Managing Planetary Dust during Surface Operations

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I. Effects of Dust on Surface Operations

From experience on Earth it might appear that dust on a planetary surface, be it the Moon, Mars, or any of various asteroids, would be a nuisance but not a serious problem. During the NASA campaign of the 1960's the principal dust concern was that spacecraft might sink into fine particles on the surface, and perhaps even be lost. But Ranger 7 photographs in 1964 *showed "a big rock sitting calmly on the surface and not sinking out of sight. So thus anybody in his right mind would conclude that the bearing strength of the lunar surface was not an issue."*[1] When the major fear was shown to not be an issue, attention turned to other challenges of landing and working on the lunar surface. The dust mitigation equipment carried to the Moon by the first Apollo astronauts consisted of a 4" brush for dusting off equipment and spacesuits, and a finer brush for the camera lenses.

But lunar dust was found to cause both more problems and more severe problems for the Apollo astronauts then anyone anticipated.[2] The first dust-related problems experienced by the Apollo astronauts occurred when they landed the Lunar Module (LM). The Apollo 11 crew reported that *"Surface obscuration caused by blowing dust was apparent at 100 feet and became increasingly severe as the altitude decreased."* This was even more of a problem for Apollo 12 where there was total obscuration in the last seconds before touchdown to the extent that there was concern that one of the landing feet could have landed on a boulder or in a small crater. In addition during the Apollo 12 landing the velocity trackers gave false readings when they locked onto moving dust and debris during descent. Dust set into motion by the landing rockets continued to a greater or lesser extent for all of the Apollo landings.

But even more severe issues faced the astronauts once they left the LM and started to move about the surface. Dust was found to quickly and effectively coat all surfaces it contacted, including boots, gloves, suit legs, and hand tools. Consequences included the Apollo 11 astronauts repeatedly tripping over the dust covered TV cable, and a contrast chart on Apollo 12 becoming unusable after being dropped in the dust. This was particularly troublesome on Apollo 16 and 17 when rear fender extensions were knocked off of the Lunar Roving Vehicle (LRV) and dust "rooster tailed" and showered down on top of the astronauts. Dust coating was the precursor to other problems such as clogging of mechanisms, seal failures, abrasion, and the compromising of thermal control surfaces. In addition, valuable astronaut time was spent in ordinary housekeeping chores like brushing off and wiping down equipment – which often proved ineffective.

For example, Pete Conrad noted that the suits were more worn after 8 hours of surface activity that their training suits were after 100 hours and further reported that their spacesuits were worn through the outer layer and into the Mylar® multi-layer insulation above the boot. Gauge dials were so scratched up during the Apollo 16 mission as to be unreadable. And after falling onto the surface, Harrison Schmitt reported that the sun shade on his face plate was so scratched that, because of the glare, he could not see out in certain directions.

Further, an insulating layer of dust on radiator surfaces could not be removed and caused serious thermal control problems. On Apollo 12, temperatures measured at five different locations in the magnetometer were approximately 38 °C higher than expected because of lunar dust on the thermal control surfaces. Similarly, on Apollo 16 and 17 the LRV batteries exceeded operational temperature limits because of dust accumulation and the inability to effectively brush off the dust. John Young remarked that he regretted the amount of time spent during Apollo 16 trying to brush the dust off of the batteries – an effort that was largely ineffective. (This was contrary to ground-based tests which indicated that dusting the radiator surfaces would be highly effective.) This led him to remark in 2004 that *"Dust is the number one concern in returning to the moon."*

Figure 1:Apollo 17 astronaut Eugene Cernan covered in moon dust. Credit: NASA

Perhaps the most alarming possibility is the compromising of astronaut health by topical irritation and inhalation of lunar dust. The Apollo crews reported that the dust gave off a distinctive, pungent odor, (David Scott suggested it smelled a bit like gun powder) suggesting that there are reactive volatiles on the surface of the dust particles. Dust found its way into even the smallest openings, and when the Apollo 12 crew stripped off their clothes on the way back to earth, they found that they were covered with it. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back.

After Apollo there was a nearly 40-year hiatus in lunar surface missions, but the lessons were still not learned. In 2013, the Chang'e 3 landed on the lunar surface carrying with it the YuTu rover.[3] When the rover was deployed from the lander it was announced that all of the scientific tools apart from the spectrometers had been activated, and that both the lander and rover were "functioning as hoped, despite the unexpectedly rigorous conditions of the lunar environment". The rover demonstrated its ability to endure its first lunar night when it was commanded out of sleep mode, but days later China's state media announced the rover had undergone a "mechanical control abnormality" caused by the "complicated lunar surface environment". It is widely believed that the problem was caused by dust clogging the mechanisms of the rover.[4]

Dust has complicated missions to the surface of Mars as well. The Sojourner rover was deployed onto the martian surface in 1997. Although the Viking landers had been nuclear powered, the Pathfinder/Sojourner mission included establishing the viability of using photovoltaic cells to power Mars surface vehicles. Included on Sojourner was an experiment to measure the amount of dust deposition from the atmosphere. A steady dust accumulation at a rate of about 0.28 percent/day was measured.[5] In the absence of a dust cleaning technology, this appeared to limit the lifetime of solar-powered vehicles on Mars. However, both Mars Exploration Rovers "Spirit" and "Opportunity" have experienced multiple dust clearing events, thought to be tied to dust devils that have rejuvenated their photovoltaic systems at regular intervals.[6] This has enabled Opportunity to continue to rove the martian surface for more than 14 years. However, after 5 years Spirit became immobilized in "soft soil" and 10 months later lost contact, likely because the photovoltaic cells became so covered with dust that they could not generate enough power to operate.[7]

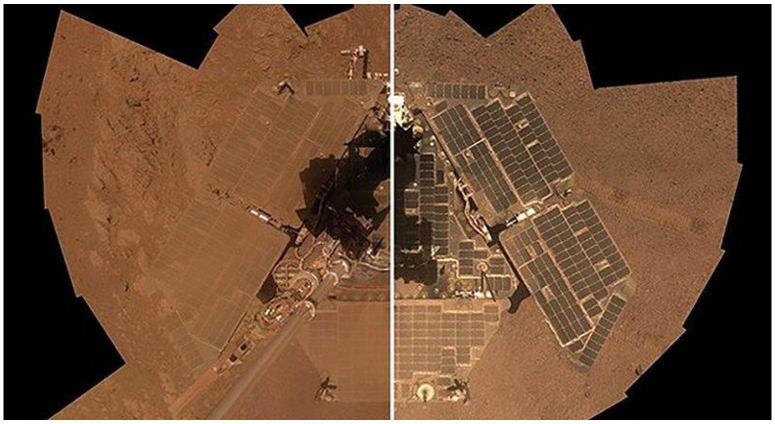
Figure 2: Dust accumulation on Opportunity rover after 10 years on the martian surface.

Although in popular culture asteroids are usually depicted as being bare rocks whirling through space, we know now that this in general is not the case. Asteroids have diverse histories with some thought to be "primitive", that is essentially unchanged since condensing out of the nebula that formed the solar system, and others being formed through a variety of evolutionary processes. As a result the composition and morphologies of asteroids are hugely variable. It has been known since the 1970s through optical polarization studies, such as those of Hapke[8] and parallel studies, that surface grain sizes in the range of 30-300 μm are present on the surface of at least some asteroids.

To date ten asteroids (excluding Vesta and Ceres) have been imaged close-up from spacecraft, and each has shown evidence of a regolith layer. In the 1990s, flyby observations of 951 Gaspra and 243 Ida by the Galileo spacecraft revealed surfaces with degraded crater morphology and evidence of retained crater ejecta, suggesting that regolith formation and evolution processes were at work. In addition, the NEAR Shoemaker images of 433 Eros revealed infilled craters, distributed boulders, and abundant slump features[9]. Images from the asteroid Lutetia taken from the Rosetta spacecraft flyby revealed fine regolith with a grain size less than 50 μm. By examining the sharper edges of the impact craters in many of the images it has been reported that the depth of the regolith may be as deep as 600 m.[10] The most detailed information has been collected from the Hayabusa spacecraft when it explored tiny 25143 Itokawa in 2005[11]. The low density (1.8 – 2.9 g/cm^3) of the asteroid is taken as confirmation that it has considerable void space within its interior, that it is in fact a "rubble pile", that is, nothing but regolith and dust. The lack of impact craters on the surface as well as scattered boulders and "ponds" of dust in low lying areas all lend credence to this model.

Since the Rosetta Lutetia flyby, it's become clear that each asteroid surface is different, even for similar classes of asteroids. Dawn spacecraft images of Vesta, the second largest asteroid in the asteroid belt, suggested that regolith mobility and fine-scale mixing are part of the complex assortment of global processes acting on an airless planetary surface over time.[12] Dawn's spacecraft images of the dwarf planet Ceres show a hydrogen-enriched regolith of tiny 1-10 micron grains.[13] Asteroid Ryugu, before the Hayabusa 2 encounter showed from thermal inertia measurements that the regolith's smallest grain size is on the order of 10 mm.[14] Since the

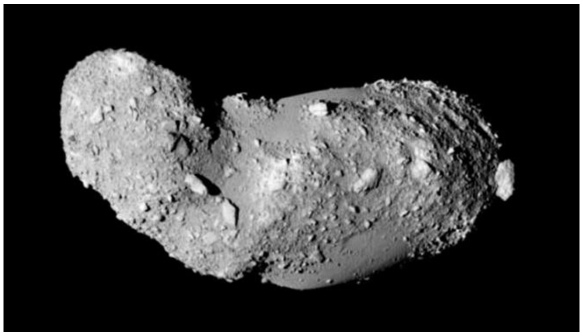
Figure 3: Itokawa, a rubble pile asteroid

spacecraft's orbit insertion with the asteroid in July 2017, Ryugu's surface is seen to be strewn with boulders with a wide variety of particle sizes. But in all cases operations on asteroids will be carried out in vacuum and under microgravity conditions where electrostatic and cohesive forces dominate dust interactions. This regime is challenging to physically simulate and thus has not been well studied

II. Effects of Planetary Surface Environments on Dust Transport

Perhaps the most vexing of the problems associated with planetary dust is that its transport around and adhesion to surfaces is dominated by poorly understood surface environments. There are five independent mechanisms known to adhere solids, and the total adhesion between two bodies is their sum. Diffusion, where the atoms or molecules on the surfaces of two materials intermix to form an interface layer of mixed composition, is not a mechanism that is expected to play a part as dust particles land on solid spacecraft surfaces. Mechanical interlocking, where irregular surfaces of adjacent particles latch onto each other, on the other hand is likely in the case of airless bodies because of the formation of impact agglutinates, which can have very complex shapes. Chemical bonding, primarily between Lewis acids, which are electron pair acceptors, and Lewis bases, which are electron pair donors may also be important. Since minerals are often a matrix of strong Lewis acids, such as metal ion, and the strong Lewis base, oxygen, chemical forces can be quite strong, but they act only at very short range. Similarly, van der Waals adsorption, cause by "flickering dipoles" among the atoms is another force that can be quite strong, but requires near contact of particle surfaces. But one force, the electrostatic force, dwarfs all of the others both in its strength, and in its range.

Apollo mission planners did not anticipate the dominant role that electrostatic would play. The dust just seemed to jump up and cling to everything. (Think about how maddening the sticking of styrofoam "peanuts" can be when trying extricate something out of a box filled with them.) This is due to a combination of environmental factors that are very different from our everyday experiences. All dust grains on even the driest deserts of Earth are coated with water. Without this surface film of water the dielectric constant of the dust grains is much higher, allowing each grain to hold more charge.

Dust grains are charged through a complex set of interactions between the solar wind and the lunar surface, the details of which are still poorly understood. The solar wind is made up primarily of dissociated hydrogen atoms, that is, free protons and free electrons. As the solar wind curves around the limb of the moon more electrons than protons make it down to the surface giving the dark side of the Moon a negative charge that has been measured to be hundreds of volts.[15] But the sun pours out a torrent of ultraviolet light and when this hits the illuminated side of the Moon it knocks electrons off of the dust grains by the photoelectric effect and the result is that dust particles gain a positive charge, estimated to be around 40 volts.[16]

With no atmosphere, the demarcation between the day and night (the terminator) in the moon is very sharp. Current theory suggests that these charge differences are large enough to cause dust grains to actually levitate and hop across the terminator.[17] A recent reanalysis of data taken by the Apollo Dust Detector Experiment, which ran for many lunar days, appears to support the reality of this transport.[18] This electrostatic levitation offers a means of particle segregation, transport and removal on small bodies as well. The process could explain the lack of fine particles on 25143 Itokawa's surface, the high surface porosity on some large (100+ km asteroids)[19], the fine dust deposits or "dust ponds" accumulating in craters on asteroid Eros and comet 67P,[20] and the intermittently appearing radial spokes in the rings of Saturn.[21]

Apollo mission planners also did not fully appreciate how sharp the microscopic features of the lunar dust grains would be. The dominant erosion mechanism on the moon is the breakup of the surface by meteorites. The Moon is constantly bombarded by tiny particles orbiting the sun. These tiny particles never reach the surface of the Earth because they burn up in the atmosphere. But they do reach the lunar surface and as they collide with the surface both the bullet and the target break into tiny shards. These collisions can also induce enough local heating that some of the particles melt and aggregate upon solidification into smaller particles forming agglutinates. These “gardening” processes have been occurring over the surface of the Moon for billions of years and the result is that the Moon is covered with broken rock (regolith), and the top layer of this regolith is what makes up the lunar dust.[22]

We can expect to see similar processes occurring on all airless bodies including Mercury, other moons, asteroids, and Kuiper belt objects. There will no doubt be differences depending on the size of the body and its location relative to the sun, but complex interactions between the solar wind and the surface and micrometeorite weathering can be expected to be features on all of these bodies.

In contrast, the erosional processes on Mars are similar to those on Earth. Even though the martian atmosphere is thin, that is a density of only about one percent that of Earth, it is still dense enough to protect the surface from most of solar ultraviolet radiation, and from micrometeoroid weathering. Large-scale water erosion is believed to have ceased billions of years ago, but aeolian erosion and dust transport are even more active than they are on the Earth. This is most dramatically seen by large scale dust storms that that regularly engulf large areas, and sometime even the entire planet.[23] In addition to these huge storms, small dust devils have been photographed that hurl the grains together and into the regolith at high speed. As a result Martian dust grain are more rounded, looking more like Earth wind-blown dust that the dust found on the Moon. Martian dust also forms soft agglomerates that can be shattered in collisions.[24] Thus, the dust on Mars is not expected to be as problematic as on the Moon.

Dust transport on asteroids has much in common with that on the Moon. Small airless planetary bodies with evolved regolith can similarly acquire a charge from solar radiation and solar wind in interplanetary space and hence may exhibit electrostatic behavior including levitation and transport similar to that occurring on the Moon. The smaller the particle, the more influenced it is by electrodynamic forces, with the charges on the particles, and hence its dynamics, varying as the asteroid rotates through its day-night cycle. The fine dust deposits, or “dust ponds” in craters on 433 Eros by the Near Earth Asteroid Rendezvous-Shoemaker mission, is an example of dust transport across vast regions without winds or flowing water.[25]

Katzan and Edwards developed zeroth-order models to determine on what lunar surface human activities dust contamination would have the most impact.[26] Spacecraft landing and launch were found to have the most impact of any activity. They would result not only in the transport of a substantial amount of fine material, but transported at high velocity, abrading nearby structures and mechanisms. Mining and construction were also identified as activities that would cause considerable dust contamination. Mining involves digging, dumping, and transporting of regolith to processing facilities, and the removal of the waste material from those facilities. In this case much more material would be moved than in launch and landing, but at much lower velocities. Other activities such as the operation of rovers, walking, and the removal of dust from sensitive surfaces such as solar arrays and thermal control surfaces will also transport significant amounts of dust. Although the science community has been focused on natural dust transport processes, they will be insignificant compared to human dust transport.

III. Snapshot of Dust Mitigation Technologies

Following the lead of Afshar-Mohajer[27], dust mitigation technologies can be categorized into active and passive technologies. Active technologies are those that are used to clean a surface or to protect it from dust deposition through external forces. Fluidal, mechanical, and electrodynamic/electrostatic methods fall into this category. Fluidal methods refer to those in which liquids, gels, foams, and gases are applied to carry the particles away from the surfaces. Mechanical methods include brushing, blowing, vibrating, and ultrasonic-driven techniques. Electrodynamic/electrostatic methods for dust control are inspired by the solar-based electrostatic levitation mechanism, though control of uncharged or low-charge particles requires an inventive charging mechanism different from the natural charging that occurs through photoemission and electron impingement.

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

Active Technologies

Fluidal Methods

The feasibility of using fluidal methods to clean dust from extraterrestrial surfaces was initially tested for thermal control surfaces (TCSs). Northrop Space Company and NASA Marshall Space Flight Center (MSFC) collaborated to determine the degradation of TCSs and then to examine potential dust mitigation methods[28]. Among the methods tested, an incompressible fluid (inhibisol methyl chloroform) jet was found to be the most promising method for removing dust from TCSs. Later, the idea of using gases (particularly CO_2), and using gels, foams, or liquids on the Moon for removal of fine dust from space optics was proposed by Peterson and Bowers[29], and Wood[30], respectively. With the gel and foam solutions, once the deposited fine dust is suspended with the foaming solution, a blower probe removes the mixture from the surface. Alternatively, by spraying liquid or blowing compressed CO_2, the thrust of the fluid may overcome the adhesion forces over the surface to be cleaned (similar to the standard method of removing dust from semiconductors in the electronic industry).

Mechanical Methods

A mechanical brush and a vibrational surface were the first mechanical approaches to be developed for removing dust from contaminated surfaces. However, neither of these methods was effective. Aliberti split the mitigation of lunar dust into two stages—loosening and removing—and reviewed a series of fluidal/mechanical methods using hybrid mitigation technologies to loosen the particles with one technique and remove them with another[31]. The brush-blower device was found to have the best overall characteristics for planetary surface dust removal. Fernandez et al. suggested a robotic dust wiper primarily to protect UV sensors on Mars[32]. Although the cleaning efficiency of the dust wiper was higher than 93%, the technology was not recommended to protect surface areas larger than 30 cm2 per wiper from 5 µm particles, as the power requirement to rotate levers would be limiting.

Gaier *et al*. performed an extensive series of experiments on the effectiveness of lunar dust brushes for TCSs[33]. Under Earth-ambient conditions, nylon bristles were effective for cleaning AZ-93 TCS, and an electrically conductive Thunderon® bristle brush was effective at removing dust from aluminized FEP Teflon® (Al-FEP) TCS. However, when the same tests were repeated under simulated lunar conditions, none of the brushes were effective on all TCSs. These results illustrate how important it is to test dust mitigation techniques under realistic environmental conditions. Further experiments under simulated lunar conditions showed that dust removal effectiveness was almost insensitive to the rotational speed and tip geometry of the brushes, and longer, more flexible brushes in both the round and fan brush bristle arrangement proved to be more effective than short-bristle strip brushes.

Protection of mechanical components such as gear boxes, motors, bearing housings, and seals is another important challenge for future space exploration because of the wearing effects of particles deposited on their seals. To address this issue, the effectiveness of a spring-loaded Teflon seal was evaluated by Delgado *et al*.[34] Preliminary results indicated minimal seal and shaft wear after 1,000,000 rotating cycles with no lunar dust simulant (JSC-1A and LHT-2 M) passed through the seal-shaft interface.

Electrostatic/Electrodynamic Methods

Introduced by researchers at NASA Kennedy Space Center and University of Arkansas (Biris *et al*.[35]), the Electrodynamic Dust Shield (EDS) is perhaps the most thoroughly tested electric-based technique in dust removal technology. The electric curtain consists of a set of conducting electrodes separated from one another by an insulating material. Since the electric curtain is connected to an AC power supply, a nonuniform electric field with spatial periodicity is created around the electrodes. When charged particles approach the electrodes, they undergo periodic motions resulting from the normal forces (which form standing waves) and tangential forces (which form traveling waves) to be shifted away from the surface protected by the electrodes.

Experimental investigation on the EDS performance as an active self-cleaning method for removing deposited dust from both lunar and Martian surfaces has been conducted by various research groups. A linear relationship between the removal efficiency and the applied voltage was observed with 10 kV corresponding to 95% removal efficiency of the JSC Mars-1 simulants. The EDS removal efficiency was insensitive to the dust materials. The frequency determines how quickly the surface could be cleaned.

Kawamoto and Hara applied the EDS concept to remove particles trapped in fibers of the astronauts' suits (Figure 3–3)[36]. Experimental tests were conducted at ambient pressure on copper electrodes insulated in a thin layer of polyester film and stitched into the outer layer of a spacesuit contaminated with 10 mg FJS-1 lunar dust simulants (<53 µm). To improve the cleaning efficiency, they coupled the EDS with a mechanical vibrator. The hybrid technology increased the cleaning efficiency up to 90%. The majority of the particles remaining over the cloth surface were smaller than 10 µm. Removal of particles smaller than 20 µm with only EDS (without vibration) was not effective. More recently, proof of concept tests using carbon nanotube fibers, which have lighter weight and greater strength and fatigue resistance than copper, were found to be effective as well.[37]

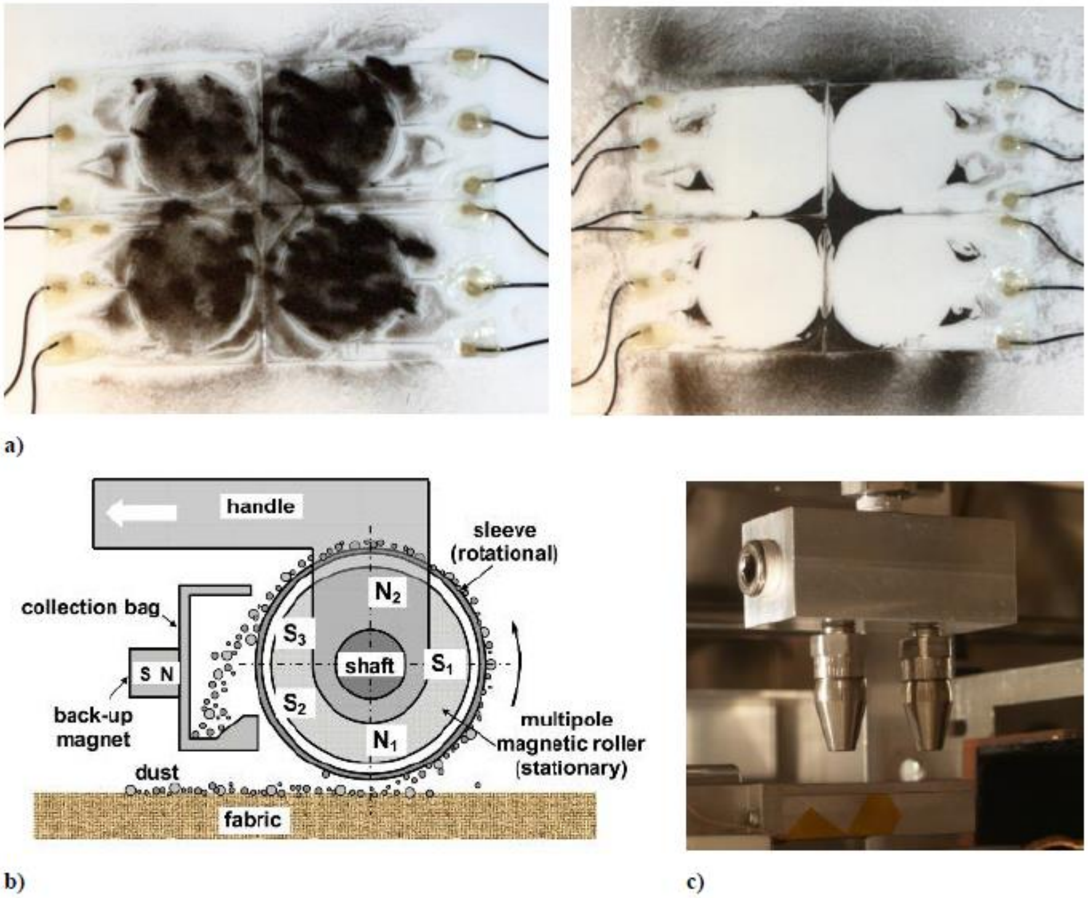

Figure 4: Among others, activated dust mitigation technologies include a) dynamic dust shields, b) magnetic cleaning devices, and c) gas jets.

Alternatively, Kawamoto and Inoue developed a magnetic cleaning device that used magnetic force via a multipole magnetic roller to separate lunar dust from the spacesuits[38]. Although the separation rate of this device was about 90%, the capture rate was low and the overall cleaning rate was about 40%. Hybrid application of the electrodynamic and magnetic forces for above-mentioned cleaning technologies led to 80% cleaning efficiency.

The lunar dust control technology proposed by Clark et al., the Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment (SPARCLE), involves charging the dust layer with beams of high-current electrons or ions emitting from a gun-shaped probe[39]. The SPARCLE probe is connected to an automated robotic lever scanning the dust layer line by line to charge the deposited particles, thereby covering a surface with highly energetic electrons/ions. The experimental results showed that the negative charge on initially-neutral particles rapidly increased, causing adequate electrostatic repulsion to lift up the particles from the negatively charged surface and to implant them in the surrounding positively charged chamber walls.

An Electrostatic Lunar Dust Collector (ELDC) proposed by Afshar-Mohajer et al. was a low voltage electrostatic collector for collecting naturally charged lunar dust before deposition[40]. Not only did the ELDC prevent charged lunar dust from being deposited, it also required thousands of times smaller electric field strengths than the EDS, owing to the absence of surface forces. The electric power consumption of the ELDC was determined to be negligible compared to the produced electric power, and the cleaning frequency of the collection plates was estimated to be three times as much.

Dust removal by electrostatic precipitation, an efficient and mature technology on Earth, can be adapted to the challenging Martian environment that limits the electrostatic potentials. Electrostatic precipitators do not require consumables, do not induce a pressure drop in the atmospheric intakes, and their maintenance can be automated. Calle, *et al.*, developed an electrostatic precipitator in a flow-through configuration that could be integrated into a dust removal system for a plant to produce oxygen from the martian atmosphere[41]. Initial results with the prototype in a no-flow configuration showed dust removal efficiencies of 99%.

Passive Technologies

Passive Methods

The simplest passive method may be the fender design for lunar roving vehicle (LRV) wheels proposed by Mullis[42]. His design consisted of a Lucite fender with flapped edges that enclosed the top, both sides, and front and rear of a full-sized LRV wheel. When the fenders were damaged during Apollo operations, the astronauts replaced sections with plastic maps, which proved highly effective.

Berkebile *et al.*[43] and Gaier and Berkebile[44] showed experimentally that electrostatic adhesion forces dominate over van der Waals forces under ultrahigh vacuum conditions such as those found on the lunar surface. Thus, passive methods should be based on minimizing electrostatic forces. This was borne out in tests where Gaier *et al.* successfully decreased the dust adhesion to metallized FEP TCSs by control of the work function [*]of the surface[45]. Similar results were obtained using a proprietary ion beam coating developed by Ball Aerospace and Technology Inc., which combined a work function-matching coating with a textured surface. This contrasts with the same test carried out with metallized FEP samples that had been textured using a Hall oxygen ion beam that etched away part of the surfaces to leave conical structures (< 1 µm in height) over the surfaces. The textured surfaces decrease the contact area between the surface and the dust particles, and hence would decrease van der Waals forces between the two, but have little effect on the electrostatic forces. Indeed, experiments showed that dust was not cleared from these surfaces.

The idea of applying transparent adhesive tapes over the protected surfaces and then peeling them away after collecting an adequate amount of dust was also proposed by Tatom *et al.*,[46] however, arsenic trisulfate taping shield performed poorly, and because astronauts are involved in removing the contaminated tape and residue is likely to be left on the surface, this idea has not been investigated further.

Methods to Remove Dust from Habitable Spaces

Filtration was the technique used for collecting airborne fine lunar dust inside the Apollo command and lunar module pressurized cabins. Applications of high-efficiency particulate air (HEPA) filters with 99.97% particle collection efficiency for 0.3 µm particle size is the recommendation for future human explorations. Lower efficiency media can be used in prefiltration stages to protect and prolong the life of the high-efficiency media. Several reviews on all aerosol filtration methods are available (e.g., Spurny[47]). However, extraterrestrial particles have jagged and irregular shapes that may damage the regular HEPA filters commonly used inside clean rooms.

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[*] The work function of a material is the minimum quantity of energy that is required to remove an electron from its surface.

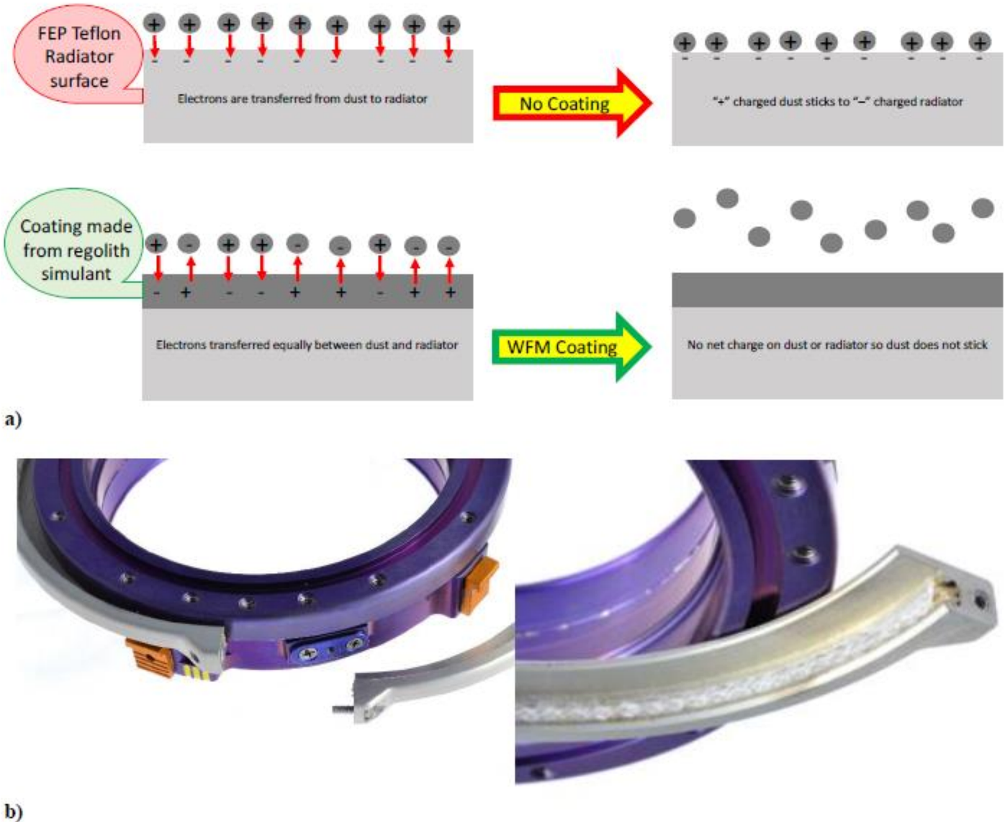

Figure 5: Among others, passive dust mitigation technologies include a) work function matching coatings and b) dust resistant bearing designs.

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

Since much of the lunar dust contains metallic iron particles, Eimer and Taylor suggested an active lunar air filter with a permanent magnet system (LAF-PMS) that would use the magnetic properties of lunar dust for removing indoor particles[48]. The LAF-PMS is a multistage filter made of a series of magnet plates that are arranged in rows at a certain distance. By placing opposite poles of two permanent magnets near each other, a large magnetic field is created to trap passing particles. Switching the magnetic polarity of the magnets is the suggested solution for cleaning the contaminated filters. The proposed filtration by this method is expected to remove particles larger than 20 nm.

Bango *et al*. reported on the feasibility of using electrospray technology as a way to capture fine particles from spacecraft atmospheres without producing the hazardous ozone that is generated in most high-voltage dust removal systems.[49] The demonstrated electrospray techniques (which used safe materials with few consumables, operated at a few watts, and created a very small pressure drop) compared to traditional filters, effectively removed small particles from the air. This technique can remove even the smallest particles from the long-term habitation environment, but is less suitable for removing a heavy dust burden from areas such as an airlock. A complete flight-like unit was fabricated for testing in a simulated closed spacecraft environment, but has not yet been evaluated.

Engineering and Operational Solutions

The designs of space suits for future planetary exploration will incorporate lessons learned from Apollo suits[50]. Engineering solutions can include active damage sensing to monitor degradation due to dust and pressure garment bearings designed for easy changeout of saturated dust seals

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

To address this concern, one possible solution uses a “Layered Engineering Defense” plan in which “layers” help mitigate the effect of dust on the suit materials, control the transfer of dust on the suits, reduce or eliminate forward and backward contamination of the crew and their habitation, and minimize cleaning and protection (interior and exterior) and the use of air quality contamination zones[51]. The space suits would need to be brought inside a habitable volume for nominal and contingency maintenance, which would introduce some amount of dust into the habitable volume. However, because the removal of dust from the suits would be a multiphase operation, the amount of dust introduced into the suits and the crew cabin would be limited. Operational controls, air quality zones, and ingress/egress methods (such as air showers, mudrooms, rear-entry airlocks, suitport-airlocks, and suitports) would mitigate the transfer of dust into the cabin. An alternate ingress/egress method is needed to provide particulate mitigation and backward and forward planetary protection. In this method, crewmembers would don/doff the rear-entry EVA suit through a bulkhead, so that they would not have to walk through the dust while entering/exiting and donning/doffing the suit. Cabin filtration in the area where the suits are kept would be necessary for dust mitigation and planetary protection. Alternate methods such as rear-entry airlocks/suitlocks and suitport-airlocks could include a chamber large enough for suit maintenance to be performed in a secondary chamber or mudroom. This would further contain contamination and increase air quality while the crewmember moves to the cleanest areas of the vehicles, such as habitats, pressurized rovers, and ascent vehicles.

With a suitport, suitport-airlock, or rear-entry suitlock, the majority of the dust remaining on the suit would be kept on the other side of the habitation zone boundary. Depending on the design of the habitat, the ingress/egress methods could add one or two zones to keep the contamination out of the crew quarters.

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

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

Dust-Tolerant Connectors

Standardized commodity connectors that can be repetitively and reliably mated and de-mated during extravehicular activities will be required for structural integrity and commodities transfer between linked surface elements during exploration missions. The dusty environments of the Moon, Mars, and asteroids will clog and degrade the interface seals of these connectors, which could cause hazardous commodities to spill, contaminating the flow stream and degrading mechanisms. Mueller developed prototype dust-tolerant connectors (quick disconnects and umbilical systems) that can be repetitively and reliably mated and de-mated during extravehicular activities on the lunar surface[52]. Quick disconnect fittings are needed for the EVA spacesuit's Primary Life Support Systems as well as for liquid-cooled garment circulation and suit heat rejection. Umbilical electromechanical systems (connectors) are needed between discrete surface systems for transfer of air, power, fluid (water), and data. These connectors must be capable of being operated by crew members or robotic assistants.

Electrical connector concepts combining dust mitigation strategies and electrical cable diagnostic technologies have significant application for lunar and Martian surface systems, as well as for terrestrial applications in dusty environments. Circuit failures in wiring systems are a serious concern for the aerospace and aeronautic industries. Often, such circuit failures result from vibration that occurs during vehicle launch or operation. Lewis developed prototype connectors that combine dust mitigation and cable health monitoring with automatic circuit-routing capabilities[53].

IV. Evaluating Dust Mitigation Strategies

Because the nature of dust migration and removal strategies are understood to be strongly affected by non-terrestrial environmental factors such as high vacuum and charge sources, the effectiveness of the proposed dust mitigating technology must be verified in a simulated-environment laboratory, where the artificial conditions can be locally controlled, and in the field, where longer tests with more realistic (sometimes, unpredictable) conditions can be conducted. These two types of investigations can be considered complementary: design verification can be performed in the laboratory under imposed and controlled conditions, while system validation can be done when operations are simulated in terrestrial analogs, even if all features of the non-terrestrial environment cannot be involved.

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

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

V. Conclusions

Experience with both human and robotic exploration systems has shown that planetary dust has the potential to disrupt exploration and mining operations on the Moon, Mars, and asteroids. The structure and transport of the dust is dependent on the environment. Since there are a wide variety of planetary environments that may be the destination of future human exploration operations, it is not likely that a single solution will be found that works best for all of them. The first step in designing an effective dust mitigation system is to understand the mechanisms of dust transport from the planetary body surface to the spacesuit, spacecraft, or mechanism that is to be protected. For example, since it has been shown that electrostatic forces dominate the adhesion on airless bodies, it follows that mitigation technologies that mitigate electrostatic forces will be the most effective. Techniques that are very effective to remove dust under terrestrial conditions may fail under extraterrestrial conditions which may include different atmospheric compositions and pressure, ultra-high vacuum, high radiation, or low gravity. The verification of the mitigation technologies must be carried out in high fidelity testing environments.

Historically, dust mitigation has not been a high priority in mission planning, and as a result funding for dust mitigation technology development has been sporadic. Given that the lead times to develop these technologies probably exceed a decade, there is a danger that either missions will be delayed because of underdeveloped technologies or, more likely, that missions will be sent with poorly tested and perhaps ineffective dust mitigation.

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