	JAXA Wakabayashi	<50 l	
JAXA	TVAC with simulated lunar surface	1.5 m diameter x 1 m	Horizontal cylinder	1e-05 Pa (vacuum); 1e-03 Pa (dust)	No	Simulated lunar surface	JAXA Wakabayashi	>50 l	

NASA

SURVEY OF POSSIBLE LUNAR SIMULATION FACILITIES

Site	Facility	Size	Configuration	Vacuum (Torr)	Cryo	Primary Use	Contact	Volume ft^3	Volume m^3
MSFC	V10	1.5' diam x 1.5' long	Vertical cylinder	5.E-08	LN2	Life cycle	Debra Terrell	3	0.1
JPL	22" Vac Chmbr	1.5' x 1.5' x 1.5'	Cube	1.E-06	LN2		Greg Peters	3	0.1
MSFC	X1	1.5' diam x 2' long	Glass bell	1.E-06	LN2	Thermal vacuum	Debra Terrell	4	0.1
KSC	EDS Test		Horizontal cylinder	1.E-06		EDS dust mitigation studies	Carlos Calle	5	0.2
GSFC	243	2' diam x 2' high	Vertical cylinder	5.E-07	Yes	Thermal vacuum	Ed Packard	6	0.2
GSFC	244	2' diam x 2' high	Vertical cylinder	5.E-07	Yes	Thermal vacuum	Ed Packard	6	0.2
MSFC	V4	2' diam x 2.5' long	Horizontal cylinder	1.E-06	No	Vacuum bake out	Debra Terrell	8	0.2
MSFC	V8	2' diam x 2.5' long	Horizontal cylinder	1.E-06	No	Vacuum bake out	Debra Terrell	8	0.2
GRC	LDAB	2' diam x 3' long	Horizontal cylinder	2.E-09	Yes	Dust effects and	Jim Gaier	9	0.2
GSFC	240	3' diam x 3' long	Horizontal cylinder	1.E-07	Yes	Thermal vacuum	Ed Packard	21	0.6
GSFC	241	3' diam x 3' long	Horizontal cylinder	1.E-07	Yes	Thermal vacuum	Ed Packard	21	0.6
MSFC	V5	3' diam x 4' long	Horizontal cylinder	1.E-06	LN2	Vacuum bake out & thermal vaccum	Debra Terrell	28	0.8
MSFC	V6	3' diam x 4' long	Horizontal cylinder	1.E-07	LN2	Thermal vacuum	Debra Terrell	28	0.8
GSFC	281	3' diam x 4' long	Horizontal cylinder	1.E-07	Yes	Thermal vacuum	Ed Packard	28	0.8
GRC	VF-10	3.3' diam x 5' long	Horizontal cylinder	8.E-07	No	Thermal vacuum	Henry Speier	43	1.2
JPL	Build 79	4' diam x 5' high	Horizontal cylinder	1.E-06	Yes	Cryogenic test chamber	Mary Barmatz	63	1.8
GRC	VF-9	2' w x 5' h x 8' long	Rectangular	1.E-03	No	Atomic oxygen	Henry Speier	80	2.3
JPL	Building 148	4' diam x 6.5" long	Horizontal cylinder	1.E-06	LN2	Micro-thruster testing	Steve Snyder	82	2.3
MSFC	V1	4' diam x 7' long	Horizontal cylinder	5.E-07	No	Optical cleanliness	Debra Terrell	88	2.5
MSFC	V9	4' diam x 7' long	Horizontal cylinder	1.E-06	LN2	Thermal vacuum	Debra Terrell	88	2.5
MSFC	V2	4' diam x 10' long	Horizontal cylinder	5.E-08	No	Optical cleanliness	Debra Terrell	126	3.6
MSFC	V3	4' diam x 10' long	Horizontal cylinder	5.E-08	LN2	Life cycle & vacuum bake out	Debra Terrell	126	3.6
MSFC	V11	4' diam x 10' long	Horizontal cylinder	1.E+08	LN2	Launch depress & thermal vacuum	Debra Terrell	126	3.6
GRC	VF-2	3.5' diam x7' long	Horizontal cylinder	1.E-06	No		Henry Speier	166	4.7
GRC	PIF-H	6' diam x 6' long	Horizontal cylinder	1.E-06	No		Henry Speier	170	4.8
JPL	Building 148	5.5 diam x 7.5' long	Horizontal cylinder	1.E-06	LN2	Patio Chamber	Steve Snyder	178	5.0
JPL	B149 Arc Jet	3.5' diam x8' long	Horizontal cylinder	1.E-06	LN2	Ion engine testing	Steve Snyder	190	5.4
GRC	VF-13	5' diam x 11.5' long	Horizontal cylinder	4.E-07	No		Henry Speier	226	6.4
GRC	SMIRF	6' diam x 8.3' long	Horizontal cylinder	1.E-05	Yes		Wayne	235	6.6

Site	Facility	Size	Configuration	Vacuum (Torr)	Cryo	Primary Use	Contact	Volume ft^3	Volume m^3
JPL	B312	5' diam x 12'	Horizontal cylinder	1.E-06	LN2	Ion engine testing	Steve Snyder	236	6.7
GRC	PIF-V	6' diam x 9.5' long	Horizontal cylinder	5.E-07	No		Henry Speier	268	7.6
JPL	Building 148	6' diam x 10' long	Horizontal cylinder	1.E-06	LN2	High bay chamber	Steve Snyder	283	8.0
JPL	B149 Big Green	6' diam x 10'	Horizontal cylinder	1.E-06	LN2	Ion engine testing	Steve Snyder	283	8.0
GRC	VF-1	5' diam x 15 ' long	Horizontal cylinder	3.E-07	No		Henry Speier	294	8.3
GRC	VF-3	5' diam x 15' long	Horizontal cylinder	4.E-07	No		Henry Speier	294	8.3
GRC	VF-4	5' diam x 15 ' long	Horizontal cylinder		No		Henry Speier	294	8.3
GRC	VF-8	5' diam x 15' long	Horizontal cylinder	4.E-07	Yes		Henry Speier	294	8.3
GSFC	237	7' diam x 8' long	Horizontal cylinder	5.E-07	Yes	Thermal vacuum	Ed Packard	308	8.7
GSFC	239	7' diam x 8' long	Horizontal cylinder	5.E-07	Yes	Thermal vacuum	Ed Packard	308	8.7
GRC	CW-19	7' diam x 10' long	Horizontal cylinder	5.E-07	No		Henry Speier	385	10.9
GRC	VF-67	3.3' diam x 10' long	Horizontal cylinder	1.E-07	No	Sterling testbed	Henry Speier	418	11.8
MSFC	V7	8' diam x 10' long	Horizontal cylinder	5.E-07	LN2	Optical cleanliness & thermal vacuum	Debra Terrell	502	14.2
MSFC	Sunspot	10' diam x 12' long	Vertical cylinder	1.E-06	LN2	Thermal vacuum	Debra Terrell	942	26.7
MSFC	Rome	10' diam x 13' long	Vertical cylinder	1.E-07	LN2	Thermal vacuum	Debra Terrell	1021	28.9
GRC	VF-11	7.25' diam x 27' long	Horizontal cylinder	1.E-07	No	Electric propulsion testbed	Henry Speier	1114	31.5
GRC	VF-7	10' diam x 15' long	Horizontal cylinder	4.E-07	No		Henry Speier	1178	33.3
GSFC	225	10' diam x 15' long	Horizontal cylinder	1.E-07	Yes	Thermal vacuum	Ed Packard	1178	33.3
GSFC	238	11' diam x 14' high	Vertical cylinder	5.E-07	Yes	Thermal vacuum	Ed Packard	1330	37.6
GRC	VF-61	12' dam x 24' long	Horizontal cylinder	4.E-08	No		Henry Speier	1356	38.4
MSFC	12 ft Chamber	12' diam x 14' high	Vertical cylinder	1.E-04	No	Little used (outdoors - rough pumped, have diffusion pumps)	Jeff Hamilton	1583	44.8
GRC	VF-12	10' diam x 30 ft	Horizontal cylinder	8.E-08	Yes		Henry Speier	2355	66.6
JPL		10' diam x 40' tall	Vertical cylinder	1.E-07	Yes		Andy Rose	3140	88.9
JSC	Chamber B	13' diam x 27' high	Vertical cylinder	1.E-06	Yes	EVA (human rated)	Mike Montz	4769	135
MSFC	20 ft Chamber	20' diam x 18' high	Vertical cylinder	1.E-08	LH2	Heavy use (outdoors)	Jeff Hamilton	5652	160
GRC-PB	K-site	25' diam	Sphere	7.E-07	Yes	Cryogenic fluids research	Jeff Chambers	8177	231
MSFC	V20	20' diam x 27' long	Horizontal cylinder	1.E-06	LN2	Thermal vacuum	Debra Terrell	8478	240
GRC	VF-5	15' diam x 60' long	Horizontal cylinder	1.E-07	Yes		Henry Speier	10598	300
GSFC	290	27' diam x 40' high	Vertical cylinder	1.E-07	Yes	I-up spacecraft testing, has antechamb	Ed Packard	22891	648

Site	Facility	Size	Configuration	Vacuum (Torr)	Cryo	Primary Use	Contact	Volume ft^3	Volume m^3
GRC	VF-6	25' diam x 70' long	Horizontal cylinder	5.E-07	Yes	30 kW solar simulator	Henry Speier	34344	972
GRC-PB	B-2	38' diam x 62' high	Vertical cylinder	1.E-06	Yes	Full-up upper stage	James Zakany	70279	1989
LaRC	16 m Chamber	55' diam x 64' high	Vertical cylinder	1.E-05	LN2		Lucas Horta	152053	4303
JSC	Chamber A	55' diam x 90' high	Vertical cylinder	1.E-06	Yes	Human Spacecraft	Mike Montz	213716	6048
ARC	Aeolian Facility	50' x 50' x 100' high	Vertical box	4.E+00	No	Martian Wind Tunnel		250000	7079
GRC-PB	SPF	100' diam x 125' high	Vertical cylinder	5.E-06	Yes	Full-up spacecraft testing	Jerry Carek	981250	27769
KSC	Regolith Test Bin	8 m long x 8 m wide 8 m high	Cube containing 120 tons of regolith (BP1-)	Ambient atmosphere, sealed	No	Rovers, spacesuits, mechanical components testing	Rob Mueller	N/A	N/A
GRC	Simulated Lunar Operations (SLOPE) Laboratory	12 m x 3 m 0.3 m soil tank	Soil tank, plus 6 m x 0.3 m adjustable tilting soil tank for sloped operations	Ambient atmosphere	No	Simulated vehicle getting "stuck" in high-sinkage soil. Mobility of vehicles & wheels	Phil Abel	N/A	N/A
GRC	Traction and Excavation Capabilities (TREC) Rig	Two adjacent soil bins, each 2 m x 1 m 0.75 m	Motorized rails for driving implements, wheels (mobility systems) and tools through length of soil bin. 6-axis load cell force measurements.	Ambient atmosphere	No	Single-wheeled tested and excavation tools/digging force testing	Phil Abel	N/A	N/A
GRC	The Dunes - Outdoor mobility testing and demonstrations	100 ft x 80 ft covered with 6 in. of sand	Large hill with 3 sides of different slope angles (10, 15, 20 deg), plus obstacle course	Ambient atmosphere, outdoor	No	Outdoor test area for extended cross-slope testing with larger scale vehicles	Phil Abel	N/A	N/A
GRC	Particulate Flow Loop	36 in x 10 ft	Sealed flow loop	Ambient and low pressure (down to Martian pressure)	No	Test filters for ECLSS and ISRU	Juan H. Agui	N/A	N/A

Legend for color coding:

Component Testing
Subsystem Testing
System Testing
Additional Facilities Applicable to Dust Mitigation Testing