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International Space Exploration Coordination Group Assessment of Technology Gaps for Dust Mitigation for the Global Exploration Roadmap

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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, with this paper addressing the former. 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. The participating agencies for the Dust Mitigation Gap Assessment Team were ASI, CSA, ESA, JAXA, and NASA. The team was asked to 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. In addition the team was tasked to produce a gap assessment in the form of a summary report and presentation identifying those GER Critical Technology Needs, including opportunities for international coordination and cooperation in closing the identified gaps. 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.

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Nomenclature

ISECG	=	International Space Exploration Coordination Group
GER	=	Global Exploration Roadmap
GER2	=	Second GER release, August 2013
GTDM	=	GER Technology Development Map
R&D	=	Research and Development
SME	=	Subject Matter Expert
TWG	=	Technology Working Group

I. Introduction

THE International Space Exploration Coordination Group (ISECG) was established in response to "The Global Exploration Strategy: The Framework for Coordination" developed by fourteen space agencies and released in May 2007. Member states include ASI (Italy), BNSC (United Kingdom), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia). This Framework Document articulated a shared vision of coordinated human and robotic space exploration focused on Solar System destinations where humans may one day live and work. Among the many Framework Document findings was the need to establish a voluntary, non-binding international coordination mechanism through which individual agencies may exchange information regarding their interests, plans and activities in space exploration, and to work together on means of strengthening both individual exploration programs as well as the collective effort.

In 2015 the 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, with this paper addressing the former. The ISECG approved the recommended Gap Assessment teams, and tasked the TWG to formulate the

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new teams with subject matter experts (SMEs) from the participating agencies. The participating agencies for the Dust Mitigation Gap Assessment Team were ASI, CSA, ESA, JAXA, and NASA. The team members are the authors listed on this paper. The team was asked to 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. In addition the team was tasked to produce a gap assessment in the form of a summary report and presentation identifying those GER Critical Technology Needs, including opportunities for international coordination and cooperation in closing the identified gaps. Dust is a principal limiting factor in returning to the lunar surface for missions of extended duration. Viable technology solutions have been identified, but need maturation to be available to support missions to the moon, near Earth asteroids, and Mars.

Upon acceptance of the Dust Mitigation Gap Assessment Report on February 9, 2016, the ISECG charged the team with publicizing this report. This summary, and its public presentation at the AIAA Space 2016 Forum and Exposition was prepared with that goal in mind. The full 71 page report is available to agencies on the web at https://www.globalspaceexploration.org/documents.

II. Objectives and Approach

The gap assessment approach involved four tasks addressed by the team. The first task was to identify the known dust mitigation challenges. In this the team was able to build upon several studies that were undertaken in the past to construct a comprehensive list. The second task was to catalog the extensive work that has been done, particularly in the past ten years, to develop dust mitigation solutions. The third task, which was the focus of the study, was to then do an assessment of the gap between the known challenges and the known solutions in order to better define what work would be needed to close that gap. The last task was to identify partnership opportunities among the agencies to efficiently close those gaps. Each of these tasks is discussed in more detail below.

III. Dust Mitigation Challenges

The Dust Mitigation team started by leveraging prior work by each of the participating agencies, particularly the more extensive NASA work done to date. The Apollo experience teaches the regolith dust, if not properly mitigated, can cause multiple problems in multiple systems which range from the irritating to the dangerous.[1] As was pointed out in the Advanced Integration Matrix Study of 2005:

> *"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."*[2]

NASA Photo

Figure 1. Gene Cernan (Apollo 17) covered with dust after an EVA on the lunar surface.

In that regard, a taxonomy 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:

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- 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 within the report. Each major discipline area above was divided into the major systems that make up that discipline. And each System was further divided into their component subsystems. Detrimental effects of dust exposure were then identified for each system and subsystem. In addition to identifying the effects resulting from dust exposure, the team also did an initial identification of performance characteristics where available. 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. An example of the first and second level Dust Mitigation Challenges is shown in Table 1. 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.

Table 1. An Example from the Dust Mitigation Challenges table in the report.

Dust Mitigation Challenges (Requirements Drivers)	Effect due to 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. Then each subsystem was further broken into functional elements and components. The effects of dust on these follow.	The LSS must handle a 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. It is assumed that physical and functional barriers to surface dust intrusion into the habitable vehicle cabin are >95% effective.
1.1 Atmosphere Revitalization 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.

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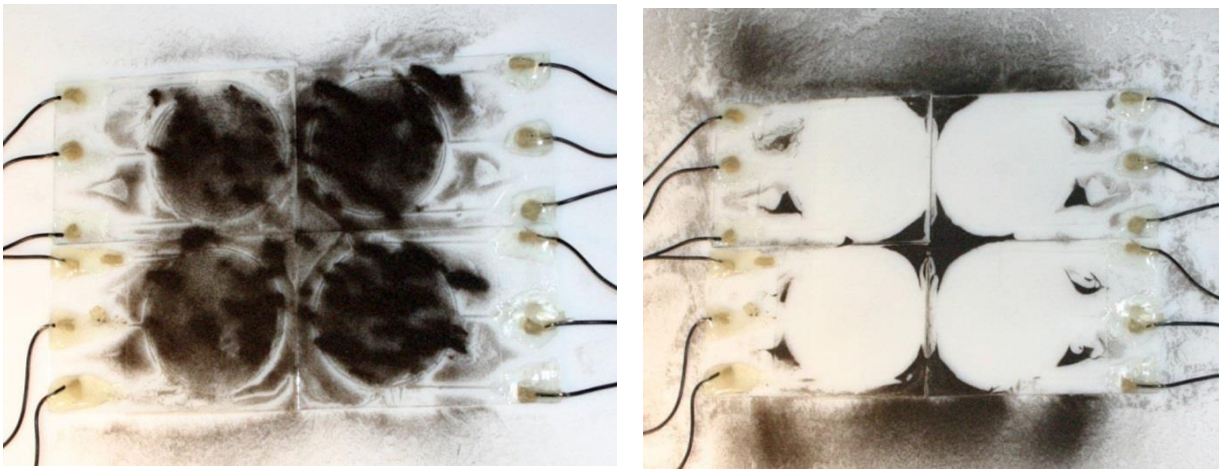
IV. Dust Mitigation Solutions

Spurred principally by NASA's Constellation Program[3], a great deal of creative energy and effort has been devoted to understanding the effects of lunar dust on multiple spacecraft systems. An effort was made in the report to briefly summarize the state of the art. This should not be thought of as a definitive review, but does demonstrate the breadth of both the problems and approaches that are being examined to tackle the problem. No "silver bullet" has been found that will mitigate the detrimental effects of dust for all systems under all conditions. At this stage, it seems more likely that a wide variety of approaches will be used, and in many cases multiple approaches may be used for even a single application.

Mitigation technologies can be broadly 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 take advantage of the high dielectric strength of regolith dust which can be charged and then removed by a sweeping electric field. Figure 2 shows a sampling of existing or proposed active technologies.[4,5,6]



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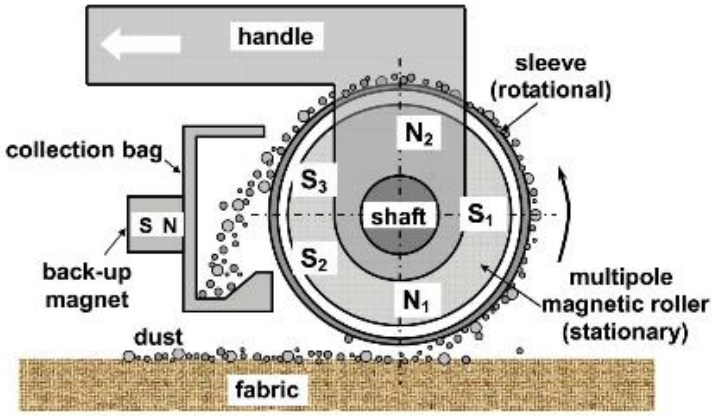

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Figure 2. Among others, active technologies include a) dynamic dust shields[4], b) magnetic cleaning devices[5] and c) nitrogen gas jets[6].

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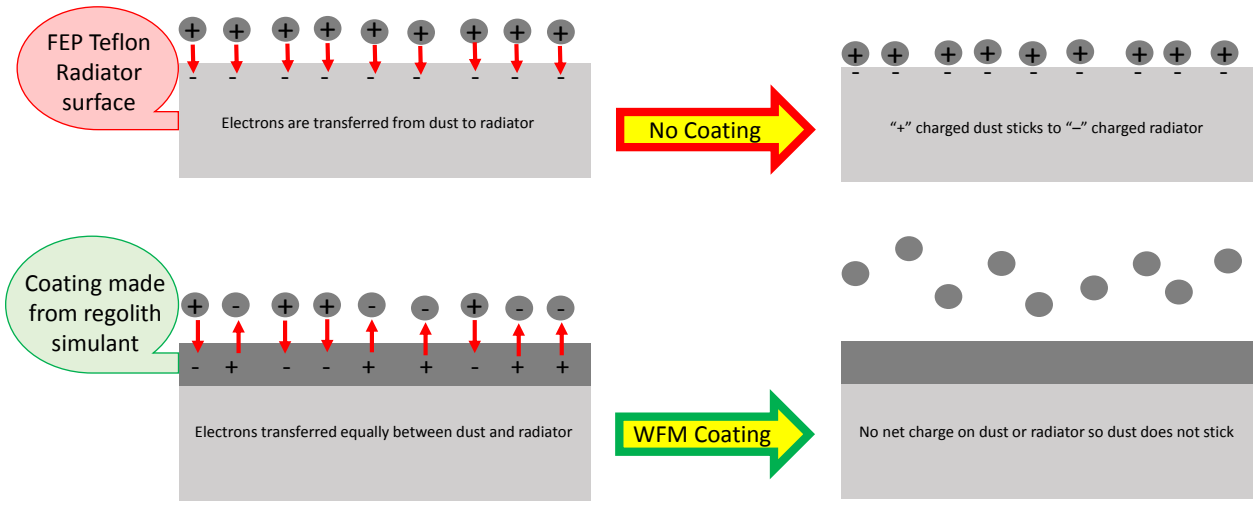
Passive technologies are those in which items have their surfaces modified or coated in order to minimize adhesive forces. Either transported dust fails to adhere to the surface, or lowers the adhesion to the point where the dust is removed by gravity or more easily by an active system. This also includes dust seals, traps, or tortuous paths that make it difficult for dust to enter sensitive areas, such as bearings. Figure 3 shown a sampling of existing or proposed passive technologies.

In addition to active and passive mitigation technologies several engineering and operational solutions have been proposed as well. Operational control may be as simple as a "Welcome Mat" grate where astronauts can stamp their feet to dislodge loose dust, or siting critical infrastructure in less dusty locations. Perhaps surface spacesuits will be left behind on the surface so as to not bring large quantities of dust into the spacecraft. This will also, no doubt, include routine maintenance and housecleaning of surfaces that capture dust either incidentally or by design.



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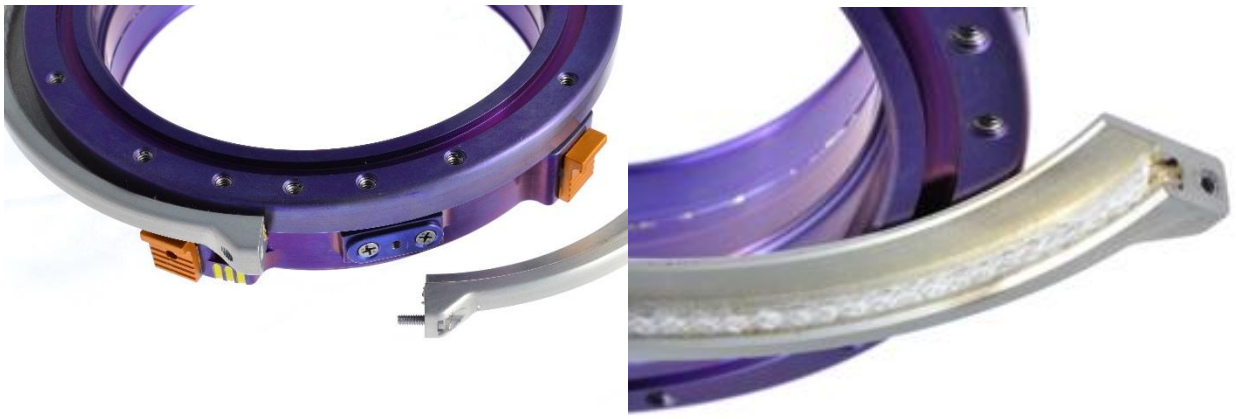

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Figure 3. Among others, passive technologies include work function matching coatings[7] and dust resistant bearing designs.

Engineering solutions include dust resistant bearing designs, easy to change-out mechanisms likely to be degraded by dust, and multiple protective layers over optical surfaces that can be peeled off when dust degradation reaches a bothersome level. They also include technologies such as suitports, which are designed to keep dusty spacesuits outside of a habitat or rover while allowing the occupant access through a rear hatch (Fig.4).

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With a suitport, suitport-airlock, or rear-entry (suitlock) the majority of 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 (Fig. 5). 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.

It is clear that it will not be possible to "play in the dirt" without getting dirty. Exploration will be a dirty business, and systems must be robust enough to be durable to unforeseen circumstances. More than one Apollo astronaut fell to the ground while attempting to accomplish their tasks, and they were only on the surface for 3 days or less. When they are on the Martian or lunar surface for weeks or months, there will be multiple opportunities to test the robustness of the systems.

The characterization and modeling of the dusty environments themselves requires extensive experimental activities. Data acquired during completed or in progress missions will serve to better understand the dust presence and behavior in different planetary surfaces and to create/correlate models describing the local dust cycle and interaction.

The verification of the proposed dust mitigating Technology's effectiveness will strongly benefit from test campaigns in relevant environments, to be reproduced both in laboratories, where the artificial conditions can be locally reproduced and controlled, and in field tests, where longer duration test can be performed and more realistic (sometimes, unpredictable) conditions can be encountered and faced. The investigations that can be performed in the two type of facilities can be considered complementary: design verification can easily be performed by laboratory testing under imposed and controlled conditions, while system validation can happen during operations simulation in terrestrial analogs.

Figure 4. Suitport mock-up used during an analog field test.

Layered Engineering Defense Plan Example

1st Layer – Mission Architecture Design

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

2nd Layer – Hardware Design

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

3rd Layer – Operational Design

- 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

4th Layer – Contamination Control

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

Regolith simulants under terrestrial conditions will not necessarily mimic planetary regolith under its native conditions. In fact, 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, planetary environments are dry, tend to be chemically reducing

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(except for Mars which is more oxidizing than Earth), and constantly bombarded by high energy electromagnetic and particle radiation. The surface chemistry of any material will be different in these two environments.

Utilize Air Quality Contamination Zones

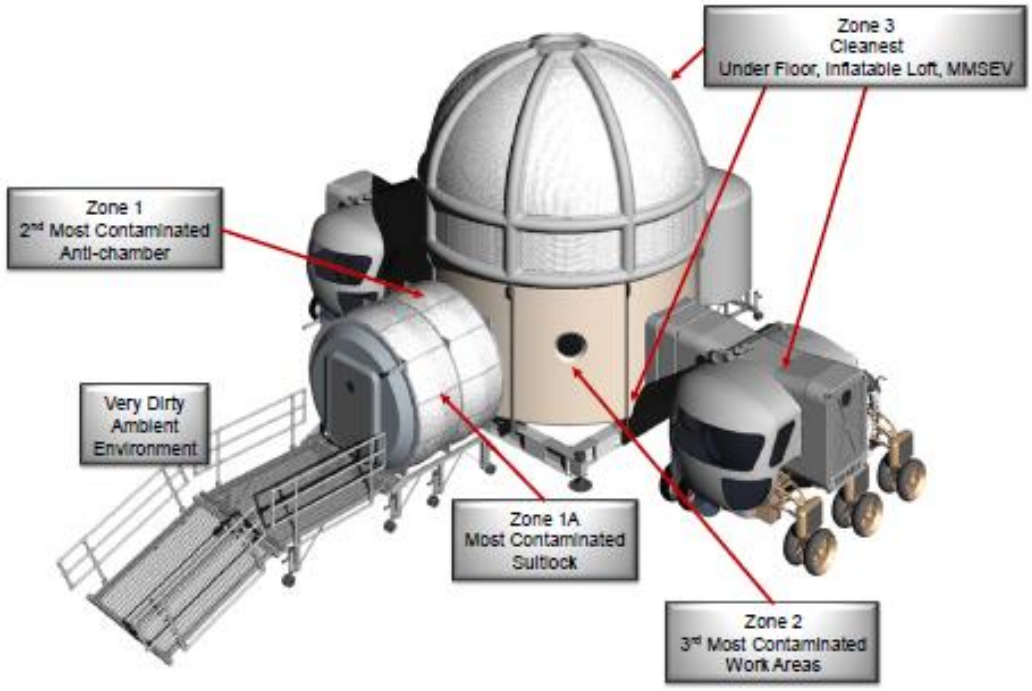

Figure 5. Example of a layered engineering approach to dust mitigation.

Airless planetary environments are expected to "activate" the surfaces of the regolith particles. Activation includes any process that enhances 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 than 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. In 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. The report contains a list which, while dated, 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 Belljar (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 (Fig. 6). Many more chambers exist at other space agencies, universities, and private companies throughout the world.

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 the minor constituents will in some cases have major impacts. Small amounts of sulfur in the regolith

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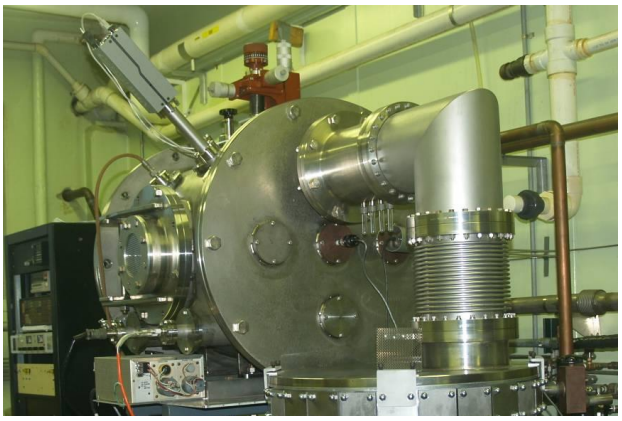
can poison catalysts, and metallic iron on the surface of nano-sized dust particles may cause a dramatic increase in its toxicity. A list of currently available regolith simulants is included in the report.

In addition to environmental simulation chambers, there exist a number of planetary analogue 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 which minimize dust impacts. 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.



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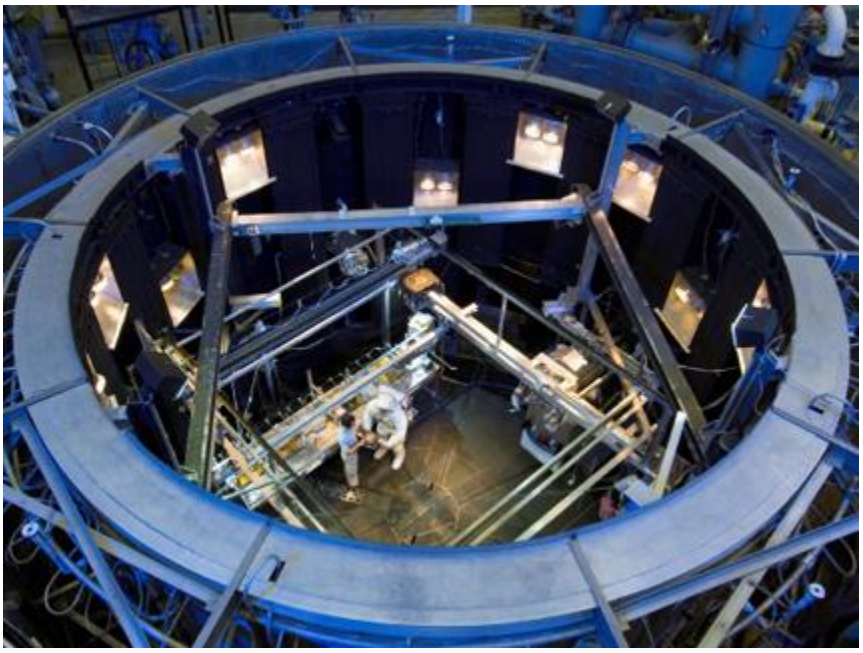

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Figure 6. Three NASA facilities used to study dust interactions. a) Lunar Dust Adhesion Bell Jar (NASA Glenn Research Center) b) Martian Surface Wind Tunnel (NASA Ames Research Center) c) Chamber B (NASA Johnson Space Center.

Each site is usually more representative for specific aspects and local conditions (temperature/humidity, dust size and chemical properties, etc.). For example, the Sahara desert can be considered a good analogue to Mars also for what concerns dust abundance and interaction. In fact, to mobilize dust it is necessary to have a dry and hot

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environment to provide the conditions for lifting dust from the surface (while cold deserts bear always too much humidity to provide large amounts of dust to the atmosphere). Hence, the Sahara desert is the arid area with the largest concentration of airborne sand and dust and it shows a complex Aeolian circulation that intrudes and transports both sand and dust. Sand is basically transported near the sedimentary interface with saltation processes, while dust is present as suspended load. A list of commonly used sites is included in the report.

V. Gap Assessment Summary

A pivot table within the paper breaks 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. For this reason, pivot tables were developed to cover thirteen basic Key Technical Challenge Areas:

- Rotary Seals
- Linear Motion Seals
- Static Seals
- Mating Connectors
- Filters (Mechanical, Gas Scrubbers, and Other)
- Human Health (Biological)
- Thermal Control Surfaces
- Optical Surfaces
- Other Surfaces (Performance)
- Flexible Materials including Fabrics
- Chemical Contamination and Corrosion/Oxidation
- Characterization of Dust and Regolith
- High-Fidelity Simulation Chambers

An example from the Technology Gap table is shown in Table 2.

Table 2. An example of an entry in the Technology Gap table of the report.

	Key Technical Challenge Areas	ECLSS	EVA & Airlocks	Mobility & Robotics	ISRU	Ascent/ Descent Vehicles	Systems
1	Rotary Seals	Fans, louvers, pumps	Articulation Joints - Bearings	Wheel bearings, motor bearings, steering & suspension linkages, hinges	Drill & tool bearings, motor bearings, linkages, hinges	Landing gear, deployment ramps	Fans, Wheels, Antenna

This assessment examined four categories of gaps: the Technology Gap (Table 3), the Experience/Knowledge Gap (Table 4), the Funding/Research Gap (Table 5), and the Schedule Gap (Table 6). The paper describes each gap category, discusses the assumptions made in the creation of the tables, and then identifies where these gaps are found. An exception is the table for schedule gap, which is created by defining a mission schedule before defining a development schedule. According to this analysis, technology efforts to close the dust mitigation gaps to meet the putative launch dates for most of the GER missions needed to have started before this analysis was begun.

VI. Partnership Opportunities

It is clear from the analysis done in the preparation of this report that the job that lies ahead will entail a significant effort and that the initiation of the effort is long overdue. The committee was unanimous in the opinion that the best way forward would be to maximize partnership opportunities among the agencies. Four areas were identified as having potential to accelerate the development of dust mitigation technology.

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The first of these was data sharing. The Dust Mitigation Gap Assessment Report is a step in this direction. For the first time SME's from the world's space agencies have addressed this problem together and defined the challenges, progress, and remaining gaps. Although much of the progress in this area is in the open literature, it is archived in disparate places rather than being centralized. A platform for archiving this data was developed and is hosted by the CSA, and it is hoped that this can be expanded and heavily utilized. One challenge is that there is also a substantial fraction of dust mitigation work that has not been published in the open literature and in some cases is proprietary.

TABLE 3. 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.

TABLE 4. 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.

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Table 5. 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.

Table 6. GER Mission 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.

The second area for partnership opportunity is in research and development activities. This is envisioned as maintaining a common technology roadmap and interagency communication to minimize duplication of effort, and encourage synergy. Perhaps joint, interagency projects could be developed, and existing exchange programs could be expanded to include dust mitigation technology research and development. Holding periodic joint seminars or conference with a dust mitigation focus, perhaps in association with ongoing international meetings such as the AIAA annual Space Conference and Exposition. Visiting key dust mitigation R&D sites could deepen the understanding of ongoing efforts around the world and lead to enhanced collaboration.

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A third area for partnership opportunities is the sharing of testing and simulation facilities. Test chambers for different dusty environments (lunar, Mars, asteroids, etc.) are difficult and expensive to build-up and often are underutilized. It was suggested that a working group could be assembled to create and maintain a "Dust Simulant Facilities Register" and facilitate cooperation and the use and upgrade of present chambers rather than standing up new ones. The International Space Station is a unique, international facility that could perhaps be used as well.

The last area identified was partnering in component, subsystem and system development. If the way forward in exploration of the solar system is through international flight projects, then key components made under the auspices of different space agencies must work together. It is therefore only natural that the technologies developed to protect these systems have commonality. Perhaps the best way to design, build, and test such technologies is by the agencies working together from the initial design through manufacturing and test.

VII. Key Findings and Summary

This paper represents material from the final report to the ISECG, summarizing the results of the Dust Mitigation Gap Assessment team, with the team's key findings listed in the summary below.

- 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 proved beneficial. While currently limited to sharing information, further opportunities are expected as commitment to narrowing the technology gap continues.

It was the goal that the subject matter material within this study, available on the web at https://www.globalspaceexploration.org/documents, 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 document can also point the way for efficient use of the resources of the world's space agencies by enumerating available simulants, facilities, analog sites, and areas of active research. The hope is that this will spur collaboration and cooperation among the agencies. 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.

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