THERMAL IMPACTS OF LUNAR DUST FOR ROVERS

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ABSTRACT

Experience and ground tests have shown that lunar dust coverage can severely degrade thermal system performance, and with the push to go back to the Moon for longer than a few days, lunar dust is being recognized as a significant technical challenge. The Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR) will be operating on the lunar surface for long durations and roving at high speeds with interaction with astronauts and other robotics, which will cause dust to transfer to the vehicle, potentially to critical thermal surfaces. Dust coverage results in a change of overall optical properties, increased resistance to heat rejection due to the insulating effect of a dust layer, and even abrasion to thermal surfaces and soft goods. This paper provides an overview of what is currently known and unknown about what will happen to thermal surfaces exposed to dust on the Lunar South Pole, some dust mitigation options and testing guidance, and what resources can be used to help overcome this problem.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

α = Solar absorptivity
α_{dust} = Solar absorptivity of dust
α_{new} = New solar absorptivity of the contaminated surface
$\alpha_{pristine}$ = Absorptivity of the pristine surface
BOL = Beginning of Life
CLPS = Commercial Lunar Payload Services
DSNE = Cross-Program Design Specification for Natural Environments
ε = IR emissivity
ε_{dust} = IR emissivity of dust
ε_{new} = New IR emissivity of the contaminated surface
$\varepsilon_{pristine}$ = IR emissivity of the clean surface
EDS = Electrodynamic Dust Shield
EOL = End of Life
FEP = Fluorinated Ethylene Propylene (trade name Teflon)
HLS = Human Landing System Program
ITO = Indium Tin Oxide
LDES = Lunar Dust Effects on Surfaces
LRV = Lunar Roving Vehicle (Apollo)
LTV = Lunar Terrain Vehicle

PAC = Percent Area Coverage
PAC_{dust} = PAC covered by dust
PR = Pressurized Rover
VDA = Vapor deposited aluminum
VIPER = Volatiles Investigating Polar Exploration Rover

INTRODUCTION

Lunar dust is expected to be a major challenge upon return to the surface of the Moon during the Artemis missions. The surface is covered in a thick layer of regolith composed of crystalline rock fragments and minerals, including breccias, agglutinates, and glasses[1]. Many of these fragments are small particles under 20 μm in diameter, which categorizes them as dust[2]. Lunar dust is greyscale in color, sharp, ferromagnetic, toxic, insulating, and erosive. The grains are electrostatically charged from solar radiation, which enhances their adhesion to a variety of surfaces, and they can sometimes chemically react with exposed surfaces[1]. They are known to behave differently in atmosphere, ground testing vacuum levels, lunar vacuum levels, and the lunar surface environment, which makes them difficult to model, analyze, and test[3]. Dust transfer mechanisms and adhesion forces are a topic of intense study.

The Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR) are human-rated rovers which will operate on the lunar south pole. Both rovers have the expected lifetime of ten years and will carry a crew of two astronauts on missions to conduct research and collect samples on the lunar surface. Lunar dust can be a significant a hazard for rover hardware, including thermal systems. Experience from the Apollo missions indicates that dust contamination causes degradation in thermal performance. At least five instances of radiator degradation were noted in Apollo 12 through 17, and even after cleaning, radiators were still overheating due to the ineffectiveness of cleaning methods[4]. This paper outlines the expected impacts to rover thermal systems from a lunar dust environment, some tips and recommendations for testing hardware in a simulated dust environment, and some possible dust mitigation techniques which may be usable on future rovers such as LTV and PR. There are also still many unknowns left to characterize when it comes to dust, which are outlined in the "Unknowns" Section.

THERMAL IMPACTS

The first known impacts from lunar dust on thermal systems are the effective change in optical properties due to dust settling on the surface, the insulating effect of the dust layer, and degradation which can occur to thermal hardware as dust is moved across the surface. Each of these topics are discussed in more detail in this section.

Optical Properties

Temperatures of objects in space are highly dependent on their optical properties, mainly solar absorptivity α and IR emissivity ε. Solar absorptivity is the ratio of how much energy the surface absorbs in the solar wavelength range- the higher the absorptivity, the more heat will be absorbed. IR emissivity controls how much energy the surface emits in the IR wavelengths. The higher the emissivity, the more heat can be rejected by that surface. Contamination of a surface by lunar dust can alter the overall optics of the surface by making them more like those of the dust than the original spacecraft surface. Once a layer of lunar dust of sufficient thickness is covering the surface, the thermal balance of the surface will be controlled by the lunar dust layer rather than the optics of the surface. The optical properties of lunar dust are then of high importance for thermal engineers working on the LTV and PR.

There are two distinct regions on the Moon with slightly different chemistries and properties: Mare and Highlands, and it is helpful to know if the spacecraft will encounter one or both soils, as their optical properties differ slightly. Mare regolith is found in the darker regions of the Moon, once thought to be oceans, and has a higher solar absorptivity than that of Highlands regions. Highlands regions have an absorptivity of around 0.84 while Mare absorptivity is around 0.93. Both Mare and Highlands regolith have a high emissivity of around 0.95-0.98[5]. LTV and PR will be landing on the South Pole of the Moon, which is considered a Highlands region. For a radiator that typically has a low α and high ε, lunar dust coverage will increase the overall α and cause the radiator to absorb more heat from the Sun, reducing its thermal performance. Changes to the optical ε of a radiator are not as much of a threat since the ε of dust is comparable to that of a well performing radiator. However, if there is dust coverage beyond a certain threshold (and this threshold can be very small), there may be significant impacts to the effective emissivity and heat rejection capability of the radiator. This is discussed in detail in the following section.

The exact impact of lunar dust contamination on optics is more challenging than one would think, but a starting point representation can be determined using the Rule of Mixtures, shown in Eqs. 1 and 2.

$$\alpha_{new} = PAC_{dust}\alpha_{dust} + (1 - PAC_{dust})\alpha_{pristine} \quad (1)$$

$$\varepsilon_{new} = PAC_{dust}\varepsilon_{dust} + (1 - PAC_{dust})\varepsilon_{pristine} \quad (2)$$

where αnew and εnew are the new absorptivity and emissivity of the coated surface, αdust and εdust are the absorptivity and emissivity of the dust, αpristine and εpristine are the pristine absorptivity and emissivity of the surface, and PACdust is the Percent Area Coverage of dust on the surface. The Rule of Mixtures does not capture the true absorptivity or emissivity of the surface with dust coverage due to the nonuniform particle shapes and sizes, the complex structure formed on the surface, and potential transmissivity of some dust particles. However, the rule of mixtures is a good place to begin when other data is unavailable, knowing that this estimate is not conservative.

Limited research has been done thus far investigating the change in optical properties with various amounts of coverage by lunar simulants. A 1967 Earth-based test program for Apollo did investigate the change in solar absorptance with dust coverage on S-13, Aluminized Teflon, and Clear Silicon coated plates and showed that the total solar absorptance increased non-linearly with the fraction of dust coverage. The test used crushed basalt as the simulant and looked at several different particle size distributions. After the simulant was dry-dusted onto the plates, solar absorptivity and IR emissivity were measured with a Gier-Dunkle integrating sphere and a Perkin Elmer 13U Spectrophtometer. Results for S-13 are shown in Figure 1. Testing showed that the percentage of surface covered by the dust was the primary factor influencing surface optics and that particle size distribution and the total weight of dust were not significant[6]. However, this testing occurred in atmosphere and only examined spectral changes rather than testing heat absorptance of the surface itself from a solar source, so it is possible that some factors not considered could be significant. Gaier et al. (2008) conducted more recent testing in a simulated lunar environment with JSC-1AF lunar simulant applied to AZ-93 and AgFEP substrates. They monitored the temperature of the surfaces as they were heated with a solar simulator and cooled in a cold box. They then utilized thermal modeling to ascertain α and ε in both clean and dusted states and used image processing to determine in PAC how much dust was on each sample. It was found that even a sub-monolayer of dust significantly degrades the performance of both coatings and that α may increase by as much as 50 percent with as little as 12 percent dust coverage. Furthermore, ε may decrease as much as 16 percent with 54 percent dust coverage[7].

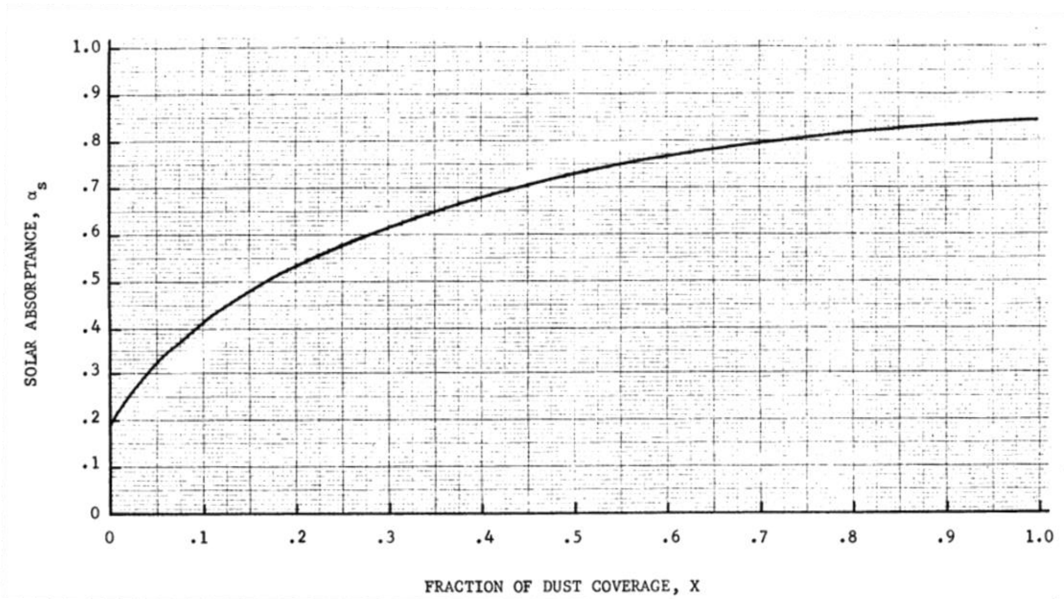

Figure 1. Variation of total solar absorptance with dust coverage of S-13 plate is nonlinear[6].

<u>Insulating Effect</u>

As dust collects on external rover surfaces, not only do the optics of the overall surface change, but there is also an additional barrier to heat transfer between the vehicle and the environment. This dust layer can act similarly to other insulation, like foam or multilayer insulation (MLI) blankets and is both radiative and conductive in nature. The heat from a spacecraft surface transfers conductively from the spacecraft to the individual grains of dust, through the grains, and from grain to grain until it reaches the top of the dust layer. Heat is also transferred radiatively from the spacecraft surface to the grains, between the grains, and from the grains to space. Figure 2 shows this complex heat transfer path.

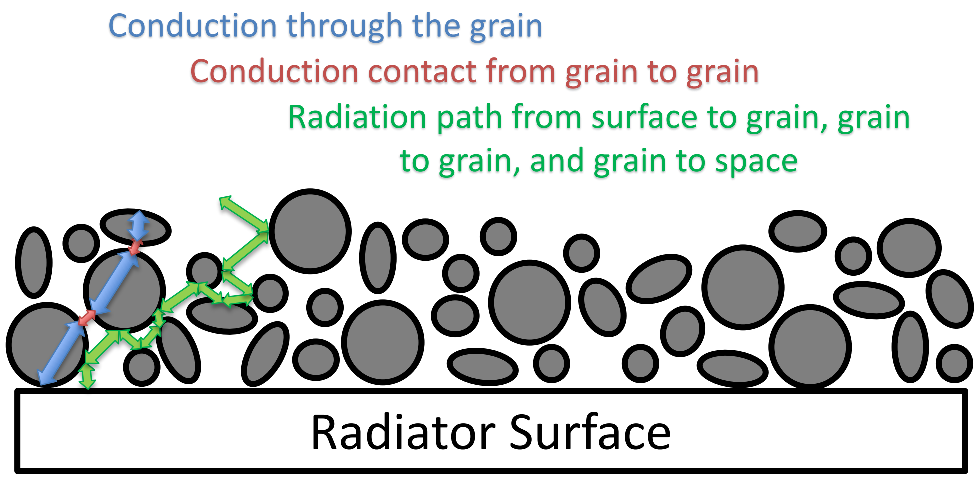

Figure 2. There is a complex heat transfer path from a dusty spacecraft surface to the environment.

The first challenge for conduction through the grains involves the extremely low thermal conductivity of the regolith itself. Thermal conductivity of lunar regolith has been calculated in situ during Apollo 15 and 17 as well as in the lab from Apollo samples, and it is well described in the DSNE, HLS Lunar Thermal Modeling Guidebook, and other sources[5, 8]. Table 1 shows the thermal conductivity values from Apollo 15 and 17 measurements that provide a general sense of how insulative lunar regolith is. Thermal conductivity changes with temperature, composition, density, and more, but regardless of these factors, it is extremely low for dust. The contact between the grains is a major factor behind lunar dust's low conductivity. The shape and size of the grains as well as the overall structure the dust settles in greatly impacts the regolith's conductance. Unlike Figure 2 above, grains are not always circular or ovular, and most are very rough and sharp[1]. The contacts between them are very small, and because of the large variation in grain size, there may be substantial gaps of empty space between some grains and less surface area for conductive heat transfer. Heat transfer across these gaps occurs via radiation between the grains. The dust itself has high reflectivity in the IR wavelength, so heat will be reflected many times before it is absorbed by the dust layer. All of this leads to a dust layer that acts as a very effective insulator.

Table 1. Thermal conductivity of Lunar Regolith[5]

Depth	Value	Units	Reference
35-234 cm	1.4×10^{-2} – 2.5×10^{-2} (Apollo 15) 1.72×10^{-2} - 2.95×10^{-2} (Apollo 17)	W/m-K	Langseth et al. 1973a Table 9-VI
2-15 cm	1.0×10^{-2} – 1.5×10^{-2} (Apollo 15 & 17)		Langseth et al. 1973b
0-2 cm	0.9×10^{-3} - 1.5×10^{-3} (Apollo 15 & 17)		

Because of the insulative quality of a dust layer, the effect it has on heat transfer may be simplified in the same manner as MLI: by using an effective emissivity. When tested with calorimetric methods like Gaier's, the actual value obtained is more of an effective absorptivity and effective emissivity than actual optical measurements because of the inclusion of conduction and radiation through and between the dust grains. The more dust that is deposited on the surface the less the emittance of the surface matter and heat transfer through the grains begins to dominate.

More testing is needed in this area to increase understanding of the insulative properties of dust on hardware on the lunar surface. Tests utilizing a calorimetric method to calculate emittance of a surface based on how much heat is being rejected with different simulants and particle sizes would be helpful in characterizing sensitivity to the soil type. Testing on more surface types could reveal dependencies on surface roughness or other surface properties. The total effect of lunar dust contamination on the heat rejection capability of the surface could then be better understood by monitoring solar absorptivity as well as effective emissivity. This could be accomplished by including a solar simulator in the test like those performed by Gaier et al.[7].

Abrasion

A third potential impact of lunar dust to thermal performance is abrasion of surface coatings as seen in Figure 3. Lunar dust is not like soil or sand on earth–it has been shown to be extremely abrasive due to the complex, jagged shape of the grains[1]. If dust is rubbed against or cleaned off a sensitive surface, the surface may be abraded such that the optical properties no longer match that of the pristine surface. This could be detrimental for a radiator or for soft goods which may have a thin and delicate outer coating like vapor deposited aluminum (VDA) or Indium Tin Oxide (ITO). Jimenez (2022) found that multiple commonly proposed dust cleaning methods, including Teflon brushes and some cloths, caused mild-to-severe damage to aluminized Mylar and AZ-93 white paint samples due to the cleaning tool scraping dust across the delicate surfaces[10]. Gaier et al. (2011) also observed thermal surface abrasion from brush testing[11].

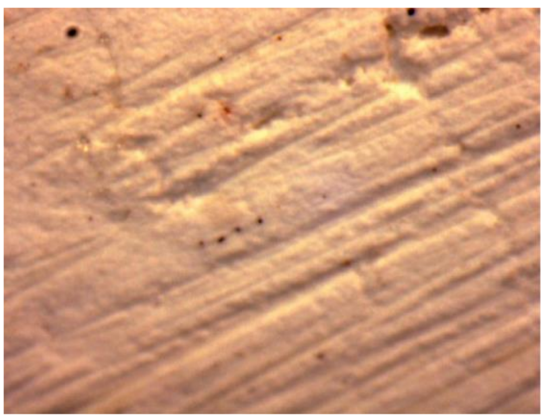

Figure 3. Abrasion lines are clearly visible on the 100x photomicrograph of AZ93 that has been brushed with a nylon bristle brush[11].

Lunar dust can also be chemically reactive due to broken, unsatisfied chemical bonds on the grains caused by bombardment from micrometeoroids, solar wind, and radiation. The fractured silicate bonds remain reactive after breakage due to a lack of lunar atmosphere that would otherwise neutralize the active surfaces. Active grain surfaces could react and fuse with rover surfaces exposed to lunar dust, making the particles difficult to remove. When attempting to separate the bonded grains, either the grain or the surface could fracture. Fractures not at the bond interface would leave residual dust or roughen the surface by removing part of the surface material. As a result, particles that react with and bond to surfaces have the potential to severely abrade that surface when removed[1].

For areas where dust is expected to rub on surfaces during operation (such as soft goods protecting a robotic arm, or on the bottom of the rover protecting instruments or cameras) scratch resistant and durable materials should be considered and optical properties must be measured in Beginning of Life (BOL) and End of Life (EOL) conditions for thermal models.

Abrasion testing on rover hardware with regolith simulants may be necessary to reduce risk of failure or degradation of properties. Abrasion testing for the Volatiles Investigating Polar Exploration Rover (VIPER) used sandpaper at a similar grit to lunar simulant to abrade multiple different MLI blanket outer materials. One of the MLI materials is shown in Figure 4 after abrasion testing. To account for unknowns with the lunar dust environment, this test evaluated samples with considerable margin, pushing materials to their limit rather than testing to what was expected for the project lifetime[12].

Figure 4. VDA/0.5 mil Kapton/Kevlar/0.5 mil Kapton material after abrasion testing for VIPER project shows significant degradation of the VDA layer[12].

TIPS FOR TESTING WITH DUST

Guidance for testing systems in a simulated lunar dust environment are found in NASA-STD-1008, but there are a few specific items for testing with thermal systems that are not included in the standard. Even so, one tip that is discussed in the standard bears repeating here due to its importance–the simulant bake-out procedure. Lunar regolith simulants, particularly the fine dust particles, can become clumpy and need to be baked out according to NASA-STD-1008 before being used for testing. This is mainly due to humidity that is not present on the lunar surface but will be present in a cabin environment. Without a bakeout procedure, the dust will be uneven and unrealistic[13].

Many simulants of lunar regolith and dust are available, both through NASA and commercially. Simulants have been designed to replicate actual Apollo samples in various aspects: mineralogically, chemically, mechanically, etc. Simulants are not typically designed with thermal properties such as solar absorptivity, IR emissivity, heat capacity, or thermal conductivity in mind unless they are unknown to the writers of this paper, so though simulants are expected to replicate real lunar dust fairly well, there is still some variability in the thermal properties. Simulants can also widely vary in particle size, ranging from fine powders to coarse sand-like substances that would settle differently on a surface. For any testing involving lunar dust simulants, it may be necessary to characterize the simulant properties if they could impact results. Many tests run trials with multiple simulants to understand how simulant properties may affect the outcome. The optical properties of several dust simulants are shown in Table 2 below. These values are not generally measured, and it may be difficult to find them elsewhere. Thermal conductivity and heat capacity of many simulants are already known and can be found through vendor websites or individual researchers, though some have yet to be characterized. Section 5.4 of NASA-ST-1008 has more information on what resources are available to those searching out advice on testing with lunar dust simulants[13].

Table 2. Thermal conductivity of Lunar Regolith[14]

Sample	Region	Solar α	IR ε
Apollo Lunar Mare Sample	Mare	0.811-0.834	-
OPRL2N	Mare	0.804	0.9
Exolith LMS 1	Mare	0.777	0.895
JSC 1A	Mare	0.794	0.903
Apollo Lunar Highlands Sample	Highlands	0.557-0.619	-
Exolith LHS 1	Highlands	0.603	0.873
NU LHT 2M	Highlands	0.631	0.882
NU LHT 4M	Highlands	0.638	0.876
OPRH4W30	Highlands	0.618	0.879
OPRH3N	Highlands	0.671	0.885
OPRH3W20	Highlands	0.674	0.887
OPRH3W25	Highlands	0.667	0.884
OPRH3W30	Highlands	0.665	0.883
OPRH3W35	Highlands	0.645	0.875
NU LHT Agglutinates	Both	0.698	0.887

Determining the amount of dust on test surfaces is a challenge when evaluating the impact of dust on optical properties. It is important to quantify hardware's exposure to particulates during testing, especially if attempting to validate assertations that the component or surface is insensitive to certain levels of dust exposure. Most experiments have measured dust coverage in one of two ways: calculating PACdust using image processing and counting the number of pixels containing dust over the total surface, or in areal density, in units of mg/cm2, by weighing the sample before and after dust is applied. Both methods have their strengths and shortcomings. In theory, image processing can be used without disturbing the dusted surface and can be calculated easily with software. However, it cannot account for dust particles stacked on top of each other, obscuring more dust beneath them. The structure of the dust as it settles on the surface is very complex, as seen in Figure 5 below, and it is nearly impossible to not have some dust particles on top of others[9]. The more dust is on the surface, the less reliable and useful the PACdust measurement is. It can also be very difficult for these measurements to be repeated as slight changes in methodology may yield different answers. For materials with multiple colors, a color close to that of the dust, or with surface features already, like slight roughness or woven fabric, this method may not work well due to the inability of a camera to differentiate between the dust and the underlying surface. Using weight per area as a method for determining how much dust is on a surface enables dust to be accounted for even when it is on top of other dust. This method requires the use of a scale that is capable of measuring at least down to the milligram. This method also requires that the test surfaces be small enough to fit into the scale and be handled by personnel. The act of measuring samples like this introduces human error by allowing some grains to be knocked or rolled off. In general, image processing is preferable for smaller amounts of dust, when evaluating changes in optics specifically, or when mass cannot be measured. Mass per area is better for larger amounts of dust when the grains start to stack on top of each other and when evaluating the thermal impact beyond changes in optics. Ideally, both methods could be used if the test is looking at a range of dust coverage amounts.

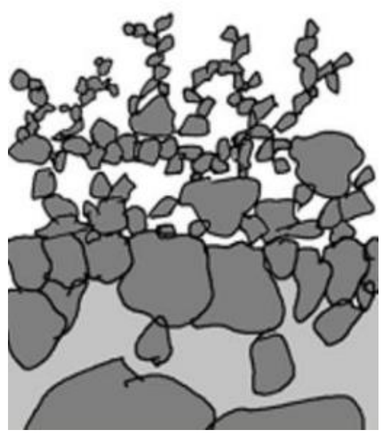

Figure 5. Lunar dust settled on a surface in complex 3-dimensional structures often called "fairy castles," which consist of towers and branches leaning at high angles and connected by thin bridges and arches[9].

Applying lunar dust to thermal systems during testing can be a challenge. Many tests will require a vacuum environment to capture the appropriate heat transfer methods, though it may not always be possible to apply dust to the hardware in-vacuo. In many ground tests, dust has been applied to the surface of interest in atmosphere and then the component has been placed into the vacuum chamber for testing[17]. Others have designed systems which can apply dust inside a vacuum chamber[11,15]. The level of vacuum achieved can significantly impact test results depending on what is being studied, and sometimes even levels of 10^{-6} Torr are not enough to replicate the lunar environment, which has a pressure as low as 10^{-12} Torr. For dust mitigation testing, too high of a pressure could result in inaccurate results that will not be replicated on the Moon. This was observed during Apollo LRV brush cleaning testing on Earth, shown in Figure 6. The misleading test results were conducted at a pressure of 10^{-6} Torr, which is typical of vacuum testing at NASA. The results made it appear as if Teflon brushes were effective at clearing dust from thermal surfaces. However, during the mission, astronauts noted that dust remained on the LRV's radiators even after many brushings and led to the vehicle's overheating[16].

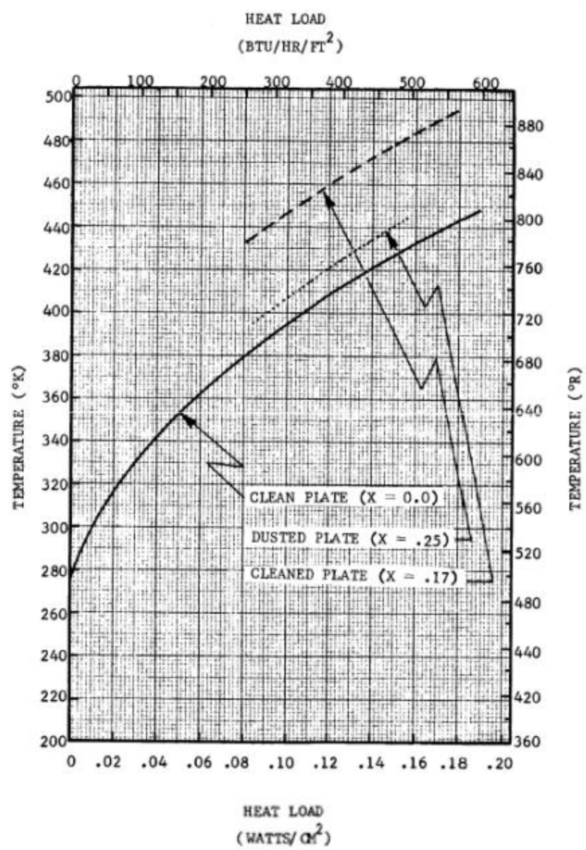

Figure 6. Ground testing results which showed temperatures and heat load comparisons between a clean, dusted, and cleaned plate were misleading. The plate was cleaned by Apollo dust brush[16].

Depending on the environment or dust level that is required for a test, dust may need to be applied liberally or at very specified amounts. Many prior studies have chosen to ensure that dust is equally distributed across the test surface, and there are several different dust deposition methods for applying simulant to a test surface, such as tumblers and vibrating sieves. Aerosol-based dust distributers are especially popular when a small, even amount of dust (such as a monolayer) is desired[17]. They may also be better suited for testing delicate surfaces, such as radiators, that could be damaged by other deposition methods and more closely resemble the dust transport mechanisms these components will experience on the lunar surface, mainly dust that has been lofted by vehicle activity or suspended above the surface via electrostatic forces[18].

Thermal modeling and analysis using software can be a helpful tool for estimating the impact of lunar dust coverage on thermal systems and comparing performance between BOL and EOL assumptions. The HLS Lunar Thermal Analysis Guidebook is an excellent resource for guidance on developing thermal models on and around the lunar surface. It recommends modeling radiators that will experience dust accumulation from vehicle-based forces as having the optical properties of the regolith. For a stationary radiator, or if sufficient dust mitigation methods will be applied, the surface can be modeled as only having a monolayer of dust from accumulation via electrostatic forces. The addition of the monolayer can be assumed to change the surface's optical properties to lie somewhere between that of regolith and the pristine surface. The Rule of Mixtures or a nonlinear relation similar to what is shown in Figure 1 can be used to estimate solar absorptivity of the contaminated surface. Assuming 100% coverage of the monolayer is advised unless there is a specific justification for an alternate assumption[8]. The authors of this paper suggest further modeling assumptions be made to account for the insulating effect of dust on a spacecraft surface, especially when modeling thermal radiators and when modeling dust coverage greater than a monolayer. One way this could be done would be to model dust similarly to how a thermal blanket is modeled by using an effective emittance.

APPROACHES

It can be difficult to advocate for dust mitigation due to the uncertainty in predicted exposure and the lack of knowledge of the performance of thermal systems during and after exposure to dust contamination, especially when other significant design challenges exist which can be quantified and are competing for resources. Requirements cannot be written at this time to bound the system to meet exposure to a certain amount of dust; exposure will vary depending on the con-ops and design of the vehicle. Furthermore, true exposure levels will have to be learned over multiple missions. Still, there are many potential design approaches that can be taken regarding lunar dust. The first is to assume dust will not be a problem and to accept the risk. Since the LTV and PR will be operating and moving across the lunar surface, one can hardly argue that dust will not get onto external sensitive surfaces. This approach is not recommended and will not be acceptable given the severity of the consequences and the high likelihood of thermal degradation and failures due to lunar dust coverage outlined in the sections above. The second option is to determine how much dust will be on the LTV and PR thermal systems and how that dust will impact thermal performance. Once performance degradation is better defined with adequate testing and analysis, then the project can choose to either mitigate the dust or accept it. This approach may save cost in the long-term if the dust environment proves to be tolerable by the system as designed, but it invites the risk that it will be difficult and costly to implement any serious design changes if dust needs to be mitigated to meet performance requirements. The final option is to assume dust will be a problem and to design mitigation methods early in system development. This option reduces the risk to schedule by developing dust mitigation strategies and including them in the baseline design instead of waiting until later in the project lifecycle when it is more challenging to implement changes and there is less time to be fully confident in mitigation strategies. The LTV and PR projects will need to balance these approaches to develop a design that meets requirements while being cost effective and meeting the challenging Artemis schedule.

In any approach which is acceptable to NASA, the system will need to be tested under reasonable or conservative environmental conditions. LTV systems should be tested according to SMC-S-016 and NASA-STD-1008[13]. PR will have similar testing standards. The "Tips for Testing with Dust" Section contains helpful information on testing systems with lunar simulants.

DUST MITIGATION

Dust mitigation will be required by LTV and PR to prevent regolith contamination to crew, equipment, and payloads. Specifically, mitigation for thermal systems is needed so the rover can efficiently reject heat, keep components within their operating temperatures, and meet its expected lifetime. Methods of dust mitigation may be accomplished in the following order: avoid, remove, and tolerate, as first written about in NASA/TP-2022-000000 Lunar Dust Mitigation – A Guide and Reference – First Edition. Avoiding dust is optimal, as it keeps surfaces closer to their pristine conditions and limits the need for time and resources to clean dusty components. For example, moving sensitive surfaces such as radiators to the top of the vehicle keeps them furthest away from the dust kicked up by the rover wheels, and angling surfaces allows for more dust to slide off with assistance from gravity. Adding fenders is an option that can greatly reduce the amount of dust lofted onto the vehicle. When an LRV fender broke on Apollo 17, the dust spray from the wheel was several meters high. It coated the LRV and the astronauts in excessive dust and caused thermal issues for the LRV batteries. In addition to fenders over wheels, removable or permanent structural covers could shield all or portions of delicate radiator surfaces during dusty operations and were part of the Apollo LRV design. Oversizing radiators would make them more tolerable to a small dust coating by accounting for performance degradation from an added dust layer, however, this action would increase the overall mass and cost[1]. Removing/cleaning dust routinely or as needed can return components to operating closer to their BOL state. However, cleaning dust off surfaces takes valuable crew time. and it is difficult to remove all dust from a system since the charged particles can cling to surfaces and are very small. Continuous cleaning may also damage a surface, as described in the "Abrasion" Section. Beyond avoidance and removal, some level of dust tolerance will be needed, as it would be impossible to keep all rover surfaces entirely dust-free. In reality, a lunar rover is likely to employ a combination of all three methods (avoidance, removal, and tolerance) based on mission requirements and resources. Dust mitigation methods can further be classified as passive or active methods and are further discussed below. Typically, methods of avoiding dust exposure are passive techniques, while dust removal measures are active techniques. A hybrid approach of both active and passive techniques is anticipated to be more effective at achieving dust mitigation.

Passive Mitigation

Passive mitigation methods are defined as requiring no power or human intervention to limit dust exposure. This can be accomplished several ways. Some of the more popular passive mitigation options are surface modifications through specialized coatings or materials with low surface energy, such as super-hydrophobic coatings, which reduce adhesion forces to make dust particles less likely to stick and easier to remove. They are created by changing the surface topography, surface chemistry, or a combination of the two. Laser patterned copolyimide coatings are one type of passive mitigation coating studied by NASA in addition to other low surface energy polymers and thin-film optical coatings. The copolyimides contain a surface modifying agent and laser-patterned microscopic surface features that limit available surface area for adhesion[19]. The Lotus coating engineered at NASA's Goddard Space Flight Center is a nano-textured, bio-inspired, super-hydrophobic, customizable, and self-cleaning coating that also repels dust by reducing surface energy and contact area. Shown in Figure 7 below, it has been tested on thermal surfaces, including white paint and Kapton, and in simulated space environments[20]. Charge dissipative coatings using indium tin oxide films have been researched as another coating option. These coatings would limit the build-up of electric charges on a surface that could attract charged lunar dust particles[18]. Work function matching coatings developed by the NASA Glenn Research Center match the minimum energy to remove an electron from a surface to the energy of lunar dust to limit charge transfer and adhesion[21].

In addition to NASA-developed passive coatings, several companies are also researching passive dust mitigation coatings by using novel techniques or by further developing NASA's passive coating designs. For example, the company AMSENG is developing several options for their own charge dissipative coatings which are less porous than other available coatings and are able to withstand the space environment[22]. In addition, Smart Materials Solutions, Inc., is creating scalable and nano-textured dust mitigation coatings with surface geometries designed to reduce dust adhesion[23]. These are only a few examples of the continuing commercial research and development regarding dust mitigation coatings.

With many available options at different stages of development, when selecting a passive coating for use in design and testing, it is important to consider not only its effectiveness at dust mitigation, but also its scalability, durability, and longevity in the harsh space environment.

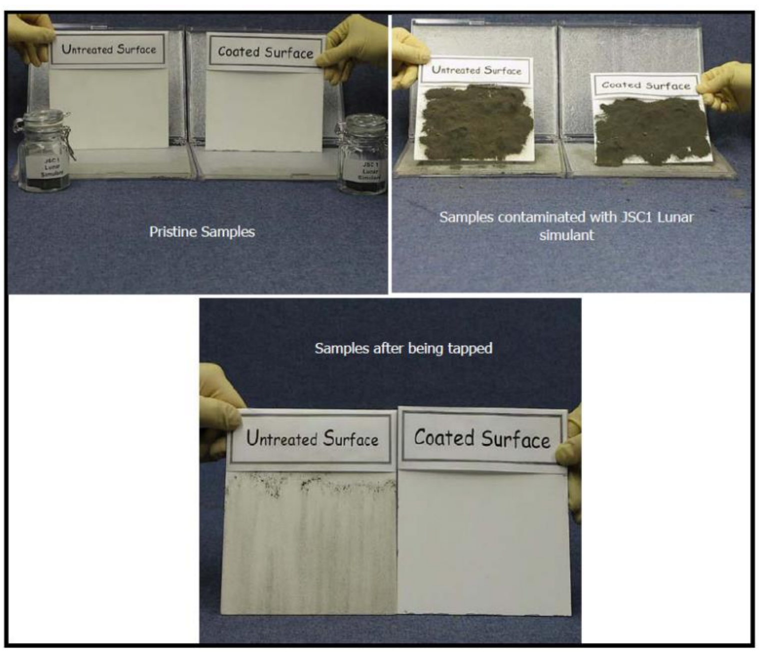

Figure 7. The Lotus coating has been demonstrated compared to an uncoated surface[20].

Active Mitigation

Active mitigation methods require power or astronaut intervention to remove dust. Brushing was a primary, but not entirely effective, method of active dust mitigation during Apollo. The brushes used by the astronauts could not brush finer layers of particles away[4]. Brushing would also be impractical for a long-duration mission since repeated cycles would scrape dust across a surface and abrade it. Since Apollo, studies have examined the effectiveness of different types of brushes at removing regolith, in addition to wipes and cloths. Gaier et al. (2011) tested multiple brushes shown in Figure 8 in atmospheric conditions before testing the promising brushes in simulated lunar conditions. They found that the Zephyr Fiberglass and Escoda Fan Nylon brushes were effective at removing dust and restoring optical properties to 90% of their pristine α/ε for Z93 and AlFEP in a simulated lunar environment[11]. Some cloths also have demonstrated an improved efficacy at removing dust and limiting surface damage from repeated use, such as terry cloths and microfiber cloths. However, like brushes, their effectiveness is highly dependent on the type of surface to be cleaned. In addition, studies have examined adhesive and pliable cleaners, but many leave behind residue or outgas and are not rated for space[10].

Figure 8. Brushes which were used in the study by Gaier et al. are shown as follows: (a) nylon, (b) PTFE, (c) Thunderon, (d) B&B Carbon, (e) Black Gold Fan, (f) B&B Glass, (g) Black Gold Fan, (h) Locked Fan, (i) Zephyr Lightning, (j) Escoda Fan[11].

Compressed gas is another active mitigation method being explored. Gas could be exhausted from strategically placed vents or the end of an articulating arm to blow dust from a surface. This method would be scalable and adjustable through varying the pressure and amount of gas used, and the gas itself could come from spare commodities. However, it would be challenging to control where the re-lofted dust would land. While pressurized gas was not used for regolith removal on Apollo rovers, it has been used for Martian vehicles. The Mars Perseverance rover employs a gaseous Dust Removal Tool (gDRT) to blow away drill cuttings using a few quick puffs of inert nitrogen gas. A similar tool has been proposed for use on lunar rovers to extend equipment lifetimes[24]. Alternatively, handheld tools that do not require gas are also being developed. Work is being done at Kennedy Space Center (KSC) to develop static ionizer tool for astronauts to remove dust and neutralize electrostatic charge from materials and researchers at the University of Colorado Boulder and Jet Propulsion Laboratory (JPL) are working on a “Moon Duster” that repels dust on hardware using an electron beam[25,26].

Many of the above active techniques could be attached to robotic end effectors for increased automation. Employing robotics could allow for more quick and precise cleaning and dust removal in areas of the rover astronauts cannot easily reach, such as high surfaces. They may also be better suited for large or delicate surfaces like radiators that would require much crew time to manually clean.

The Electrodynamic Dust Shield (EDS) is a NASA-developed active dust mitigation technology that can be applied to many optical and thermal surfaces. EDS uses an electrode array to generate an electric field that can lift and carry the dust particles off the EDS-applied surface within a few seconds. The technology is notable for its applicability to both flexible and rigid structures, as well as both opaque and transparent surfaces. Its ability to clear simulant as well as pristine regolith collected during the Apollo missions has been tested in high vacuum (10^{-6} kPa) under lunar gravity on a reduced gravity flight. EDS has also been sent to International Space Station to evaluate its ability to withstand the harsh space environment and will soon be tested on the lunar surface as a Commercial Lunar Payload Services (CLPS) payload. It can remove both charged and uncharged particles in the range of 10 to 300 µm with a 95-99% clearing efficiency. The technology is scalable to large surfaces, however, it does require high-voltage input power to function. New three-dimensional versions of EDS have been developed for thermal radiator paints, including AZ-93 and A276. Figure 9 shows the before-and-after results of an EDS performance test, where a dusty surface becomes almost completely cleared[24,27,28].

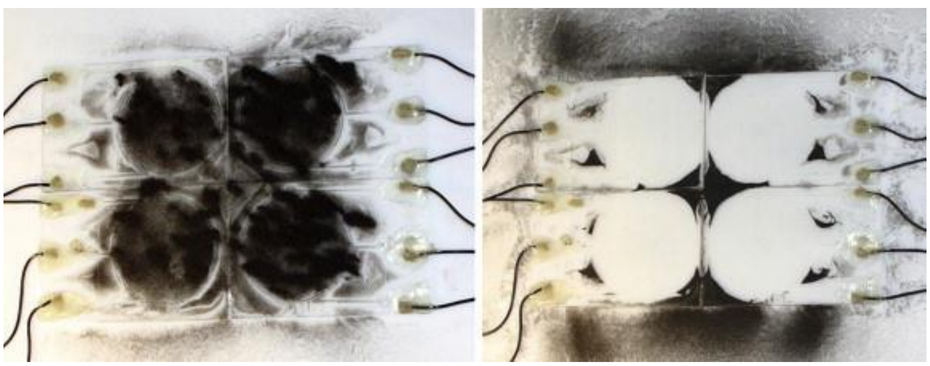

Figure 9. EDS was demonstrated in a 2011 performance test[24].

UNKNOWNS

There are still many unknowns in the natural and induced environment that need to be examined to ensure the LTV and PR will meet thermal performance needs before and after exposure to lunar dust. Though astronauts have been to the lunar surface and brought back regolith samples, they did not land in the South Pole, the site of future Artemis missions where LTV and PR will roam. Regolith in the South Pole is expected to be similar to that found elsewhere on the surface (Highlands), but there may still be some surprises. Of particular concern to thermal engineers are thermal conductivity and particle size distribution. Both regolith properties, among others, could strongly impact the structure of the dust layer and how insulative the layer could be, as discussed in the "Thermal Impacts" and "Tips for Testing with Dust" Sections of this paper. There is little to no concern about optical properties of the surface being different from what is currently shown in the DSNE because they are known values measurable from orbit. However, the combined effect of the change in solar absorptivity and the insulating quality of the South Pole dust layer still begs further study. Both aspects will be important for LTV and PR which will have thermal surfaces in and out of sunlight during the mission.

The induced environment is also a significant challenge to characterize. A defining question is: how much dust will adhere to thermal surfaces on the vehicle? This question leads to more questions–how will dust be lofted onto the thermal surfaces and what quantities will loft? From there, engineers may be able to determine how much of this dust sticks to the rover surface, evaluate the thermal impact, and implement a corresponding mitigation strategy, if needed. However, even determining how to make an estimate is an ongoing challenge. LTV and PR will be new vehicles designed for a longer lifetime than the LRV and operating in a different region of the Moon. Estimates of expected dust levels will be important in making decisions on dust mitigation, but the methods for making such estimations are not concrete, as numerous variables are involved, such as adhesion, cohesion, size, shape, surface roughness, particle composition, and particle charge. Many properties of dust and the vehicle are relevant, as well as the dust transfer mechanisms. Dust can be lofted by various methods–engine plumes, roving, EVA activity, and robotic activity. Simply being near dust-coated objects may still result in dust transfer due to tribo-electric charging.

Lander activity can loft a lot of dust. Plume Surface Interaction (PSI) is a multi-phase discipline that describes the lander environment due to the impingement of hot rocket exhaust on regolith and is a subject of ongoing investigation for multiple groups around NASA, academia, and industry. Because there is no atmosphere on the moon, regolith will follow a ballistic trajectory until it strikes something, be that the ground, the lander, or other hardware in the vicinity such as the LTV or PR. However, that movement is complicated by the rocket plume. There are preliminary multi-phase flow simulations which can help predict dust lofting due to lander plumes, but there are still high levels of uncertainty[29]. The gaps include scaling to flight-relevant vehicles and environments, large uncertainties with Apollo data, and uncertainties on the significance of relevant parameters. Ground testing may be carried out when possible using a regolith bed in a vacuum chamber and a plume of either inert gas or hot fire.

NASA-STD-1008 contains a table of potential planetary external lunar dust sources with associated accumulated surface loading, but the table is incomplete at the time of this writing. Human-generated surface transported dust currently has an estimated loading of 40 g/m^2, which was the maximum estimated dust movement observed in Apollo walking and rover video archives. This is at best a starting point, but it should be used with caution as the source does not provide information on where this loading was on the LRV or suit or how it was estimated. Dust lofting from vehicle motion could be calculated with the basic equations of motion assuming a certain vehicle and tire design and that the dust particle could come off the wheel at any time. The dust particle movement from the rover wheel is then based on how fast the rover is moving and the direction the tires are turned. A model built using these principles may be able to shed light on what parts of the rover will be impacted by dust and what is of lesser concern, but it might not be enough to determine dust load amounts.

Modeling of dust transfer is made difficult by the complex integration of the forces of gravity, plasma charging and triboelectric charging, and those forces involved in dust adhesion and cohesion, like van der Waals forces. While plasma charging is fairly well understood for orbiting vehicles, simulating that with tribo-charging on the lunar surface has not been done. It is also extremely difficult to combine these in ground testing. For triboelectric dust transfer, whether dust will loft and potentially transfer to the surface of interest can be simplified by comparing the

Coulomb force with the lunar gravitational force. If the Coulomb force on the particle is greater than the gravitational force, it will loft. The Coulomb force can be calculated with experiments to determine the electric field using the geometry of the design, distance away from the dusty object, and the electric potential on the surface or surface charge density[30]. This can indicate if the dust lofts, not how much, but is a good first step if there is uncertainty if an operation will cause dust to loft.

Adhesion of dust to different surfaces is also still being investigated. Adhesion is primarily governed by van der Waals forces in the short-range and electrostatic forces in the long-range[31]. Surface energy of the dust and surface, surface roughness, particle size, particle shape, substrate orientation, surface temperature, and surface charge are all variables that may impact adhesion. Surfaces can reduce adhesion through possessing a low surface energy and certain surface topographies; such methods are employed by several of the passive coatings discussed in the "Dust Mitigation" Section[19]. Dove et al. (2010) found that bombarding some surfaces with an ion beam lowered the van der Waals force and reduced adhesion[31]. Some coatings can be more porous than others and trap more dust on a surface, and as mentioned previously, they can have different levels of electric potential and charge density. Particles can also more easily imbed into pliable surfaces[19]. Every surface has unique properties and will have varying forms of interaction with dust, so any surface of interest should be included in adhesion testing. Barker et al. (2022) developed a method for measuring dust adhesion forces to various lunar materials, including thermal coatings. Their method uses centripetal force created from the rotation of the test stand to shed dust under high vacuum and with UV conditions, but it has only been tested thus far with one simulant on a handful of different surfaces[15]. It is similar to an earlier method used by Dove et al.[31]. There are also several other methods for quantifying adhesive forces of dust[19,32,33]. It should be noted that dust accumulation is distinct from dust adhesion because the particles interact with each other very differently than they interact with a pristine surface. Dust cohesion between particles is better understood than dust adhesion to a surface. Dust may not continue to collect on surfaces that are already contaminated.

While testing standards for lunar dust are outlined in NASA-STD-1008, there also remains uncertainty about the impact of simulant choice when testing. As mentioned earlier, different simulants may produce different results during testing, and repeated tests with additional simulants may be necessary for work that has been presented here. As mentioned in the "Tips for Testing with Dust" Section, changing the vacuum level at which a test is run can lead to noteworthy changes in experiment results, and too high of a vacuum test could lead to inaccurate conclusions about the effectiveness of a dust removal method. Verification of test results and confidence in test data will be important in certifying flight hardware, so understanding the unknowns and uncertainties surrounding dust and dust testing can lead to a more comprehensive test plan and balanced interpretation of data.

CONCLUSIONS AND RESOURCES

Lunar dust poses a significant risk to the performance of rover thermal systems due to its unique properties. The small particles are highly abrasive, sharp, adhesive, and insulative. Lunar dust accumulation can significantly impact the optical properties of radiators and other thermal surfaces by increasing solar absorptivity, and if enough dust is present, it can also decrease effective emissivity. Both the increase in solar absorptivity and the decrease of effective emissivity result in higher surface temperatures when in the sun. The jagged texture of the grains can abrade surfaces as they are moved across. Ground testing in a simulated lunar environment can aid in evaluating the performance of hardware exposed to lunar dust and the effectiveness of dust mitigation methods. However, there are several vital details to consider for testing, including simulant choice, dust deposition method, level of vacuum, and method for quantifying dust accumulation.

Key decisions will be how to approach dust mitigation and what method(s) to use. Dust mitigation methods can involve avoiding, removing, or tolerating dust and can also be classified as active or passive. There are many methods that have been studied and used before or are currently being developed and tested, each having their own strengths and weaknesses for the designer to consider. There are still many unknowns associated with lunar dust, especially involving characterizing the induced environment, that engineers should be aware of. Both LTV and PR will encounter significant amounts of dust while roving the lunar surface during their long-duration mission, so it is critical that the importance of the lunar dust problem and its implications to rover thermal systems is understood.

Many resources are available to aid engineers in the design and testing of rover systems in relation to lunar dust. As mentioned previously, NASA-STD-1008 is a NASA technical standards document that contains guidance and requirements for lunar dust testing. *Lunar Dust Mitigation: A Guide and Reference* (NASA/TP-20220018746) is a NASA technical publication that defines lunar dust and presents many different approaches to dust mitigation. It describes how dust can impact different systems and what dust mitigation technologies and strategies are available for those systems. SLS-SPEC-159, known as the DSNE, provides specifications on environmental conditions on the lunar surface, including lunar regolith properties and parameters for the lunar thermal environment. The HLS Lunar Thermal Analysis Guidebook advises thermal engineers on best practices for conducting lunar thermal analyses in compliance with the DSNE, including guidance on how to account for lunar dust in thermal models. All of these documents are cited below. In addition to this paper, the combination of these additional resources should provide the engineer with a fundamental knowledge of the lunar dust environment, dust impacts to thermal systems, dust mitigation strategies, and dust testing.

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