

# Asteroid, Lunar and Planetary Regolith Management

## A Layered Engineering Defense

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February 6, 2014

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## **Asteroid, Lunar and Planetary Regolith Management A Layered Engineering Defense**

*"A common sense, layered, engineering design defense can solve any apparent problem with dust during long-term human activity and habitation in the lunar environment."*

*Harrison H. Schmitt  
Ames Research Center  
Lunar Dust Symposium  
February 2, 2004*

### **Abstract**

During missions on asteroid and lunar and planetary surfaces, space systems and crew health may be degraded by exposure to dust and dirt. Furthermore, for missions outside the Earth-Moon system, planetary protection must be considered in efforts to minimize forward and backward contamination. This paper presents an end-to-end approach to ensure system reliability, crew health, and planetary protection in regolith environments. It also recommends technology investments that would be required to implement this layered engineering defense.

### **Executive Summary**

Space System Engineers design their individual components and systems for reliability, as they should. And, for cross-cutting challenges, such as regolith contamination, an integrated systems strategy needs to be considered. This same philosophy applies to the NASA Office of the Chief Technologist Space Technology Area Roadmaps (STARS). Discrete technologies are scattered throughout the roadmaps. An integrated, cross-cutting strategy - a layered engineering defense - is needed.

The fundamental basis of the design relies on selecting materials that do not accumulate dust and dirt, innovative material fabrication and processing, engineering design that incorporates design for cleaning, robustness and reliability, and effective operational procedures.

The layered engineering defense presented in this paper incorporates contamination prevention, exterior cleaning and protection, interior cleaning and protection, and maintaining air quality. This strategy was developed through a series of studies, workshops, focus groups, technical interchange meetings, and NASA Lunar Regolith Community of Practice (LunRCoP) Webinars. The community surveyed particulate management best practices and technologies across NASA centers, industry, academia, and other government agencies. The approach also includes lessons learned from Apollo surface missions. It depends mostly on sound operations and engineering design though some technology investments will be required.

Contamination prevention includes surface stabilization, reducing dust contamination during EVAs, incorporating suitlocks into element designs, eliminating contamination from suits and equipment in habitable volumes, and pass-through glove boxes to ensure habitable volumes are not contaminated. Systems design should incorporate best practices to include material selection and design for clean-ability. Best practices should also be applied to operations. For example, contamination prevention procedures and automated cleaning operations will reduce the amount of crew time required for managing regolith-particulate contamination.

Exterior (outside the habitat or spacecraft) cleaning combines passive and active cleaning technologies to reduce degradation of key elements, such as solar panels and radiators. Exterior protection includes employing dust covers and dust repellent and/or dust-tolerant mechanisms. Note that for the purposes of this paper cleaning refers to cleaning of accessible surfaces.

Interior (inside the habitat or spacecraft) cleaning includes active systems such as air showers, magnetic filters, and vacuum cleaners. Interior protection incorporates protective personnel equipment (PPE) and dust covers for connectors. Maintaining air quality involves establishing contamination zones within the habitable volume using air flow to reduce the number of particles that enter clean areas.

Example technologies that are being developed and proposed are included. The recommended technologies required to implement this strategy will be presented in the form of capability needs in a table in the appendix. Trade studies should be performed to identify the most effective technical solutions, and then those technologies should be developed. Among the criteria for selection mass and power requirements should be key considerations. Consumable requirements are important component in this analysis.

## Regolith

Regolith is defined as the layer of loose material covering the bedrock of the earth and moon, etc., comprising soil, sand, rock fragments, volcanic ash, glacial drift, etc. Because the Moon does not have an atmosphere and running water erosion forces that weather the Earth do not exist. Asteroids and meteors strike the lunar surface creating craters and large rocks. High energy particles and micro-meteors continuously bombard the Moon further breaking these rocks into very fine dust.

When lunar samples were brought to Earth during the Apollo missions scientists in the receiving laboratory sorted and catalogued rocks greater than 1 centimeter. The sub-centimeter portion was further broken down into “coarse fines” (1cm-1mm) and “fine-fines” (sub-millimeter) and although the definition was sub-centimeter, in practice, it is the sub-millimeter fine-fines are called soil. The portion of the soil less than 50 micrometers was informally called dust.

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Recently some have re-defined dust. These new definitions set the upper limit of dust as the portion of the regolith less than 10 or 20 microns. For the purposes of this paper dust is

defined in the traditional sense as less than 50 microns and includes lunar, Martian and asteroid regolith.

As particle size decreases adhesive, cohesive, and excitatory forces become very strong. This is important from an engineering perspective because the smaller particles will tightly adhere to surfaces they contact and tend to stick together.

### Layered Engineering Defense

#### Background

We learned during the Apollo surface missions<sup>1</sup> that when NASA crews and assets interacted with the lunar surface, everything got dirty. Working crew members, rovers, and landing modules raised dust and dirt from the surface that was deposited on assets. (Figures 1 and 2).



Figure 1.  
Astronaut Harrison Schmitt, Apollo 17  
Human activity transports regolith



Figure 2.  
Astronaut Gene Cernan, Apollo 17  
Regolith contamination in lunar module cabin

NASA initiated the concept of a “layered engineering defense” dust mitigation approach as part of the 1990’s Space Exploration Initiative (SEI) based on the “lessons learned” from Apollo. The drawing below depicts that concept (Figure 3).

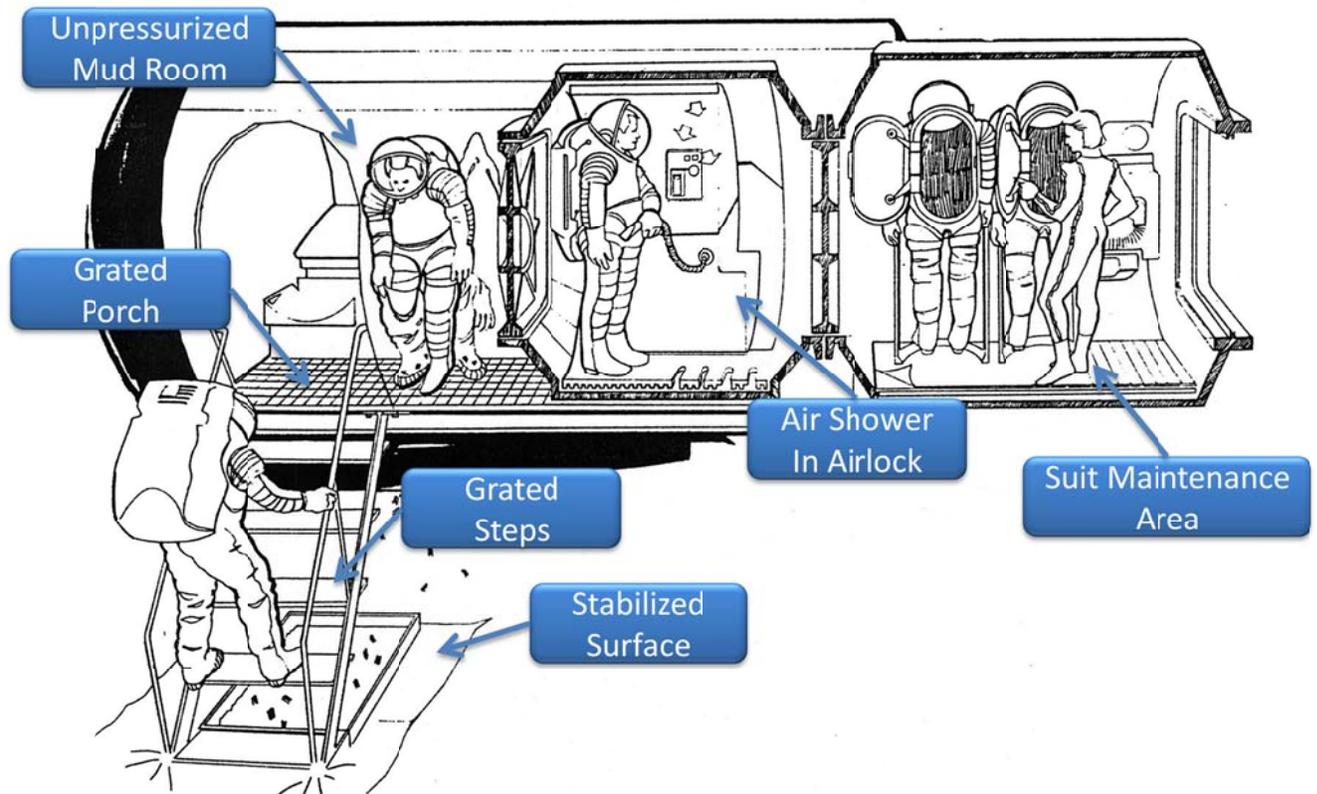


Figure 3.  
SEI Concept  
Early Layered Engineering Defense Approach

### Strategy

The first two layers of defense are materials and engineering design. Materials, when possible, should consist of smooth, dust and abrasion resistant surfaces. Pockets, folds, and other points on space suits that could trap dust should be minimized and designed so they do not collect dust. Specialized surfaces that reject dust, either because of inherent surface properties or through active means, should be considered in original design where appropriate.

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Engineering design should incorporate dust covers for sensitive equipment and employ grates on floors to collect dust. Best practices for cleanable design should be followed and include minimizing gaps where dust and dirt can collect, designing rounded corners, and including human factors experts throughout the design process to assess crew access.

Operational design is another key component for particulate management. Suit and contaminated equipment ingress to habitable volumes should be eliminated where practical.

Where feasible, automated operations such as continuously active or automated cleaning systems, will reduce the amount of crew-time required for managing regolith particulate contamination.

### Contamination Prevention

For architectures that include bases or pre-positioned assets, surface stabilization in high traffic areas and near the habitat entry points would reduce contamination by creating a surface that would minimize dust transport. Properly prepared roads, Macadam (coarse gravel), as well as establishing keep-out zones, minimize regolith transport and deposition. Berms and landing pads are needed to protect surface assets from contamination and damage due to high-velocity particle impacts.<sup>2</sup>

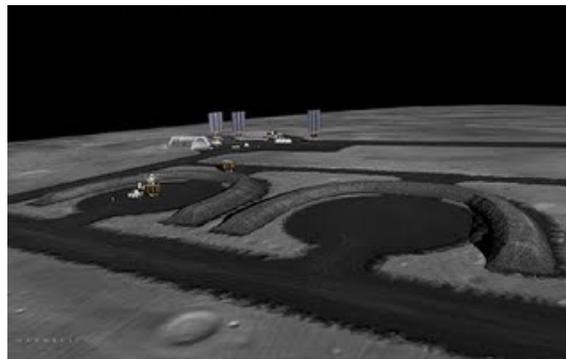


Figure 4.

Lunar base concepts include berms, landing pads, and roads

Because of the unique nature of lunar soil, containing nanophase metallic iron, microwave sintering/melting has been proposed for stabilizing the surface. With such equipment as shown below, rocket landing pads, complete with sintered berms, could be prepared, as well as roads.<sup>3</sup> In fact, the University of Tennessee has suggested a “lunar lawnmower” concept to sinter the lunar surface over smaller areas, such as a lunar crater, shaped parabolically, for use as an dish-antenna.

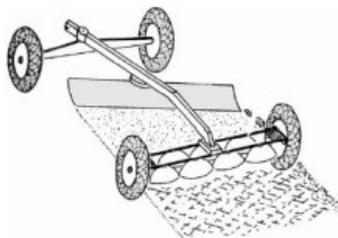


Figure 5.

Cartoon-sketch of a "lunar road paver"

Other suggested methods for stabilizing the surface include excavation<sup>4</sup>, e.g., grading and compaction, and using palliatives<sup>5</sup>. Caterpillar and Honeybee have extensive experience designing and manufacturing equipment for moving earth<sup>6</sup>. The Department of Defense has used palliatives in the desert to form landing pads for helicopters.

Representatives from organizations experienced in these types of processes presented their experiences to the (Lunar Regolith Community of Practice) LunRCoP to help NASA understand the technologies and to brainstorm methods where those technologies might apply to human spaceflight.

Another surface treatment that has been proposed is the deployment of Combustion Synthesis Fabric (CSF), which has the potential to be an early ISRU-derived product. CSF is a fusion of three principal technologies, each of which is COTS: loose-weave fiberglass fabric, Chemical Vapor Deposition (CVD), and Combustion Synthesis.<sup>7</sup> Combustion Synthesis Fabric (CS Fabric) is intended to stabilize or enclose large masses of unconsolidated regolith.

Particles on the undisturbed lunar surface are lightly bound together to form a "duricrust" that is a few mm to 5 mm thick. Another possible concept that has been suggested for surface stabilization is use the binding process for the "duricrust." In the Apollo Lunar Surface Stereo Close-up photos (Figure 6), you can see this crust along the edges of boot prints, where it is cracked and in some cases shoved aside as thin sheets. When dissecting the Apollo drive tube cores (the larger ones) scientists observed tabular "clods" mixed into the regolith that are the same scale (thickness) as the plates of disturbed duricrust. The "clods" were sampled separately from the surrounding matrix and put into stainless steel vials for future analysis. What binds these particles is unknown, though it may be related to impact-generated vapor and/or surface charging conditions. If the binding process for the duricrust was understood, that information might be used to design a surface stabilization process.

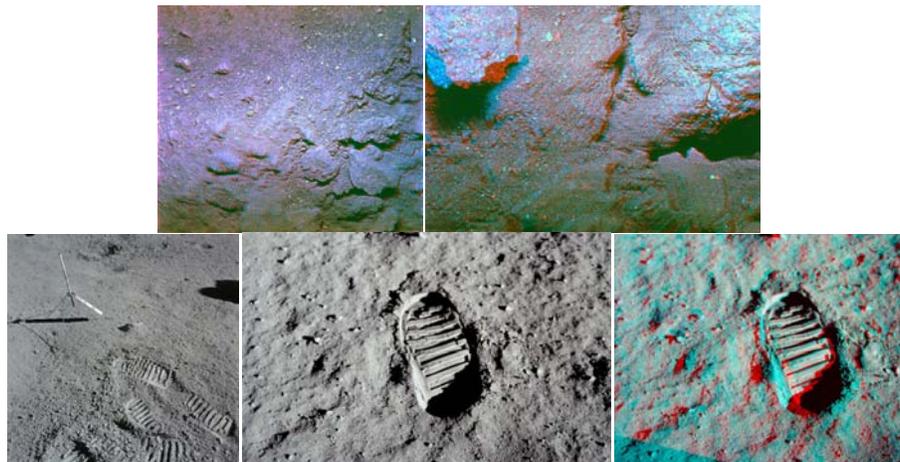


Figure 6.

Understanding the process that forms the duricrust may lead to surface stabilization technologies  
Courtesy of Eric Jones, The Apollo Lunar Surface Journal

In addition to surface stabilization, reducing contamination on suits and equipment that is generated during extravehicular activity (EVA) would also reduce the amount of dust and dirt contamination in habitats, as well as lessen the thermal load for the life-support system because of the “black-body effect” on increased dust. Several concepts have been suggested to accomplish this goal.

Suit ports, such as those used in hazardous materials cleanup operations, allow crewmembers to ingress habitats and rovers without bringing regolith into the habitable volume. This helps to maintain a healthy environment for the crew and equipment.

Suits may be left outside the habitat as has been considered for the Space Exploration Rover (formerly the Small Pressurized Rover and the Lunar Exploration Rover). As the primary potential vector for dust to enter habitats, leaving the suits outside and periodically cleaning and maintaining those in a separate facility would be an ideal engineering and operational solution.

In order to protect the suits and to allow access to the suits for repair a very small airlock called a suitlock is added to the structure. NASA has created a low-fidelity suitlock on the Space Exploration Rover as shown in Figure 7.

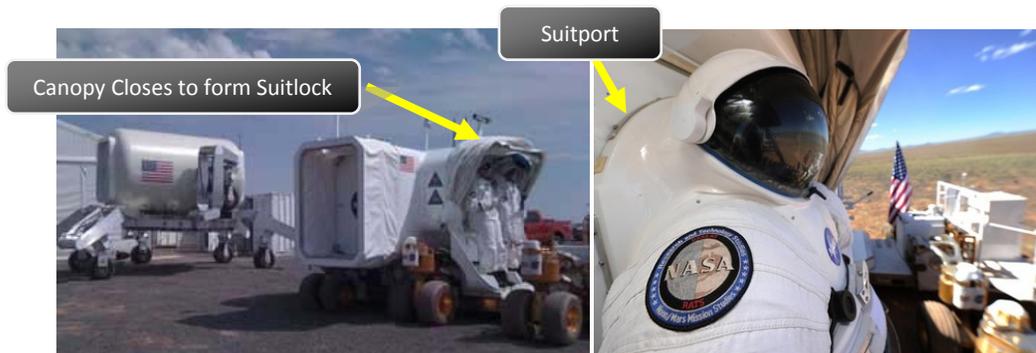


Figure 7.

Suitport and Suitlock on NASA's Space Exploration Vehicle

Novel constructs, such as the Active-Active Mating Adapters developed for the NASA Space Exploration Vehicle (SEV), allow vehicles to dock, eliminating the need to perform EVAs to traverse between rovers and habitats (Figure 8). These docking adapters will need to include active provisions such as retracting dust covers to limit contamination from dust deposited on hatch surface areas while operating undocked.



Figure 8.  
Two Space Exploration Vehicles dock using an active-active mating adapter

Other concepts have been proposed, such as pressurized or unpressurized articulating jet ways (Figure 9) that connect surface elements, reducing EVA contamination between immobile assets that would otherwise raise and transport regolith onto spacesuits and other mission assets. These solutions will require care in design and implementation to avoid tripping and entanglement hazards for EVA like those encountered with electrical cables during Apollo EVA's. This consideration is especially important in lunar and other low gravity environments.



Figure 9.  
Articulating Jet way at Munich Airport

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Crews could also use grated surfaces from landing modules by placing them as walkways in high traffic areas. Tarps placed on the surface have also been suggested. Combustion Synthesis Fabrics may provide an ISRU-derived material that integrates conveniently with the regolith.

Each of these concepts has its pros and cons, but each is compatible with the multiple approach philosophy for consideration during trade studies.

In concept, the canopy would close to create a pressurized suitlock for access to suits and equipment for repair and maintenance. Particulate management for suitlock and airlock is addressed in the interior cleaning and protection section.

Samples and equipment that are brought into habitats and rovers also are a source of particulate contamination. Glove-boxes with exterior ports help to reduce this risk.

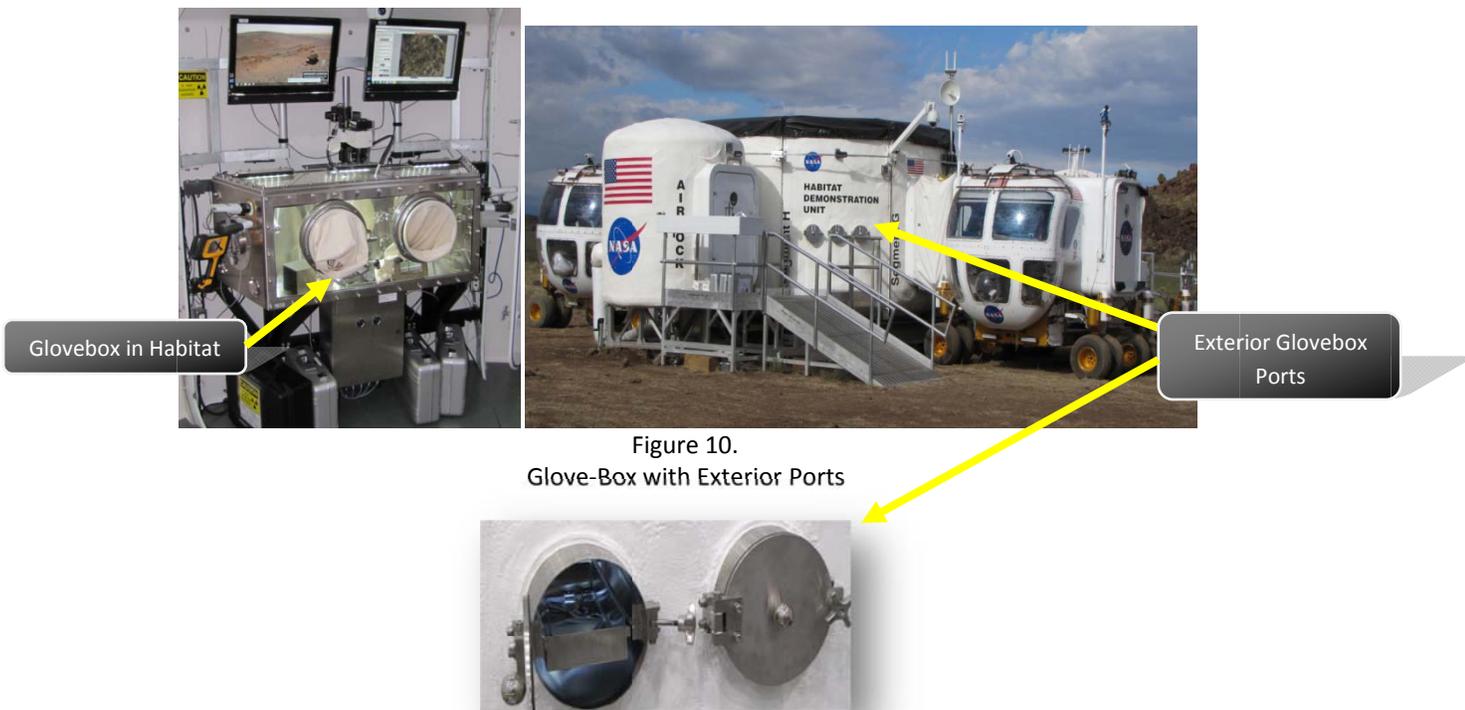
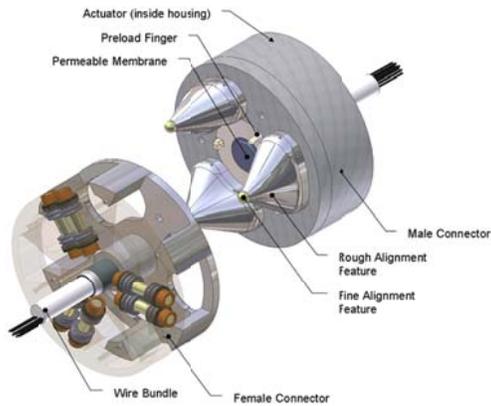


Figure 10.  
Glove-Box with Exterior Ports

These glove-boxes will be crucial for Mars missions in order to mitigate forward and backward contamination and meet Planetary Protection requirements. They will also provide an ambient environment to preserve samples.

Dust tolerant utility (electrical and fluid) connector will enable recharging of Astronaut resources without the need to enter habitats (Portable Life Support System would need communications, power, water, and oxygen). In addition, these connectors are required for robotic systems such as rovers (for Environmental Control and Life Support System). Utility connectors would also need to handle radial and angular misalignment<sup>6</sup>.



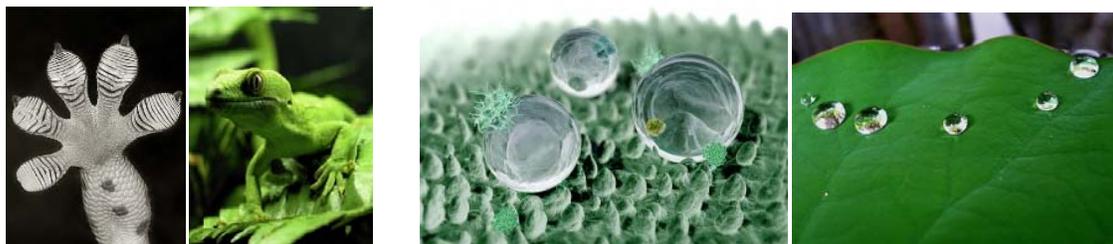
Dust-tolerant connector concept for consumable recharge with angular and radial misalignment features

Electrical connector prototype undergoing testing with lunar simulant JSC-1AF, at 1 torr pressure, N2 atmosphere

Figure 11

Exterior Cleaning and Protection

Passive-cleaning technologies, such as lotus and gecko inspired self-cleaning surfaces, combined with active-cleaning technologies, such as the Electrodynamic Dust Shield (EDS) (Figure 13),<sup>8</sup> a vibratory surface cleaning system<sup>9</sup>, and the Space Plasma Alleviation of Regolith Concentrations in Lunar Environments by Discharge (SPARCLED),<sup>10</sup> are needed to reduce degradation of key elements such as solar panels and radiators. (Figures 12 and 13).



Gecko Feet Stay Clean

Water Beads on Lotus Leaf

Figure 12.

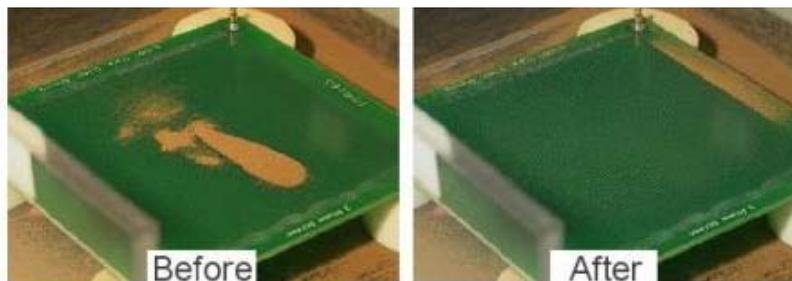


Figure 13. Electrodynamic Dust Shield

These cleaning technologies also reduce the amount of time that crews will have to work to keep things clean. During the Apollo surface missions, crew members struggled to stay within timelines because of the amount of cleaning operations they had to perform before re-entry into the Lunar Module (LM).

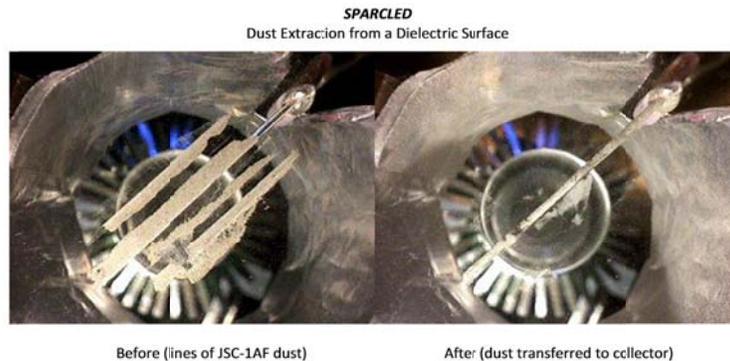


Figure 14.

During Apollo, space-suit cleaning primarily consisted of brushing and vacuuming. Brushing produced varying results and abraded surfaces. Therefore, using brushes is not recommended. The principle cleaning technology for suits is the air or CO<sub>2</sub> shower, perhaps aided by brushes with magnets attached. The air shower is discussed further in the interior cleaning and protection section. Other potential space-suit cleaning technologies include the EDS and SPARCLED.

The vibratory surface cleaning technology uses piezoelectric buzzers located under a transparent film over a solar panel that, when activated, would generate standing modes of oscillation to “shake off” dust from the solar panel.

Spacesuit fabrics can be outfitted with the EDS technology to prevent the accumulation of dust and to remove dust from spacesuits. (Figure 15). Reliability problems with heavily flexed electrical wiring and the need to cross multiple rotating spacesuit mobility joints without inhibiting mobility would need to be addressed. Passive dust resistant surfaces may be a first choice path in development or the electrodynamic shield technology may be restricted to regions on the suit based on special demand (e.g. boots and lower legs) or easier implementation based on the mobility design (e.g. helmet, torso, etc.).

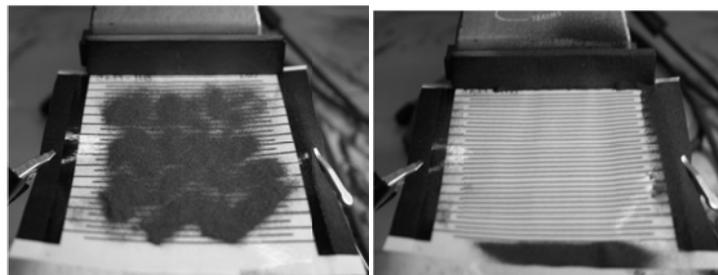


Figure 15.

Lunar simulant dust removal with an Electrodynamic Dust Shield on fabric

Helmets and other equipment that are susceptible to abrasion will be difficult to clean. Because of the high magnetic susceptibility of lunar soil, brushes with magnetic strips attached may prove useful (Taylor et al., 2005). Strippable coatings, such as those used on motorcycle helmet visors, can maintain a clean surface without abrasion that would be caused by cleaning operations. An active dust mitigation technology, such as the EDS, can also protect helmets and visors without abrasion. The EDS coating can be integrated with the helmet material, as well as with the visor, using transparent electrodes (Figure 16).<sup>11</sup>

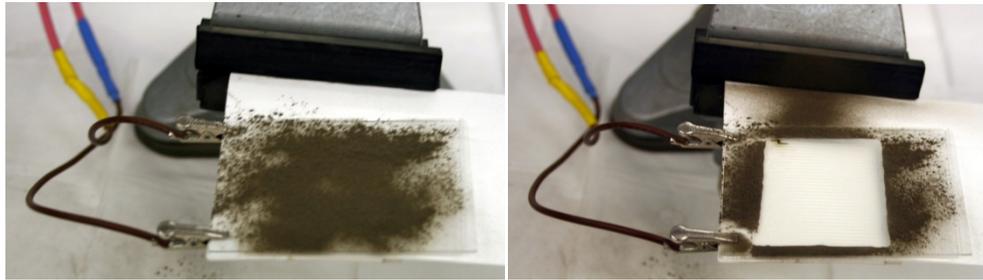


Figure 16.

Lunar-simulant dust removal with a transparent Electrodynamic Dust Shield  
 A transparent EDS coating can be integrated with the visor material for dust protection without abrasion

Exterior protection includes dust covers and dust-tolerant mechanisms. Dust covers for connectors and joints will reduce damage due to dust and dirt entering these points. (Figure 17).



Figure 17.

Apollo umbilical dust cover was developed to keep dust out of the fluid connectors on the spacesuit

Suit covers can be used to reduce contamination on space suits. A modular system could be donned when beginning EVA and doffed prior to airlock or suitlock ingress (Figure 18)<sup>12</sup>.



Figure 18.

ILC Dover's Reusable Space Suit Cover System

Porches should be grated such that when crew members “stomp” their feet to knock off dust and dirt, it will fall through the grate leaving the porch relatively clean. Note that very small particles may not “fall through” in a low gravity environment as adhesion forces may be stronger than gravitational forces.

Dust tolerant connectors and seals will be required to prevent contamination of oxygen, water, fuel, and other critical fluid systems, as well as power systems. After being operated in the dusty environment, fluid connectors will be required to meet specific leak-rate requirements, and electrical connectors will be required to meet resistance requirements. To some degree, dust tolerant connectors were developed for emergency use with the Apollo Extravehicular Mobility Unit (EMU) or pressure suit.



Figure 19.

Photo of the plug side of a dust-resistant quick-disconnect system for cryogenic interfaces

Consideration should also be given to using non-contacting and conducting (Figure 20) connections to mitigate contamination in critical connector receptacles. Wireless energy transfer and optical communications are examples of technologies which do not require contact for operation.



Figure 20.

Oral B Toothbrush is an example of an application that uses wireless energy transfer.

Finally, all systems that may be exposed to planetary or lunar regolith must be designed for maintainability in dusty environments. Modularity and encapsulation should be implemented to the largest extent possible to ensure that regolith is not introduced into critical mission systems. Additionally, designs and operation should minimize disassembly and ensure that

regolith does not infiltrate vital mission systems. Exterior surfaces should be cleaned prior to disassembly, and then exposed surfaces should be covered with protective covers.

### Interior Cleaning and Protection

Air showers are used across many industries. This technology could be used to clean space suits and equipment in the airlock or suitlock prior to bringing them into the habitable volume. It would be preferable to have a separate cleaning facility, such as the one proposed in the SEI concept, so that suits are not brought into the habitat. If suits and equipment must be brought in, they should be maintained and repaired in a glovebox or vent hood, and crews should follow appropriate bag-in/bag-out procedures.

Suits, major suit subassemblies, and large equipment would require a very sizable glove-box or vent hood for effective cleaning / maintenance. These may be too large to fit in a glove-box. Partial cleaning in an air-lock or suit-lock volume and perhaps local dust collection at a work site that would incur lower facility penalties in an exploration setting may be more practical.

### **Airlock Cleaning – Updated Concept Minimum Volume Airlock**

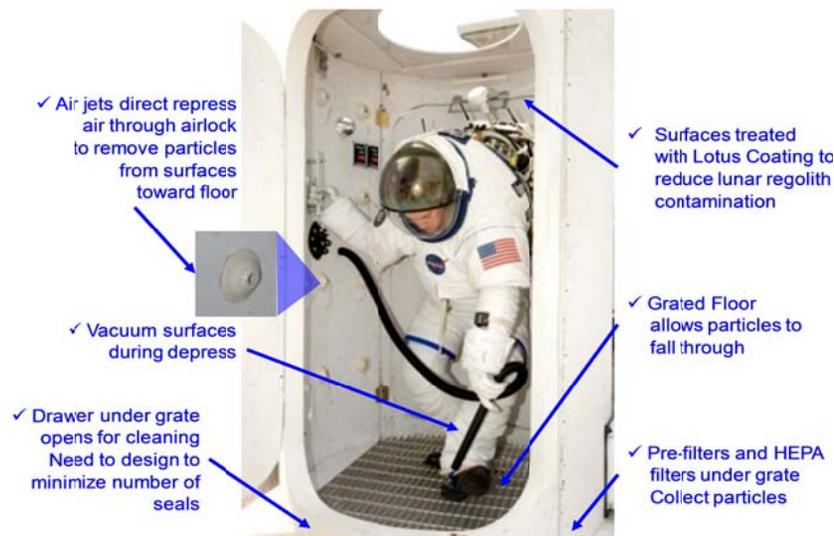


Figure 21.

Example: Minimum-Volume Airlock with Air Shower and Vacuum

The air shower features directional jets that create turbulence to remove dust from space suits and equipment with the general flow downward, moving the dirt under the grated floor to be collected by filters. Suggested filtration includes electrostatic filters with pre-filters to prevent clogging and self-cleaning magnetic filters.

Because of the strong magnetic susceptibility of a majority of the dust<sup>3</sup>, it has been proposed that magnetic catchers be placed under the floor gratings. Likewise, magnetic “wall-paper” could be used to help clean the fine dust from the air.

For lunar dust thin-sheeting magnetic collectors under the grating could be renewed on a roller system. There must also be an acceptable method for cleaning and/or replacing the filters.

The example air shower (Figure 21) includes a vacuum hose and Lotus Coatings. The operational concept for the air shower uses air evacuation during depressurization, to create suction for cleaning using the vacuum hose; while the air shower operates using re-pressurization to blow air through the jets.

For Mars, where the atmosphere contains carbon dioxide, cleaning technologies used on Earth, such as liquid or supercritical CO<sub>2</sub>, and CO<sub>2</sub> snow, may provide more contamination control that may be needed to meet strict human toxicity and planetary protection requirements<sup>13</sup>. Electromagnetic techniques may be helpful on Mars as well as the Moon as at least portions of the Martian dust are magnetic.

For other destinations, where CO<sub>2</sub> is not prevalent waste gases could be collected, compressed and used for pressure cleaning. Two concepts that have been suggested are collecting methane waste from the Sabatier oxygen recovery process and collecting CO<sub>2</sub> from waste treatment processes.

A dust collecting technology broadly used on Earth, an Electrostatic Precipitator, can be used on Mars inside habitats, as well as on atmospheric gas collecting systems for ISRU.<sup>14</sup> This technology is a particulate collection system that charges and removes dust particles from a flowing gas using electrostatic forces acting on the pre-charged particles.

Electrospray technology recently developed under NASA SBIR funding may also be a useful alternative for airlock and habitat atmosphere cleaning and in removing dust from contaminated surfaces<sup>17</sup>. In this technology very small quantities of electrically charged fluid (most likely water) are emitted as micron size droplets that collect dust particles and are collected electrostatically. It can operate at very low air flow velocities and pressure drop reducing power penalties and reduce or eliminate filter media consumption or cleaning requirements.

Employees in the lunar sample lab at NASA Johnson Space Center have said that, by far, the best method from removing lunar dust from surfaces was just to rinse the surface with plain water. A water shower has been suggested as part of planetary surface airlocks. There are challenges with this concept, including how to prevent suit damage. This concept should also be evaluated during trade studies.

Connectors and other sensitive equipment located inside the airlock or suitlock also need to be protected by magnetic systems, protective covers, dust covers, and/ or strippable coatings.

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Separate facilities for maintenance and repair such as shops, mudrooms, and garages should be considered as layers of the defense to avoid the workload and stress imposed on the crew by cleanup, and loss of the sanctuary that is represented by habitable volumes.

Although not recommended, space suits and equipment may have to be brought into the habitable volume or a separate facility for maintenance and repair. These items, as well as the airlock or suitlock, should be cleaned as thoroughly as possible prior to crews entering to retrieve them. Wet and dry wipes and magnetic brushes work well for removing dust and dirt. When considering brushes designers should consider the material's abrasion susceptibility. While in the airlock, crews should don protective personnel equipment (PPE) such as gloves, respirators, booties, and safety glasses. Vent hoods or glove-boxes should be used and transfer of this equipment should be performed using bag-in/bag-out procedures common throughout the Department of Energy.<sup>15</sup> This is a common practice in clean rooms, hazardous materials handling, and in other sectors.

As with exterior operations, interior designs and operations should minimize disassembly and ensure that regolith does not infiltrate vital mission systems. Exterior surfaces should be cleaned prior to disassembly, and then exposed surfaces should be covered with protective covers.

A sink with drain filters should be located next to the airlock/suitlock for crew members to wash any regolith contamination that may be on their skin.

### Air Quality

Maintaining air quality is accomplished by establishing contamination zones within the habitable volume using air flow.<sup>16</sup> This concept is used across many industries, academia, and other government agencies. The Department of Energy uses this principle to contain radioactive particles. Auto companies use air movement when painting to prevent surface contamination. Hospitals use air to prevent spread of germs.

An Electrostatic Precipitator that removes dust from the air flow is a very effective and proven dust filtration technique.<sup>14</sup> Self-cleaning magnetic systems also may work as filters.

For human spaceflight missions, controlling airflow with pressure differentials can help control regolith that enters the habitat. It can also control other contamination within the environment leading to a safe work environment for the crew, as well as mission systems.

The example zone-concept shown in Figure 22 uses a docked configuration of a Habitat and two Space Exploration Rovers (SEVs). The contamination zones are established by creating pressure differentials that cause the air to move from the cleanest to the dirtiest zones. Zone 3 consists of the living areas (the SEVs and loft) and under the floor (contains avionics boxes) and are maintained as the cleanest areas. Zone 2 consists of working areas on the Habitat Demonstration Unit's first floor where general and suit maintenance and geology operations are performed. Zone 1 consists of the antechamber in the suitlock, and Zone 1A consists of the suitlock.

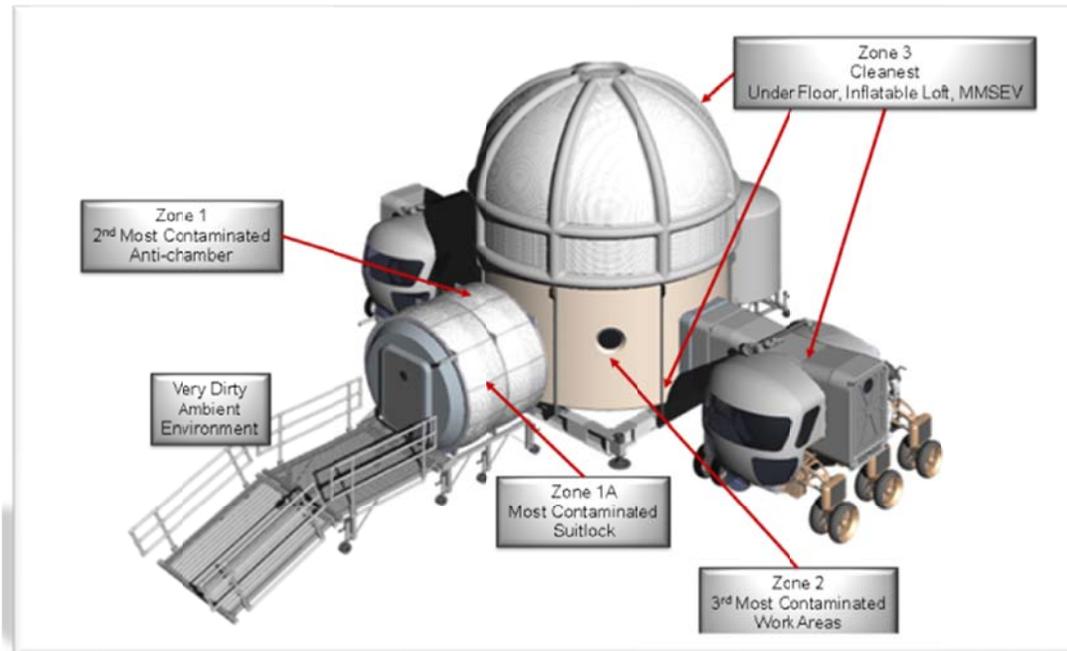


Figure 22.  
Surface Habitat with Space Exploration Rovers  
Contamination Zone Concept

Because of potential health concerns, lunar regolith human-exposure limits are being established, as will most likely Martian and asteroid regolith limits. For lunar regolith the Lunar Airborne Dust Toxicology Assessment Group (LADTAG) is currently conducting research and will set recommended exposure limits. These limits are for respirable particles with aerodynamic diameters of less than three micrometers. It should be noted, however, with up to four intense short term exposures to lunar dust, no Apollo astronaut ever showed any long-term adverse effects.

Because of the very fine particle size, detectors must be capable of differentiating between dust particles and smoke. This technology is well established and detectors are available commercially. Alarm systems must answer with the appropriate alarm. Pressure differential indicators are also required to ensure that air flow between contamination zones is functioning properly.

Appropriate simulants are required for testing equipment to ensure that they operate within specifications in dusty environments. Recognizing that no truly representative simulants will be available due to the unique environments in which lunar and Martian dust is generated, it is important to develop these simulants now in order to fill the requests for simulant tomorrow. In addition, multiple simulants are desirable to test equipment that could operate in different environments and on different planets; each unique environment requires its own simulant series. Thus, the presented layered engineering defense must include the development of simulants to test the technology necessary for human exploration of the Solar System.

## Technology Needs Recommendations

Appendix A identifies the capabilities needed to implement this layered engineering defense strategy. The second column lists example technologies that would allow NASA to reach each capability. Finally, the last column identifies the missions that each of these technologies support.

Note that the technologies listed in the table are those known to the LunRCoP. The list is not intended to dismiss other technologies, and these should be assessed as they are identified in future trade studies.

Trade studies should be performed to evaluate the most technically and cost-effective technologies to address each capability. A regolith management portfolio should then be developed that includes promising technologies for each capability to ensure a layered engineering defense. Risk mitigation plans should be developed to ensure that each capability is available in time to meet mission schedules.

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## Appendix A

Capability	Example Technologies	TRL Level	Design Reference Missions	Remarks
Surface Stabilization	Sintering Duricrust Inspired Stabilization Excavation Grading Compaction Palliatives Combustion Synthesis Fabric	3 1 4 4 4 4 3	Mars Lunar Base	1. Duricrust has been observed and reported. Development of the concept has not been performed. 2. All the other technologies are commercially available and employed in relevant environments on Earth. Limited testing on the ground has been performed as part of the ISRU and Desert RATS programs.
Create "Tunnels" to minimize regolith transfer during EVAs	Active-Active Mating Adapter Articulating Jet ways	7 3	Deep Space Asteroid Lunar Sortie Lunar Base Mars	Both these technologies are commercially available and are commonly applied on Earth. The mating adapter is also used for space applications, such as the ISS.
Suitlock	Suitport Pressurized Canopy System	4-5 4-5	Deep Space Asteroid Lunar Sortie Lunar Base Mars	Both these technologies are commercially available and are commonly applied on Earth for handling hazardous materials. These technologies have been demonstrated on the ground as part of the Desert RATS test
Sample Handling	Glove box with Exterior Ports	4	Asteroid Lunar Base Mars	Glove box technology is widely used in Earth applications for protective handling and transfer of materials.
Passive Cleaning	Lotus Coating Gecko Coating	4 3	Asteroid Lunar Sortie Lunar Base Mars	Lotus and gecko coating are commercially available for applications on Earth. Lab-scale testing has been performed of the
Active Cleaning	EDS SPARCLED Magnetic Brushes Vibratory Surface Dust Cleaning	5 4-5 4-5 7	Asteroid Lunar Sortie Lunar Base Mars	1. The principle of an EDS has been exploited for Earth applications. 2. SPARCLED is a technology proposed specifically for space applications. It has been demonstrated at TRL between 4 and 5. 3. Magnetic brushes and vibratory surface cleaning are established

## Appendix A (continued)

Capability	Example Technologies	TRL Level	Design Reference Missions	Remarks
Dust Tolerant Mechanisms	Dust Tolerant Seals	4	Asteroid Lunar Sortie Lunar Base Mars	These technologies are applied for commercial applications on Earth. Optical communications capability has been demonstrated on manned space missions.
	Dust Tolerant Connectors	4		
	Dust Tolerant Bearings	4		
	Wireless energy transfer	3		
	Optical communications	7		
Dust Covers	Umbilical Dust Cover	4	Asteroid Lunar Sortie Lunar Base Mars	These technologies are widely applied for commercial applications on Earth. Very limited testing has been performed in space relevant environments.
	Modular Suit Cover System	4		
	Strippable Coatings	4		
Maintainability	Modularity	7	Deep Space Asteroid Lunar Sortie Lunar Base Mars	These technologies are in wide use for commercial applications on Earth and the principles have been applied to hardware for manned missions, including Apollo, ISS and
	Encapsulation	7		
	Minimize Disassembly	7		
Air and Airlock Cleaning	Low Power/Mass Air Shower	3	Asteroid Lunar Sortie Lunar Base Mars	These technologies are available for a wide range of commercial applications on Earth, but have not been demonstrated in a relevant environment for space applications.
	Low Power/Mass Air Handler	3		
	Low Power/Mass Vent hood	3		
	Electrostatic Precipitator	3		
	Electrospray	3		
	Water Shower	3		
Low Consumable Filtration	Electrostatic Filters	3	Asteroid Lunar Sortie Lunar Base Mars	These technologies are widely used on Earth, but have not been demonstrated in a relevant environment for space
	Magnetic Filters	3		
Gas Cleaning	Liquid and Supercritical CO <sub>2</sub>	3	Mars Lunar Base	1. CO <sub>2</sub> cleaning technologies are widely used for applications on Earth, but have not been demonstrated in a relevant environment. The CO <sub>2</sub> shower is a special application of CO <sub>2</sub> snow for use in a space surface exploration application. For this specific application the TRL is 3. 2. Methane recovery and waste gas processing are well established chemical engineering unit operations on Earth. There has been very limited lab-scale testing as part of the ISRU program.
	CO <sub>2</sub> Shower	3		
	CO <sub>2</sub> Dry Cleaning	3		
	Sabatier Methane Recovery	4		
	Waste Processing Gas	4		
Failure Isolation, Detection and Recovery (FIDR)	Dust Detector	7	Asteroid Lunar Sortie Lunar Base Mars	Particle detection and monitoring are commonly employed in cleanroom and other applications on Earth. Particle detectors have also been demonstrated on the ISS.
	Dust Alarm	7		
Simulants	Powder Processing	7	Asteroid Lunar Sortie Lunar Base Mars	These technologies are well established for production and characterization of test materials. Simulants have been prepared for use in ground testing.
	Particle Characterization	7		
	Simulant Formulation	7		