Dust Control Research for SEI

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Abstract

A study, at NASA Johnson Space Center, of dust control requirements for surface habitats has focused on identification of the dust problem, identifying dust control techniques and dust control technology areas requiring research development. This research was performed for the Surface Habitats and Construction (SHAC) technology area. Dust control consists of two problems: (1) how to keep it out of the habitat; and (2) once the habitat or airlock is contaminated with dust, how to collect it. This paper describes the dust environment, the Apollo experience and dust control methods used, future EVA operational considerations, and dust control concepts for surface habitats.

Introduction

The Apollo exploration missions captured Mankind's imagination; and it also captured large quantities of lunar dust. A layer of fine dust-like particles, regolith, covers the Moon's surface. Lunar and Mars dust can adhere to most objects and be such a problem that new exploration systems will be influenced by it. The Apollo missions experienced many problems associated with lunar dust contaminating the Lunar Module and surface equipment. Dust is a potential problem for any surface element, system or activity that is repetitive or has long-term exposure. A study on the problems and concerns of dust control has been completed at the Johnson Space Center. The goal of dust control is to limit dust penetration into a mechanism or environment. If an effective dust control program is not implemented, then the results will be a higher number of mechanism failures, an increase in maintenance, repairs and resupply, and contamination of the living environment. Contamination of the living environment is of particular concern due to its effect on the crew's health and the crew accommodation systems.

The main focus of this effort is to investigate the dust control problems for surface habitats associated with the SHAC technology. However, in order to fully assess the dust problem, all surface systems were initially investigated. Dust control concepts and techniques have been identified for surface habitats and various options researched as possible solutions. Apollo mission data was used extensively in the research of dust related problems and techniques.

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This study's main emphasis is the lunar environment; however, the Mars dust environment is also of concern for surface habitats and systems and is briefly addressed. The reason for focusing attention to the lunar problem is that the Moon has been proposed as the first human exploration mission, a return to the Moon. The Moon's dust is known to be abrasive and damaging to extravehicular activity (EVA) sorties. Not as much is known about the Mars dusts. The lunar dust is considered to be worse than the Martian dust because it is much harder and more abrasive.

The Dust Environment

The lunar regolith is a complex mixture of five particle types: 1) crystalline rock fragments, 2) mineral fragments, 3) breccias, 4) agglutinates, and 5) glasses. Lunar regolith is very different from its terrestrial counterpart. First, its mineral composition is limited. Second, it has reached a "steady state" in thickness, particle size distribution, and other properties. A narrow range of physical properties are dictated by the limited particle types and sizes, the lack of atmosphere, and the absence of water and organic material (Heiken, 1991). Table 1 gives a description of the lunar dust characteristics and provides information considered important to system designers.

The lunar surface environment is described as a dead, harsh and extremely hostile place; thus making human activities, survival, and scientific operations difficult and very challenging. One of the Moon's many hostile design characteristics includes the ultra-fine pulverized lunar dust. Lunar dust is a complex composition of mineralogical chemistry and physical characteristics [Table 1]. Lunar dust is comprised of micron-sized particles with sharp, irregular shapes and very hard minerals. The combined effects are an extremely abrasive, cohesive and a penetrating material. The granular shape, hardness and possible electrostatic charging are hazards to friction-sensitive surfaces, materials and mechanisms.

The Mars surface has some significant differences from the lunar surface; it is more like Earth yet unique in its own features. There are four classes of Martian surface material, they are: (1) drift, (2) crusty to cloddy, (3) blocky, and (4) rock (NASA 1988). The surface material "drift", at the Viking I site, indicated a low cohesion of small grain-sized particles (<100 microns). This material is principally composed of silicates with an admixture of oxide and carbonate minerals (Glass, 1982). Table 2 gives a description of the Mars dust characteristics.

The Dust Problem

Lunar dust that is undisturbed on the surface is not a problem. Only when disturbed by natural mechanisms or human activity does it become a problem. The natural mechanisms for lunar dust transport include meteorite and micrometeorite impacts, and a phenomenon that suspends lunar dust by the electrostatic effect at the Moon's sunset terminator. Soil particles on the sunlit side, near the terminator, become positively charged because of the photoelectric effects from solar ultraviolet radiation and rises above the surface several meters. The human activities that transport dust include spacecraft landing, mining and construction, vehicle operation (rover), and "walking." Newtons laws of motion apply to the dust particles because of the lack of atmosphere. Thus dust is "projected" as it interacts with human activities. This was very evident from the Apollo extravehicular mobility units (EMU) and from the examination of Surveyor III. (Katzan, 1991)

The Martian surface is a dynamic environment compared to the Moon's surface. Mars has a low atmospheric pressure -- 6.1 mbar compared to Earth's 1,013.2 at sea-level -- and the atmosphere is primarily composed of carbon dioxide (95%). Mars experiences winds and consequently dust storms. However, due to the low atmospheric pressure, high winds of

57.6 km/hr recorded at the Viking I site are only equivalent to about 5.76 km/hr here on Earth. Sand-sized grains are picked up and blown around, but the softer clay-type material ruptures on impact with other objects. This does not create a sand-blasting effect, but rather a wind-driven sand that can contaminate mechanisms and systems. (Glass 1982)

Characteristics	Description	Remarks
Size	90%<1000 microns(1 mm) 70%<100 microns(0.1mm)	Very small with high ingress and penetration.
Shape	Angular/Subangular Sharp	Embeds into fabrics.
Color	Dark Grey / Brown, Black	-
Bulk Density (0-30 cm)	1.58 +/- g/cm^3	Higher density deeper.
Hardness	5 - 7 (Mohs Scale)	Very hard material.
Porosity (0-15 cm)	52 % +/- 2 %	Volume of void space.
Cohesion (0-15 cm)	0.52 kPa	Higher cohesion deeper.
Friction Angle (0-15 cm)	42°	Holds together, trenching.
Toxicity	Primarily Non-toxic	-
Corrosiveness	Not active in vacuum	No chemical reaction w/o solution.
Electrostatic	Highly charged	Highest charge during lunar night.
Magnetic	38 +/- gammas: Apollo 15	Not global, local fields.
Thermal Conductivity	0.9 - 1.3 W/cm°K	Good insulator.
Compressibility (loose)	0.3 (Compression index)	Top 10 +/- cm compressible.
Penetration Resistance	0.15 N/cm^3	Based on LRV tracks.

Table 1. Lunar Dust Characteristics (NASA 1991, Heiken 1991)

Characteristics	Description	Remarks
Size ("drift" material)	80%<100 microns(0.1mm)	Fine-grained with high ingress and penetration.
Shape	Smooth and Weathered	Like baking powder.
Color	Yellowish Brown, Reddish Grey	Iron-rich clay material. -
Bulk Density (0-30 cm)	1.5 g/cm^3 +/- 0.5 g/cm^3	Higher density below "Drift."
Hardness	Similar to Earth Clay	Soft, ruptures on impact.
Porosity	60 %	Volume of void space.
Cohesion	1.6 +/- 1.2 kPa	Low cohesion @ +/- 1 cm
Friction Angle (0-15 cm)	18° +/- 2.4°	Small angle of internal friction.
Toxicity	Strong oxidants	Peroxide, alkali, alkaline.
Corrosiveness	Chemically Active	Contamination & materials
Electrostatic	Little to no charge	-
Magnetic	-	3 - 7 % "Drift" is Magnetic.
Thermal Conductivity	1 - 3 W/cm°K (est.)	For the fine drift material.
Compressibility (loose)	-	Like powder.
Penetration Resistance	-	Depends on depth of "Drift."

Table 2. Mars Dust Characteristics -- Drift Material (NASA 1988, Glass 1982)

Upon further examination, the problem can be divided into two distinct subproblems. First, "how to exclude dust from contaminating surface systems or mechanisms", and second, once contaminated "how to remove or clean this dust from a system or mechanism?"

The Apollo Experience

The Apollo Missions provides significant insight and knowledge of the lunar dust problem. From these brief, but very valuable experiences; important data is available about system designs and potential failures. Lessons learned from the Apollo missions include the effects of dust on crew health, habitation and airlock systems, EVA equipment, experiment packages, and lunar surface equipment. The Technical Crew Debriefing reports consistently mention the problems the Apollo crew and equipment experienced during their missions. From these reports, a few selected quotes provide a first-hand insight about the lunar dust problem.

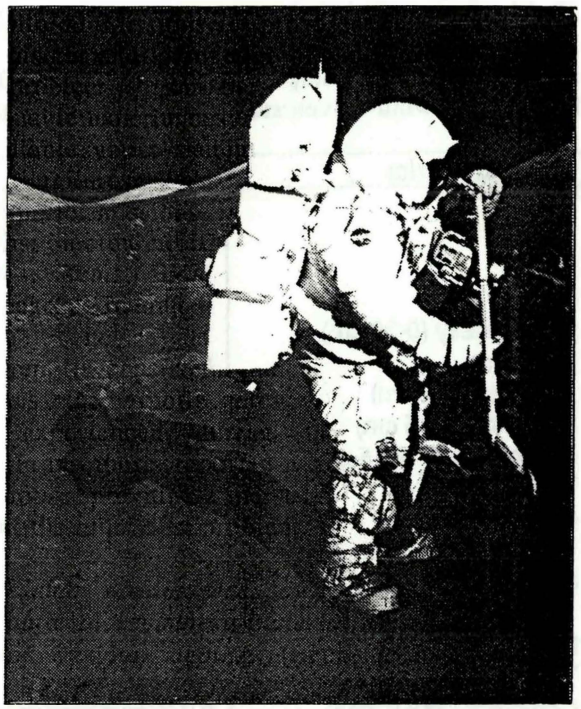


Figure 1. Apollo 17 EVA (NASA AS17-134-20425)

"*The entire lunar surface was covered with this mantle of broken-up material, fine dust of varying depth.*" [Bean, Apollo 12]

"*After lunar liftoff...a great quantity of dust floated free within the cabin. This dust made breathing without the helmet difficult, and enough particles were present in the cabin atmosphere to affect our vision. The use of a whisk broom prior to ingress would probably not be satisfactory in solving the dust problem, because the dust tends to rub deeper into the garment rather than to brush off.*" [Bean, et al., Apollo 12]

"*I got quite concerned with not only the wear and tear on the suits, but the effects of dust on the suits. On our final hookup back on the LM ECS system for ascent, it was all we could do to get our wrist locks and suit hose locks to work.*" [Conrad, Apollo 12]

"*Our hands were black when we started taking each other's glove wrist rings off. We got our hands dirty and I didn't get the dirt (dust) off my hands until after we landed.*" [Young, Apollo 16]

"*I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon.*" [Cernan, Apollo 17]

During the Apollo missions dust control was progressive through the program. Apollo 11 crew did little more than stomp their feet before entering the Lunar Module (LM), while Apollo 17 crew spent much more time on dust removal.

Dust control for the Apollo J-Missions became more important as the length and number of EVAs increased. Granted the missions had a relatively short surface stay and the Lunar Module volume was small and austere; but nevertheless, the crew took more time to clean themselves. Some of the Apollo dust control methods used, prior to entering the LM, included the addition of filters for the ECS, stomping their feet, use of a dust brush, a vacuum in the Command Module (Fig. 2), moist wipes or cloths, placing the lower part of

their suit into a jettison bag, fenders on the rover and dust covers for experiments, suit connectors and sample containers.

Despite the increased time expended on dust control and clean-up on the "J-Missions" (Apollo 15 - 17), dust related anomalies still occurred. A few of the more significant problems reported are:
1. EVA suit wear, suit wrist disconnects and abrasively worn gloves.
2. Degraded Thermal Control Systems: a 10% dust film (not even noticeable to crew) degraded the reflective surfaces, resulting in higher thermal temperatures.
3. Degradation of optical properties that included abrasions to the helmet visor, optical lenses and read-out displays.
4. The failure of Velcro for attachments when saturated with dust.
5. The accretion of dust on experiment sensors which affected the accuracy of the data gathered.

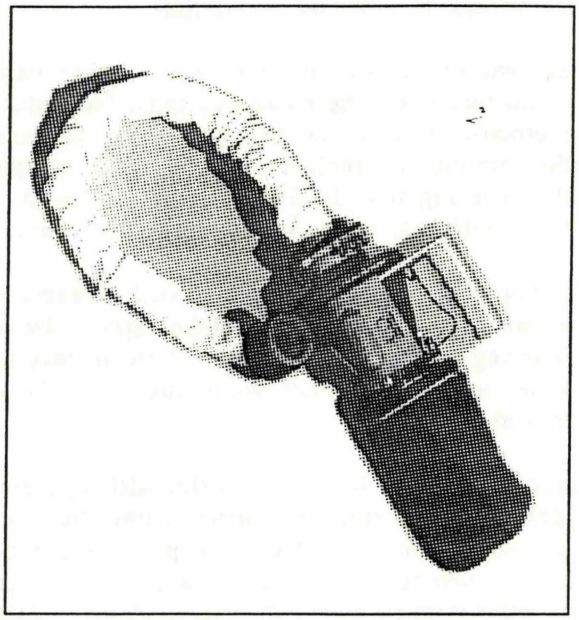


Figure 2. Apollo Dust Vacuum (NASA 74-26770)

6. The malfunction of the Lunar Rover's tool carrier gate type latch, which had gross mechanical tolerances. The dust, with the lack of atmosphere and subsequent humidity for lubrication, brought the latch to a grinding halt.
7. The malfunctioning of EVA sampling tools -- similar to the problem of the tool carrier latch.
8. The human physiological affects of dust. In some cases once the dust got under the crew's fingernails, it could not be washed out. The dust was only removed by the growth of the fingernails. Also the crew were exposed to inhalation of the ultrafine dust particles. Research by Dr. Ferin (Ferin, 1991) indicates that rats exposed to ultrafine TiO_2 and Al_2O_3 particles had acute inflammatory response and particles had been translated to the lung pulmonary tissue itself. The Russians (Kustov, 1989) used lunar soil (dust) from the Luna-16 probe samples on rats and found pathological changes in the lung tissue, a decrease in oxygen consumption, and a decrease in body weight.

After assessing the lunar dust and associated effects, the problem can be summarized as: "Lunar dust poses hazards to humans, surface system mechanisms, and surface operations." This statement identifies the fact that if dust control is not provided, then dust will result in physiological health risks, an increase in mechanism malfunctioning, and substantial EVA time will be required for servicing EVA equipment. The exclusion and removal of dust will provide improved working conditions, better crew health, higher morale, increased productivity and an increase in the life of systems and equipment.

Concepts and Techniques

The concepts and techniques for dust control for surface habitats can be categorized into three main areas: (1) mitigation of the problem at the site, ie. site stabilization; (2) dust control systems for the habitation elements; and (3) EVA operations.

Site Stabilization

Alleviation of the problem at the habitat site can include a number of options: (1) removal of the top layer of dust; (2) sintering the top layer; or (3) covering it with pre-fabricated "mats" (panels or sheets of material).

Removal of the top layer of dust -- that varies from several centimeters to tens of centimeters -- can be an energy intensive task. However, the task can be accomplished robotically prior to the first permanent habitat's arrival. A range of options on how to eliminate the dust include sweeping it off, scraping it off, or collecting it and putting it in piles or using it in In Situ Material Utilization (ISMU) plants. The various strategies require different equipment to carry out the objectives.

A simple device would be a robotic sweeper that sweeps up the dust, puts it into a container and hauls it to another spot. However, it will generate tremendous dust scattering during its operation; although this technique will remove the dust from the habitation site, it will not remove all of it and does not appear to be an efficient method of removal.

Sintering the top layer of regolith, although not a new concept, is another option. Two types of thermal sintering processes have been proposed, conventional radiant heating and microwave heating. Of the two processes, microwave heating will produce the desired sintering depths of five to ten centimeters. This sintering depth will produce even melting and solidification of the dust particulates, creating a "paved" area for site development. Conventional heating uses infrared waves to melt the soil and relies on the soil's conduction properties to heat the inner layers. However, due to the poor thermal transmission properties, only the top 0.317 - 0.635 cm (1/8" - 1/4") can be sintered. Some doubt exists regarding the strength of this thin sintered crust to withstand vehicular and pedestrian traffic without breaking up into sharp -- potentially dangerous -- shards. Infrared heating uses solar concentrators to focus the Sun's energy and could sinter the top layer relatively easily. Microwave heating requires much more energy to convert electrical energy to microwaves at approximately 50% efficiency. Microwave sintering at 2.45 GHz and 900°C nominally takes 15 minutes (Eagle, 1991). An unknown is how much area can be sintered at one time and how much infrastructure is required to support this level of effort.

The use of prefabricated panels, modular platforms or sheets of material is an option for the problem of soil stabilization. Depending on the materials used, it may be advantageous for medium to long-term stays. Terrestrial construction projects use "mats" to assist their construction vehicles when environmental conditions impede progress and requires improvement. A similar technique can be used to place "mats" on the lunar soil. These "mats" can be prefabricated on Earth or they can be ISMU-derived. The use of prefabricated "mats" will have a mass penalty associated with their transport to the surface. The ISMU-derived "mats," or units, require a processing facility that could be part of a larger ISMU production facility. In either case, something is required from Earth and the "mats" will require emplacement. The advantage of prefabricated "mats" is that they do not require an ISMU facility and could be used early in a mission phase. The ISMU-derived units are typically small units, ten(s) cm^2, and would not be available early in the program (as current mission architectures are being proposed). Consequently, pre-fabricated "mats" can provide a near-term solution to the problem, and depending on the material or fabric selection may be durable enough to last for many years.

Short-term stays, such as a manned sortie of several days to the Moon, will not justify the heavy mass penalties involved for site stabilization. These techniques are only suitable

for a permanently inhabited Lunar Base. The tradeoff is between the wear and tear of EVA suits and equipment, habitat dust control systems, filters, long-term expected use of the facility and resupply of filters, suits, equipment, etc.

Dust Control Systems

The methods and types of systems used for dust control and collection can range from wet wipes and vacuums to electrostatic precipitators and mechanical filter systems. Seals and protective covers play an important role in protection of sensitive mechanisms, such as bearings, from dust exposure.

Wet wipes were used in the Lunar Module to clean off read-out displays and helmet visors and were found to be an effective means of cleaning off surfaces covered with a fine layer of dust. Wet wipes will be helpful for lunar dust clean-up procedures, but they can only be used on hard, scratch resistant surfaces since a paste of lunar dust and water is extremely abrasive. Research is required for better wipe solutions and lubricants to increase the efficiency of clean-up.

A vacuum cleaner (Fig. 2) in the Apollo Command Module was used for dust removal and cleaning. Vacuums can be an effective method to remove loose dust particulates for containment in disposable filters. A similar vacuum device could be used on a Lunar Excursion Vehicle (LEV) for dust removal during equipment and sample container transfer prior to Earth return.

Filters are essential for dust collection systems, whether they are vacuums, electrostatic precipitators (EPs), or mechanical filtration. Filters will be located in the air handling subsystem of the habitat's environmental control and life support systems (LSS), and in the airlock.

Mechanical filtration is more effective than other systems for collecting and retaining small particles, and is the preferred method of dust collection. A mechanical filtration system has the ability to capture large and small particulates more efficiently than EPs. Filter efficiency increases as dust collects on the filters. With the sharp subangular shape of the lunar dust, collection of the dust will be easily trapped within filters.

The use of electrostatic precipitators has been suggested for dust removal from the pressurized environment of the airlock and habitat. They are commonly used for commercial use to remove airborne smoke, dust, and fumes from the environment. A typical precipitator incorporates a pre-filter, ionizing section, collection cell, post-filter, and blower assembly to move contaminated air through the unit. In operation of a typical unit, dust is drawn through the pre-filter into the high density ionizing field which charges all dust, regardless of particle size. Charged particles are stripped from the air moving through the precipitator and retained on oppositely charged collecting cell surfaces. A post-filter collects any particles that may blow off the cell plates. These precipitators have an effective filtering range of 0.01 - 100 microns (0.00001 - 0.1 mm). Lunar dust typically is finer than 100 microns and the airborne lunar dust brought into the habitable environment is roughly finer than 20 microns. However, the low conductivity of lunar dust will cause problems collecting and retaining the charged particles, especially the larger particulates. The end result is a light positively charged dust layer that has little depth of accumulation on the collection plate surface. Once the plate is fully coated, the remaining particles will pass through the cell uncollected. (AERCOLOGY, 1991)

EVA Operations

Another aspect of dust control is the effect of EVA activities on the dust control systems. The most obvious, but probably not a very likely solution, is to not expose the crew to

dust, no EVAs. The choices here include (1) not sending humans to the Moon or Mars; (2) using robotics and workstations to do everything, either from Earth or at the outpost; or (3) put crew into a pressurized man-machine device, a Man-in-the-Can. Depending on the extent of robotics, humans activities will include exploration, mining, construction and servicing equipment for EVA sorties and surface operations.

Since EVAs are a part of surface operations, then consideration should be given to dust control for the suits, equipment and tools to be used. Previous and current experiments, conducted at the Johnson Space Center, are testing how lunar dust reacts with different materials (Kosmo, 1991). The selection of an appropriate material for the suit cover-layer, boots and gloves that repels dust and that can be cleaned-off will be a major factor in dust control. The feasibility of using a disposable cover garment is being investigated. Many attributes require investigation, such as (1) the material; (2) the ease of donning and doffing a removable cover layer while in a pressurized suit; (3) whether it should be a full "jump suit" style or "hip waders" and pull-on sleeve protectors; and (4) whether to have them disposable or reusable.

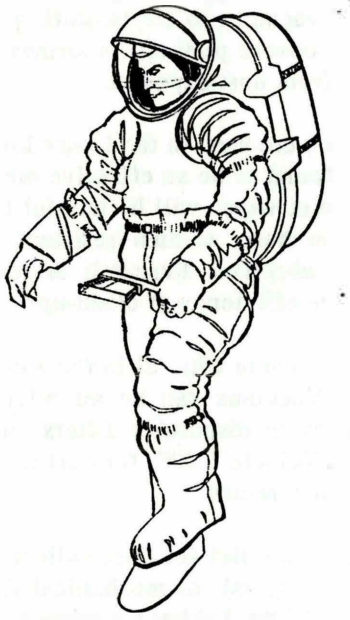


Figure 4. EMU Dust Protection System

Upon return to the habitation complex from an EVA, the crew will go through several steps for removal of the regolith or dust from their suit. The following procedure is a suggested step-by-step dust control and removal technique for planet surface operations to consider upon returning to the habitat from an EVA..

1. Stomp-off or shake-off the loose bulk regolith or dust.
2. Physically brush off what did not fall off in step 1.
3. While still outside in the dust-off area, remove the cover garment.
4. Move into the first Airlock chamber, the Crew Lock, and take a dust removing "air shower". The "air-shower" uses the repressurization air to blow-off the dust and collects it in filters in the floor.
5. At this point the crew member can hook-up LSS to their PLSS using an umbilical, but the crew member should remain in the suit until the suit is vacuumed off with a hand-held unit.
6. Use the hand-held dust vacuum to remove the remaining dust. This will not remove ALL the dust, but will greatly reduce the exposure.
7. The EVA suit is berthed with the support suit ingress stand. The crew member doffs the suit and moves into the Equipment Lock, leaving the suit in Crew Lock for the Post-EVA Assistant to clean it thoroughly.
8. The EVA crew member removes their dust gloves and booties and enters the habitat dust-free.
9. The Post EVA Assistant, wearing protective clothing, booties and, if necessary, a facial mask, goes into the Crew Lock and washes or wipes off any remaining dust residue (assuming a smooth textured surface).

10. Finally, move the EVA suit into the Equipment Lock and connect it to the Servicing and Maintenance Rack for other routine post-EVA servicing.

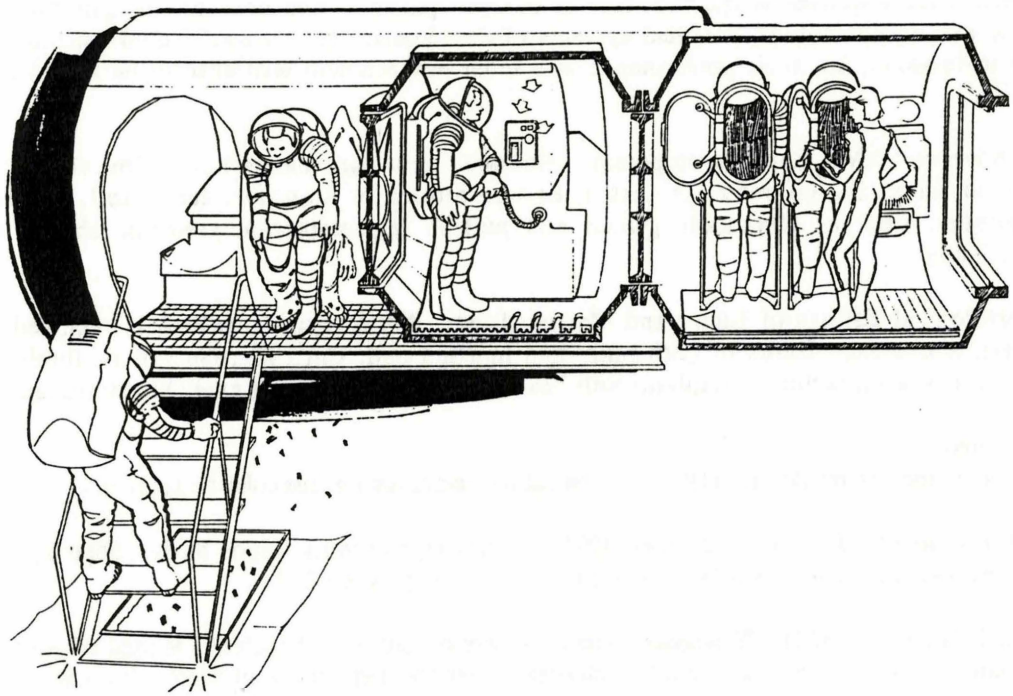


Figure 5. Dust Anti-Room for an Airlock (Frassanito & Associates)

Conclusions and Recommendations for Further Research

Dust control for the Moon and Mars will vary somewhat on the control problems and the techniques that will be used to solve the problem. What the two different environments have in common is a very fine-grained material that can penetrate systems and mechanisms if left unprotected. Also, the level of contamination in the habitat environment, before it becomes a health risk, is unknown. We are fairly familiar with the lunar soil and its effects on the living organisms, but little is known about the Martian soil and its effects. For this reason, the first human mission to Mars will have to be carefully conceived to control dust contamination. Prior to human space exploration, robotic exploration will be required to test and retrieve samples for human physiology research.

As long as proper research and development is devoted to lunar dust control and removal, dust will not be a major problem to lunar and Martian explorations. Different phases of lunar exploration will require varying techniques for dust control. For instance, a Phase 2 Exploration Mission that has 2-4 crew members on the surface for several days will only need to brush themselves off, use a vacuum, wet wipes and mechanical filtering systems for an airlock. However, a Phase 4 Lunar Base Development that has 10 - 18 crew members for a long stay time will require a more comprehensive dust control system. This may include site soil stabilization, an airlock dust-off room, an advanced LSS air systems, progressive housekeeping clean-up systems, and robotic systems.

<u>Recommendations</u>

From the data gathered during this research, several areas require additional research.

1. Site Stabilization Techniques: Research into various techniques is required to determine the feasibility of site stabilization and the systems required to implement it. Technology development on microwaving process, surface collection equipment and soil admixtures need better definition.

2. Dust Removal and Control Systems: Research on the various removal and collection techniques and how dust behaves in a 1/6 and 1/3 gravity pressurized environment is needed. Also required, is the behavior of charged particles and how they accumulate on EMUs and equipment. Mechanical systems of dust control for terrestrial applications are well understood, but their performance in a lunar environment will need to be tested and verified.

3. Advanced EVA Suit Development: Research into suit material selection continues with an emphasis on material that does not attract or transport lunar soil. Other techniques, such as disposable gloves and pull-on leg protection garments should be investigated.

4. Biological Effects of Lunar and Martian Dust: Physiological research is required to determine exposure limits of both lunar and Martian soil. Until Martian soil is obtained, terrestrially manufactured simulants will have to be used as the best available substitute.

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