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Lunar Dust Mitigation: A Guide and Reference
First Edition (2021)

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Acknowledgments

Creating a lunar dust mitigation guidebook that is both in-depth yet useful in general is a daunting task, requiring input from quite a number of subject matter experts. Fortunately, there are numerous highly capable scientists and engineers, both within NASA and outside, who have been willing to collaborate.

Gratitude first goes to the contributing authors, who have shared of their expertise to benefit the lunar exploration community. An individual key to the completion of this guide is Project Manager Dr. Erica Montbach, who kept tasks moving toward the end goal despite the distributed, extended nature of the challenge. Michael D. Anderson and intern Seemi Zameer are responsible and also thanked for, respectively, the comprehensive bibliography compilation and the initial images permissions list used in assembling a “final” document.

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Acknowledgment is due also to Michael Johansen for “commissioning” a lunar dust mitigation guide. The recognized need is to familiarize a new group of potential hardware builders and mission designers with the hazards posed by the lunar surface conditions, specifically the unique (to human experience) microscopic particulates of lunar regolith.

Too many to name have contributed helpful suggestions and recommendations, serving as a reminder that this version of the guide is at best a snapshot of current knowledge, intended to be supplemented, extended, and even eclipsed by what we learn as we return to exploring and probing the Moon.

As this specific document nears public release, NASA is on the cusp of generating and capturing new information about previously unexplored regions of the Moon, with potential implications for human exploration over many years to come. Lunar dust mitigation has been written about since the Apollo Program and is far from a demonstrated “solved” problem. So, a thank you is due to all of the contributors responsible for helping lay out what we do know, with the expectation and request that as we collectively learn more, that knowledge will be shared to the benefit of all.

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Summary

On the surface of the Moon, lunar dust presents unique challenges to long-term operations due to the ubiquitous presence of dust particles in the lunar environment, the dust’s potential to electrostatically charge, and its possible chemical reactivity. Whether to avoid exposure, to attempt removal, or simply to tolerate lunar dust infiltrating a system becomes a complex question involving length of required service life, dust effects and critical risks, and mass and complexity trades for the entire system. This publication provides a snapshot of advice from topical experts for specific areas of concern to systems targeted for deployment on the lunar surface.

Following introductory overview commentary, dust mitigation approaches appropriate to the lunar surface are first addressed for typically static structures such as optical surfaces, radiators, and other thermal control surfaces, followed by regolith exposure concerns for communications equipment and non-optical sensors. The broad topic of mechanisms and mechanical assemblies is broken down to address relevant component-level concerns, including issues affecting bearings and seals, as well as concerns specific to softgoods (fabric) components of spacesuits. Finally, human health issues and concerns are briefly addressed, though the emphasis of this publication remains with components directly exposed to the harsh lunar surface environment.

A description of some lunar surface hazard details, in particular characteristics of lunar surface dust, follows in Appendix A, and more detailed explanations of quantification issues for particulates are given in Appendix B. The simple inertial removal of particles from a surface is discussed in Appendix C, followed by a summary of terrestrial best practices for dust mitigation recommended within select industries in Appendix D. The aggregated bibliography of references is very useful and can serve as a constructive start to finding further information.

1.0 Introduction and Rationale

With return to the lunar surface set as a priority, safely and for more than a few days at a time, lunar dust is once again being recognized as a unique challenge. As this guidebook’s first edition nears completion, more than half a century has passed since humans last walked on the lunar surface. Most of the men with direct exposure to lunar dust are no longer with us, nor are the vast majority of the Apollo-era engineers who contributed to serial attempts at dust mitigation on successive Apollo lunar landing missions (Gaier, 2005).
In the intervening decades, multiple nations have flown spacecraft past or orbited the Moon, gathering accumulating evidence that the lunar surface may hold resources valuable to human exploration beyond the surface itself (e.g., regolith minerals). In particular, the NASA Lunar Prospector orbiter mission, launched in 1998, detected hydrogen at both lunar poles, possibly in the form of water ice. The Lunar Crater Observation and Sensing Satellite (LCROSS), manifested with the Lunar Reconnaissance Orbiter (LRO), launched in 2009. LCROSS became the first NASA hardware to reach the lunar surface since Apollo 17 in 1972 and was an impactor, with its Centaur upper stage creating a rich plume from Cabeus crater, near the lunar south pole. Water and other valuable ejecta were detected in the plume, driving interest in visiting a lunar pole to map the potential usable resources (Williams, 2023). Eventual use of local materials such as water could enable much longer-term human exploration.

The lunar environment is unique in human experience due to the lack of air to slow the motion of lightweight objects, to transmit sound, and to carry heat; the extreme temperature differences between sunlight and shadow (also experienced in orbit); and a layer of pulverized rock on the lunar surface that can be electrostatically charged and tends to cling to and even bond with engineering surfaces that it contacts.

For a particle of the lunar surface, the underlying physics is that the regolith has spent years (millions? billions?) exposed to hard vacuum, full solar spectrum (ultraviolet (UV), x ray, etc.), solar electron and ion (mostly proton) bombardment, and the occasional cosmic rays, in addition to micrometeoric “gardening” due to the lack of shielding atmosphere or global magnetic field. On Earth, fracture surfaces are almost instantly passivated by (typically) oxygen or water in the atmosphere reacting with the freshly broken molecular bonds. In the lunar environment, those surfaces can remain pristine for a long time and can even be kept clean under energetic photon bombardment (to desorb stray molecules) and/or ion bombardment, similar to cleaning surfaces using an ion gun in an ultra-high vacuum chamber. That unpassivated, chemically reactive state is the lunar regolith particle surface condition of most concern in dust mitigation efforts.

Chemically reactive particle surfaces that contact typical engineering surfaces may bond, at which point removing that particle risks damaging the engineered part, either by fracturing and leaving residual material or by pulling part of the original surface away. Whether that has any consequence to the part functionally is the next question, and incorporating dust tolerance into the design is recommended if exposure to reactive lunar particulates cannot be avoided. To measure dust reactivity effects terrestriallly, Dr. James Gaier investigated the difficulties and some methods for activating particulate surfaces of simulants, using the purpose-built lunar dust adhesion bell jar (LDAB) he had assembled to provide higher fidelity lunar dust effects testing (Gaier & Sechkar, 2007).

For differentiating current commercial dust mitigation approaches, particle size distribution and morphology used for testing should be a consideration in addition to surface chemistry. Replicating lunar particle surface chemistry is hard to do, but even here on Earth, the smaller particles are typically more difficult to deal with than larger particles. Engineering surface topography modification, for instance, can be particle-size-scale dependent because the aim is to minimize contact area with the particles, independent of reactive or passivated surface chemistry. A more detailed (and technical) description of lunar surface hazards, lunar surface dust in particular, can be found in Appendix A. At the time of this writing, Erin G. Hayward is leading an effort at the NASA Marshall Space Flight Center to construct a “Guidebook to Ground Testing for the Lunar Surface Environment,” to be available soon, with scope beyond “just” lunar dust mitigation.

Rather than an exhaustive listing of robust equipment suppliers or a detailed analysis of single dust particle interactions within a bearing, this guidebook is intended both to serve as a handy reference pointer for seasoned lunar instrument designers and to steer first-time lunar hardware builders away from terrestrial “common sense” practices that were ineffective against lunar dust during the Apollo-era lunar surface visits.

The overview in Section 2.0 serves as an introduction to the handbook’s detailed discussion of (overlapping) dust mitigation approaches appropriate to the lunar surface, organized in Sections 3.0 to 7.0 by specific areas of concern. Appendix A provides a description of various lunar surface hazard details, in particular characteristics of lunar surface dust. More detailed explanations of quantification issues for particulates are given in Appendix B. The simple inertial removal of particles from a surface is discussed in Appendix C, followed by a summary of terrestrial best practices for dust mitigation recommended within select industries in Appendix D. Nomenclature is given in Appendix E.

The aggregated bibliography of references, while extensive and very useful, should not be construed to be exhaustive and can serve as a constructive start to locating the most up-to-date data and information.

2.0 Dust Mitigation Overview

2.1 The ART of Lunar Dust Mitigation

The “ART” of lunar dust mitigation is a mnemonic; as with terrestrial dust hazard approaches, mitigation strategies fall broadly into three categories: Avoid, Remove, or Tolerate. The most attractive approach, if it can be accomplished, is to simply avoid dust exposure. For ball bearings on a rotating
shaft, for instance, avoiding dust could involve a combination of rotating seals, grease capture, and/or shielding, and even avoidance by design, such as placement of components away from dust sources. Although this approach may work for the bearing, it has simply moved the dust exposure out to the seals.

Another common approach with dirt is removal, whether inertial (shaken, not stirred), liquid or pneumatic (gas) stream, or physical scraping to mechanically dislodge the particles. Electrostatic or magnetic fields may remove some classes of particles, in some cases even down to the dust particle size range. As mentioned in the introduction, pristine lunar surface particles may exhibit chemically reactive facets that can bond with exposed hardware surfaces, so operational reliance on cleaning should typically be less favored than avoidance of regolith altogether.

A third approach to handling dust exposure is simply tolerance of the particulate presence, such as that rotating shaft seal protecting a ball bearing, which cannot itself avoid dust exposure. For moving parts, dust tolerance may involve abrasion-resistant materials or hard surfaces and may also require by-design features, such as loose-fit articulation joints of wear-resistant (hard) materials. Static structures such as radiators and solar arrays may require oversizing to tolerate some level of performance degradation when dusty. Inherently more tolerant designs, such as flexures instead of limited rotation bearing joints, may be possible in some applications.

Whether to avoid, remove, or tolerate lunar dust exposure is a decision to be based on length of required service life, mass and complexity trades, and value (criticality) of the system. When evaluating different approaches to surviving the lunar surface, the quantification of “to what” and “to how much” a system has been exposed becomes critical for valid comparison, both within and across laboratories and development teams. A more detailed explanation of exposure quantification issues can be found in Appendix B.

2.2 Technique Categorizing: Avoid, Remove, Tolerate

In considering lunar dust mitigation strategies as a whole, operational approaches (concepts of operations, or ConOps) could be productively employed in many cases and are likely mission specific. Construction of rocket-plume-resistant landing pads, potentially with berms for plume deflection; slightly removed landing areas with consolidated or raised-grid connecting roadways; shielding of susceptible infrastructure by design from activity-generated particulates; and any number of clever operational strategies can reduce the dust and particulate exposure of valuable lunar assets. These are methods to decrease the lunar environment “source term,” the amount of material potentially impacting lunar assets. While potentially very valuable, such ConOps mitigations depend on specific mission plans and possibly on cooperation by all entities in the vicinity; the many useful operational approaches to dust mitigation are therefore not a focus of this guide.

Of the three primary dust mitigation strategies—avoid, remove, and tolerate—such infrastructure and possible operational measures typically fall under the avoid heading. Environmental dust reduction could lessen the anthropogenic source term globally, for instance by providing solid or plume-entraining landing pads for arriving rockets, by locally fabricating and constructing raised-grid astronaut walkways, or simply by consolidating and binding a robust layer of regolith for light traffic to avoid tracking through loose regolith particulates. Many methods to decrease or avoid dust exposure can be categorized as passive techniques. As mentioned previously, various seals can be designed to avoid dust exposure for interior protected components, including sealing methods that attempt to capture any encountered particles (within limits, e.g., oiled felt barrier or grease pack for moderate temperature ranges), all with the goal to avoid dust exposure of vulnerable interior parts.

Techniques to remove lunar dust encompass a broad range of mechanical methods, including gas or other fluid streams, inertial separation schemes (impulse, shaking, or vibrating), and physically scraping or wiping exposed surfaces. Electrostatics and/or electrodynamics forces are another approach to particulate removal and, as with mechanical methods, may show strong dependence on factors such as particulate size, shape (angularity), surface reactivity, and particle composition. Removal typically involves active techniques, for example, electron beam charging of particles on an exposed surface, taking advantage of the lunar vacuum. How to measure dust removal effectiveness depends critically on accurately determining “before and after” particulate loading, or at least having some functional criterion for dust removal success.

Given the difficulty of completely avoiding lunar dust and of reliably removing dust once encountered, designing systems to tolerate some anticipated level of dust exposure is often prudent. For apparatus with relatively large, exposed functional surface area, such as solar arrays or radiators, slightly oversizing the active area can mitigate some performance degradation, with mass–balance tradeoff decisions to be made against avoid or remove alternatives. Mechanically active components such as wheels, blades, and excavation buckets that must contact regolith can be designed for abrasion resistance (hard and/or tough surface materials); can by design incorporate wear-insensitive dimensioning, such as loose-fit joints; and/or can be designed for easy, even autonomous field replacement. Flexure joints instead of limited-angle rotary connections could be appropriate in some limited applications to provide dust tolerance. As with techniques targeting removal of regolith,
reliable measurement of particulates down to the nanometer scale is crucial to quantifying systems’ tolerance to dust exposure, and/or to documenting insensitivity to particles below a given size, for instance. Limited operational lifetime experiments and demonstrations may argue their insensitivity to anticipated low dust exposures, but again, particulate quantification would be needed to verify those claims.

2.3 Specific Areas of Concern

Whether on Earth, the Moon, Mars, or elsewhere, the introduction of particulates onto or into a functioning engineered system is rarely welcome. Lunar dust specifically presents unique challenges to operations on the lunar surface due to its ubiquitous presence, its tendency to electrostatically charge, and its potential chemical reactivity.

A detailed discussion of lunar dust effects and some recommended mitigation approaches follows in Sections 3.0 to 8.0, grouped by areas of concern. Each of these sections and Appendix A to Appendix D were contributed by topical experts familiar with the subject matter, with the recognized potential for subsequent updates and gap-filling data to be incorporated in later editions of this publication.

Mitigation approaches will first be addressed for typically static structures, including optical surfaces, radiators, and other thermal control surfaces. Regolith exposure concerns for communications equipment and non-optical sensors will then be addressed. Next, the broad topic of mechanisms and mechanical assemblies will be broken down to address concerns at the component level, including issues affecting bearings, gears, and seals, as well as concerns specific to soft-goods (fabric) components of spacesuits. Finally, a discussion of human health issues and concerns will address the toxicology, transmission, and biological impacts of lunar dust.

Table 1 identifies the coauthors of this paper who served as topical experts and authored the individual sections.

3.0 Optical Surfaces

Removal of lunar dust from optical surfaces such as camera lenses, helmet visors, photovoltaic (PV) cells, viewports, and windows must be done in a way that does not cause damage to the surface. During the Apollo missions, special brushes were designed and used to remove dust from camera lenses. This technique was successful for the relatively short-duration lunar surface activities but would be impractical and unsuccessful for the longer duration Artemis missions. Repeated use of brushes pushing the abrasive lunar dust over camera lenses or helmet visors during daily extravehicular activities (EVAs) for missions lasting several weeks will likely result in damage to the lens or visor. This technique is also impractical for the larger surfaces of PV cells.

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Table 1.—Authorship of Individual Sections
Successful dust mitigation methods for optical surfaces may be passive, active, or a combination of the two. Passive technologies generally use surface modification methods to lower the forces of adhesion between dust particles and the modified surfaces. Surfaces can be modified with the addition of coatings, such as the lotus-leaf-inspired nanotextured coating (Margiotta & Peters, 2010), or directly modified by chemical or physical means (Wohl et al., 2009). Active technologies use forces generated by electric or magnetic fields; fluids in motion, such as high-pressure gases; mechanisms, such as piezoelectric-driven vibrating membranes or brushes; or mechanical agitation of the surface itself. Appendix C presents a more complete discussion of physical vibration to remove lunar particulates from exposed surfaces.

3.1 Passive Dust Mitigation Technologies for Optical Systems

Surface modification methods reduce the surface area in contact with lunar dust particles, decreasing the adhesion forces without significant modification in transmissivity. Several approaches reduce the surface energy by chemical means. The lotus coating approach, inspired by the water-repelling surface of the lotus leaf (Figure 1), introduces silica, zinc oxide, and other oxides to create a nanotexture on the surface, thus reducing the surface energy (Figure 2). In the lotus coating technique, a hydrophobic layer is added to the nanotextured surface, producing a surface with superhydrophobic properties (Margiotta & Peters, 2010).

Another approach introduces polyhedral oligomeric silsesquioxane (POSS) molecules on a polyimide that is activated with an oxygen plasma to achieve similar results (Figure 3). A different approach uses laser ablation to physically alter the surface. Because the lower energy topography is generated from the surface itself, laser ablation reduces interfacial interactions that may be problematic. The laser-ablated surfaces showed superhydrophobicity with water contact angles greater than 150° (Wohl et al., 2009).

Figure 1.—Scanning electron microscope (SEM) images of lotus leaf (Margiotta & Peters, 2010). (a) and (b) Surface microstructures. (c) Surface nanostructures.
Figure 2.—Contact angles of water droplet on uncoated and coated surfaces (Margiotta & Peters, 2010). (a) Uncoated sample with contact angle <90°. (b) Lotus-coated surface with contact angle >150°.

Figure 3.—Water droplets on polyimide surface before and after polyhedral oligomeric silsesquioxane (POSS) (Wohl et al., 2009). (a) Optical photomicrograph of surface. (b) Water contact angle before POSS deposition. (c) Water contact angle after POSS deposition.
3.2 Active Dust Mitigation Technologies for Optical Systems

3.2.1 Electrostatic/Electrodynamic Methods

The electrodynamic dust shield (EDS) is an active dust mitigation technology developed by NASA at the Kennedy Space Center that uses dynamic electric fields generated by electrodes embedded in a material to actively remove dust from the surfaces of those materials. It is based on the electric curtain concept developed by F.B. Tatom and collaborators at Kennedy in 1967 (Tatom et al., 1967). The EDS has been developed for many applications, including optical systems, thermal radiator coatings, PV cover glass, and seals (Calle et al., 2011).

In general terms, the EDS technology consists of a series of electrodes connected to a multiphase alternating current (AC) source operating at voltages in the low kilovolt range, currents in the milliampere range, and very low frequencies. For optical systems, transparent indium tin oxide (ITO) electrodes are used on optical surfaces, such as camera lenses, solar panel cover glass, astronaut helmet visors, and viewports.

The EDS is able to move electrostatically charged and uncharged dust particles in the 10- to 300-µm range at vacuum. During several experiments run at vacuum on a reduced gravity flight at lunar gravitational conditions, the EDS was able to remove simulant particles in the 400-µm range as well as Apollo 16 lunar fines (Calle, Arens, et al., 2009). At vacuum, the removal force is the sum of the electrodynamic force and the gravitational force. The strength of the electrodynamic force depends on the particle charge, but uncharged particles can also be removed, because neutral particles generally contain charges of opposite polarities that balance out. The electric field generated by the different electrode configurations of the EDS is a diverging/converging field, which generates a dielectrophoretic force that polarizes and moves these neutral particles. The theoretical framework of the EDS has been described in several publications (Calle et al., 2006; Calle et al., 2007; Calle, Buhler, et al., 2009).

Figure 4 shows before and after photographs of the EDS particle removal at high vacuum. Simulant was deposited at vacuum on the four glass EDS panels by means of a shaker on a translation stage operated remotely.

In collaboration with the Florida Solar Energy Center, Kennedy researchers implemented the EDS on the cover glass of several PV panels to determine performance in laboratory conditions with a solar simulator as well as in outdoor conditions (Sorloaica-Hickman et al., 2011a). The EDS was used with polycrystalline silicon and gallium arsenide multijunction solar cells in indoor and outdoor test facilities. UV aging of the EDS coatings was evaluated with 396 h of exposure in a xenon source test chamber. Light transmission in the 190- to 750-nm range was measured with a Jasco V-670 spectrometer before and after each UV-aging 99-h increment. Figure 5 shows the PV/EDS laboratory setup used in the testing. Figure 6(a) shows current–voltage (I–V) PV measurements indicating a slight reduction after UV aging, likely due to aging of the glass substrate rather than the coatings.

The effects on the PV/EDS assembly of dust addition and removal were also measured. A thin layer of dust was deposited on the PV cover glass and the EDS was activated to remove the dust. Figure 6(b) shows PV efficiency with dust and after dust removal. This study showed that the EDS do not degrade the performance of the solar cells tested beyond the expected UV degradation of plain cover glass.
Additional PV/EDS performance experiments were performed in the Kennedy laboratory with ITO on glass EDS panels over commercial solar cells at vacuum. Dust deposition on four solar cells was performed at vacuum using a dust shaker on motorized translation stages. Figure 7 shows the output of these four assemblies before and during dust deposition and after dust clearing by EDS activation (Calle et al., 2011).

Glass EDS panels along with EDS panels for thermal radiators and spacesuit fabric were flown on the Materials International Space Station Experiment (MISSE)–11 in 2019 (Figure 8) (Johansen et al., 2019). The glass EDS and thermal radiator panels were activated with high-voltage power supplies dedicated to each panel. The payload was returned to the Kennedy laboratory early in 2021 and postflight analysis was performed. Additional glass EDS panels were scheduled to fly on MISSE–15 in the fall of 2021.
3.2.2 Electrostatic Tool for Lunar Dust Control

The Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment (SPARCLE) tool uses a focused electron beam to impart a negative charge to dust particles on surfaces. A metal plate at a positive potential is placed in the vicinity of the surface (Figure 9). The SPARCLE probe scans the dust layer with a raster motion to charge the dust. The force due to the electric field thus generated lifts the particles away from the surface, collecting on the plate (Clark, 2010).

4.0 Radiator and Thermal Control Surfaces

All spacecraft require a thermal management system to maintain a tolerable thermal environment for the spacecraft crew and/or equipment. While there are various subsystems and components of a thermal control system (Hurlbert, 2010), the heat rejection subsystem is likely the most affected by lunar dust, primarily due to potential direct exposure and the significant impact the dust may have on performance. The overall purpose of the heat rejection subsystem is removal of excess heat energy produced by the space vehicle to the surrounding environments encountered during the mission. Because of the criticality of the heat rejection subsystem, this section of the guidebook is focused on the radiators included in these systems relative to dust contamination.

Radiators have been identified as an enabling technology for human exploration and development of space. They are common, standard components of the heat rejection subsystems of space vehicles and can be the largest component of the overall thermal control system. Radiator performance depends on the radiating surface area, the optical properties (e.g., emittance) of the radiator surface, the operational temperature of the radiator, the effective sky (viewed) temperature of the surroundings of the radiator, solar radiation and atmospheric irradiation levels, convection to or from the surrounding atmosphere if applicable, and other conditions that could affect the nature of the radiator surface, such as dust accumulation or oxidation.

Dust is expected to be a major contributor to the local environmental conditions at the lunar surface. There is evidence from Apollo and uncrewed lunar missions that significant dust may be accumulated on external space vehicle surfaces (Figure 10). Any dust adhesion to the radiators may affect their heat rejection capability. As an example, on one Apollo mission, the lunar rover vehicle had a broken fender, which led to excessive dust buildup and thermal issues for the battery pack radiator (Pendleton et al., 2007). A primary reason overall heat rejection may significantly change is that the surface optical properties are altered with dust accumulation (Figure 11). This
has been definitively shown in prior research, including work by Gaier, Ellis, and Hanks (2012); Gaier, Siamidis, and Larkin (2010); and Gaier et al. (2008), where “it was found that even a submonolayer of simulated lunar dust can significantly degrade the performance of both white paint and second-surface mirror type radiators under simulated lunar conditions” (p. 1).

Because of the potential impact of dust on a radiator and subsequent changes to the overall thermal system performance, steps must be taken to preclude and/or account for it. The best means of handling the dust is to prevent it from adhering to radiator surfaces. Design considerations to preclude dust exposure might include positioning of the radiator on the space vehicle, such as locating it higher up from the surface and/or horizontally on top of the space vehicle to reduce direct exposure. Structures to shield or block dust might also be utilized, although this addition might increase mass, volume, and so forth, presenting a disadvantage to the overall vehicle design. Because there may be activities (e.g., rover or drilling activities) proximate to the vehicle that can also disturb the dust, it is recommended to locate radiators away from those known operations. A study by Keller and Ewert (2000) indicated that for construction of a lunar base, “heat rejection systems [should] be either located far from any landing sites or be protected from dust producing mechanisms” (p. 571).

Other advanced techniques to preclude dust buildup include special coatings or treatments that may be applied to surfaces, such as a NASA-developed coating to dissipate electric charge (Keesey & Jenner, 2019). While the surface optical properties required for radiators likely preclude use of this specific solution, future research may yield other coating or treatment options. Other advanced concepts are also under consideration, such as using the natural electric charge of the Moon’s dust to preclude adhesion and/or for removal options. Efforts to develop an electrodynamic dust shield (EDS) that could prevent dust accumulation and remove dust adhering to surfaces are described in Calle et al. (2011), and use of an electron beam to clean dusty spacecraft and spacesuit surfaces is discussed in Farr et al. (2020). Spacecraft designers and engineers are advised to regularly research and review new articles and publications in the coming years as there may be significant technology advances given the priority of future Moon missions.

While methods to preclude dust should be employed, it is likely that some contamination of radiator surfaces will occur.
Designers and engineers must attempt to predict and account for this over the lifetime of the space vehicle. A critical aspect is determining the expected dust buildup over time, which also could vary depending on the specific mission and planned operations. This is especially important if the dust layer may exceed a monolayer, given that information and test data for these conditions are scarce. Early evaluation of the effects of thick Mars dust coatings on the emissivity of various surfaces (Hollingsworth et al., 2006) showed significant change in the optical properties. More research is needed to include evaluation with lunar dust and variance in the absorptivity of the surface coatings as well.

Both computer modeling and testing are needed to better understand and plan for the impact of dust on radiators and other space vehicle surfaces. The Human Landing System Lunar Thermal Analysis Guidebook (NASA, 2020a) has a section dedicated to accounting for lunar dust in models; however, it is largely focused on the research and data available for dustings not in excess of a monolayer and for specific selected surface coatings. Because the data and testing are limited to date, programs are underway not only to provide additional data but also to support refinement of computer models and parameters. Ongoing research is evaluating impacts from heavier buildup of dust, testing more surface coatings and treatments, and quantifying expected dust adhesion. Some of this ongoing work leverages earlier research, such as current efforts to expand the work of Hollingsworth et al. (2006) by performing like testing with lunar simulants. In addition to ground-based efforts, early uncrewed missions are planned via NASA’s Commercial Lunar Payload Services (CLPS) program with some payloads that could gather data on environment conditions. One example of a CLPS mission dedicated to evaluating how lunar dust interacts with various surfaces is the Regolith Adherence Characterization (RAC) payload (Northon, 2019) selected by NASA, which will provide visual data on how regolith sticks to various materials exposed to the Moon’s environment. Another example is the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) payload (Warner, 2020), which will capture video and still image data of a lander’s plume proximate to the lunar surface until after engine shutoff. This can provide critical information on dust disturbance to inform future lunar and Mars vehicle designs and operations. Again, designers and engineers are advised to keep abreast of results of ongoing work that can be applied to future missions.

The lack of sufficient data and operational experience at the lunar surface requires a conservative approach relative to dust. Per the Human Landing System Lunar Thermal Analysis Guidebook (NASA, 2020a), when designing a lunar spacecraft thermal system, “It is highly recommended that projects assume 100 percent monolayer coverage, unless a lesser percentage seems justified based on the specific architecture and application” (p. 105). If a heavier dust loading is projected, then ongoing monitoring and maintenance may be needed. Active mitigation may be critical for the thermal system to continue to operate. The same guidebook states, “If the dust coverage is thick enough (i.e., more than a monolayer) then heat must first be conducted through the dust before it is radiated to space. Often, this results in effective environmental sink temperatures that are too extreme and the need for mitigation measures in order for the thermal design to close” (p. 105). Removal of dust from the radiator surface may be necessary, although optimal methods have not been identified. This is further complicated in that radiator surface coatings may be easily damaged (e.g., scratched), which alters their optical properties as well. Because of this, it is unlikely that a brush would be used to clean a radiator, as was tried in Apollo (Figure 12). For the design phase, a recommended approach is to oversize the radiator surface to account for degraded performance over the expected operational lifetime. However, this also comes with disadvantages, such as increased spacecraft mass.

In summary, thermal management systems are a part of every spacecraft, and radiators are a standard critical component to allow heat rejection. For lunar missions, some level of dust contamination is likely and must be accounted for relative to radiator surfaces. Previous missions have demonstrated dust buildup that can significantly change the surface optical properties of radiators. The optimal means to preclude performance impacts is to prevent dust from adhering to the radiator surface, including both design options and mission/operational considerations. Even with preventative measures, it is likely that some contamination of radiator surfaces will occur and must be accounted for. Attempts to predict dust loading should be made as early in the design cycle as possible to support evaluation of options to minimize dust buildup and to compensate for performance degradation. Computer modeling and testing are needed to evaluate the impacts of dust on radiators and other space vehicle surfaces, and some guidance is provided in publications such as The Human Landing System Lunar Thermal Analysis Guidebook (NASA, 2020a). With new technology and ongoing test programs, designers and engineers are advised to regularly review the research findings for application to future missions.
5.0 Communications Antennas and Electronics

Future missions to the Moon will require robust communications systems for astronauts and for various assets. Redundancy will be used throughout the architecture, and human communications will typically require high data rates. From the 2019 Lunar Communications Architecture Study Report (Lunar Communications Architecture Working Group, 2019), primary communications links for a future lunar mission will include the following:

- Earth to Moon—Uplink from Earth to cislunar (lunar orbit, surface, or relay satellite)
- Moon to Earth—Downlink from cislunar, lunar orbit, or lunar surface to Earth
- Crosslink—Link between relay spacecraft
- Proximity link—Link between relay satellite and service user (e.g., orbital spacecraft descent/ascent vehicles, landers, rovers, astronauts with portable communications device, surface communications towers, and human habitats)
- Lunar surface to lunar surface—Communications between landed assets

Figure 13 depicts conceptual lunar communications links for a future mission with proposed frequency bands shown.

Primary communications concerns with lunar dust include transmission (attenuation through dust), dust accumulation and adhesion to sensitive surfaces, and electronics. Although communications systems will likely use other technologies, such as gimbals or optics, these will be covered in their appropriate sections.

5.1 Historical: Apollo Missions

Earlier missions of Gemini and Mercury used up to seven frequencies in separate radio systems for command and data handling, telemetry, ranging, and communications to Earth. With Apollo, a unifying S-band (USB) system operating at 2.2 GHz enabled a simplified design on a single carrier frequency. The USB system handled all of the aforementioned functions, plus television communications. Figure 14 shows a picture of the USB transponder. In addition to the USB, Apollo carried landing and rendezvous radar; a parabolic radar antenna (on top of the Command and Service Module (CSM)); a parabolic S-band antenna (which provided all telemetry, voice, range communications to Earth); and two in-flight, very high frequency (VHF) antennas that provided communications between astronauts, the Lunar Module, and the CSM.

Because the Lunar Module was not returned to Earth, no analysis on the module’s S-band antenna has been performed.
Figure 13.—Conceptual communications links for future lunar missions (adapted from Lunar Communications Architecture Working Group, 2019). Acronyms defined in Appendix E.
Apollo 12 and 14 used an erectable antenna 3 m in diameter (Figure 15) to communicate back to Earth. The antenna was intended to be deployed in about 15 min by a single astronaut, but deployment on the lunar surface proved much more difficult. Thus, two people were required to deploy and align the antenna on the Moon. The antenna was supported with a tripod (1.5 m tall, 1.5 m wide, with a mass of 6.1 kg), but it was easy to tip over on the surface. A sight glass in conjunction with a flexible crank was used to facilitate fine-pointing the antenna to Earth (Figure 16). Friction in the crank arm easily caused the whole structure to move.

5.2 Electrical Properties

Research regarding lunar regolith electrical properties has been performed in the past, both during and after Apollo. Both general conductivity and permittivity of the lunar regolith are briefly discussed. More thorough analysis can be found in Chapter 9 of the Lunar Sourcebook (Heiken, Vaniman, & French, 1991).
5.2.1 Direct Current Electrical Conductivity

Electrical conductivity is a measure of how easily current flows through a material. Most metals have high conductivity, allowing current to easily flow through them; copper is one such example. Because the lunar regolith contains primarily silicates, which typically are insulators, the regolith has a low electrical conductivity. However, there are thermal and charging effects that can affect the conductivity. Soil and rock samples were characterized from Apollo missions. Two soil samples, which are more analogous to lunar dust, showed similar direct current (DC) conductivity. Equation (1) is for Apollo 15 sample 15301,38; Equation (2) is for Apollo 15 sample 16015,6.

\[ \sigma = 3 \times 10^{-18} \times e^{0.0237T} \]  

\[ \sigma = 3 \times 10^{-14} \times e^{0.0230T} \]

where \( \sigma \) is the DC conductivity in Siemens per meter and \( T \) is the temperature in Kelvin. For comparison, at 20 ºC in Earth atmosphere, glass has a conductivity of \( 10^{-11} \) to \( 10^{-15} \) S/m.

5.2.2 Electrostatic Charges

Without an atmosphere or magnetic field, the Moon is subject to the effects of solar radiation and solar wind. During the daytime, lunar dust becomes positively charged and elevates from the surface. Conversely, on the night side, the dust becomes negatively charged and falls back to the surface. At the termination, the transition between night and day, the dust can stream violently in parabolic movements. This phenomenon was observed by Apollo astronauts and lunar orbiters (Mazumder et al., 2008). It has been calculated that electrostatic levitation may loft particles as high as 10 km above the lunar surface.

Unfiltered solar irradiation of the lunar surface also affects the electrical conductivity of lunar soils, with large conductivity increases in Apollo samples measured both as a function of wavelength and of temperature (Alvarez, 1975). Plots of conductivity over time, with and without illumination, demonstrate the effects. As described in the Lunar Sourcebook (Heiken, Vaniman, & French, 1991), Figure 17 shows changes with time in surface electrical conductivity produced as the result of ultraviolet (UV), visible (VIS), and infrared (IR) radiation:

Conductivity rises rapidly at the start of irradiation (time = 0 on horizontal axis), then drops rapidly when the irradiation ceases ("OFF"). The effect is greater at higher temperatures (295 K; upper curves) than at lower temperatures (100 K; lower curves). Note that the two highest curves were obtained with all three light sources on (VIS, IR, UV). (534)

Figure 17.—Surface electrical conductivity of lunar soil 63501,52 due to UV, VIS, and IR irradiation. Adapted from Alvarez (1977) in Heiken, Vaniman, & French (1991).

5.2.3 Permittivity

Of particular interest for communications is the relative permittivity (also known as dielectric), \( \varepsilon_r \), and conductivity, \( \sigma \), of the lunar dust and soil. Permittivity is a complex value that contains the real (\( \varepsilon' \)) and imaginary (\( \varepsilon'' \)) components (\( \varepsilon = \varepsilon' + j\varepsilon'' \)). Permittivity is the property of a material or medium that indicates its ability to conduct electrical energy (i.e., electric fields). The relative permittivity of a material is a complex value, and is the ratio of the material’s permittivity to that of vacuum (\( \varepsilon_0 = 8.854 \times 10^{-12} \)), such that \( \varepsilon = \varepsilon_0 \varepsilon_r \). The dielectric loss is the complex (imaginary) part of permittivity (\( \varepsilon'' \)), often described in terms of the loss tangent (\( \tan \delta = \frac{\varepsilon''}{\varepsilon'} \)), a description related to the resistivity of the material, or how “lossy” it is. Therefore, the electromagnetic propagation of a wave in a medium is determined by the frequency dependent permittivity of the medium.

Apollo 17 conducted an in situ Surface Electrical Properties experiment to measure the electromagnetic energy absorption and reflection characteristics of the lunar soil (Figure 18). The experiment used a transmitting cross dipole antenna near the
Lunar Module and a receiving dipole antenna that was placed on the ground at various distances, using the Lunar Roving Vehicle (LRV) for transport. The Lunar Module antenna would transmit continuous signals at discrete frequencies between 1 and 32 MHz and the LRV antenna would receive the signals through the regolith at the different locations. Unfortunately, only data from Station 2 were recorded properly (NASA, 1973a).

Data from the Apollo 17 Surface Electrical Properties experiment showed the surface has a low permittivity and conductivity; the report estimated $\varepsilon_r \cong 3$ to 4. It was concluded that due to low loss tangent ($\tan \delta = \varepsilon'_r/\varepsilon''_r$, where $\varepsilon'_r$ is the real part of permittivity and $\varepsilon''_r$ is the imaginary part of permittivity), there is no water at the Apollo 17 site. In addition, with the low loss tangent, it is predicted that radiofrequency (RF) transmission through ~10 m of lunar regolith should be possible.

Lunar dust relative permittivity has been tested from Apollo missions 15 to 17. Per Olhoefert and Strangway (1975), the regression relative permittivity of all lunar samples is

$$\varepsilon'_r = 1.919^\rho \quad (3)$$

where $\varepsilon'_r$ is the complex permittivity and $\rho$ is the bulk density in g/cm$^3$ of the lunar samples. Figure 19 shows a plot of relative permittivity of all samples tested.

Furthermore, the loss tangent can be given by

$$\tan \delta = 10^{(0.038(\%TiO_2+\%FeO)+3.12)\rho-3.260} \quad (4)$$

where $\tan \delta = \varepsilon'_r/\varepsilon''_r$, and $\rho$ = bulk density in g/cm$^3$. From the data, the permittivity is a function of bulk density but not chemistry. However, the loss tangent (imaginary permittivity) is dependent on both bulk density and the chemistry. At lower frequencies, below 1 MHz, data indicate that the real permittivity ($\varepsilon'_r$) is independent of temperature <400 °C. Above 1 MHz, permittivity is independent of chemistry, temperature, and frequency. The loss tangent is mostly independent of temperature <200 °C but dependent on density, chemistry, temperature, and frequency. Minimum loss tangent for soil is near 10 MHz. In general, the low permittivity of the lunar dust will allow transmission to and from the lunar surface with minimal attenuation effects.

5.3 Communications Design Considerations, Best Practices, and Mitigation

Various aspects of the design of a lunar communications system must take into consideration the effects of lunar dust. Prevention, mitigation, and tolerance strategies must be considered.
5.3.1 Radiofrequency Transmission

Due to the low permittivity and low density of the lunar dust above the surface, RF transmissions will suffer little effect on the propagating signal. However, it is recommended to model estimated attenuation from lofted dust to ensure enough margin to close the link at all applicable frequencies. Similarly, an understanding of the particle size relative to potential operational frequencies, particularly if entering into the terahertz range or optical communications, is recommended to predict potential “atmospheric” absorption.

5.3.2 Antennas

Exposed antennas will be susceptible to lunar dust effects relating to dust adhesion. Preventing dust exposure to antenna surfaces is recommended, but it is not always practical. For example, stowing antennas when not in use will help reduce exposure to dust but will limit transmission times.

Although a small amount of dust accumulated on an antenna surface (e.g., reflector) is likely to have little effect, it is recommended to analyze and define the tolerance of allowable accumulated dust. This may include analyzing beam patterns, frequency and phase shifts, gain, and so forth. Furthermore, methods to remove dust from an antenna radiating surface should be considered. The gain for a reflector is directly related to the surface accuracy (i.e., surface roughness). It is recommended to analyze potential abrasion from removing dust or ballistic impact from dust and how it will affect the antenna surface over time. As an example, Ruze’s (1966) equation to define surface finish requirements taking into account potential effects from lunar dust can be used. For the example calculation, at a surface roughness of 1/20 RMS, it can be expected to have around 1 dB loss. For the aforementioned scenarios, analyses over the expected lifetime of the antenna need to be considered in the antenna design.

Dust mitigation for antennas should focus on preventing exposure to the radiating surface. Various durable coatings, such as SiO2, that will protect the surface from either abrasion (e.g., wiping away dust) or dust impact should be investigated. Another means of mitigating the dust effects might be to induce a repelling charge to prevent or remove particulate accumulation if the antenna design can accommodate an electric charge.

5.3.3 Electronics

Because lunar dust can be electrically charged, electronics protection for communications must be carefully considered. Electronic components are highly susceptible to electrostatic and charged particles. It is recommended to identify proper electrostatic discharge (ESD) requirements for all components, following NASA Technical Handbook 4002 (NASA, 2022b). Proper grounding and shielding should be addressed early in the design, and methods defined for sealing sensitive electronics to prevent lunar dust from coming in contact with electronic devices. If exposed to the charged dust, active components may experience a catastrophic failure. This may include, but is not limited to, components and subsystems such as field programmable gate arrays (FPGAs), power amplifiers, low noise amplifiers, and mixers.

It is recommended to define a process for removing and connecting cables and waveguides, especially when around lunar dust. The lunar dust can easily cause damage by accumulating in connector threads and in waveguide cavities and flange faces. It is recommended to define processes for appropriately cleaning the connections. It is also recommended that coaxial cables and connectors be sealed to prevent dust from entering the cable.

5.4 Summary

Electrical properties analyses of lunar soil and rocks have been conducted previously, and overall, they are mostly in agreement. The dust and soil show low permittivity, a lunar regolith property mostly dependent on density. The imaginary part of permittivity is also dependent on composition. The low permittivity indicates that there should be little signal attenuation when transmitting data through lunar dust. However, analysis should be conducted to ensure no interference. Antenna reflector surfaces are more vulnerable than other components of antennas due to the stringent surface accuracy requirements. Higher frequency antennas require more pristine surfaces. Preventative measures may include the use of a radome to enclose the antenna and components. Mitigation considerations, such as coatings or electrostatic discharge particle removal techniques (when the antenna is not active), could be explored. However, inducing an ESD at an antenna may have consequences for the electronics if not done properly.

Electrical components and devices must have proper ESD shielding and grounding in place to prevent catastrophic failures. Sealing the electronics in the packaging will be important to prevent dust contamination. Connectors, cables, and waveguides will all be susceptible to contamination. More analysis on the nature of particle charging and means of potentially repelling the particles will be of interest for both antennas and electronics.

6.0 Mechanisms and Mechanical Assemblies

Dust mitigation for mechanisms and mechanical assemblies in general could fill volumes as a function of the environment, the type of machinery, and the end-use applications. Lunar dust
concerns will be addressed here starting at the component level, including bearings, gears, and seals, as well as concerns specific to soft-goods (fabric) components of spacesuits.

6.1 Bearings and Gears

6.1.1 Introduction

Future lunar surface missions, such as those planned in Artemis, will undoubtedly require rotating mechanisms to sustain life, enable science, utilize resources, and perform most conceivable surface operations. Previous missions to the Moon’s surface, including the Apollo landings and exploratory rover missions, have utilized many different rotating mechanisms, from drivetrain systems to drills to swinging hatches. Common to all rotating systems is some type of load-bearing component between the rotating and stationary parts that allows rotation while constraining translation. These components are commonly referred to as “bearings,” and they can take on various forms, but all essentially provide the same function.

Historically, manned lunar missions have all been relatively short-lived. The Apollo lunar landing missions (11 to 17, excepting 13) logged a total of just over 80 h of operation on the lunar surface. Even with that small total operating time, lunar dust posed issues for certain operations. Future missions, with goals of a permanent human presence, will severely stretch those requirements and will require rotating mechanisms that can function for very high cycle counts with little to no maintenance.

The omnipresence of lunar regolith particles on the surface of the Moon, therefore, poses a significant challenge to mechanism designers that must be overcome, or at least mitigated, to achieve the long life needed in this challenging environment. Regolith dust particles can make their way into the internals of bearings and gears and cause damage ranging from mild torque increases to accelerated wear to immediate lockup, with an extremely variable range of damage along that spectrum. An indication of the potential damage lunar dust particles can cause for bearings can be observed in Figure 20, which shows bearing race damage caused by lunar simulant intentionally mixed into the lubricant.

![Figure 20.—Photograph of bearing after 72-h run time at 1,600 rpm with lunar simulant (OPR40W30) in grease (Rheolube® 2000, Nye Lubricants, Inc.).](image-url)
A wide variety of systems will be required and utilized over the course of human operations on the Moon, each with a potentially diverse array of rotating mechanisms, including such hardware as spacesuit joints (elbow, waist, etc.), rover drivetrains (wheel bearings, steering and suspension joints, etc.), excavation equipment (drills, diggers, etc.), deployment mechanisms (antenna masts, solar panel booms, cranes, etc.), and so on. With such a range of mechanisms that will eventually be put in service on the lunar surface, there is not likely to be a singular solution or design practice appropriate for all. This section will summarize past design practices for lunar bearings and gears, practices that are currently being planned, and likely future advances to provide a sampling of best practices and potential future improvements for designers.

6.1.2 Lunar Surface Mechanism Considerations

It is important to note the environmental conditions on the lunar surface that are relevant to bearing design for lunar mechanisms. These environmental conditions should be considered in any thorough mechanism design activity.

Temperatures on the lunar surface can range from around 30 °K in permanently shadowed polar craters to 400 °K at the equator during lunar day. These extreme temperatures, and specifically the temperature range for a given application, must be taken into account for bearing and gear designs, not only for lubricant performance but also for material selection and differential thermal growth. Heaters are often used in mechanisms expected to experience extreme cold temperatures, below about 200 to 250 °K, because liquid lubricants typically cannot operate below these temperatures. Solid lamellar film lubricants can be used without heaters for extreme cold, with dichalcogenides such as MoS₂ often employed for vacuum applications.

Atmospheric pressure on the lunar surface is essentially nonexistent. Pressure on the order of $10^{-12}$ torr is typical on the night side. At this extreme vacuum condition, lubricant selection is also critical. Lubricants with very low outgassing characteristics must be used (see Jones et al., 2000). In addition, with no atmosphere, dust particles behave differently than they do on Earth. Lofted particles take on ballistic trajectories and do not “float” or diffuse when they are disturbed by outside influences (e.g., rocket exhaust plume). This could be an important consideration for the design of seals and barriers. The extreme temperatures and pressure also make Earth-based testing and demonstration difficult. Because of the extreme high vacuum conditions, humidity is also extremely low. Low humidity can be a factor in the lubrication environment and also contributes to a tendency for electrostatic charge buildup in dust particles. Some researchers have suggested electrostatic techniques to shield hardware from dust, taking advantage of the tendency for dust particles to pick up electric charges (Calle et al., 2008).

Gravity is about one-sixth that of Earth’s, which can affect loads experienced by bearings and gears in mechanisms where structural (or other) mass is the primary load source.

6.1.3 Historical Experience

The Apollo-era missions provide the only feedback of real in situ experience to designers, because most hardware that has gone to the Moon has not come back. The Apollo astronauts who experienced life on the Moon offer valuable knowledge of the challenges associated with lunar regolith. In one of his most oft-quoted comments, Gene Cernan said, “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other … mechanical problems except dust” (NASA, 1973b, p. 20-12). This powerful statement from one of the few people to have gained relevant experience shines a spotlight on dust mitigation as a critical technology gap that remains to this day.

For bearings and gears, dust mitigation typically reduces to a seal problem, especially in historical terms. The approach to long life was to keep as much dust out of the bearing or gear contact as possible. Historically, that meant rotary seals between the environment and the component. Seals are covered in some detail in Section 6.2, but they are also discussed in this section as they relate to bearings.

For bearings and gears, historically, designs were not significantly different from standard practices of the time. Standard design practice was, and still is, commonly used to specify important parameters such as geometry, materials, fits, precision, lubricants, loads, and speeds. Standard design practices and typical requirements for space mechanisms are outlined in several relevant standards, such as NASA–STD–5017 (NASA, 2022a) and American Institute of Aeronautics and Astronautics (AIAA) S–114 (AIAA, 2020), and handbooks, including the NASA Space Mechanisms Handbook (Fusaro, 1999) and the European Space Tribology Laboratory (ESTL) Space Tribology Handbook (Roberts et al., 2013). In bearings, custom designs (geometry and/or material) often require many months of lead time and are cost prohibitive and therefore unjustified for most applications. As a result, materials for lunar mechanism bearings have typically been common bearing steels (M50, 52100, 440C) for many applications, and geometries are commonly dictated by standard bearing geometries available in the industry. Lubricants are often typical vacuum-compatible space lubricants, including polyalphaolefins (PAOs), multiply alkylated cyclopentanes (MACs), and perfluoropolyethers (PFPEs). For more on space lubricants and their specific uses, the reader is referred to Jones et al. (2000) and Jones and Jansen (2008).
One important historical example of lunar mechanism bearing applications subjected to extremely high dust exposure is the traction drive assembly of the Apollo LRV used in several Apollo missions (Apollo 15, 16, and 17). The LRV traction drive assembly, shown in Figure 21, was a hermetically sealed, self-contained motor, harmonic drive, and wheel assembly affixed at each corner of the LRV to provide the motive force to drive the vehicle. Due to their position immediately adjacent to the tires, these mechanisms were subjected to significant dust exposure. The bearings in this mechanism (outside of the hermetically sealed part) were what is referred to as “open” designs, with no integrated seals or “closures,” as bearing seals are also often called. Rather, dedicated shaft seals outboard of the bearings were used to protect the internals of the mechanisms, including bearings and the harmonic drive gearing. Bearing closures come in two basic varieties: shields and seals. They can be further broken down into contacting and noncontacting. As an example, Figure 22 shows one manufacturer’s closure options. The choice of closure (or lack thereof) is specific to each application and carries with it trade-offs between the various performance characteristics, such as resistive torque, heat generation, leakage, and maximum speed.

![Figure 21.—Lunar Rover Vehicle traction drive assembly (Lunar Roving Vehicle Operations Handbook, 1971).](image)

![Figure 22.—Some general bearing closure types (Boca Bearings, 2022; used with permission).](image)
Another historical example of bearings exposed to lunar regolith are the EVA suit (spacesuit) joint bearings. In the spacesuit application, bearings are less protected from the elements as they are not buried inside a structural element with sufficient space for rotary shaft seals. Figure 23 shows a section view of an Apollo EVA suit wrist bearing, Figure 24 shows photographs of the bearing during disassembly, and Figure 25 is a cross-section view of a typical joint design. In Figure 24(b), one can clearly see the ball groove (denoted by arrows) and two pressure seals, one to each side of the groove. The spacesuit bearings are somewhat unique as they utilize anodized aluminum for the raceways, and the seals are pressure seals to maintain internal suit pressure. The seals are designed in such a way as to flex toward the sealing surface with internal suit pressure; they are not specifically designed to prevent dust intrusion. There was a problem with one wrist bearing in an EVA activity, but the issue was related to the latch for the wrist disconnect rather than a bearing problem. Christoffersen et al. (2009) conducted an investigation into the bearing race surface condition to attempt to determine if dust had an accelerated wear effect on one wrist bearing from an Apollo 16 EVA suit. The bearing was disassembled and scanning electron microscope (SEM) images were taken of the race and ball surfaces. A bearing that had been used only for intravehicular activities and not exposed to lunar regolith conditions was imaged as a control. Results of the SEM imaging suggested that there was no discernible difference between the two bearing samples, suggesting that regolith either did not infiltrate the bearings in significant quantity or did not cause significant accelerated wear, or a combination of both.
6.1.4 Current Practice

Next-generation spacesuit bearings for the Exploration Extravehicular Mobility Unit (xEMU) and a prototype rover drive system are analogs to the Apollo-era spacesuit and LRV. Both provide current examples of bearing design practice similar to historically used designs.

The rover propulsion drive assembly shown in Figure 26 is similar to the LRV traction drive assembly from the Apollo era in the sense that it provides propulsion for the rover’s wheels. The prototype hardware, likewise, would have a similar architecture: a motor and gearbox inboard, with bearings and seals facing the environmental side of the assembly. The first line of defense from lunar regolith for the bearings and gears is a system of seals similar to that used by the LRV. In the prototype assembly, the outermost seal is a face seal. The next level of protection is a labyrinthian passage to provide a tortuous path for any particles that get past the face seal. After the labyrinth is a shaft seal, such as a spring-energized polytetrafluoroethylene (PTFE) seal. Finally, in some designs there could be another face seal before the bearing. The performance of this type of seal system was to be tested at NASA for effectiveness at preventing dust particles from infiltrating the assembly in the Game Changing Development program’s Dust Mitigation Mechanisms project. This general arrangement is common to other lunar mechanisms as well.

The xEMU is the next-generation spacesuit NASA is developing for the Artemis program to enable spacewalks and EVA on the Moon and Mars. Joint bearings for the xEMU bear a striking resemblance to the Apollo-era suit bearings, but they do have some minor differences. One difference is the addition of a dust seal outboard of the outermost pressure seal. Figure 27 shows a concept sketch of a suit joint bearing. Clearly visible in
the sketch are inward-facing dynamic pressure seals similar to the seals of the Apollo suits. In addition to those seals, there is a generic environmental seal, like the Apollo version, on the pressure side, but with a dust lip seal on the vacuum side.

6.1.5 Technology Gaps and Advanced Development

Current practice is largely based on heritage designs, which have performed well for their intended purpose. However, the demands of future lunar operations will far exceed the demands of the Apollo missions and the early Artemis exploratory missions. If a long-term human presence on the lunar surface is to become a reality, mechanisms with orders of magnitude longer life, and possibly more extreme environmental exposures, will be necessary. Rovers will have to drive much farther than the current U.S. maximum of ~36 km; suit joints will see much more use and will have to endure many more rotation cycles; and other mechanisms, such as in situ resource utilization (ISRU) excavation equipment, will be exposed to relatively “dirty” operations. In general, heritage designs are not likely to provide long life in these conditions. Thus, technology development is required to advance bearing and gear technologies that have either better protection from dust or higher tolerance of dust intrusion, or both. The first step to develop better dust performance is to understand the current capability. NASA is presently engaged in several activities to quantify how well current designs and technology can tolerate lunar dust. For bearings, testing is underway to expose bearings to lunar simulant in various environments to understand how much dust can get inside and how much damage it causes. These tests will be followed by testing on advanced technology seals and bearings to try to improve upon heritage designs. Testing includes a prototype actuator test at Kennedy Space Center as well as component-level bearing tests at Glenn Research Center. Bearing tests will evaluate candidate bearing seal concepts as well as advanced materials and coatings for their ability to provide extended life in the presence of lunar simulants.

6.2 Seals

6.2.1 Introduction

In future missions to the Moon, numerous lunar surface systems will require seals that are able to effectively and reliably operate in the presence of lunar dust (International Agency Working Group, 2016). Life support systems responsible for atmosphere revitalization, water recovery, solid waste processing, and thermal control will require leak-tight seals in valves, pumps, and fluid connectors. Many extravehicular activity (EVA) systems will also require low leakage seals. Airlocks, suitports, habitation modules, and pressurized rovers will require dust-tolerant seals for hatches, doors, and docking systems to minimize leakage and ensure that crews have sufficient breathable air for extended lunar surface missions. Spacesuits and portable life support systems will require low leakage seals in valves, bearings, quick disconnects, and other connectors. Rovers and robotic mobility systems will require dust-tolerant seals in steering and suspension systems (e.g., linear sliding seals in typical vehicle shock absorbers) and for rotating parts such as motors and bearings. Seals will also be important for ISRU systems, where they will be used in sample processing chambers, excavation equipment, and gas processing systems. In each of these applications, contamination, damage, or compromise of the seals or sealing surfaces could cause the seals to leak and result in degraded operations, the inability to meet mission objectives, loss of mission, or loss of crew.

6.2.2 Apollo Experiences

Space-rated vacuum seals and their sealing surfaces need to be kept clean to exhibit the extremely low leak rates required for extended duration missions. This was made evident during Apollo missions where dust-contaminated seals exhibited higher leak rates. Gaier reviewed the documentation from the six Apollo missions that landed on the lunar surface (Apollo 11, 12, 14, 15, 16, and 17) and catalogued the effects of lunar dust on EVA systems (Gaier, 2005). Issues with seal failures, clogging of mechanisms, and abrasion were all identified. During the Apollo 12 mission, for example, the Extravehicular Mobility Suits (EMSs) that the crew wore during EVAs experienced increases in seal leakage and pressure decay after each EVA. Although Pete Conrad’s suit was functioning properly before the first EVA, it developed a leak of 0.15 psi/min afterward and then leaked even more at 0.25 psi/min after a second EVA. The maximum allowable leak rate was set at 0.30 psi/min, so it is unlikely that a third EVA could have been performed safely with this suit. Between EVAs, the helmet and glove disconnect seals on the suit were cleaned and relubricated with Krytox™ (The Chemours Co.) oil and grease. However, this cleaning process was not completely effective to keep the seals from leaking after repeated exposures to lunar dust.

In addition to the issues noted with the EMS seals, dust also caused problems for the seals on the Apollo Lunar Sample Return Containers. These containers, or “rock boxes,” were used to return samples of lunar regolith to Earth (Figure 28). Three seals, a pair of L608–6 fluorosilicone O-rings and an aluminum knife-edge seal that pressed into a soft indium alloy (90 percent indium, 10 percent silver), were designed to seal the containers after they were loaded with samples to maintain the lunar ambient pressure in which they were loaded (Smithsonian National Air and Space Museum, 2022; Proctor & Dempsey, 2007). However, of the twelve containers that were brought
back, four had substantial leaks due to dust on the sealing surface or other impingements. The seals on the lunar environmental and gas sample return containers also failed because of dust, which resulted in the samples being so contaminated upon return to Earth that they were of little worth (Gaier, 2005).

6.2.3 Recent Dust Testing of Seals

Recent testing has also shown that dust-contaminated seals exhibit higher leak rates than clean seals. Oravec et al. performed tests to evaluate the performance of silicone O-ring seals (AS568A size 2-309, nominal outer diameter 0.832 in.) contaminated with JSC–1A lunar simulant (Oravec & Daniels, 2014). The test articles were evenly coated with an average weight of 6.3 ±1 mg of simulant (Figure 29), and leak tests were performed at four different levels of compression. Leak rates for the contaminated O-rings were then compared with those for as-received, uncontaminated O-rings. Although space-rated vacuum seals are often coated with a light layer of space-rated vacuum grease, these tests were performed without any grease on the seals. Leak rates for the O-rings contaminated with simulant were immeasurably high for all but the highest level of compression, and even at that point, the leak rate was four orders of magnitude higher than what was measured for an as-received seal (Figure 30). After the contaminated O-rings were leak tested, they were cleaned with an acid brush in a uniform circumferential pattern (Figure 29(c)) and tested again. After
cleaning, the average weight of the simulant remaining on the test articles was 2.2 ±0.4 mg, and leak rates returned to near as-received levels. These test results indicate that some seal designs may be able to be cleaned to improve their performance.

Garafolo and Daniels (2011) performed tests on larger face seal designs to evaluate the effects of dust contamination on seal leak rates. In this study, the test articles were composite seals with silicone sealing bulbs vacuum-molded into a metallic retainer, and they were approximately 12 in. in diameter. As in the study by Oravec et al. (2014), these seals were tested without grease and after contamination with JSC–1A lunar simulant (Figure 31). Two levels of simulant were uniformly applied to the test article, 1.1×10⁻⁴ lbm (50 mg) and 3.3×10⁻⁴ lbm (150 mg), and leak tests were performed for both levels of contamination. As shown in Figure 32, the leak rate increased slightly for the lower level of contamination but was considerably higher for the higher level of contamination. As with the study by Oravec et al. (2014), the seal in this study was also cleaned and tested again. In this case, the seal was cleaned with pressurized air, and 2.2×10⁻⁴ lbm (100 mg) of simulant remained on the seal after cleaning. The leak rate of the cleaned seal decreased after some of the simulant was removed, but it did not return to the baseline leak rate for the as-received seal.

Figure 30.—Average leak rate and corresponding uncertainty for 2-309 silicone O-rings at four levels of compression in three conditions: as-received, contaminated with JSC–1A lunar simulant, and after cleaning with an acid brush. Adapted from Oravec & Daniels (2014); used with permission.

Figure 31.—Silicone sealing bulb of composite seal contaminated with JSC–1A lunar simulant (Garafolo & Daniels, 2011; used with permission).

Figure 32.—Leak rates in four conditions for composite seals with silicone sealing bulbs vacuum molded into a metallic retainer: as-received, contaminated with JSC–1A lunar simulant (2 levels), and after cleaning with pressurized air. Adapted from Garafolo & Daniels (2011); used with permission.
Tests have also been performed to evaluate the durability and effectiveness of seals that would be used to prevent dust from entering mechanism compartments. Delgado et al. performed tests on spring-loaded PTFE seals to evaluate their ability to keep lunar simulant out of mechanical component gearbox, motor, and bearing housings (Delgado & Handschuh, 2010). A series of rotating shaft tests was run against the seals to determine their ability to prevent lunar simulant from passing through the seal/shaft interface (Figure 33). Seals of three different diameters (0.375 in., 0.75 in., and 1.5 in.) were tested against either stainless steel or anodized aluminum shafts of the same diameter with the shaft rotating at a constant speed of 20 rpm. After completing baseline tests without simulant in ambient dry-room conditions, tests were performed in vacuum using the lunar simulants JSC–1A and LHT–2M. For all the tests that were performed, no simulant was observed to pass through the seal/shaft interface for up to 10,000 cycles, and only a minimal amount of wear was observed on the seals and shafts. Seal weight loss was minimal, with only flakes of PTFE observed on the downstream side of the seal.

In a different study, Delgado et al. (2013) performed tests on a low-temperature mechanism seal designed to prevent dust from entering an actuator compartment. The seal assembly and rotating shaft were oriented vertically within a vacuum bell jar capable of achieving 10^{-7} torr. Following initial break-in tests under atmosphere and vacuum, the seal was tested under vacuum with NU–LHT–2M lunar simulant applied to the top of the seal/shaft interface as shown in Figure 34. The shaft was rotated at a constant speed of 39 rpm during testing. Only 0.4 mg of simulant passed through the seal/shaft interface in the first 511,000 cycles while under vacuum despite a chip on the secondary sealing surface. After the test setup was reassembled and an additional 140,000 cycles were completed, 1.8 mg of simulant was found to have passed through the seal/shaft interface. Posttest inspection revealed wear marks on the test shaft sealing interface in areas where simulant was found packed between the sealing surfaces of the seal and shaft.
6.2.4 Seal Design Considerations and Best Practices

Many factors must be considered when selecting a seal design and material(s) for a particular application. The most important function for a seal is typically to minimize leakage through the interface when it is sealing, so the maximum allowable leak rate should be defined to help select the type of seal to use for the application. The fluid that is being sealed should be identified, and materials that are compatible with that fluid should be utilized. The operating conditions for the seal should also be defined early in the design process. This includes the expected operating temperature range, pressure differential across the seal, maximum design pressure, and any unique environmental conditions to which the seals may be exposed. In addition to lunar dust, seals may be exposed to other conditions in space, such as vacuum, atomic oxygen, ultraviolet radiation, and ionizing radiation. Expected exposure durations should also be defined. Materials that can withstand, or at least tolerate, these exposures should be utilized for the seals. For example, the properties for many seal materials change at cold or warm temperatures, so materials that can operate across the expected temperature range should be selected.

In space applications, seal outgassing contaminants must be minimized so they do not compromise the functionality of critical systems such as windows, lenses, star trackers, solar arrays, radiators, and other surfaces with highly controlled optical properties. Seals that are used near any of these systems must meet the outgassing requirements defined in sec. 3.2.2.1 of NASA SSP–30426, Space Station External Contamination Control Requirements (NASA, 1994), with a total mass loss of less than 1.0 percent and a collected volatile condensable material (CVCM) of less than 0.1 percent. Seal materials may also need to meet the stricter requirement of less than 0.01 percent CVCM defined in sec. 4.2.3.6 of NASA–STD–6016, Standard Materials and Processes Requirements for Spacecraft (NASA, 2020), depending on the application.

In addition to the seal materials themselves, the characteristics of the sealing surfaces should be carefully defined. For O-rings and other elastomeric seals, best practices include utilizing surface finishes on sealing surfaces of 32 µin or better for liquids and 16 µin or better for gases and vacuum conditions (Parker Hannifin Corp., 2007). Surface finishes on the groove or gland in which the seal is installed and on the opposing sealing surface should be machined with a circular lay with tool marks that follow the direction of the groove or sealing surface in a circumferential direction. Tool marks or scratches across the sealing surface could provide leak paths past the seal and should be avoided. Sealing surfaces should typically be flat and parallel to each other as much as possible to ensure that the seals are fully and evenly compressed in the interface.

The amount of space available for the seal should also be defined as early as possible during the design process to ensure that the seal design chosen for the application will be able to fit in the required location. For example, there is a requirement for manned space systems that all seal locations with diameters larger than 6.0 in. (15 cm) have a minimum of two seals for redundancy (NASA SSP–50021, sec. 3.2.2.7) (NASA, 2009). This redundancy allows the sealed interface to be single-fault tolerant so it can still satisfy the leak rate requirement even if one of the seals is compromised.

The amount of movement expected at the sealed interface should be defined. Even in static interfaces, thermal exposures and vibrations can cause deflections at the sealing interface during use, and the seal must be able to remain in contact with the sealing surfaces during those movements to maintain an effective seal. For dynamic applications, the operating conditions should be defined. For a hatch, door, or docking system, this could include the number of times the interface will be opened and closed during use. In locations where the seal will be sliding against the opposing sealing surface during use, the sliding distance, rate, and number of sliding cycles should be defined, and the material and roughness for the sealing surfaces should be carefully considered to ensure proper seal function. For example, surface roughness values less than 5 µin are typically not recommended for dynamic O-ring applications (Parker Hannifin Corp., 2007). For a shaft seal, the rotation rate, number of rotations, and type of rotation (e.g., continuous or oscillating) should be defined and considered when selecting the seal design.

For applications in which the seal will be compressed to seal the interface, the maximum allowable compression load should be defined, and seal loads must stay below prescribed limits so full closure can occur without overloading the mechanisms that compress the seals. Similarly, if the sealed interface must be reopened at some point during a mission (e.g., hatches, doors, or docking systems), the amount of adhesion between the seal and the opposing sealing surface must remain low so the seal can be separated from the sealing surface without damaging the seal or overloading the separation mechanisms. A light coating of space-rated vacuum grease (e.g., Braycote® (BP Lubricants USA, Inc.) 601 EF) is often applied to the surface of the seal to minimize adhesion between the seal and the opposing sealing surface. Grease can also be used to aid with seal installation and assembly and to help seat the seal properly in the groove or gland in which it is installed. Grease can help protect seals from damage by abrasion, pinching, or cutting and can help to protect some seal materials from environmental degradation. It can also reduce the overall leak rate in vacuum applications by filling the fine features in adjacent sealing surfaces.

The desired life for the seals should be defined. This can be in terms of the number of operating cycles or missions for
which the seals are expected to operate and/or the duration of those operating cycles or missions. If there is a possibility for maintenance or replacement of the seals, that should be identified, as well as the minimum amount of time the seals would need to operate before the possibility of maintenance, repair, or replacement. If the seals are intended to be replaced at some point, provisions for access to the seals should be considered during the design process. Finally, the potential risks and hazards of seal failure should be identified. The likelihood and consequence of each risk should be assessed, and mitigation approaches should be identified and pursued to ensure mission success.

6.2.5 Dust Mitigation Approaches

As noted in Section 2.0, the three main strategies for dust mitigation are to avoid, remove, or tolerate the dust.

6.2.5.1 Avoid

There are multiple ways to avoid exposing seals to dust. One is to locate them in areas where they will not be exposed to dust or where the exposure will be minimal. If possible, the interface should remain closed during use to prevent dust from getting to the seals and critical sealing surfaces. Covers or protective layers of material can be installed over sealed interfaces, joints, or mechanisms to help minimize the amount of dust that reaches the seals. If a sealed interface must be opened during a mission (e.g., hatches, doors, or docking systems), covers can be installed over the seals or sealing surfaces after they are opened to minimize dust exposure and protect them from potential damage. Another unique approach to avoid exposing seals to dust is to integrate electrodynamic dust shield (EDS) technology near the sealed interface to help minimize the amount of dust that reaches and deposits on the seals.

6.2.5.2 Remove

If dust cannot be prevented from getting to the seals, it can potentially be removed from them. In locations where the seals can be accessed, various cleaning tools and methods (e.g., brushes, wipes, pressurized air, and vacuum systems) can be used to clean dust off the seals. As noted earlier, testing has shown that some seal designs may be able to be cleaned with brushes or pressurized air to improve their performance (Oravec & Daniels, 2014; Garafolo & Daniels, 2011). More recent testing has shown that candidate hatch and docking system seal designs can be cleaned with wipes and wiper blades to remove dust from the seals and, in some cases, reduce their leak rates back to acceptable levels. Integrating EDS technology near the seals to remove dust that has settled on them, the sealing surfaces, or other areas of the interface is another possible approach.

6.2.5.3 Tolerate

Finally, if seals are to be used in locations where dust exposure cannot be avoided and the dust cannot be easily removed, they must be designed to be tolerant of the dust during use. Tests can be performed to characterize the performance of the seals when exposed to dust simulants and determine how much dust they can tolerate before they “fail” (e.g., before leak rates become too high). For example, researchers at the Glenn Research Center are currently performing such tests on representative seals for hatches and docking systems. Another approach for tolerating dust is to utilize multiple seals in an interface for redundancy so that if one seal gets dirty and fails, another one can continue to seal the interface. For dynamic interfaces, abrasion-resistant materials or surfaces can be used to improve seal durability and extend the time before maintenance, repair, or replacement is needed.

6.2.6 Technology and Knowledge Gaps

The IAWG Dust Mitigation Gap Assessment Report (International Agency Working Group, 2016) identified numerous areas where there are technology gaps between the state of the art and the Technology Readiness Level (TRL) required for extended human lunar missions. According to that assessment, there are no TRL 3 solutions for static seals or linear motion seals for extended lunar missions and only possible TRL 3 solutions for rotary seals. NASA TRL definitions state that a technology is at a TRL of 3 after “analytical and experimental critical function and/or characteristic proof of concept” has been demonstrated to validate predictions of key parameters. However, technologies with a TRL of 3 are still quite low on the TRL scale and have not yet been demonstrated in a relevant or operating environment, nor have they been flight qualified. Therefore, a fairly large technology gap exists for seals that will be required for future lunar missions.

Although it has been recognized that seals and their sealing surfaces must be kept clean to exhibit the extremely low leak rates and durability required for future extended duration lunar missions, in most cases the performance of seals contaminated with lunar dust has not been thoroughly characterized. Therefore, the scope of the concern for seal dust contamination is not well understood. Researchers at NASA are currently performing tests to help address this knowledge gap. As noted earlier, Glenn researchers are performing tests on representative seals for hatches and docking systems to characterize their performance when exposed to lunar simulants and to define the conditions that cause seal leak rates to become unacceptable at representative temperatures and pressures. Tests are also being performed to evaluate candidate seal cleaning methods, alternate surface treatments, and other unique dust mitigation
approaches. At Kennedy, researchers are developing dust-resistant actuator seals for rotary joints and rotary bearing technologies for longer-term sustained operation in lunar dust environments. These dust-tolerant mechanisms are currently being developed for rover wheels; however, future work should be applicable to robotic arms, antennas, solar arrays, and ISRU systems. Researchers from Kennedy and Glenn are also collaborating to develop and test seal designs with embedded EDS technology that could aid in both keeping dust from getting on seals and expelling dust that lands on them. Lessons learned from all of these tests will improve the understanding of seal dust contamination concerns and help to mitigate risks for initial lunar missions. As these and other tests are completed, this guidebook will be updated to incorporate lessons learned and provide additional guidance for future seal designers for lunar surface systems.

7.0 Spacesuit Fabrics

The major concern for spacesuit fabrics is our lack of knowledge, which covers three areas: the physical properties of the regolith at the lunar south pole, the effectiveness of our testing methods on textiles, and most important, the scarcity of textile engineering efforts in the past 30 years to develop a fabric that protects the entire spacesuit from lunar dust contamination.

To understand the areas of concern for developing best dust mitigation practices, this section presents the current challenges for textiles, the nature of the lunar regolith, and the approaches for testing textiles.

7.1 Challenges for Textiles

Finding lunar mitigation techniques for textile products represents a unique challenge for human exploration of the Moon, because all fabrics are top assemblies of possibly several fibers, each of which may have been processed differently and thus have many different fiber physical, mechanical, optical, thermal, and electrical properties.

Fabrics are top assemblies. Specifically, they are an assembly of fibers that must, in most applications, constantly withstand tensile, abrasive, twisting, and bending forces. What keeps textile fibers together is the formation of yarns. These yarns are the basic cohesive structure to make woven and knitted fabrics as well as braids, cords, and ropes. In contrast to woven and knitted fabrics, webs of entangled fibers are formed to make nonwoven fabrics.

Most fabrics are made of yarns, which are themselves made of strands of multifilaments or staple (short) fibers that form the plies of a yarn. A single or one-ply yarn is a single strand of fibers held together by at least a small amount of twist. Plied yarns are usually designated by a number, such as 20/3, meaning that three singles or three one-ply yarns twisted together form a plied yarn. The first number (or the larger number) indicates the “size” of the singles in the yarn. This assembly of fibers is held together only by friction and twists and is the foundation of fabrics and cords. It is also why exposing textiles to lunar dust is a challenge. The coarser dust can deposit on the surface of the fabric, finer dust can make its way between the yarns, and the finest dust can penetrate the fabrics and travel between the plies and between the fibers. Fabrics will act as filters and get damaged in the process by sharp dust particles.

This is what all the astronauts of the Apollo program who walked on the Moon experienced. They commented on the dust and how it went everywhere and stuck to surfaces, and particularly to the spacesuits. After the astronauts returned to Earth, the spacesuits were examined to evaluate the effects of the fine lunar dust on the fabrics. The outer fabric of the spacesuit, which had been engineered for flame resistance and thermal management of the suit, came back in shades of gray due to dust sticking to the fabric and caught in the fabric, and with broken fibers and tears in some places.

In the final report of the Dust Management Project (Hyatt & Straka, 2011), the authors highlight the many operational challenges posed by the regolith. The regolith can affect EVA performance as it contaminates spacesuit materials and mechanisms. The report describes lunar dust mitigation technologies for many surfaces, but not for textiles; such mitigation technologies would not be effective on fabrics that are constantly submitted to dynamic stresses.

Dust mitigation coating using the lotus effect was proposed as a mitigation approach to protect multilayer insulation (MLI) surfaces, spacesuit visors, and other EVA materials and tools. Such coatings with lotus effect were applied to AZ93 paint, aluminum, stainless steel, Kapton® (DuPont Electronics, Inc.) polyimide film, and other materials but not to fabrics of spacesuits.

The use of EDS technology was a more promising approach to dust mitigation because it consisted of introducing EDS screens into the fabric of the outer layer of the spacesuit. Once activated, the grid would collect the dust, which could then be removed in an airlock under a CO2 shower. This approach, while attractive, was not validated by testing because it required the development of new fabrics with EDS screens and required a CO2 shower.

This excerpt from the Dust Management Project final report (Hyatt & Straka, 2011, p. 31) speculates:

This dust removal process is dependent on the astronauts’ EVA suits having EDS grids as part of the suit design. Dust will accumulate on the suits from the Moon’s surface. The
activation of the EDS screen will remove most of the dust, and approximately 10% dust loading of micron-size particles will remain. Van der Waals adhesion force will keep these small particles adhered to the suits. The astronauts will then be sealed in the CO₂ shower, located in the shadow of the vehicle to maintain temperature, and sprayed with CO₂ to 0.1 to 0.2 atmospheres obtained from the habitat O₂ scrubbers. The CO₂ gas will crystallize on the dust particles, reducing the Van der Waals force and allowing the micron-size particles to be removed, and allowing the astronaut to enter the habitat. Initial test has shown that a dust loading of 8% can be reduced to 3.5%.

Aside from the lack of mitigation approaches for managing lunar dust on textiles, there is a specific concern that we have evidence only for one type of textile product from the Apollo program, the glass fiber fabric from Owens-Corning known as Beta fabric. Most of this evidence is anecdotal. There are some qualitative data taken from cameras on the Moon as well as some SEM imagery. This knowledge is insufficient to engineer a fabric not only impervious to lunar dust but also reusable.

### 7.2 Challenges With the Regolith

Although many physical properties of the regolith are known, most of our knowledge comes from the Mare region of the Moon.

To understand the unique challenges the regolith poses for textile products, the following excerpts from the Dust Management Project report (Hyatt & Straka, 2011, p. 58) highlight all the regolith properties that must be considered. Each excerpt is followed by comments for the development of new textile products.

**Particle Shape:** The equipment required to get the appropriate information has just become available. Simulant data has been gathered and is under reduction. No Lunar regolith has been granted for comparison at this time. Current TRL=2–3.

The unoxidized lunar dust particles have sharper edges than their simulants. This will lead to more laceration and breakage of textile fibers that become directly exposed to these particles. Cut-resistant fabrics usually include cut-resistant fibers, such as Kevlar® (DuPont Safety & Construction, Inc.) poly(paraphenylene terephthalamide (PPTA), or contain ceramics printed on the front of the fabric. In order to preserve the most important property of textiles, which is drape, the ceramic half beads are spaced on the cloth. These fabrics prevent tear propagation only from a cut. Such fabrics do not protect from lunar dust contamination. Research is needed to apply ceramics with appropriate triboelectric properties on coated fabrics.

**Surface Energy:** Surface energy has been determined for simulants to the TRL=6 level; however, no Lunar regolith was granted so the TRL=1 [for Lunar] regolith. Since there is no comparison between Lunar regolith and simulant, the overall TRL=2–3 for simulant until such comparison is made.

Surface energy changes of fabrics contaminated with lunar dust are useful only if the surface tension of the fabric is known. Fabrics made of different materials (different fibers and blends of fibers, different finishing treatments, presence of various dyestuffs, and other additives) have different surface tensions. Consequently, surface energy data are fabric specific. Such measurements may be useful if laundry is done in lunar habitats. Then, the knowledge of the surface energy of the regolith will be needed to develop laundry detergents that can dislodge the inorganic particles caught in the fabrics and prevent their redeposition during laundering.

**Magnetic Susceptibility:** Magnetic susceptibility on a per particle basis has been determined for simulants to the TRL=6 level; however, no regolith was granted so the TRL=1 for regolith. Since there is no comparison between regolith and simulant, the overall TRL=2–3 for simulant until such comparison is made.

Fabrics can have magnetic properties if magnetic powders such as iron, cobalt, nickel, and ferrite are added to a spinning solution and if fibers having magnetic properties are obtained by wet spinning. Hence, it is possible to engineer fabrics that could repel or attract lunar dust. However, their applications may be limited as they could interfere with communication and other systems if used in the spacesuit.

**Surface Activation:** The equipment required to get the appropriate information has just become available. Attempts to adapt it to providing information for simulants has started. No regolith has been granted for comparison at this time. Current TRL=1.

No information on surface activation is available at the present time.

**Adhesion:** The equipment required to get the appropriate information has just become available. Attempts to adapt it to providing information for simulants has started. No regolith has been granted for comparison at this time. Current TRL=1.
Surface resistivity of fabrics and tribocharging play a role in adhesion. Fluoropolymer fibers, such as the expanded PTFE fibers used in the outer layer of the International Space Station spacesuit, have some of the highest electronegative charges, and glass fibers, such as the Beta fiber used in the Apollo program, have some of the highest electropositive charges. However, the Beta glass fibers were coated with PTFE. The yarns of this fabric were tightly packed together and covered by a thin continuous film of PTFE. While PTFE has been the material of choice for increasing the resistance to abrasion of the spacesuits’ outer fabrics, it is the worst that can be used in the environment of positively charged regolith in lunar daylight.

**Abrasion:** It is difficult to assess this global topic since it covers the span of skin, fabric, metals, ceramics, plastics, etc. Nonetheless, some progress has been made in certain areas. Fabric has been evaluated in simulant by two independent methods. For metals and plastics, technology has been developed to a useful stage and quantitative data taken. These methods are not suitable for use with regolith due to the quantity of abrasive required. The current TRL for Fabrics is 2–3.

A characteristic of most fabrics is that they have a large surface area for their mass and that if uncoated, all the yarns on the surface will be abraded. The fabric will easily weaken and tear. This means that surface abrasion can quickly reduce the useful life of fabrics. Regular brushing of fabrics that attract lunar dust will add to the abrasion caused by a fabric wearer’s movements in the dusty environment. Coating or laminating is needed to extend the useful life of fabrics exposed to the lunar dust. We will need engineered coatings that have antistatic properties and that repel the lunar dust during EVA. We will need some of the highest electronegative charges, and glass fibers, such as the Beta fiber used in the Apollo program, have some of the highest electropositive charges. However, the Beta glass fibers were coated with PTFE. The yarns of this fabric were tightly packed together and covered by a thin continuous film of PTFE. While PTFE has been the material of choice for increasing the resistance to abrasion of the spacesuits’ outer fabrics, it is the worst that can be used in the environment of positively charged regolith in lunar daylight.

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This construction was the result of textile engineering to tailor a fabric for use in vacuum and exposure to solar radiation as well as thermal extremes. The GORETEX® yarns on the face of the fabric will interact with the lunar dust in ways we cannot know until the fabric is on the Moon.

### 7.3 Testing Methodologies

There are current efforts to study the effects of lunar dust simulants and the regolith on this fabric. These efforts start with the development of testing apparatus and methods for evaluating various materials after exposure to lunar dust simulants.

The current focus is on evaluating the forces of adhesion of fabrics. The apparatus in use or in development are the following:

- **Lunar Dust Adhesion Bell Jar (LDAB)—in use**
- **Lunar Dust Adhesion and Mitigation—Sticky Dust Apparatus (Donald Barker)—in development**
- **Glove boxes—some in use and some in development.** Most of the glove box testing is done to evaluate how dust sticks in Earth gravity to surfaces or damaged materials

The Lunar Dust Adhesion Bell jar (LDAB) is an apparatus designed for evaluating the adhesion of lunar dust to the surface of various materials. Within the LDAB, lunar simulant is dried by heating to 200 °C in vacuum for 24 h. The simulant is also subjected to an air plasma for 60 min to oxidize organic contaminants from the surface, and to a hydrogen/helium plasma for 60 min to simulate the effects of the solar wind. The plasmas also emit a large amount of energetic vacuum UV light, which can generate free radicals on the particulate surface (Gaier & Sechkar, 2007).

EVA-quality cameras may be helpful in detecting lunar dust on fabrics by discoloration, or down to the roughly 1-µm optical
resolution limit with magnification. Small dust particles are profuse and historically very challenging to remove from spacesuits. EVA-quality cameras are used to detect lunar dust simulants and microspheres on test fabrics as well as those freed from fabric due to mechanical agitation (simulating one crew member dusting off another). With favorable lighting, small surface smudges and even tiny freed particles may be detectable with EVA-quality cameras via scattering. The performance of imaging experiments may help in targeting eventual dust mitigation procedures, keeping in mind the limits of optical detection.

One imaging experiment at Johnson Space Center consisted of contaminating white fabrics with two types of lunar dust simulant (EVA NU–LHT–2M and Greenspar90) and with other contaminants (soda glass spheres 1 to 50 µm, and stainless steel spheres 1 to 50 µm).

The goal of the study was to determine if an EVA-type camera could detect the regolith before and after it had been mechanically brushed off the fabric. In parallel, a microscope (OMAX M83EZ–C50S) with a 5-megapixel camera and image processing software was used for evaluating the state of the fabric samples during the process. Dust particles could be observed both on fabrics and in the air. A detailed consideration of optical detection techniques is contained in Appendix B.

### 7.4 Recommendations for Spacesuit Fabric Lunar Dust Tolerance

At this time, one should attempt to develop reusable fabrics that repel lunar dust and prevent contamination of the inner layers of the spacesuit. One should first consider the best practices on Earth. Individuals who work in environments with microscopic solid particles that are dangerous to human health do three things:

1. Wear a respirator.
2. Wear a disposable outer layer.
3. Take a shower after removing their inner layers of clothing.

These three best practices should first be tried with existing fabrics. If this is inadequate, the goal should be to engineer disposable composite fabrics that can protect the entire spacesuit for at least 8 h. The first practice, wearing a respirator, is substituted by the closed vent loop of the spacesuit. The second practice, wearing a disposable outer layer, requires trying existing disposable protective fabrics, then engineering new disposable protective fabrics that are tailored specifically for lunar usage. The last practice, regardless of prior actions, should be a shower-like activity. This last practice could be done in a minimum of two successive airlocks (lunar mud rooms). In the outermost airlock, the astronaut would doff the disposable spacesuit protective layer after each EVA and put it into a trash container. The suited astronaut would then enter the inner airlock equipped with EDS screens and CO2 shower to collect the loose dust, as mentioned in Section 7.1.

Engineering a disposable outer layer is less risky than repeatedly, directly exposing the spacesuit to lunar dust, but such a garment is complicated to design and fabricate because it must cover the entire spacesuit, the Portable Life Support System (PLSS), and their interfaces. It would have to contain a nonwoven filter fabric with a coated or laminated surface with the appropriate triboelectric properties necessary to repel lunar dust and form a physical barrier to dust particles. This disposable fabric or other thin material should also possess thermal-optical properties allowing the astronauts to perform an 8-h EVA without losing the suit’s radiative properties needed in vacuum environments.

Ideally, the disposable outer layer should be flame retardant in the lunar lander atmosphere. Also, its design would have to be complex and possibly modular to accommodate the PLSS worn with the suit. When returning from an EVA to the lunar lander, removal of the disposable outer layer and removal of loose dust on the spacesuit would be consecutively performed in two airlocks as one method to avoid lunar dust in the habitat.

### 8.0 Human Health

As we return to the Moon, concerns arise regarding lunar dust and its interaction with the human body. Celestial dusts are of particular concern because they are associated with various occupational toxicologies, with risks dependent on the level of exposure. There is also an increasing interest in other dust-related diseases, such as cancer, asthma, allergic reaction, and respiratory irritation, as well as a whole range of nonrespiratory illnesses, which may occur at much lower levels of exposure. This guide is intended, therefore, to help educate and train people in the prevention and control of dust exposure as well as the reduction of human health impacts. This section will cover established information and considerations regarding the concerns that lunar dust presents to human health. The primary document to consult for NASA lunar dust human health concerns currently remains Scully et al. (2015), Risk of Adverse Health and Performance Effects of Celestial Dust Exposure.

As we look back over the course of the Apollo-era missions (Apollo 11, 12, 14, 15, 16, and 17), we find that lunar dust had a major impact on astronaut crews and equipment. The Apollo astronauts were exposed to lunar dust that was inadvertently

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1Reflects the opinion of the Section 7.0 author.
brought into the lunar modules after each of the surface field trips. Some of the astronauts reported that the dust was irritating when inhaled; however, crew exposures to dust were limited to only a few days. Although an immediate allergic reaction could be severe, none of the astronauts reported serious long-term detrimental effects from these short exposures. Future crews may be exposed to lunar dust for months, so it is important to determine if longer exposures could be hazardous to their health (McKay et al., 2015). Apollo crews also reported that the dust had a distinctive, pungent odor (Astronaut David Scott suggested it smelled a bit like gun powder), suggesting that there are reactive surfaces or volatiles on the dust particles. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back (Gaier & Graps, 2019). The toxicity of lunar dust presents a potential serious risk for human health, especially in the fine and ultrafine (respirable-size) ranges (Scully et al., 2015).

### 8.1 Toxicology of Lunar Dust

Terrestrial studies of lunar dust toxicology provide a substantial basis for concern that prolonged exposure to respirable native lunar dust could be detrimental to human health. Celestial bodies such as the Moon, where a substantial portion of the surface dust is in the respirable range, and where the dusts have large reactive surface areas and contain transition metals or volatile organics, present increased risks of adverse effects from dust exposure. It is possible that in addition to adverse effects to the respiratory system, inhalation and ingestion of celestial dusts could pose risks to other systems. The physiochemical features of mineral dusts that affect or may affect toxicity are size, morphology (shape, sharp edges, fractured surfaces, and surface defects), surface area, surface reactivity, and solubility.

Lunar dust appears to have many of the characteristics of terrestrial particulate matter (PM) that cause adverse health effects. It has been observed that freshly fractured lunar regolith is able to produce large amounts of highly reactive oxygen species (Hurowitz et al., 2007), which are known to induce inflammation and adverse effects on cellular metabolism. Some peculiarities of lunar dust might trigger new toxicity paths and exacerbate the classical inhaled particle effects of terrestrial dusts. Exposed surfaces will be generated by mechanical abrasion of bedrock and regolith. Furthermore, on the Moon, dangling bonds and charges will be more abundant and persist for much longer periods of time in the absence of oxygen or liquid water, both of which assist defect healing and surface reconstruction (Scully et al., 2015).

Lunar regolith is the layer of unconsolidated rocks, pebbles, and dust over lunar bedrock. Lunar dust is defined as particles less than 20 μm in size and constitutes about 20 percent, by weight, of the lunar soil. The highly respirable fraction of the dust (less than 2.5 μm in size) constitutes 1 to 3 percent of the mass fraction of mature lunar soil. Lunar dust possesses properties that have been associated with toxicity of mineral dusts. The surfaces of dust particles on the Moon are likely to be reactive due to broken, dangling chemical bonds resulting from comminution due to micrometeoroid bombardment, proton bombardment from the solar wind, and UV and intergalactic radiation (James et al., 2014).

### 8.2 Transmission of Lunar Particles

The transport of inhaled particles in the airways is generally considered to be governed by three principal transport mechanisms: inertial impaction, which affects mostly particles of aerodynamic size 10 μm and larger; sedimentation, which dominates the size range 0.5 to 10 μm; and diffusion, for particles smaller than 0.5 μm (West, 2000).

As a consequence of these different transport mechanisms, the location in the bronchial tree where particles deposit also varies, and as a result, so does the time it takes to subsequently remove the deposited particles from the lung. Both the site of deposition and the time for removal have the potential to affect the magnitude of the toxicological effect of a given particle load delivered to the lungs, and so the changes in deposition in reduced gravity may alter the toxicological potential of an airborne dust. Thus, large particles deposit primarily in the nasopharyngeal region (the nose and back of the throat) and do not reach the lungs. The medium-sized particles are generally considered to deposit in the small airways. Particles smaller than 100 nm in diameter deposit primarily in the alveolar region of the lung, except for the very smallest particles (smaller than 5 to 10 nm), which are primarily deposited in the nose.

### 8.3 Biological Impacts of Lunar Dust

The importance of particle size in determining the health effects of dust exposure has long been recognized. The U.S. Environmental Protection Agency (EPA) regulations for particles smaller than 2.5 μm (termed PM2.5, with a 24-h exposure limit of 35 μg/m³) are more stringent than those for particles smaller than 10 μm (termed PM10, a 24-h exposure limit of 150 μg/m³). Early regulations controlled only total suspended particles. However, this was replaced with a standard for PM10 in 1987 and subsequently augmented with a standard for PM2.5 in 1997, which was then revised
downward in 2006. Such changes reflect recognition of the importance of the smaller size fractions in impacting human health (U.S. EPA, 2020). Small particles pose the greatest problems, because they can get deep into the lungs, and some may even get into the bloodstream. Exposure to such particles can affect the lungs and the heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms, such as irritation of the airways, coughing, or difficulty breathing (Brook et al., 2010).

8.4 Dermal Effects

From Scully et al. (2015, pp. 12–13):

Crew members can be directly exposed to celestial dust in several ways. After crew members perform extravehicular activities (EVAs), they may, as Apollo astronauts did, introduce into the habitat dust that will have collected on spacesuits and boots. Cleaning of the suits between EVAs and changing of the Environmental Control Life Support System (ECLSS) filters are other operations that could result in direct exposure to celestial dusts. In addition, if the spacesuits used in exploration missions abrade the skin, as current EVA suits have, then contact with these wounds would provide a source of exposure. Further, if celestial dusts gain access to the suits’ interiors, as was the case during the Apollo missions, the dust could serve as an additional source of abrasions or enhance suit-induced injuries. Severe abrasion could compromise the protective barrier provided by the skin and thereby increase the risk of infection and the risk of fluid loss. The abrasive effect of lunar dust on skin has been evaluated with a transdermal-impedance technique that measured changes in resistivity of pig skin, a high-fidelity surrogate for human skin, after abrasion with lunar soil simulant (JSC–1A), as well as with authentic lunar dust (Jones et al., 2009). The transdermal-impedance technique measures damage to the stratum corneum, the dry, outermost layer, which is important for the barrier function of the skin. The results of these studies show that JSC–1A is abrasive as commercial sandpaper and that authentic lunar dust is similarly abrasive suggesting the potential for abrasion to exposed skin of crew. This is especially a concern if dust finds its way within EVA suits, boots, under fingernails, etc.

8.5 Ocular Effects of Exposure to Lunar Dust

The following is summarized from Scully et al. (2015) and Meyers et al. (2012):

The ocular toxicity of lunar dust was determined in a two-tier study according to recommendations promulgated by the Organization for Economic Cooperation and Development (OECD). The first procedure involved application of a 100-mg sample of the respirable-sized, jet-milled dust, which had been maintained in ultrapure nitrogen until the first experimental procedure in the ocular study, directly to the surface of cultured human keratinocytes. The EpiOcular™ procedure used is employed worldwide as an in vitro test to replace or inform in vivo testing of many kinds of products. Following the standard protocol, the dust samples were applied in duplicate to six cell samples, which were assayed for viability 3, 30, and 60 min after application of the dust. The assay ascertains chemical irritancy by enumeration of viable cells after a standard incubation period in which the cells are in contact with the dust. The test of lunar dust was co-studied with materials known to be negative in the assay and materials known to elicit a positive result. Once the first-tier result had shown only a minimal irritancy for the dust, it was possible to advance to the in vivo method with confidence that the dust was unlikely to be exceptionally irritating to rabbit eyes. Although the in vitro test showed minimal irritancy, the Lunar Airborne Dust Toxicity Advisory Group (LADTAG) working team decided that an in vivo test was needed for completeness of the ocular toxicity study. The second tier involved application of nonrespirable dust particles (mass mean diameter of 51 μm) to the eyes of three rabbits to determine primarily mechanical irritancy. The amount applied to the right eye of each animal was 70 mg, with the contralateral eye being the control. The reaction of the eyes was scored using the Draize criteria from 1 to 72 h after application of the dust.

Summary of the two-tier studies show the first tier used an in vitro (EpiOcular™) procedure to expose cultured human keratinocytes. Results showed minimal chemical irritancy, so testing proceeded to a second tier that involved application of particles to the eyes of three rabbits to determine mechanical irritancy. With a maximum possible score (Draize criteria) of 110 points, jet-milled lunar dust only produced a score of 4 points, which showed minimal irritancy of slight redness and swelling of the conjunctiva after 1 h which resolved within 24 h.

8.6 Cardiovascular Toxicity

There is a growing body of evidence that particulate matter (PM) is associated with cardiovascular effects in humans,
especially in urban areas (Pope et al., 2004; Brook et al., 2010). Most urban particulate pollution is not mineral dust, but when desert-sand dust pollutes the air, an association to cardiovascular effects can sometimes be made (Mallone et al., 2012; Morman & Plumlee, 2013); however, the association is not consistently found (Karanasiou et al., 2012) and may vary with particle size (Tobias et al., 2011). Although researchers have used a wide array of sensitive endpoints to deduce any adverse effects at the point of entry of the dust (lungs), the potential for adverse effects on the cardiovascular system should be assessed using lunar dust. This is particularly true in light of the attention NASA gives to the cardiovascular changes during spaceflight (Hamilton, 2008). The LADTAG and the standing review panel have both suggested a need to post this as a knowledge gap and conduct further research; however, funding for such an investigation was not available. There are several relatively simple preparations that could be used to explore cardiovascular effects in laboratory animals with lunar dust that was allocated (jet-milled) and unused in previous pulmonary toxicity studies. For example, in rats exposed by intratracheal instillation (ITI), endothelins, vasopressors, vasodilators, catecholamines, and oxidative stressors could be measured to assess acute cardiovascular effects (Vincent et al., 2001).

8.7 Pulmonary Effects of Exposure to Lunar Dust

Studies were designed to obtain data that would support a recommendation for an exposure limit based upon a time-weighted average exposure, as is the basis for an Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL), and account for episodic exposures to airborne lunar dust for missions involving no more than 6 months’ duration (Scully, Lam, & James, 2013).

From Scully et al. (2015, p. 17):

Taken together the results of the ITI and inhalation studies led the JSC [Johnson Space Center] Toxicology Group to recommend 0.5 mg/m³ as a safe concentration for periodic exposures during a 6-month mission on the lunar surface. The Group noted that their recommendation was likely to be conservative but it should not be applied to dust from regions of the Moon, such as the poles on the dark side, until those dusts are studied to determine their similarity to mare and highland dusts. The results and recommended PEL were presented to the Office of Chief Health and Medical Officer’s (OCHMO) staff and to an external Review Committee organized through NASA’s Research and Education Support Services in December 2013. The Review Committee produced a report and recommendations in late January 2014. The original recommendation was revised based on input from the Review Committee, and a final 6-month episodic exposure limit for airborne lunar dust of 0.3 mg/m³ was presented to the Medical Policy Board in April 2014 and accepted for incorporation into NASA Standard 3001.

A recent study that assesses the toxicity of exposed mammalian cells to lunar regolith simulant finds this soil is toxic to both human lung and mouse brain cells. Results showed up to 90 percent of human lung cells and mouse brain cells died or had DNA damage when exposed to simulated lunar dust particles.

From Caston et al. (2018, p. 139):

In an effort to understand the biological impact of lunar regolith, cell cultures derived from lung or neuronal cells were challenged with lunar soil simulants to assess cell survival and genotoxicity. Lunar soil simulants were capable of causing cell death and DNA damage in neuronal and lung cell lines, and freshly crushed lunar soil simulants were more effective at causing cell death and DNA damage than were simulants as received from the supplier. The ability of the simulants to generate reactive oxygen species in aqueous suspensions was not correlated with their cytotoxic or genotoxic affects. Furthermore, the cytotoxicity was not correlated with the accumulation of detectable DNA lesions. These results determine that lunar soil simulants are, with variable activity, cytotoxic and genotoxic to both neuronal and lung-derived cells in culture.

8.8 Acute Toxicity of Lunar Dust

From time to time during this project, the investigators were asked to consider developing a database for setting a single-event evaluation for an acute situation in which a large amount of dust happened to enter the lunar habitat. This would require that human subjects be exposed to lunar dust at various high concentrations to observe their reactions to the material. Ultimately, the credibility of such a scenario was questioned; therefore, human exposures to lunar dust were never initiated. It should be pointed out that heavy air pollution by volcanic ash, which has properties similar to lunar dust, can cause respiratory irritation (asthma and bronchitis) but no lasting respiratory symptoms—unless the ash contains a substantial amount of crystalline silica, the particles are very fine (respirable), and exposures are repeated over years (Horwell & Baxter, 2006). Repeated, acute exposures to lunar dust over several years are not considered a credible scenario; however, the immune (allergenic) response of acute exposures may warrant investigation (Lam et al., 2013).
Acute toxicity of lunar dust and immunological/allergenic potential has limited evidence; however, it would be arrogant to dismiss the well-documented experience of the Apollo flight surgeon, and it is true that a certain amount of uncertainty will always remain with a material like lunar dust. As previous flight evidence stated, Apollo crewmembers reported no symptomatology that would suggest lunar dust is allergenic. That is not to say that some crew did not have adverse effects from lunar dust exposure, but reports of rhinitis, irritated eyes, and/or stuffiness likely resulted from a common inflammatory mechanism (part of a normal immune response) that is not antibody mediated. Focused research may still be warranted in terms of immunology. It is suggested that Medical Operations should be prepared for a range of individual responses to lunar dust exposure. Because there are some commonalities in physiological response and treatment regardless of whether an inflammatory reaction is due to allergens or physical insult, it may be reasonable to carry appropriate countermeasures (e.g., nasal steroids and saline for eye irrigation).

8.9 Differences in Lung Deposition Based on Reduced Lunar Gravity

Early in the lunar dust toxicity project, experts weighed the issue of how the Moon’s lower gravity—one-sixth of Earth’s—might affect the toxicity of lunar dust in the lung. One of the major mechanisms of dust deposition in the lung is sedimentation, which is highly dependent on the gravity vector. This possibility has been well studied in human subjects using the lunar gravity that can be created in parabolic aircraft flights. Using particles of 0.5 and 1 μm, it was found that, although deposition is proportionally more distal in reduced gravity, the absolute amount of dust deposition is substantially less (Darquenne & Prisk, 2008). In light of this observation, it was decided that no adjustment or correction factor was needed to deal with differences in dust deposition at Earth gravity, where rat exposure experiments were performed, when estimating human susceptibility during lunar exploration at one-sixth of Earth’s gravity.

8.10 Surface Reactivity of Dust on Lunar Surface

The consensus is that particle surface reactivity of lunar dust is likely a secondary consideration. Uncertainty may persist regarding the ability to mimic in situ reactivity conditions. NASA studies show poor correlation of reactivity and toxicity of studied dusts.

In tailoring human exposure limits for the initial Artemis missions (polar region, short mission duration), Apollo 14 soil is an intermediate soil, hence dust from this soil is thought to be a reasonable representative for the purposes of the assessment. Overall conservatism and intent in setting an exposure limit must be considered given the limited ability to test all regolith types in all lunar regions. The fine surficial lunar dust (most relevant to crew exposures) is understood to have the least variability among varying landing sites (i.e., variation in depth is more significant than variation between equatorial and polar sites). Tailoring for a mission duration less than 7 days (compared with 180-day standard) is warranted. Mission requirements for the lunar surface and for a proposed lunar-orbiting outpost are 7-day PEL at 1.6 mg/m³, and 30- to 180-day PEL at 0.3 mg/m³, respectively.

From Rask (2020, p. 1):

In summary, a series of in situ measurements of lunar dust free radical chemistry at the Artemis landing site, combined with LADTAG-like studies of freshly collected lunar dust specimens, will reveal the true chemical reactivity of in situ lunar dust and generate scientific data that can be compared to the chemical reactivity and biotoxicity of samples from Apollo landing sites. Furthermore, results from in situ measurements and biotoxicity studies of freshly collected specimens can also be used to validate, or require revision of, the current astronaut permissible exposure limit.

Lastly, there is potential for polar volatiles of toxicological concern, given lunar observations and missions have provided credible evidence that permanently shaded regions of the lunar poles may serve as cold traps for a number of specific volatiles in addition to water vapor. The exact source for these volatiles is debated and may include endogenous lunar geological sources or trapped contributions from solar wind. Overturning of the regolith by micrometeorites (impact gardening) can bury volatiles and protect them from surface losses. These volatiles include constituents of potential health concern (e.g., ammonia, carbon monoxide, elemental mercury, hydrogen sulfide, methane, and sulfur dioxide). Given the nature of the impact studies, estimates of concentration are very rough and can vary by several orders of magnitude, with efforts underway to gather more refined data using lunar rovers. Volatiles should not be a nominal concern with respect to retention on surface lunar dust particles on suits, tools, and so forth due to their volatility and the effect of space vacuum when liberated. The main concern is that the polar ice/subsurface regolith may be of interest to ISRU and/or geological researchers who might request that samples be stored in the habitable volume. Toxicological awareness and proper containment need to be maintained in these instances to ensure crew protection during the mission.
8.11 Concerns and Potential Risks to Other Organ Systems

From Scully et al. (2015, pp. 18–19):

The harmful effects to tissues directly exposed to lunar dust (lung, cornea, skin) have been examined, as described above, but an extensive and growing body of literature raises substantial concern that exposure to celestial dust could have harmful effects on other directly, or indirectly, exposed tissues. The risk of adverse effects caused by inhalation of celestial dusts to the nose, pharynx, trachea, and larger air conducting areas of the respiratory system and irritation or damage to the mucosa of the gastrointestinal system by ingested dust remains to be assessed. The risk of adverse effects of celestial dusts on systems such as the cardiovascular, nervous systems and immune systems that may be secondarily, or indirectly affected by inhaled or ingested dusts also remains to be characterized. The residence time of particles depositing in the upper respiratory system, nose, pharynx, trachea, and larger air conducting areas are typically very short due to mechanical clearance provided by nose blowing, sneezing, or the mucociliary escalator (Lippmann et al., 1980). Most particles are removed from the tracheobronchial region within 24 hours. However ultrafine particles may submerge into the mucus of the airway fluid, which may result in their prolonged retention in this region (Schürch et al., 1990; Stahlhofen et al. 1995). Local deposition is important and build-up of concentration on some surfaces can be sufficiently high that the capacity for clearance can be exceeded. Local retentions could account for nasal cancers in furniture workers and for laryngeal cancers in cigarette smokers (Lippmann et al., 1980). Dietz et al. (2004) demonstrated that occupational exposures to cement dust is a risk factor for laryngeal carcinoma. Cement dust contains a mixture of heavy metals that are known human carcinogens (Ogunbileje et al., 2013). These findings are concerning given that Martian dusts contain substantial amounts of heavy metals (Schuerger et al., 2012). The finding of a weak association between silica or silicosis and laryngeal cancer (Chen et al., 2012) also raises concern of possible adverse effects of inhaled celestial dusts in the upper portions of the respiratory system. Particles cleared from the respiratory tract move to the oropharynx and are then swallowed and thereby transferred from the respiratory system to the gastrointestinal (GI) system (Kreyling and Scheuch, 2000; Lippmann et al., 1980). Thus, ingestion, indirectly by transfer from the respiratory system, or directly, provides another potential route of exposure to celestial dusts. Therefore, potential risk of adverse effects of ingested dust upon the GI system must be considered. A “borderline” association between exposure to dust and the diffuse form of stomach cancer has been found for miners and quarry workers (Santibañez et al., 2012). Lin et al. (2014) recently reported evidence for the association between exposure to chrysotile (white asbestos) mining dust and excess mortality from cancers of the stomach, esophagus, and liver among workers with high cumulative exposure to this mineral dust. García-Pérez et al. (2015) found excess cancer mortality (colorectal cancer) in the vicinity of Spanish facilities that produce cement. A meta-analysis of studies of occupational exposure to asbestos found that exposure is associated with a moderate increased risk of stomach cancer (Fortunato & Rushton, 2015). The durations of occupational exposures in the studies related above far exceed the acute exposures that are likely to be experienced by crews exploring celestial bodies, but these finding will take on greater significance and relevance when extended habitation on celestial bodies increases the extent of exposures.

Clearly, avoidance of lunar dust inhalation will be important for future explorers, but with increased human activity on the Moon it is likely that adventitious exposure will occur, particularly for individuals spending long periods of time on that body. A detailed understanding of the health effects of lunar dust exposure is thus important, and further defining the cellular and biological impact of materials from various parts of the lunar surface is warranted. It will be critical to study actual lunar regolith samples for their effects on cell function and the integrity of the cellular DNA (Caston et al., 2018).

8.12 Human Health Summary, Considerations, and Recommendations

- The highly respirable fraction of dust (less than 2.5 μm, or PM2.5) is a fine particulate and poses the greatest potential health risk because these particles can be inhaled deep into the lungs and even enter the bloodstream.
- Dermal effect concerns result from lunar simulant testing that showed abrasive dust has the potential to work like commercial sandpaper, with potential for abrasion of exposed skin of crew. This is especially a concern if dust finds its way into EVA suits, boots, under fingernails, and so forth.
- Ocular effect concerns result from testing of lunar simulant only. First-tier testing showed minimal chemical irritancy, and second-tier testing showed that application of particles to eyes determined some mechanical irritancy, which resolved within 24 h.
• Cardiovascular effect questions require more research to understand the role lunar dust would have in affecting the cardiovascular system. There is limited insight into the effects of lunar dust nanoparticles on human health, with more research needed.

• Pulmonary effects of actual lunar dust interaction during controlled animal (rat) ITI testing can be extrapolated to safe occupational exposure limit recommendations of 180-day permissible exposure limit (PEL) at 0.3 mg/m³, proposed 30-day PEL at 0.3 mg/m³, and a proposed 7-day PEL at 1.6 mg/m³, currently.

• Acute toxicity of lunar dust and immunological/allergic potential has limited evidence, with more research needed. There is limited evidence of chemical reactivity of lunar dust once it is exposed to atmosphere and humidity, such as inside a human habitat.

• Surface reactivity of dust on the lunar surface is likely a secondary consideration. NASA studies show poor correlation of reactivity and toxicity of studied dusts. Volatile, potentially reactive materials are present in permanently shadowed areas at the lunar poles and may present a hazard to crews and their equipment or other valuable resources.

• The control of dust entry into EVA suits, habitat, and vehicle internal volumes should include dust detection and monitoring.

9.0 For Further Reading

In addition to using this general guide, hardware and mission designers are encouraged to consult, as needed, some of the source materials used to construct this overview, starting with the Lunar Sourcebook (Heiken, Vaniman, & French, 1991). Although key information is summarized in Appendix A, including subsequently published data, the Lunar Sourcebook remains an encyclopedic compilation of useful lunar data despite being published over 30 years ago.

A compilation of lunar dust effects observed during Apollo missions remains a useful collection of cautionary information (Gaier, 2005). While a hardware testing summary guide beyond “just” lunar dust is still being prepared, in order to select an appropriate simulant for terrestrial testing, both the Lunar Regolith Simulant User’s Guide (Schrader et al., 2010) and NASA Standard 1008 (NASA, 2021) are useful in determining what simulant characteristics to target and what the testing requirements are, respectively. An updated Lunar Regolith Simulant User’s Guide is also in preparation.

In February 2020, the NASA Engineering and Safety Center (NESC) sponsored a workshop titled “Lunar Dust and Its Impact on Human Exploration,” resulting in both a workshop report (Winterhalter et al., 2020) and a subsequent book (Levine, 2021).

10.0 Concluding Remarks

Lunar surface interactions with equipment built or landed on the Moon will pose challenges atypical to our common experience on Earth. The combinations of hard vacuum, resultant temperature swing extremes and gradients, surface charging and charge differentials, hard radiation, and the occasional micrometeorite impact present unique challenges to equipment on the lunar surface. In addition to these challenges, and compounding them, is the Moon’s finely pulverized regolith, the lunar dust.

A number of concerns, considerations, and mitigations for components and subsystems have been addressed in this version of a lunar dust mitigation guide, compiled some 50 years after the Apollo program and just as we embark upon exploration of new areas of the Moon. The available technology to extend equipment operational life on the lunar surface is still evolving, and a combination of operational practices and hardware/softgoods design may emerge from collective lessons learned over the next years to produce reliable equipment lifetime predictions.

This guide is focused primarily on lunar dust mitigation outside any human habitat, but human health effects are also a major concern due to the respirable mineral particulates in lunar regolith and most simulants. While Section 8.0 may serve as an overview to many of these concerns, a fairly comprehensive discussion of health effects can be found in Scully et al. (2015).

Explicitly not addressed in this guide are questions of where regolith contaminants are coming from and, consequently, how much regolith any given apparatus will be exposed to, over what particle size range, and at what velocity and reactivity, as well as in what charge state the particles will arrive (the regolith exposure source term). What fraction of exposure will be in the harder-to-remove “dust” size range is another variable that argues for the avoid exposure approach, to the extent possible.

Independent of any new technologies that become available, some combination of avoid, remove, or tolerate approaches will be needed, with size, mass, and power requirements, as well as cost, all potentially factoring into future design decisions. Normal wear and tear on equipment—whether during initial, entirely robotic missions or during combined human and robotic exploration of the lunar surface—will require replacement or repair options. The lunar surface extremes and lunar dust likely will only accelerate the need for maintenance and increase the resources required to maintain operations, so dust mitigation technologies should very positively factor in to total cost evaluations for long-term-mission planning.
Appendix A.—Lunar Dust—What Is It?

A.1 Introduction

Understanding the properties of lunar dust is essential to developing mitigation strategies to allow for a safe return to the Moon. Lunar dust is the finest fraction of the bulk lunar regolith, a fine-grained sandy material coating nearly the entire lunar surface. The regolith has been formed from the action of meteorites impacting the lunar surface, progressively fracturing and disintegrating exposed rock into finer and finer particles. Additional modification has resulted from exposure of the surface to the solar wind and highly energetic particles from the Sun and other cosmic sources. With no lunar atmosphere, the main processes by which Earth soils are generated are entirely absent on the Moon. Earth sediments are formed primarily due to erosion from rocks by wind and water, which can both mechanically and chemically alter materials. Additionally, terrestrial soils contain a significant quantity of organic material from biologic processes on Earth.

The geologic environment of the lunar surface enhances its hazardous properties. Lack of fluid erosion allows the dust to remain angular and abrasive. Similarly, the lack of atmosphere allows dust to retain a high degree of reactivity. Dust can also become charged and electrostatically adhere to surfaces, subsequently altering the optical and thermal properties of systems. The process of regolith formation, the physical and chemical properties of dust, as well as the hazardous qualities of dust, have been described in detail in the following appendix to give a better understanding of the lunar environment.

A.2 Regolith Formation

The lunar surface is covered by a layer of loosely consolidated rock fragments known as the lunar regolith. The regolith is formed through a series of both destructive and constructive processes that result from exposure of the lunar surface to the space environment. With no atmosphere, the Moon is exposed to a constant barrage of micrometeoroids, solar particles, and cosmic radiation that a surface would normally be protected from if under an atmosphere, as on Earth. The process of alteration that forms lunar regolith is termed “space weathering” and is thought to act in a similar manner on all airless bodies in the solar system, including Mercury, Vesta, the Martian moons, asteroids, and others. Comparisons between ground-up terrestrial rocks and regolith samples returned during the Apollo program emphasize that lunar soil is significantly altered chemically and physically by a space environment beyond simple physical comminution.

A.2.1 Meteorite Bombardment

Regolith formation is a complex, multistage process that results from the exposure of pristine bedrock to the lunar environment. On the Moon, meteorite bombardment is the primary process responsible for the formation of the regolith. Billions of years of exposure to a constant flux of micrometeorites has slowly ground the lunar surface material into fine, sandy material. Large, rare impacts are responsible for breaking up large chunks of regolith, and smaller impacts further commute the exposed lunar rocks. Most of the current meteor flux is in the form of micrometeorites, with the bulk of the material impacting the lunar surface ranging in size from 10 nm to 1 mm, with an impact speed of 10 to 72 km/s. In addition to pulverizing existing material, the energy from impacts can melt a fraction of the target material, fusing regolith together while also vaporizing some volatile material. Large impacts fuse discrete chunks of material together to create regolith breccias, which are rocks composed of clasts cemented together. Microscopic impactors melt a portion of the target material, creating impact glasses capable of engulfing and fusing surrounding grains into particles known as agglutinates. These small agglutinates have different optical and structural properties from pristine mineral grains.

In addition to altering the particle size of the regolith, meteorite impacts also churn, or “garden,” the soil. Impacts produce ejecta blankets that can take buried regolith and bring it to the surface, where it is spread over the existing regolith layer. In this manner, buried immature regoliths can be layered on top of exposed mature regoliths. Over the billion-year timescale of regolith formation, particular samples of regolith can be buried and reexposed multiple times. Observations of Apollo core tube samples demonstrate several discrete layers of regolith of varying maturity and grain size, indicating the gardening of the soil. Large meteorite impacts are capable of completely penetrating the regolith layer and excavating fragments of pristine bedrock that are subsequently exposed to space weathering. Additionally, large impacts can spread regolith over significant distances, and ejecta can even create secondary impacts that further churn the soil. Intermediate-sized meteorites contribute to the local gardening in the top 5 m or so of the soil. Micrometeorites, of mass $10^{-3}$ grams or less, are the highest flux hitting the Moon and are primarily responsible for the comminution of small particles. These small yet constant impacts can be thought of as a sand blaster that consistently breaks down the regolith while bigger particles churn the soil and expose new material. While the regolith is primarily native lunar material, there is a <2 percent meteoritic component as a result of these impacts.
A.2.2 Solar and Cosmic Particles

In addition to meteorite impacts, the lunar regolith is exposed to solar and cosmic particles. These energetic particles have different effects on the lunar regolith depending on their energy level. First, the lunar surface is exposed to a constant flux of charged particles from the solar wind. This solar wind plasma is composed mostly of protons, electrons, and alpha particles with energies ranging from 0.5 to 10 keV with an average of 1 keV. These particles embed themselves in the outer layer of regolith grains, leading to both electrical charging and the implantation of solar wind gases such as hydrogen. These particles cause radiation damage in nonconducting minerals, leading to an ultrathin amorphous outer layer in regolith grains (Dran et al., 1970). This amorphous layer tends to be at most 200 nm thick, and the composition of the rim is identical to the underlying grain. Additionally, the accumulation of ions can cause material to be lost through sputtering, which leads to a slight rounding of grains. Given the slow rate of this sputtering effect, it is most easily observed in the shape of submicron grains (Bibring et al., 1974).

In addition to the constant flux of the solar wind, the Sun also sporadically emits solar energetic particles (SEPs) resulting from either solar flares or coronal mass ejections. Fluxes of SEPs consist of ions (~50 keV to 10 GeV) and electrons (~1 keV to 10 MeV) in roughly equal quantities. These particles typically penetrate the regolith to 1 mm, with electrons capable of slightly further penetration due to their smaller size limiting potential interactions with other particles (Jordan et al., 2015a; Jordan et al., 2015b). Similar to solar wind particles, SEPs can cause radiation damage in grains and embed energetic particles in the regolith with greater effect.

Finally, cosmic radiation also plays a role in regolith formation. Galactic cosmic rays (GCRs) are composed primarily of ~87 percent protons with a flux of 200 Mev to 1 GeV. GCRs are capable of penetrating regolith to depths of up to 1 m, and they are capable of producing isotopes through nuclear reactions. Experiments correlating isotope production with regolith depth have been used to calculate the exposure age of regolith samples, as greater densities of exotic isotopes indicate longer exposure to the cosmic rays.

Both SEPs and GCRs are capable of leaving tracks in dielectric minerals and glasses as the energetic particles penetrate and leave defects in the target (Figure A.1). The density of these tracks can be used to estimate the maturity of the sample, as higher density indicates longer exposure to solar particle streams. Additionally, the length of the track can be used to infer the atomic number, and thus the composition, of the material making the track. Given the ability of lunar material to record information about solar particles and the several-billion-year history of regolith exposure, lunar soils are useful sources of information about the history of the Sun.

A.2.3 Dielectric Breakdown Weathering

Regolith is composed almost entirely of silicate mineral and glassy phases, which are poor conductors. These materials are considered to be dielectric and are able to keep electric charges separated by a distance. With a strong enough electric field, however, the dielectric properties of the grain will fail, and it will conduct electricity rather than insulate. This failure is called dielectric breakdown and is the same principle behind sparking. The dielectric strength of the material is the maximum electric field it can endure before undergoing breakdown.

Various processes are capable of inducing an electric charge in the lunar surface, including exposure to the solar wind and the photoelectric effect. These are further discussed in a later section on the electrical properties of regolith (A.5). Under normal circumstances, grains do not see high enough charging to experience dielectric breakdown. However, given that...
electrical conductivity decreases with decreasing temperature, it has been hypothesized that regolith in the cold permanently shadowed regions (PSRs) could see significantly more charging than other regoliths. With especially high fluxes of charged particles resulting from SEPs and GCRs, it is possible that the resulting electric fields could overcome the dielectric strength of the lunar material.

Lunar regoliths have jagged, irregular edges and various inclusions and vesicles, both of which increase local electric fields and reduce the dielectric strength (Jordan et al., 2015a). If grains did develop an electric field sufficiently strong to induce breakdown, the resulting process could fracture grains along existing weaknesses and contribute to regolith comminution. This hypothesis has been pursued as one explanation for the unusually low porosity of regolith in the polar regions. The Lunar Crater Observation and Sensing Satellite (LCROSS) impact appeared to indicate that regolith in the PSRs of the south pole are “fluffier” than expected, and that some aspect of the polar environment decreases the compaction of the regolith.

It is possible that the effects of dielectric breakdown could pose a hazard to robotic and human exploration of the polar regions. The strong local electric fields themselves, regardless of dielectric breakdown, could also prove to be dangerous to explorers. However, more research is needed to determine the actual electrostatic conditions in the PSRs.

A.2.4 Regolith Maturity

To describe the length of time a regolith sample has been exposed to space weathering processes on the lunar surface, two measures are used. Soils can be classified by their maturity, which is a relative index of the degree of space weathering a regolith has undergone. As such, soils are classified as mature, submature, or immature depending on the extent to which they have been modified by the space environment. To provide a more quantitative measure of regolith maturity, the concept of the surface exposure age has also been developed. Surface exposure age is the quantitative length of time a regolith has been exposed at the surface. Surface exposure ages can be estimated by examining the degree of modification that a sample has undergone from a process that occurs at a reliable rate. The various methods of determining surface exposure age are called maturity indices.

The most popular maturity index is a measure of the magnetic intensity of regolith, which is influenced by the presence of nanophase iron (np-Fe0) in the soil. As np-Fe0 is formed from the action of micrometeorites on the lunar regolith, more mature samples will contain higher concentrations of np-Fe0. Because np-Fe0 particles are ferromagnetic, the measure of the magnetic intensity to the total iron content of the soil, which includes all phases of iron present, can be used to measure the degree to which iron has been converted to the nanophase, given the relatively stable flux of micrometeorites over the past three billion years.

Additionally, the bulk agglutinate content of a soil can also be used as a rough indication of sample maturity. Higher agglutinate content indicates greater exposure of the soil to meteorite flux at the lunar surface. However, it is thought that agglutinate formation reaches a steady state with impact comminution at approximately 100 million years (100 Ma), leading to equal amounts of agglutinate destruction and construction. As such, this index is only useful in categorizing younger soils. After this point, agglutinate content ceases to increase with age.

Another index of maturity is counting the density of particle tracks from high-energy particle exposure. On a cosmic timescale of several billion years, the flux of these high-energy particles is relatively constant, and thus their density tends to linearly correlate to surface exposure age.

A.2.5 Vapor Fractionation

The intense energy and heat of meteorite impact can vaporize volatile elements in the target material. The volatiles can be transported away from the impact site and potentially be deposited on other regolith grains or escape into space. As the Moon’s gravity is too weak to support an atmosphere, the lunar surface will tend to be depleted in these volatile elements as they escape. As such, lunar regolith demonstrates mass fractionation of volatile elements. For example, when compared with unaltered bedrock, mature regolith samples are depleted in 16O and 28Si compared with 18O and 30Si. Additionally, O is depleted relative to Si, indicating that the lighter volatiles have escaped into space. Epstein and Taylor (1972) demonstrate that these depletions are more pronounced at the surface of regolith grains and directly correlated with the presence of solar wind hydrogen, an indication of maturity.

Most grains exhibit a layer of amorphous material deposited by vapor fractionation (Figure A.2). Only a portion of vaporized volatiles are able to escape into space; the rest are redeposited on the lunar surface. These layers can be differentiated from amorphous rims caused by radiation damage by chemical composition. Radiation-damaged rims result from modification of the underlying grain structure by charged particles and thus will have a chemical composition identical to that of the underlying grain. By contrast, the layers of amorphous volatile material will have a composition close to that of the soil as a whole. Additionally, the vaporization of the preexisting regolith tends to dissociate the Fe-O bonds in iron-bearing minerals. This process is responsible for concentration of np-Fe0 on the surface of grains. This is one of the most important consequences of space weathering, as it has been demonstrated to alter the optical properties of soils (Noble, 2009).
A.2.6 Maturation and Iron Content

The formation of lunar regolith alters the iron content of the material. All agglutinates and the amorphous rims of many mature mineral grains contain concentrations of nanophase metallic iron particles. These particles are typically < 30 nm in size and in the single domain range. The presence of iron in soil particles has been recognized as a consequence of the regolith formation process and has thus been utilized as a measure of regolith maturity since the Apollo missions. Previously, it was thought that these np-Fe⁰ particles resulted from the reduction of iron oxides by solar wind hydrogen liberated from micrometeorite vaporization. However, recent research has discovered that these iron particles are actually the result of the dissociation of Fe-O bonds in ferrous oxides during impact vaporization (Anad et al., 2004; Keller & McKay, 1997). As such, the np-Fe⁰ particles are deposited on grain surfaces along with other vaporized volatiles, concentrating in the resulting amorphous surface layers. Additionally, iron can be deposited on grain surfaces by being sputtered off other grains through high-energy particle impacts. This is supported by the observation that np-Fe⁰ content increases with decreasing grain size at a rate that cannot be explained by an increase in agglutinitic glass alone. The increase in surface-deposited material with decreasing grain size, as smaller grains have a greater surface-area-to-volume ratio, is responsible for the sharp increase in np-Fe⁰. Iron presence in agglutinates likely results primarily from the incorporation of this surface material into agglutinitic glass.

Given that np-Fe⁰ formation relies on the action of micrometeorites and high-energy particles, the iron formation process does not occur in terrestrial soils. As most lunar simulants are formed from basaltic Earth rocks with compositions similar to lunar material, most lunar simulants do not contain this microphase iron. The presence of np-Fe⁰ has been correlated with increased reactivity, which means that lunar simulants may not accurately reflect the reactivity of lunar regolith and dust.

A.3 Types of Particles

The particles that compose lunar dust can be divided into five types: agglutinates, mineral fragments, brecciated material, glassy material, and pristine rock (Figure A.3). Agglutinates, impact breccias, and heterogeneous glasses are regolith derived and are sometimes called the fused fraction. They result from the fusion of existing regolith material. By contrast, volcanic material in the form of glass, rock fragments, and minerals are bedrock derived, resulting from the comminution or fusion of pristine bedrock material. All particle types are found in lunar soil samples, but the concentration of each can vary significantly based on the maturity, chemical composition, and geologic context of each sampling site (Figure A.4). Lithic fragments and breccias are significantly less common in smaller size fractions as they tend to disaggregate into their constituent clasts at these sizes. While lower in concentration, the dust fraction will still contain some amount of lithic and brecciated particles.
Figure A.4.—Modal distribution of particle types in the coarse (1,000- to 90-µm) size fraction of soil. Various soils are presented from different Apollo and Luna missions. All particle types are found with varying degrees of frequency in each soil. Adapted from Simon, Papike, & Laul (1981).
A.3.1 Agglutinates

Agglutinates are an important component of lunar regolith, being responsible for many of the physical and chemical properties that distinguish lunar dust from its terrestrial counterparts (Figure A.5). Agglutinates are highly irregular particles, typically smaller than 1 mm, composed of smaller regolith grains (mineral fragments, glass fragments, and other agglutinates) bound together by a matrix of glassy material. Embedded within the agglutinitic glass are microscopic particles of metallic iron. These particles of nanophase iron (np-Fe⁰) are in the single domain range and are typically 30 to 100 Å across. These iron particles contain relatively little nickel compared with the typical composition of meteorites, indicating a non-extraterrestrial origin. Additionally, all agglutinates exhibit a rind of implanted solar wind gases.

A.3.1.1 Agglutinates Formation

Agglutinate formation is the result of high-velocity micrometeoroids impacting the regolith layer. At the point of impact, the energy of the impactor melts a small portion of the target material, which subsequently engulfs nearby regolith grains and quickly cools, trapping them in newly formed glass. The quenching process is rapid, leaving little time for the agglutinate to chemically or structurally homogenize. The impact also liberates the solar wind gases trapped in the outer layer of the impacted regolith grains; these gases either escape or are trapped within the agglutinate as gas vesicles. Additionally, the Fe-O bonds in iron oxides in the lunar soil are dissociated, forming np-Fe⁰ particles.

Being composed of quickly quenched glass, agglutinates are highly irregular in form, often exhibiting branching, twisting, or reentrant forms. On average, agglutinates have about 8 times the surface area of a sphere of the same size (Carrier, 2003). This enhances the ability of agglutinates to mechanically interlock with one another. An analogy has been used such that if well-worn Earth sediments can be thought of as smooth marbles, lunar agglutinates are more akin to children’s jacks. This increases the regolith shear strength, porosity, and other geotechnical properties, as discussed in Section A.7.

Because agglutinates are a consequence of micrometeoroid impacts, their presence is limited to astronomical bodies lacking an atmosphere that are thus exposed to space weathering. While only directly observed on the Moon, agglutinates are theorized to exist on most airless bodies, such as Mercury, the Martian moons, Vesta, and other small solar system objects. Agglutination is correlated with the micrometeoroid flux experienced by the sample. Given that the micrometeoroid flux on the Moon has remained essentially constant for the past 4,000 Ma, regolith samples that have been exposed at the surface for greater periods of time (referred to as “more mature” samples) will contain more agglutinates. Immature soils have an agglutinate content of roughly 15 percent, while mature soils average to more than 45 percent (McKay, Fruland, & Heiken, 1974). This correlation between maturity and agglutinate content appears to hold for the first ~100 Ma. Because that impact comminution is more effective at breaking up larger soil particles, and agglutination favors the assembly of smaller soil particles into larger chunks, there is a point at which these two processes balance into a steady state. This is supported by the observation that most Apollo soils with a surface exposure age greater than 100 Ma have a relatively consistent agglutinate content with one another, while the agglutinate content of submature and immature soils increases linearly with age up to 100 Ma.

Figure A.5.—Typical agglutinate particles. (a) Optical microscope image of agglutinates from Apollo 11 soil 10084, demonstrating a variety of irregular morphologies (NASA Photo S69-54827). (b) Scanning electron microscope (SEM) image of single agglutinate from soil 10084, exhibiting a reentrant shape (NASA Photo S87-38812).
A.3.1.2 Agglutinate Chemistry

Agglutinates are formed of soil grains bonded together with small amounts of impact glass and, as such, preferentially incorporate smaller soil particles into their structure. Simply put, smaller particles have a greater chance of incorporation into agglutinates because more small particles can be bound together by the same volume of glass. Additionally, the smaller soil fractions are more likely to completely melt during impact to form the agglutinate matrix. As such, the chemistry of agglutinates tends to be consistent with that of the finest soil fraction. Agglutinates tend to be slightly enriched in plagioclase-associated elements such as Al$_2$O$_3$ and depleted in FeO and MgO.

A.3.2 Glass Fragments

Lunar glass fragments are derived from one of two processes: impact vitrification (conversion of material into glass), such as the glassy matrix of agglutinates, or volcanic cooling, such as the glassy volcanic ash retrieved by Apollo 17. Glasses of both types are found in all soil samples, and glass fragments can exhibit a wide range of characteristics. Agglutinates represent one end of the spectrum, being highly heterogeneous glass samples with irregular morphologies, numerous clastic inclusions, and regions of differing chemistry within the glass itself. Conversely, some volcanic glasses are spherical and chemically homogenous, exhibiting none of the heterogeneity of agglutinates. The physical and chemical characteristics of glass fragments can be used to distinguish their origin.

A.3.2.1 Impact Glass

Impact glasses are the result of material that is melted by the high energy imparted by an impact and subsequently quenched. Such material can result from micrometeoroids in the submillimeter range to large bolides kilometers in size. Impact glasses can be distinguished from volcanic glasses, as they exhibit certain properties unique to their formation (Zellner, 2019). Impact glasses frequently contain inclusions of existing regolith or even fragments of the impactor itself. Impacts, especially microscale impacts, will frequently melt a single mineral or rock type, giving the glass a chemical composition distinct from magmas. Many impact glasses exhibit a coating of “rock flour,” a very finely powdered lithic material resulting from the pulverization of surface material (Chao, 1970). Impact glass can be observed in a variety of forms in returned lunar samples. Agglutinates have previously been discussed, but glass can also occur as sharp fragments, as rounded droplets that cooled during parabolic flight, as veiny inclusions in rocks, as splashes on grains, or as linings on microscopic impact craters. Impact glasses are more common in the finer size fractions of lunar regolith.

A.3.2.2 Volcanic Glass

Volcanic glasses (Figure A.6) are relatively similar to their terrestrial counterparts. They form when magmatic material cools too quickly for the atoms to arrange themselves in a crystalline structure. Frequently, lunar volcanic glasses result from so-called fire fountains, volcanic eruptions that spray magmatic material due to the expansion of volatile gases within the magma. This type of eruption can be observed in the Hawaiian volcanoes. Glasses derived from such eruptions frequently exhibit spherical, oblong, or dumbbell shapes as a consequence of quenching during ballistic flight.

Multiple chemical factors can be used to determine if a glass is volcanic in origin as opposed to impact derived. Volcanic glasses form from a magmatic source that had sufficient time...
and temperature to chemically homogenize as it rose from the lunar interior. As such, volcanic glasses are chemically homogenous with respect to nonvolatile elements. Volatile elements are capable of being mobile during eruptions, meaning volcanic glasses can be heterogeneous with respect to their volatile compositions. Compared with impact glasses, volcanic glasses can be distinguished by compositional clustering between multiple samples. Impact glasses result from grains of differing composition being melted and then ejected away from the impact site, resulting in potential chemical differences between grains from the same impact. By contrast, volcanic glasses erupt from a more homogenous magma source, and volcanic glasses corresponding to a single eruption should cluster when their compositions are plotted (Delano, 1986). Volcanic glasses have higher Mg/Al ratios than impact glasses or mare regolith, confirmed by Apollo 17 sampling of dark mantle deposits. Volcanic glasses have lower abundances of siderophile elements (Ir, Ni) that are associated with iron meteorite contamination. Additionally, Ni/Mg ratios are relatively consistent in volcanic glasses. Finally, many volcanic glasses (Apollo 15 green, Apollo 17 orange spherules) were formed from pyroclastic fire fountains, which are powered by gas. The volatile elements driving the eruptive process were implanted on the surface of the glass as well as trapped within vesicles. The small number of pristine volcanics with measured ages all correlate with mare volcanic periods.

A.3.3 Breccia

Breccias are fragmental rocks formed from shock induration, or the fusion of clasts together from the extreme energy of meteorite impact. Lunar breccias consist of rock, mineral, and glass fragments, indicating they are composed of preexisting regolith material subsequently fused together. Typically, the breccias are held together by a glassy matrix resulting from the liquefaction and vitrification of material from the shock waves of meteorite impact. Breccias range from weak and friable (easily disaggregated) to very coherent. The strength of a breccia is likely related to the energy of the forming shock, with more coherent breccias likely formed at much higher shock pressures closer to the impactor. Given that they are formed from existing regolith, their composition is typically close to that of the bulk regolith. Breccias decrease in abundance with decreasing size fraction, as they are more likely to be comminuted into their individual clasts at small sizes.

A.3.4 Mineral Fragments and Rock

Mineral and lithic (rock) fragments (Figure A.7) are derived from the comminution of original bedrock material. Given that rocks are aggregates of minerals, the distribution of material present as polymineralk rock fragments versus individual mineral shards is controlled by the grain size distribution of the soil and the original size of the mineral grains. Fine-grained rocks, such as the basalts of Apollo 15, are more likely to be present in the regolith as clasts containing multiple minerals. By contrast, coarse-grained material is more likely to be comminuted into individual minerals. Some lunar rocks have phenocrysts (mineral grains of large size existing in a rock matrix of finer grained materials) up to 5 cm across, which is much larger than the average grain size of the soil, and thus these rocks will be disaggregated into their mineral components in the finer fractions of soil. Polymineralk rock fragments are not common in the finest size fractions of lunar dust. Given the difficulty of identifying individual mineral phases within rock at small sizes, the mineral content of a sample is frequently identified by investigating the bulk chemistry of the sample. Individual minerals can be distinguished by their contribution to the overall chemical composition.
A significant portion of the mineral fragments making up the lunar regolith exhibit shock damage in the form of planar defects, indicating that they have undergone alteration as a result of meteorite impacts. Additionally, many lunar minerals exhibit surface radiation damage resulting from high-energy particles from the solar wind and other cosmonogenic sources. This damage is in the form of an amorphous rim on the mineral grain, typically less than 200 nm thick. As the amorphous material is formed from damaged material of the outside of the mineral, the chemical composition of the rim is identical to that of the underlying mineral. Mineral grains can also accumulate a coating of deposited volatiles vaporized during impacts that then settle on the surface of the regolith.

### A.3.5 Distribution of Grain Types in Soil

Mineral fragments, agglutinates, and other glassy phases are the most common components of the finer fractions of lunar soils. Polymineralic rock fragments and breccias are typically disaggregated into their constituent clasts in the finer fractions of lunar soil. The compositional breakdown is influenced by the environment of soil formation as well as the age of the soil. Soils formed near pyroclastic deposits, such as the orange soils of Apollo 17, will be enriched in glassy phases resulting from the presence of volcanic glass. Similarly, older soils will be enriched in impact glasses, including agglutinates, as their longer exposure to the meteorite flux allows for greater impact glass formation. Younger soils will not have undergone as much modification and will be primarily composed of lithic fragments and mineral grains.

Agglutinate content increases with decreasing grain size up to the 2- to 10-µm fraction, at which point agglutinate content decreases. At small sizes, agglutinates tend to be disaggregated into their constituent grains and glassy phases. Glasses and other materials that have undergone extensive space weathering tend to concentrate in the finest fraction. The ultrafine portions of lunar dust, from 0.1 to 2 µm in size, have been shown to consist of up to 80 to 90 percent glass modally (Taylor et al., 2001).

Table A.1 shows relative abundances of particle types across size fractions for an Apollo 16 soil sample.

### A.4 Chemical Properties

#### A.4.1 Chemical Composition

The chemical composition of a lunar soil tends to represent the composition of the underlying bedrock with a minor exotic component. Lunar material can be divided into a few different groups by composition. The main distinction is between the light highland material and dark mare material (Figure A.8), which can subsequently be divided into high-Ti and low-Ti mare based on titanium content.

The lunar highlands are the lighter, more reflective regions of the lunar surface. These regions represent the original material of the Moon’s crust, which solidified and floated over the molten interior early in its formation. The highlands are felsic in composition, a term used to describe rock containing large amounts of feldspar and other light-colored minerals. As such, highland regoliths tend to be depleted in Fe and Mg and enriched in Ca and Na. In terms of bulk chemistry, highland soils tend to be composed of 45 to 50 percent SiO₂, 15 to 30 percent Al₂O₃, 10 to 15 percent CaO, 5 to 10 percent FeO, 5 to 10 percent MgO, and 1 to 2 percent TiO₂, with trace amounts (<1 percent) Cr₂O₃, Na₂O, K₂O, P₂O₅, and SO₃. A more in-depth breakdown of the chemistry of specific highland soil samples can be found in Taylor et al. (2010).

The lunar maria (singular mare) are the darker regions of the lunar surface. The maria are the result of large-scale lava flows and consist of large plains of basaltic rock. The molten material preferentially filled the low-lying regions of the lunar surface, although not always. The South Pole–Aitken Basin is a lunar lowland not covered in mare flows. The darker color of the mare results from the mafic composition of the basalt flows. The term “mafic” is used to describe rocks with higher magnesium and iron composition. Mare materials are enriched in pyroxenes and olivines, two mafic minerals with high Mg and Fe content. The maria range in age from 1 to 4.5 billion years old, with most being formed between 3 and 3.5 billion years ago. Roughly one-third of the lunar nearside is covered by the maria, whereas only a very small percentage of the far side contains mare material.

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**TABLE A.1.—RELATIVE ABUNDANCES (vol.%) OF PARTICLE TYPES ACROSS SIZE FRACTIONS OF SOIL 64501 [From Houck (1982).]**

<table>
<thead>
<tr>
<th>Size fraction (µm)</th>
<th>250 to 500</th>
<th>150 to 250</th>
<th>90 to 150</th>
<th>75 to 90</th>
<th>45 to 75</th>
<th>20 to 45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral fragments</td>
<td>29.0</td>
<td>35.3</td>
<td>25.3</td>
<td>30.9</td>
<td>45.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Lithic fragments</td>
<td>5.8</td>
<td>0.3</td>
<td>-----</td>
<td>0.3</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Breccias</td>
<td>31.4</td>
<td>32.7</td>
<td>26.2</td>
<td>24.0</td>
<td>21.6</td>
<td>22.9</td>
</tr>
<tr>
<td>Agglutinates</td>
<td>28.1</td>
<td>27.1</td>
<td>44.0</td>
<td>34.5</td>
<td>25.7</td>
<td>22.5</td>
</tr>
<tr>
<td>Glassy phases</td>
<td>4.3</td>
<td>4.7</td>
<td>4.9</td>
<td>9.2</td>
<td>7.5</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Mare material is mafic in composition and is similar to terrestrial basalts. These rocks are primarily composed of pyroxene and olivine, two silicate minerals with higher Fe and Mg content. The mare material can be further divided based upon titanium content. The high-Ti mare material tends to be older, erupted onto the lunar surface from 3,550 to 3,850 million years ago (mya). Low-Ti material tends to be younger, corresponding to 3,150 to 3,450 mya. Mare material in bulk is composed of 40 to 50 percent SiO2, 14 to 20 percent FeO, 10 to 15 percent Al2O3, 10 to 12 percent CaO, and 8 to 11 percent MgO. High-Ti material is typically 5 to 10 percent TiO2, whereas low-Ti material is usually only 2 to 3 percent TiO2.

Some lunar soils represent a mixture of highland and mare material. While the regolith composition primarily reflects that of the underlying bedrock, many Apollo missions landed in regions on the border between mare and highland regions. There is enough lateral transport from impacts that soils in these regions demonstrated a blend in composition.

Some lunar basalts are enriched in KREEP, indicating an unusually high abundance of K (potassium), REE (rare earth elements), and P (phosphorus). These elements are typically incompatible, remaining in magma while other elements precipitate out, leaving the magma enriched in KREEP. These rocks are primarily correlated with basalt deposits on the near side.

A.4.1.1 Compositional Changes With Size

A few processes can result in differing compositions with size fraction. First, agglutinate content typically increases with decreasing size fraction. Given that agglutinates incorporate the smallest particles in the regolith into the glassy matrix, agglutinate chemistry typically skews to that of the smallest size fraction. Plagioclase, a common feldspar in highland material, is more prone to fracturing than pyroxene or olivine. As such, the smallest size fractions tend to be enriched in plagioclase fragments. In both highland and mare material, the composition of dust and very fine regolith material should skew toward a more plagioclase-rich (CaO and Al2O3) and away from a mafic (FeO and MgO) composition. Additionally, the finest size fractions demonstrate a greater abundance of nanophase iron (np-Fe0). This is due to the greater surface-area-to-volume ratio of smaller particles and thus a greater presence of surface-correlated np-Fe0. This, combined with the greater surface-area-to-volume ratio of smaller particles, tends to increase the reactivity of dust compared to larger particles.

A.4.2 Chemical Reactivity

Space weathering also gives regolith a high degree of chemical reactivity. A number of processes are capable of creating chemically active surfaces on regolith grains, which enhances the ability of regolith to undergo chemical reactions. When a mineral is fractured, the chemical bonds that link the internal crystalline structure are broken. Some of these broken bonds can be satisfied by internal reorganization, but most remain unsatisfied and reactive. The mechanical comminution of regolith by micrometeorite impact is a significant source of fractured material, but impacts from even smaller microparticles can also break surface bonds in minerals. The bond energy of a typical Si-O bond in a silicate mineral is about 2.4 eV. UV photons with a wavelength of 300 nm have an energy of ~4 eV, which is enough to break silicate bonds. Similarly, solar wind protons have energies of ~1 keV and are also capable of breaking silicate bonds. While visible and infrared light will not lead to activated surfaces, UV and x-ray photons from the Sun can.

These active surfaces will readily react with chemical species brought in contact. On Earth, these active surfaces are quickly neutralized by the atmosphere. Bogard notes that only 20 cm³ of air at 50 percent humidity has enough water vapor to neutralize 10 grams of regolith (Bogard et al., 2011). Additionally, active surfaces on Earth are only generated from physical breaking, as the atmosphere prevents other particle impacts. On the lunar surface, with very few volatiles and a nearly nonexistent atmosphere (exosphere) of 10⁻¹⁰ to 10⁻¹² torr, active surfaces readily persist and the reactivity of regolith does not diminish.
Given that no returned lunar sample has been effectively isolated from the Earth’s atmosphere, the reactivity of these samples has declined such that they are no longer representative of pristine lunar material. However, attempts have been made to quantify the reactivity that can be expected. Hurowitz et al. (2007) analyzed the contribution to reactivity from individual mineralogical species within lunar simulants by measuring hydrogen peroxide production. The experimenters found that plagioclase (in the form of labradorite) demonstrated little reactive activity, while olivine and pyroxene were significantly reactive. These results imply that mare material can be expected to be more reactive than highland material.

Additionally, Wallace et al. ground a sample of Apollo 16 soil to generate freshly broken mineral surfaces (Wallace et al., 2009). The soil reactivity was then compared with that of simulant JSC–1A–vf. Ground lunar soil was not only 10 times more reactive than unground soil, resulting from the freshly activated surfaces, but ground soil was 3 times more reactive than ground simulant. As the unground soil was similarly reactive to unground simulant, mineralogical alone cannot account for the observed reactivity. The authors proposed that defective surfaces resulting from the presence of np-Fe⁰ in the glassy material was responsible. A direct correlation between reactivity and regolith maturity was observed, supporting the connection between np-Fe⁰ and reactivity. Additionally, mare material was more reactive than highland material of similar maturity, supporting the observations of Hurowitz et al.

A.4.2.1 Mineralogy

The mineral composition of the lunar surface is relatively simple compared with that of the Earth. The bulk of lunar material is composed of a select number of silicate and oxide minerals. Given the absence of significant amounts of water, hydrated minerals such as gypsum and clay minerals that incorporate H₂O into their structure are entirely absent. Plagioclase, pyroxene, olivine, and ilmenite compose the bulk of the minerals found on the Moon. Plagioclase, properly the plagioclase feldspar series, consists of a solid solution with a composition between CaAl₂Si₂O₈ (anorthite) and NaAlSi₃O₈ (albite). In lunar material, anorthite is much more common, with the sodium end-member being relatively rare. Plagioclase is considered a felsic mineral and is the primary constituent of highland material.

Pyroxene and olivine are the most common minerals in mare material and are considered mafic in composition. Pyroxene is a group of minerals existing in a solid solution between CaFeSi₂O₆ (hedenbergite), CaMgSi₂O₆ (diopside), Mg₂Si₂O₆ (enstatite), and Fe₂Si₂O₆ (ferrosilite). Olivine exists as a solid solution between Mg₂SiO₄ (forsterite) and Fe₂SiO₄ (fayalite). Other common minerals in lunar material are oxides. Ilmenite (FeTiO₃) is an important source of titanium and iron in lunar material.

Highland soils are mostly plagioclase, with minor amounts of other minerals. Basu and Riegsecker (2000) calculated the modal mineral distribution in a variety of Apollo soils, removing contribution from impact glass, agglutinates, and breccias. This method assumes mineral distribution in agglutinates and breccias is the same as in monomineralic grains and thus is not the most accurate analysis of composition, but it provides a useful illustration of the mineralogy of soils. Highland soils were found to be composed of 60 to 90 percent plagioclase, 7 to 35 percent pyroxene, <10 percent olivine, and <3 percent oxides such as ilmenite. Figure A.9 compares the modal distribution of minerals, including contributions from glassy modes, for Apollo 14 and Apollo 16.

Mare soils tend to be 20 to 45 percent plagioclase, 50 to 60 percent pyroxene, 2 to 10 percent olivine, and <10 percent oxides by modal mineral abundance. Compared with highland material, mare soils are enriched in mafic minerals such as pyroxene and olivine and also contain a higher abundance of oxides. High-Ti mare soils typically have a higher oxide abundance than low-Ti soils, as titanium is primarily found in the form of the oxide ilmenite on the lunar surface.

A.4.2.2 Compositional Changes With Grain Size

The abundances of different grain types are strongly affected by the grain size. Both pyroxene and olivine content tend to decrease with decreasing particle size. Plagioclase is more prone to fracture and thus will be enriched in smaller size fractions. Similarly, agglutinate content tends to be increased in the finer soil fractions but decreases in fractions smaller than 2 to 10 µm as agglutinates are comminuted into their constituent clasts.

As an example for illustration, in one highland soil from Apollo 14, pyroxene content decreased from 16.2 to 3.8 percent and olivine from 2.4 to 0.4 percent comparing the 20 to 45 µm with the <10-µm size fractions. Conversely, plagioclase content increases with decreasing size, with the same sample increasing from 18.9 to 21.8 percent in the same size fractions. For comparison, agglutinate content increased from 56.4 to 66.3 percent.
In the finest fractions of dust, the mineral content of the soil tends to decrease, as glass and other space weathering products are likely to concentrate at that size. Taylor et al. noted that the 0.1- to 2-µm size fraction was composed of 80 to 90 percent glass (Taylor et al., 2001).

A.4.2.3 Chemical Changes With Space Weathering

The action of space weathering on regolith grains tends to induce some chemical changes. A full discussion of these changes is provided in Section A.2, but they are summarized here as well for convenience. Meteorite impacts are capable of vaporizing material, which can deplete the regolith in volatiles that escape to space. Additionally, these volatiles can be deposited on grain surfaces in the form of amorphous layers. Similar amorphous layers can be caused by radiation damage from solar particles. The solar wind also tends to implant hydrogen into the regolith.

Nanophase iron also tends to form from the vaporization process as the Fe-O bonds in iron-bearing minerals dissociate. Nanophase iron can increase the reactivity of lunar soils. Additionally, the lack of a lunar atmosphere prevents broken chemical bonds on fractured mineral surfaces from being satisfied, similarly increasing reactivity of lunar regolith.

A.5 Electrostatic Properties

Lunar regolith is composed almost entirely of silicate minerals and glass, which tend to be dielectric, nonconducting materials. As such, lunar dust readily accumulates an electric charge and tends to maintain this charge, especially when in the vacuum of the lunar surface. Charging from the solar wind, radiation exposure, and mechanical interactions between grains all create a complex electric environment on the lunar surface.

A.5.1 Electrical Conductivity

Lunar regolith is primarily composed of glasses along with silicate and oxide minerals, all of which are poor electrical conductors. As such, regolith grains will accumulate electric charge when exposed to a charged environment.

A.5.1.1 Dielectric Permittivity

The dielectric permittivity of a material is its ability to keep electric charges separated.

The relative dielectric permittivity for lunar materials is approximately $k' = 1.9^\rho$, where $\rho$ is the bulk density of the soil. As evidenced by the equation, dielectric permittivity is dominantly controlled by the density of the soil and is not
significantly influenced by variations in chemistry, mineralogy, or temperature for lunar surface conditions.

A.5.1.2 Loss Tangent

The loss tangent indicates the dissipation of electrical energy through a variety of physical processes. For lunar soils, the high-frequency electromagnetic loss is given by $\tan \delta = 10^{(0.038(\%TiO_2 + \%FeO) + 0.312 \rho)}$. Low conductivity combined with low loss tangent indicates that lunar soils readily charge and remain charged for long periods of time.

A.5.1.3 Conductivity

The conductivity of lunar soils is primarily dependent on temperature but is also controlled by the mineralogical components of the soil. On the lower end, the conductivity of a heavily radiation-damaged soil was found to be described by the equation, direct current (DC) conductivity $= 6 \times 10^{-18} e^{0.0237/T}$ mho/m. This was derived from experimental measurements of sample 15301.38 from Apollo 15 and is characteristic of heavily radiation-damaged soil grains with amorphous rims. Apollo 16 soils were found to have a DC conductivity $= 6 \times 10^{-14} e^{0.0230/T}$ mho/m. This equation is more typical of bulk lunar soils.

Alvarez (1977) measured the effect of UV, visible, and infrared irradiation on the electric conductivity of soils. Soils exhibited a $10^1$ magnitude increase in conductivity with IR irradiation and $10^6$ increase with UV irradiation. This effect was greater at higher temperatures.

A.5.2 Surface Charging

Unlike common terrestrial experience, on the surface of the Moon there is no electrical ground reference potential to be found. In ultra-high vacuum and with granular low-conductivity material throughout most locations, the immediate local environmental conditions will drive both surface charging and charging differentials, with multiple effects to be considered as described in the following subsections.

A.5.2.1 Plasma Charging

Several factors influence the total charge induced in the lunar regolith. On the lunar day side, the surface is directly exposed to the solar wind, a plasma stream composed of charged ions and electrons. The flux of electrons in the solar wind tends to be higher than protons. In the absence of other factors, this preferential implantation of electrons would charge the surface negatively. However, the photoelectric effect tends to overwhelm the contribution from the solar wind, as is discussed in the next section. On the lunar night side, the effects of plasma charging are more complicated. As the Moon blocks the flow of the solar wind, a wake with a significantly lower plasma density forms behind the Moon. Electrons, having lower mass, are able to fill the void more easily than protons, leading to more electron flux to the surface of the night side. This gives the night side a potential of $-35$ to $-100$ V. As the Moon passes through the Earth’s magnetosphere, the resulting potential differences can increase high-energy electron fluxes to the surface and give the lunar surface a potential exceeding $-500$ V.

These large potentials will likely not be hazardous to human activity on the surface as long as there is a uniform potential distribution. Similar to a bird sitting on a telephone wire, any object or person in the charged environment will be brought to the same potential. It is differences in potential, as opposed to the large potential itself, that induces the flow of charge and creates hazards. In regions of nonuniform surface potential, such as shadowed regions near the terminator or near the poles, electrical charging could indeed be an issue. More investigation is needed to determine if explorers will be at risk in these regions.

A.5.2.2 Photoelectron Charging

Plasma charging is only one factor in the lunar electric environment. On the lunar day side, direct exposure to UV solar radiation causes the lunar surface to eject electrons due to the photoelectric effect. From measurements of the flux of photoelectrons emitted from the surface combined with measurements of their kinetic energy, the photoelectron density above the surface has been calculated to be $\sim 100$ cm$^{-3}$. Compared with a solar wind density of $10^{-3}$ cm$^{-3}$, it can be seen that photoelectron emission dominates over electron implantation. The charge of the day-side surface can be calculated with $eV = k_B T_p \ln (J_p/J_e)$, where $k_B T_p/e$ is a nominal temperature for the photoemitted electrons of 1 to 2 eV, $J_p$ is the photoemission current and $J_e$ is the plasma electron current (Manka, 1973). The loss of electrons from the surface leads the lunar day side to develop a positive charge with a potential of 1 to 5 V. When the Moon passes through portions of the Earth’s magnetosphere, the flux of electrons from the solar wind is significantly decreased. Without the implantation of electrons to balance the photoelectric emission, it is possible that the lunar surface could see potentials up to 200 V during these periods (Freeman, Fenner, & Hills, 1973).

Additionally, any dust particles that may be above the surface, either due to micrometeorite impact, electrostatic levitation, or anthropogenic transport, will be exposed to the photoelectric effect and similarly emit electrons. This, combined with ejection of electrons from the surface, will generate a sheath of photoelectrons on the scale of meters above the lunar surface.

A.5.2.3 Effect of the Terminator

At the lunar terminator, where the sunlit side and dark side of the Moon meet, surface charging becomes more complicated. As the terminator passes over a section of the surface, the
photoelectric effect will diminish as incoming solar radiation diminishes. The surface will experience a significant change from positive to negative charge. Additionally, the hummocky cratered surface of the Moon means that within the terminator, shadowed regions can occur in close proximity to areas still exposed to solar radiation with the photoelectric effect, leading to variable surface charging in the terminator region. This rapid change in potential is hypothesized to be responsible for lateral dust transport during the passing of the terminator. The Lunar Ejecta and Meteorites (LEAM) experiment deposited during Apollo 17 was intended to measure the flux of interstellar dust to the lunar surface. LEAM utilized two sensors whose detectors were covered in a film that would allow for the determination of particle velocity. A third detector was included that did not have a front film, intended to capture lower velocity particles that were not expected to penetrate the film. The LEAM experiment recorded a greater number of particle detections than was expected from interstellar dust densities measured by Pioneer. These detections primarily occurred only on the filmless detector, indicating low-velocity particles. When plotted temporally, it was discovered that an increase in particle flux occurred as the lunar terminator passed over the apparatus. Laboratory investigation of the LEAM equipment led investigators to conclude that the device was registering impacts from highly charged dust grains with velocities under 100 m/s. For the purposes of the lunar engineer, it should be noted that the recorded fluxes of accelerated dust grains were low. The detector was 10 cm² in area, and the maximum particle flux recorded was just over 100 detections per 3-h interval. Other forms of dust transport, especially from anthropogenic activity on the surface, will likely be of more concern.

In addition to grain transport, there might be additional electric hazards associated with the passing of the terminator. Farrell et al. noted that cratered regions could block the horizontal flow of the solar wind over the surface, leading to regions with small-scale plasma wakes (Farrell et al., 2010). Electrons would be able to fill the void faster than ions, leading to pockets of “electron clouds” in the craters. An object, such as an astronaut or rover, traveling in such a region would also accumulate a static charge through tribocharging, discussed in Section A.5.3. Such an object might not be able to sufficiently discharge static electricity built up through tribocharging and could be at risk of breakdown effects.

**A.5.2.4 Grain Levitation**

In addition to dust transport from the passing of the lunar terminator, there is additional evidence for a lower density of dust levitated over the lunar day and night sides. Photos taken during the Surveyor missions, observations of Apollo astronauts, and measurements taken by the Clementine probe have all attested to the presence of an anomalous glow over the lunar horizon (Figure A.10). This glow has been attributed to light scattering from levitated dust grains. This dust levitation is most likely the result of repulsive electrostatic interactions between charged grains and the similarly charged surface. It is important also to consider the effect of the photoelectron and plasma sheaths directly overlying the surface. Grains launched into the photoelectron sheath at low velocity will charge negatively from photoelectron absorption and be pulled to the positive surface. Particles with a velocity high enough to pass through the photoelectron sheath will then experience their own photoemission and charge positive, giving them the potential to stably levitate over the positive surface. Colwell et al. (2009) estimated that only particles <0.5 µm would be sufficiently light to levitate; more massive particles would simply follow a ballistic trajectory and return to the surface.

Stubbs, Vondrak, and Farrell (2006) opted for a theory of dust fountains as opposed to stable dust levitation resulting from surface charging. In addition to evidence for a near-surface dust cloud, Apollo astronauts observed dust grains of ~0.1 µm at 100 km altitude. Stubbs, Vondrak, and Farrell (2006) interpreted this as evidence for upward acceleration of dust due to differences in surface potential, resulting in grains on ballistic trajectories that could reach over 100 km above the surface.

By contrast, the Lunar Dust Experiment (LDEX) aboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) detected no increase in high-altitude dust transport with the passing of the lunar terminator, indicating that electrostatic levitation is not the primary mechanism for dust reaching several kilometers in height. LDEX did detect a temporal correlation between dust exosphere density and meteor showers, indicating that micrometeorite bombardment might be responsible for high-altitude dust transport (Popel et al., 2018). It should also be noted that the density of the electrostatic dust cloud is expected to be low. Initial estimates during Surveyor indicated densities of up to 10⁴ m⁻³; however, recent analysis of the dust cloud by Clementine and the Lunar Reconnaissance Orbiter (LRO) indicated a density closer to 1 m⁻³ (Horanyi et al., 2021). As such, most engineering applications will see much more dust deposition from anthropogenic processes as opposed to electrostatic levitation.

**A.5.2.5 Effects of Hydrogen**

The presence of hydrogen in the lunar regolith can affect its charging capabilities. Hydrogen increases the sensitivity of the regolith to photoemission, greatly increasing the number of electrons lost and increasing the magnitude of the resulting voltage. The presence of hydrogen in the regolith likely reduced the electron work function of the regolith, requiring less energy to remove electrons. As such, Popel notes that particles over hydrogen-rich areas of regolith are likely to be larger in size and attain greater heights (Popel, Kopnin, & Dubinskii, 2019).
Conversely, the presence of water in regolith likely increases its electron work function; the work function of ice is 8.7 eV as compared with 5 to 6 eV for lunar regolith (Popel, Kopnin, & Dubinskii, 2019). This greater work function would reduce the degree of electron emission due to the photoelectric effect and reduce the ability of dust to levitate.

A.5.3 Triboelectric Charging

Dust can also become charged through triboelectric charging, also known as contact energization. When two surfaces contact, there is potential for transfer of electrons between materials, allowing for the acquisition of electric charge. The magnitude of electron transfer tends to be greater for materials with differing electron work functions\(^2\), as one material will require less energy to remove electrons from its surface than the other. The electrons will tend to transfer from the solid with the lower electron work function to that with the higher electron work function. Additionally, there tends to be little charge transfer between surfaces of the same material. Because electron transfer occurs at the point of contact between the surfaces and dust grains are dielectric, triboelectric charging tends to lead to nonuniform charge distributions over the grain surface. Nonuniform charge distribution can lead to greater adhesion, as some points on the grain will exhibit a charge that is higher than the average charge of the grain and will thus experience greater electric attraction to surfaces.

Sternovsky et al. (2002) investigated the triboelectric charging of the lunar simulant JSC–1, which is primarily composed of crushed basalt. Direct measurements of triboelectric charging have not been made on actual lunar soils in situ. The experimenters measured the electric charge generated from impact between simulant grains and a variety of metal surfaces. Little difference in charging was seen between oxidizing metals; in nonoxidizing metals, charging increased with decreasing work function. This indicates that triboelectric charging is directly proportional to difference in work function outside the solid—a distance far from the solid on an atomic scale, but very small on the macroscopic scale.

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\(^2\) The electron work function is the minimum energy required to move an electron from an electrically neutral solid to a point immediately

Figure A.10.—Depictions of the lunar horizon glow. (a) Photo from Surveyor VI demonstrating lunar horizon glow resulting from lunar dust exosphere (NASA Photo 67-H-1642). (b) Drawing of lunar glow as observed by Apollo 17 astronauts.
between the regolith and the contact surface. The experiment also observed that grains that were allowed to migrate for longer periods of time, and thus increase their potential for grain–grain contact, accumulated greater charge. In this manner, individual particles were observed to obtain a significant charge, up to $10^6 \text{e}$ for particles 125 to 150 µm in size. This indicates that triboelectric charging of grains can contribute as much charge buildup as would be expected from exposure to a low-temperature space plasma environment.

It should be remembered that these results are for a compositionally consistent lunar regolith simulant with a relatively large (125 to 150 µm) particle size. Individual grains of lunar regolith will exhibit greater compositional differences than seen in the simulant, giving a wider range of potential triboelectric effects. Additionally, the smaller size fraction of lunar regolith is potentially enriched in anorthositic minerals, giving lunar dust a different composition than the basaltic simulant studied.

In total, these results indicate that material coatings that closely match the work function of the lunar grains, thus reducing triboelectric charging, are likely to be an effective method of reducing dust adhesion to surfaces. Gaier, Ellis, and Hanks (2012) found that work-function-matching coatings increased the amount of simulant removed from surfaces by a puff of nitrogen gas by 40 to 70 percent. It will be important to determine an electron work function of actual lunar soil, not just simulant, for this method to reach its full potential.

### A.5.4 Dust Adhesion

Three forces impact the nominal adhesive character of lunar dust: electrostatic force, Van der Waals forces, and capillary force. In the vacuum of the Moon, capillary forces due to an adsorbed layer of water on dust grains will not apply. Utilizing a regolith simulant composed primarily of volcanic glass, Gaier, Ellis, and Hanks (2012) found that for common spacecraft materials, (including polyethylene terephthalate (PET), glass, polycarbonate, Ti–6–4, PTFE, polyvinyl fluoride (PVF), fluorinated ethylene propylene (FEP), Al 6061, and AZ–93), electrostatic forces dominated over the Van der Waals attraction. The experimental setup utilized a pin pushed against a torsion wire suspended plate. The pin was then retracted, and the displacement of the torsion wire at the point where the pin and plate separated was used to calculate the adhesive force between the pin and plate. In this experiment, adhesion due to Van der Waals forces was unable to be observed macroscopically in all materials except aluminum and PTFE. The pin and plate were then electrostatically charged by rapidly striking the two together, and the experiment was repeated. Relatively strong adhesion was observed and was correlated with the triboelectric affinity of the material in question. Adhesion was also positively correlated with the charge. As such, engineers concerned with limiting the adhesion of dust to surfaces will find more success by focusing on negating the effects of electrostatic adhesion than by limiting the Van der Waals forces. Additionally, the simulant was sputtered clean to remove impurities and simulate a surface akin to fresh regolith on the lunar surface. Cleaning the surface and maintaining a strong vacuum increased the degree of adhesion, indicating materials in the space weathering environment will experience greater adhesive tendencies.

Forces even stronger than the three nominal forces discussed in the previous paragraph could result if chemically reactive lunar dust particle surfaces bond covalently with engineering surfaces when in contact. As discussed in A.4.2, the surfaces of lunar regolith particles can harbor unsatisfied chemical bonds from fracture or space weathering processes, which could then react with optics, helmet visors, solar arrays, radiators, or any other exposed surface subject to lunar particle contact. To remove chemically bound material would then require essentially fracturing the bonds at the interface, or creating a fracture either in the substrate or removed particle. Whether in the engineered surface or in the regolith particle, any fracture other than at the interface alters the original surface, either by removing surface material (roughening) or by leaving residual fractured regolith bonded to the engineered surface.

### A.5.5 Dust Transport and Levitation

Lunar dust can be transported via natural factors, such as meteorite impact or electrostatic levitation. During Apollo, however, it was human activity that caused the greatest amount of dust transport. Even walking on the surface was enough to stir up the lunar dust. Katzan and Edwards (1991) provide a useful review of anthropogenic transport mechanisms. It should be noted that with no lunar atmosphere, all dust particles will exhibit a ballistic trajectory and fall at the same rate. At a pressure of $10^{-12}$ torr, there is not sufficient atmospheric density to keep even the smallest dust particles suspended.

#### A.5.5.1 Anthropogenic Transport

The first mechanism of dust transport is human activity. As was seen during the Apollo program, the dust of the lunar surface is easily disturbed through normal exploration activities. Astronauts walking on the surface stirred up the dust with their boots. When kicked with a boot while walking, dust tended to spray out in a fan-like trajectory in the direction of motion. Katzan and Edwards (1991) estimated using simple Newtonian motion that kicked dust could be transported up to 4 m vertically and 8 m horizontally by being kicked at normal walking speed around 3.6 m/s.

An additional source of dust transport was from operation of the Lunar Roving Vehicle (LRV). The wheels of the LRV would kick up surface material, which would subsequently be
deflected by the fender (Figure A.11). In the instances where the fenders of the LRV were missing or damaged, the dust would rooster-tail behind the rover, creating fountains of dust several meters tall. The spray had a tendency to cover both the LRV and the astronauts in dust. The greatest amount of sprayed dust was generated when the wheel would slip, which primarily occurred while taking sharp turns or traversing particularly bumpy terrain. Hypothetical calculations of potential dust trajectories by Katzan and Edwards (1991), once again applying simple Newtonian mechanics, indicated that dust accelerated by rover wheels operating at the maximum speed of 3.56 m/s could potentially transport dust up to 31 m. Additionally, a hypothetical LRV wheel unprotected by a fender could spray dust with a trajectory that could land the dust directly back on the rover. As such, significant care should be taken to limit dust transport in this manner.

Spacecraft exhaust from landing as well as launching the Lunar Module was observed to stir up and accelerate surface dust, which not only coated instruments left on the surface, but also slightly eroded these surfaces. The Surveyor III probe, visited by the Apollo 12 astronauts, was found to be coated in a noticeable layer of dust and exhibited surface wear from dust erosion. Mathematical modeling done by Lane et al. (2008) indicates that the smallest dust particles could reach velocities upwards of 1,000 m/s through gas jet acceleration. Additionally, the dust stream created by spacecraft exhaust was dense enough to obscure instruments from effectively measuring altitude during spacecraft descent.

A.5.5.2 Natural Transport Mechanisms

In addition to dust transport through human activity, there are natural mechanisms by which dust is transported on the lunar surface. The first of these is the transport of material ejected from the surface by meteorite impacts. The regolith experiences a ballistic trajectory from the impact site, and because most of it does not have a sufficient velocity to overcome lunar gravity, it falls back to the surface. Katzan and Edwards (1991) estimated the amount of material deposited back on the surface from micrometeorite bombardment to be 0.1 g/m$^2$. Data from the Lunar Dust Experiment (LDEX) on board LADEE has detected evidence of a dusty lunar exosphere with dust grains potentially reaching upwards of 100 km above the lunar surface. The density of the dust cloud increases with proximity to the surface but is still very low compared with dust transport from human activity. The lunar dust exosphere detected by LDEX ranged in particle size from 0.3 to 0.7 µm, with particle density ranging from 0.4 to 4 $\times 10^{-3}$ m$^{-3}$. Higher densities were correlated with the activity of meteor showers.

Photos from the Surveyor missions, as well as observations made by Apollo astronauts, have indicated the presence of a levitated cloud of lunar dust hovering above the surface. These photos revealed a bright glow over the horizon, which was attributed to light scattering by dust particles. This was initially calculated to be the result of grains approximately 10 µm in size levitated on the order of centimeters above the surface, but subsequent research has failed to produce consensus on the size and height of levitated particles, with more recent estimates indicating sizes closer to 0.5 µm (Rennilson & Criswell, 1974; Colwell et al., 2009). Additional observations from the Apollo 17 LEAM experiment support the possibility of dust transport correlated with the passing of the lunar terminator over the surface. The theory of surface charging and dust levitation has been described in the sections on the electrostatics of lunar dust. The density of grains transported is expected to be low, with recent missions (LADEE, Clementine, and LRO) indicating densities of ~1/m$^2$. 

Figure A.11.—Lunar Roving Vehicle spraying dust during surface activity on Apollo 16 (NASA Photo S72-37002).
A.6 Optical/Thermal Properties

A.6.1 Thermal Conductivity

For granular regolith in a vacuum, heat transfer is essentially limited to direct conduction of energy between contacting grains as well as radiation. Heat flux was directly measured in situ by experiments buried in the regolith on Apollo 15 and 17 and measured in the laboratory using samples from Apollo 14. The in situ Apollo heat flow experiments consisted of a probe with heaters buried up to 1 m in depth in the regolith. These experiments indicate that the top 1 to 2 cm of regolith has a thermal conductivity of $1.5 \times 10^{-4}$ W/cm², which increases by 5 to 7 times at a depth of 2 cm. At the Apollo 15 site, the heat flow at 1 m depth was $1.5 \times 10^{-4}$ W/cm². This result is due to increasing heat flow with densification of the regolith. The insulating properties of the regolith imply that very little temperature change occurs in the subsurface. Modeling by Keihm et al. (1973) indicates a diurnal variation of less than ±1 K at a depth of 30 cm (Keihm & Langseth, 1973). Thermometers buried at 80 cm depth on the lunar surface indicate no perceptible temperature change across the lunar day.

Laboratory measurements of lunar fines were conducted for material returned from Apollo 14 and 16. These measurements allowed the thermal conductivity to be plotted against the amount of the sample, fit to the equation $K = A + B(T)$, where $A$ is the conductive contribution and $B$ is the radiative contribution to thermal conductivity. Material from Apollo 12 was measured at a density of 1,300 kg/m³, making it representative of the top layer of regolith. The Apollo 12 values were found to be $A = 9.22 \times 10^{-4}$ W/m-K and $B = 3.18 \times 10^{-11}$ W/m-K. The Apollo data are only representative of the thermal conductivity at the landing sites. Recent modeling has attempted to produce a global distribution of thermal conductivity based on remote sensing. Yu and Fa found that between 60° N and 60° S, the subsurface thermal conductivity ($K_s$) varies significantly from 0.0001 to 0.0300 W/m-K, with an average value of about 0.0007 W/m-K (Yu & Fa, 2016). A strong correlation was observed between the age of the regolith and the thermal conductivity. The abnormally high values of $K_s$ (those higher than 0.002 W/m-K) were observed at very young impact craters. Outside of these craters, the variation was between 0.0001 and 0.0015 W/m-K. Differences in the thermal conductivity of mare material versus highland material were observed to result from difference in age rather than composition. Highland material and older mares (<3.92 billion years old) varied between 0.0009 and 0.0012 W/m-K, whereas variation in younger material (such as Mare Imbrium and Mare Orientale) is between 0.0005 and 0.0007 W/m-K.

Additionally, recent modeling has attempted to present a model for thermal properties at low temperatures that might be encountered at the polar regions. Previous experimentation was conducted above 150 K, whereas the LRO has recorded temperatures as low as 20 K in the PSRs of the south pole. Woods-Robinson et al. developed a model that found while the conductive component holds true for low temperatures, a decreased radiative component can lower thermal conductivities as much as an order of magnitude from what would be predicted by extending the best fit line from the Apollo data (Woods-Robinson, Siegler, & Paige, 2019).

A.6.2 Absorptivity and Emissivity

The optical properties of lunar material can be characterized through the absorptivity ($\alpha$, the fraction of light the material absorbs), the transmittance ($T$, fraction of light that passes through the material), and the reflectance ($\rho$, fraction of light that bounces off the material). Each of these properties can be measured for a specific wavelength of light, $\lambda$, and related through the equation $\alpha(\lambda) + \rho(\lambda) + T(\lambda) = 1$. Lunar regolith is for the most part opaque and has a transmittance close to zero. Thus, $\alpha(\lambda)$ is typically calculated by measuring $\rho(\lambda)$ and subtracting that quantity from 1. Using Kirchoff’s law, the absorptivity is equal to the emissivity, $\varepsilon$, for a given wavelength; $\alpha(\lambda)$ and $\varepsilon(\lambda)$ can then be integrated over 250 to 2,500 nm, the peak emission for the Sun, to get a general value of both quantities. The higher the absorptivity of the regolith, the more heating it will experience and the more heat it will transfer to surfaces it is in contact with through conduction. As will be discussed, this can have a significant effect on the $\alpha$ and $\varepsilon$ of thermal control surfaces.

The spectral characteristics of lunar regolith have been demonstrated to be representative of the mineralogical composition of the regolith in question. Clear mineral absorption bands have been observed in lunar regoliths. Mafic materials, such as basalts, are typically darker in color and exhibit greater absorbance than felsic materials. The mare regolith typically has an absorptivity of above 0.9, whereas the highlands material typically has an absorptivity closer to 0.7.

While mineralogy is important, space weathering has been shown to affect the optical and spectral properties of regolith. The deposition of amorphous rinds of volatiles on grain surfaces has been correlated to lower reflectance and diminished clarity of mineral absorption bands in the reflectance spectra. These effects are more pronounced in more mature soils. It is likely the presence of nanophase iron (np-Fe³⁺) in these amorphous rinds is responsible for the alteration in optical properties (Pieters et al., 1993). As such, more mature soils, as well as the finest fractions of soils in which weathering products are concentrated, will have diminished spectral lines. Additionally, studies of the optical properties of the finest fractions of soils have demonstrated a greater effect in mare
Soils than in highland soils. This indicates that mare soils have a greater potential for bulk np-Fe⁰ formation due to higher overall iron content in the soil (Noble et al., 2011).

This also indicates that immature regoliths can be observed using Earth-based telescopes by looking for regions where the spectral lines of the mineralogical component of soil are more apparent. Despite the diminishment of distinct spectral bands, the Lunar Soil Characterization Consortium (n.d.) found that the absorptivity of lunar soils decreases with size fraction. The LSCC measured the reflectance of lunar soils in the <45-µm range and found that reflectance increased with decreasing size. This is expected to result from the increased plagioclase content of the smaller fraction. As such, fine lunar dust, which has a greater probability of being transported and adhering to surfaces, will likely have a slightly different effect on thermal control surfaces than a coating of larger grained regolith.

With respect to thermal control, lunar dust has been found to significantly degrade the performance of thermal control surfaces. Gaier et al. (2008) measured the effects of lunar dust simulant on AZ–93, a paint, and AgFEP, a second surface mirror thermal control surface. Even a submonolayer of dust was observed to significantly alter both absorptivity and emissivity of these surfaces. As little as 12 percent dust coverage was observed to significantly alter both absorptivity and mirror thermal control surface. Even a submonolayer of dust simulant on AZ–93, a paint, and AgFEP, a second surface mirror thermal control surface.

A.6.3 Specific Heat

Some characteristics of specific heat and latent heat of melting might be useful to engineers involved with in situ resource utilization (ISRU), and some parameters have been included here. Specific heats were experimentally measured for a range of temperatures between 90 and 350 K for soils from Apollo 14, 15, and 16 by Hemingway, Robie, and Wilson (1973). A variety of compositions were sampled, ranging from sample 60601.31 containing anorthositic material from the lunar highlands to a range of breccias from the Fra Mauro to basalts from the Hadley–Apennine base.

The equation

\[
C_p = -2.3173 \times 10^{-2} + 2.1270 \times 10^{-3} T + 1.4509 \times 10^{-5} T^2 - 7.3699 \times 10^{-8} T^3 + 9.6552 \times 10^{-11} T^4
\]

(A.1)

can be used to approximate the specific heat between 90 and 350 K.

Grain size distributions of soils from Apollo and Luna sites are given in Table A.2.

Prior to the resurgence in interest surrounding lunar dust generated by the Constellation Program, most analyses of particle size distribution for lunar soils were completed by mechanical sieving. Due to the physical limitations of this method, detailed analyses of the <20 µm fraction of lunar regolith were not available. As such, much data has been compiled on the >20 µm grain size distribution of lunar soils. These data indicate that the particle size distribution across lunar samples is remarkably consistent, owing to the uniform nature of regolith generation. With the entire lunar surface subject to the same process of micrometeorite comminution and agglutination, it is the inclusion of anomalously large clasts that tend to skew size distributions; the distribution of small particles is relatively constant. Lunar soils are poorly sorted, indicating a wide range of particle sizes present in each sample.

### TABLE A.2.—GRAIN SIZE DISTRIBUTIONS OF SOILS FROM APOLLO AND LUNA SITES

<table>
<thead>
<tr>
<th>Mission</th>
<th>Number of analyses</th>
<th>Mediana</th>
<th>Meanb</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>13</td>
<td>4.40 φ (48 µm) to 3.25 φ (105 µm)</td>
<td>3.29 φ (101 µm) to 1.89 φ (268 µm)</td>
<td>Carrier (1973)</td>
</tr>
<tr>
<td>Apollo 12</td>
<td>55</td>
<td>4.58 φ (42 µm) to 3.40 φ (94 µm)</td>
<td>4.59 φ (415 µm) to 2.59 φ (166 µm)</td>
<td>McKay et al. (1972)</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>8</td>
<td>3.74 φ (75 µm) to 0.32 φ (802 µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apollo 15</td>
<td>19</td>
<td>4.3 φ (51 µm) to 3.22 φ (108 µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apollo 16</td>
<td>14</td>
<td>3.29 φ (101 µm) to 1.89 φ (268 µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apollo 17</td>
<td>42</td>
<td></td>
<td>4.59 φ (41.5 µm) to 2.59 φ (166 µm)</td>
<td>McKay et al. (1974)</td>
</tr>
<tr>
<td>Luna 16</td>
<td>4</td>
<td>3.8 φ (70 µm) to 3.05 φ (120 µm)</td>
<td></td>
<td>Vinogradov (1971)</td>
</tr>
<tr>
<td>Luna 20</td>
<td></td>
<td>~3.8 φ (70 µm) to 3.62 φ (80 µm)</td>
<td></td>
<td>Vinogradov (1973)</td>
</tr>
</tbody>
</table>

aMedian, half of particles are coarser than median and half are finer; corresponds to 50-percent mark on a cumulative curve.
bMean, graphic mean is based on three points on a cumulative curve (see Folk, 1968).

*Φ* units (φ), grade scale for granular sediment φ = −log₂ ξ (ξ is diameter in millimeters).
Mean grain sizes have been individually calculated for each soil sample. These means range from 40 to 800 µm, with most falling between 45 and 100 µm. The mean particle size across all soil samples is 72 µm, indicating 50 percent of particles by weight are smaller than 72 µm. In terrestrial soils, 70 µm is the size division between sand and silt, leading to lunar soils being described as either silty sand or sandy silt. On average, 95 percent of the lunar material is finer than 1,370 µm (1.37 mm) by weight, with 5 percent finer than 3.3 µm.

Care should be taken to note the difference between the bulk lunar regolith and lunar dust. “Regolith” refers to the entirety of the sandy lunar soil, whereas dust is only the finest fraction of the regolith. In many studies, various authors have applied different definitions of dust. For example, Spudis (2008) defines dust as the <50-µm size fraction, while Colwell et al. (2007) use <10 µm as the cutoff for dust. Particles smaller than 5 µm are capable of penetrating the human respiratory systems, and many terrestrial applications use this as the cutoff for dust. Given these variations, care should be taken to note the size definition of dust used in literature. In this appendix, lunar dust is defined as the <20 µm fraction unless otherwise specified.

Returned samples have demonstrated that 10 to 20 percent of the lunar regolith by weight is smaller than 20 µm and thus can be referred to as 10 to 20 percent dust (Figure A.12). Of particular interest for investigators researching the toxicity of dust is the <3.5 µm fraction, defined by the Occupational Safety and Health Administration (OSHA) as the respirable fraction most likely to be inhaled by the human respiratory system. Mechanical sieve studies indicated that, on average, 5 percent of the bulk regolith material was finer than 3.3 µm (Carrier, Olhoeft, & Mendell, 1991). However, more recent studies of the <20 µm fraction have indicated that this respirable fraction composes closer to 1 to 3 percent of regolith by weight. McKay et al. (2015) and Liu et al. (2008) found that by particle count, more than 80 to 90 percent of particles were smaller than 5 µm, with a statistical mode of approximately 0.5 µm (Figure A.13). McKay et al. noted in their analysis of respirable dust that individual grains as small as 20 nm were observed, although these were few in number. Numerically, the respirable dust fraction contains half the particles of a sample of lunar regolith, indicating that particle surface area is dominated by the dust fraction.

### A.7 Other Geotechnical Properties

#### A.7.1 Grain Shape

Lunar regolith grains exhibit a broad spectrum of shapes, from highly angular agglutinates to spherical volcanic glasses. On average, regolith particles tend to be moderately elongated and subangular to angular. The elongated nature of the grains gives them a tendency to pack oriented to their long axis, which has been observed firsthand in returned Apollo core tubes. This packing pattern is expected to make lunar soils anisotropic with respect to many properties, for example, thermal conductivity. The shape of regolith particles has been quantified with respect to many geotechnical parameters. Carrier, Olhoeft, and Mendell (1991) provide an in-depth discussion of these parameters in Chapter 9 of the Lunar Sourcebook. Volume coefficients, defined as the volume of a grain divided by the cube of the diameter of the circle that encloses the same area as the particle profile, were obtained by an analysis of 6,755 particles from a
single Apollo 12 sample. Particle sizes ranged from 733 to 60 µm. The resulting coefficients ranged from 0.24 to 0.37, with an average of 0.3. As such, the average soil particle has been described as a prolate spheroid with a major-to-minor axis ratio of 3 to 1.

The specific surface area (SSA) of a particle is the ratio of the surface area divided by the mass of the particle. The equivalent surface area is the ratio of the SSA of the soil in question to the SSA of a hypothetical soil of identical density and size distribution, but spherical in shape. This value for lunar soils is 8, indicating they have 8 times the surface area of an equivalently sized spherical particle. Thus, lunar soils are demonstrated to have highly irregular surfaces.

### A.7.2 Abrasiveness

Lunar dust has been noted for its highly abrasive properties. On the Apollo missions, a suite of problems related to dust abrasion caused difficulties when the astronauts were on the lunar surface. Harrison Schmidt’s sun visor on Apollo 17 became so scratched by dust that he was unable to see in certain directions. Dust was able to wear entirely through the polyimide insulating layers on some Apollo suits and caused significant wear on PET layers. Additionally, some dial surfaces became scratched and difficult to read. Gaier and Sechkar (2007) provide further analysis of systems that were impacted by abrasion during Apollo.

Kobrick, Klaus, and Street (2011) and Kobrick et al. (2010) made several studies characterizing the abrasiveness of lunar soil simulants. Abrasive wear from silica and aluminum oxide was compared with three-body wear induced by JSC–1A–F simulant, both with its standard particle size distribution and a sieved <25-µm component, and with N.U–LHT–2M highlands simulant. For soft surfaces, specifically polymethyl methacrylate (PMMA) and aluminum, the volume of material removed by the simulants was similar to that removed by the silica particles. Noticeably, the fine fraction of JSC–1A–F produced less wear than the normal fraction. This could result either from the fact that some particles tend to have a polishing effect as compared with large particles that move material, or that the finest size fractions are likely to be composed of weaker minerals. For steel surfaces, the simulants induced significantly less wear than the silica or aluminum oxide test materials.

Additionally, Kobrick et al. (2010) made a survey of the soil characteristics most likely to impact abrasiveness in an attempt to develop an index of abrasion. One such characteristic is mineral hardness, or the ability of a mineral to resist localized plastic deformation. Mineral hardness has traditionally been determined by comparison to the Mohs hardness scale through a scratch test. If a mineral is able to resist being scratched by a standard mineral of known hardness, the test mineral has a greater hardness than that of the standard mineral. Anorthite has a hardness of 6, with other less-abundant plagioclase ranging from 6 to 7. Olivine ranges from 6.5 to 7, while enstatite, a typical pyroxene, is softer with a hardness from 5 to 6. Other minor minerals could increase abrasion potential depending on landing location. The Moon Mineralogy Mapper on Chandrayaan–1 found small deposits of spinels in some fresh craters on the near side. Spinels has a hardness of 8 and could give soils in these localities a higher abrasive potential.

In addition to hardness, the toughness, or the ability of a material to resist fracturing under stress, also impacts abrasive potential. Brittle materials, such as ceramics and most minerals, will have less abrasive potential than a tougher material of the same hardness. The high friability of lunar soils indicates that they could be less abrasive than some terrestrial simulants that have higher toughness.

Finally, particle shape plays a role in abrasion potential. Particles with sharp, pointed surfaces will remove more material than those with smooth, rounded surfaces. Hamblin and Stachowiak (1995) measured the resulting abrasion from two- and three-body testing of both angular fractured quartz grains and rounded silica sand, both of which have similar hardness. The quartz grains were significantly more abrasive, demonstrating that the angular nature of lunar soil particles likely increases their abrasive potential.

### A.7.2.1 Erosive Wear

Additional investigations have indicated that lunar dust accelerated by spacecraft exhaust can cause erosive wear on surfaces. Analysis of the Surveyor 3 spacecraft materials demonstrated physical wear, including pitting and scoring, as a result of dust accelerated by the landing of the Apollo 12 Lunar Module (Figure A.14) (Immer et al., 2011). Mpazazhe et al. (2012) used aerosolized JSC–1A simulants accelerated toward an aluminum test surface to further investigate this phenomenon. The investigators found an eighteenfold increase in roughness in the area directly exposed to the jet as well as a sixfold increase in the area immediately surrounding the zone of highest wear. These results indicate that accelerated dust can have significant wear potential, especially since the simulant dust velocity of 100 m/s is less than the estimated maximum speed of dust accelerated by the Apollo Lunar Module of 1,000 m/s (Lane et al., 2008).
A.7.3 Specific Density (Specific Gravity)

The specific density of a soil is dependent on the chemical and mineralogical component of the soil and neglects volume contribution from intergranular void space. The specific density of lunar soil varies from 2.3 g/cm³ to more than 3.2 g/cm³. Glasses have a wide array of potential chemical compositions and thus the widest variation in specific density, with values ranging from 1.0 g/cm³ to greater than 3.32 g/cm³ (Duke et al., 1970). Additionally, volumetric measurements typically rely on fluid displacement. However, glasses have significant vesicular inclusions that increase the subgranular void space of regolith. These void spaces cannot easily be measured and thus reduce the apparent density of a grain. Breccias vary from about 2.9 to 3.1 g/cm³, while basalt is fairly consistent at 3.32 g/cm³. A mean value of 3.1 g/cm³ is typically utilized for bulk studies of regolith (Mitchell et al., 1972).

Recently, more attention has been given to estimating density using remote sensing data. As such, the specific density can be reasonably estimated using the weighted abundances of FeO and TiO₂, where density (in kg/m³) = 27.3 [FeO] + 11.0 [TiO₂] + 2,773 (Huang & Wieczorek, 2012). This model, combined with Lunar Prospector gamma ray spectrometer data for surface iron and titanium abundance, can be used to remotely estimate the relative density of a soil. Given the wide variation in iron and titanium abundances between mare and highland material, this model yields a range from 2.9 to 3.8 g/cm³ (Yu & Fa, 2016).

A.7.4 Bulk Density

Bulk density, ρ, is the mass of material in a given volume, including inter- and intragranular void spaces. Porosity, n, is the volume of void space between particles divided by the total volume of the sample. Bulk density, relative density, and porosity can be related through ρ = ρₛ (1 – n), where ρ is bulk density, ρₛ is specific density, and n is porosity. Void ratio is another metric common to geotechnical engineering, defined as the ratio of void space to the “solid” volume of material.

Porosity was estimated at the Apollo sites by analyzing the depth of astronaut bootprints. With each boot exerting a pressure of 7 kPa (~180 kg of suited astronaut over 410 cm² of boot area), bootprint impressions of 1-cm depth correspond to 45 percent porosity, 10-cm depth to 54 percent porosity, and so forth (Mitchell et al., 1974). The overall range of measured porosities was from 32 to 58 percent, ranging from closely packed to loosely consolidated. In the intercrater regions, porosity was an average of 44 percent with a standard deviation of 2.75 percent. Crater rims had a 2.5 percent higher porosity than intercrater regions with a porosity of 46.5 percent, as well as a much wider variability in porosity with a standard deviation of 4.3 percent (Table A.3).

Additionally, porosity was shown to decrease with depth (Table A.4). It is likely that vibrational consolidation from meteorite impacts as well as self-weighting lead to increasing compaction of lunar soil with depth.

The in situ bulk density is a controlling parameter for numerous properties of interest to lunar engineers, including thermal conductivity, electrical resistivity, seismic velocity, slope stability, bearing capacity, and radiation penetration. Various methods have been used by investigators to estimate the bulk density of regolith. The Lunokhod 1 and 2 rovers had a cone
penetrometer and made approximately 100 measurements of the density in the top 10 cm of soil, yielding a bulk density of 1.12 to 1.7 g/cm³ with a mean of 1.5 g/cm³. Bootprint and rover track analysis from the Apollo missions yielded a range of 1.4 to 1.57 g/cm³ in the top 15 cm of soil.

With the return of core tubes from the Apollo missions, investigators were able to measure the in situ bulk density of lunar soils in the laboratory, with frequent measurements made to 70 cm depth. Analyses of these core tubes indicate that bulk density is relatively variable from site to site, even from samples taken only meters apart. For example, bulk densities of cores from the Apollo 17 landing site varied from 1.57 to 2.29 g/cm³ (Mitchell et al., 1974). Additionally, bulk density showed variation with depth. The top 70 cm of soil across most sites show a general densification, especially at 15 to 30 cm depth, but below this the density profile is variable. Each landing site demonstrated a slightly different densification trend with depth. To reconcile these difficulties into useful values for lunar engineers, best estimates for the average bulk density of the top 15 cm of lunar soil is 1.50±0.05 g/cm³, of the top 30 cm, 1.58±0.05 g/cm³, and of the top 60 cm, 1.66±0.05 g/cm³ (Mitchell et al., 1974) (Table A.5). Direct density measurements have only been made in the intercrater regions. From other observations such as rover and boulder track analysis, bulk density is thought to be up to 12 percent lower in the “fluffier” regolith near crater rims (Mitchell et al., 1974). The bulk density with depth, \( z \) (cm), can be modeled with the equation \( \rho = 1.92(z + 12.2)/(z + 18) \). This model is consistent with the agreed-upon average densities of 1,300 kg/m³ at the surface, increasing to 1,920 kg/m³ with depth.

### A.7.5 Relative Density

The relative density of a soil is related to the porosity and can be used to describe the level of compaction. Whereas porosity is a measure of the void space within a soil, the relative density describes the level of packing of the soil between the most compact state and least compact state, given by the equation

\[
DR = \left( \frac{n_{max} - n}{n_{max} - n_{min}} \right) \times 100 \text{ percent},
\]

where \( n \) is current porosity, \( n_{max} \) is the highest possible porosity, and \( n_{min} \) is the lowest possible porosity. Related to the bulk density, relative density is also an important controlling factor for physical properties such as thermal conductivity, penetration resistance, shear strength, compressibility, and dielectric constant (Mitchell et al., 1974).

A soil with a relative density between 0 to 15 percent can be described as very loose, 15 to 35 percent is loose, 35 to 65 percent is moderate, 65 to 85 percent is dense, and between 85 to 100 percent is very dense. The top 15 cm of lunar soil has an average relative density of 65 percent, with density increasing to over 90 percent below 30 cm. Indeed, soil compaction has been demonstrated to rapidly increase with depth. It is likely that the action of meteorites loosens the surface soil during the gardening process while compacting lower layers of the regolith through seismic waves.

### A.7.6 Cohesion, Friction Angle, and Shear Strength

Shear strength is a measure of the maximum shear stress a soil can accommodate before failure. Shear strength affects the bearing capacity and trafficability of soils. Shear strength is typically defined by the Mohr–Coulomb equation:
\[ \tau = c + \sigma \tan \phi \]  
(A.2)

where \( \tau \) = shear strength in (kPa), \( \sigma \) = normal stress (kPa), 
\( c \) = cohesion (kPa), and \( \phi \) = friction angle.

Thus, it involves two components, one cohesion factor and
another frictional component. Both the cohesion of the soil and
the internal friction angle increase with bulk density. As the soil
becomes more compact, contacts between grains increase,
increasing the cohesive (Van der Waals) forces between grains.
The internal friction angle, defined as the ratio between normal
force and the resultant shear force in the soil at the moment of shear
failure, also increases with compaction (Table A.6). As such, the
total shear strength of the soil will also increase with compaction.
Both values were experimentally determined by penetrometer tests
on the Luna and Apollo missions (Slyuta, 2014).

The experiments undertaken on the lunar surface, compared
with penetrometer tests carried out in laboratories on Earth,
demonstrated that the lower gravitational stresses on the Moon
tended to increase the shear strength. With very low stress on the
particles near the surface, the highly irregular grains tend to
interlock, increasing strength. Highly fragile particles tended to
-crush in Earth conditions, weakening this interlocking effect of
the soil. To account for this higher shear strength near the surface,
a difference equation was proposed from the Mohr–Coulomb
equation to estimate shear strength. The new equation \( \tau = a \sigma^b \)
is used, where the normal stress (\( \sigma \)) is expressed in kPa and the
constant factors are \( a = 1.83 \) and \( b = 0.73 \) (Carrier, 1984).

### A.7.7 Compressibility

Compressibility is the change in volume undergone by a soil
when a force is applied. When the soil is subjected to a low
pressure, volume change occurs as the particles reorient to a
more compact packing pattern. Once particles are no longer
able to reorient, particle breakage and deformation occur,
-further reducing volume. One measure of compressibility is the
-compression index, which is the decrease in void space with an
-order of magnitude increase in stress. The compression index
is given through the equation \( CC = \Delta h/\Delta \log(\sigma) \).

Compression index data is available from tests done on soils
from Apollo 12 as well as Luna 16 and 20 (Figure A.15). A
range of values was obtained depending on starting density and
applied stress, ranging from 0.01 to 0.11 for the Apollo data and
0.02 to 0.09 for the Luna data, which approximately averages
to 0.03 (Carrier, Olhoeft, & Mendell, 1991).

When compared with basaltic lunar simulants, lunar soils
have high compressibility regardless of starting conditions.
This implies that the agglutinates and other irregular space
weathering derived grains with no terrestrial counterpart are
fragile and will crush under pressure. Additionally, the degree
of compression resulting from the weight of the regolith upon
itself alone, as calculated from the experimental data, does not
match the observed densification trend with depth. Lunar soils
are much more compact than can be expected from self-weight
alone. This is indicative that some other process, most likely
vibration and seismic waves from meteorite impact, is
responsible for the high degree of compaction of lunar soil.

### A.7.8 Bearing Capacity

Bearing capacity is the ability of a soil to support a load, which
is dependent on the bulk density of the soil. Bearing capacity can
be modeled with the equation \( q = 0.000577 \cdot \rho^2 \cdot e^{2.4b} \)
for typical lunar soils. Using this equation, a soil with density of 1.3 g/cm\(^3\) would
have a bearing capacity of 9 kPa. Allowable bearing capacity is
-the amount of load that can be applied to a soil before a certain
amount of soil compaction will occur. Allowable bearing
capacity data have primarily been sourced from analyses of
astronaut bootprints. Allowable bearing capacity for objects less
than 0.5 m wide are well modeled by \( q_{all} = k \cdot d_{all} \), where \( q_{all} \)
is allowable bearing capacity, \( k \) is the subgrade reaction modulus,
and \( d_{all} \) is the allowable depth of sinking into the soil. The
reaction modulus, 8 kPa/cm for the Apollo data, was calculated
from comparing depth of footprint to the known bearing capacity
of 7 kPa for the soil. Here, for example, an experiment placed on
the surface that is less than 0.5 m wide and can sink a maximum
of 1 cm with a confidence interval of 95 percent has an allowable
bearing capacity of 2 kPa.

The ultimate bearing capacity is the maximum allowable load
that can be applied to a soil before failure. The ultimate bearing
capacity is influenced by bulk density, internal friction angle,
and the shape of the support. For a 1-m-wide support on a
typical lunar soil, such as the Lunar Module 1-m-wide foot, the
ultimate bearing capacity is approximately 6,000 kPa. Slyuta
(2014) and Carrier, Olhoeft, and Mendell (1991) provide useful
discussions of bearing capacities for further investigation.

### TABLE A.6.—COHESION AND INTERNAL FRICTION ANGLE OF LUNAR SOILS WITH DEPTH
[From Carrier, Olhoeft, & Mendell (1991).]

<table>
<thead>
<tr>
<th>Depth interval, cm</th>
<th>Cohesion, kPa</th>
<th>Internal friction angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Interval</td>
<td>Mean</td>
</tr>
<tr>
<td>0 to 15</td>
<td>0.52</td>
<td>0.44 to 0.62</td>
</tr>
<tr>
<td>0 to 30</td>
<td>0.90</td>
<td>0.74 to 1.1</td>
</tr>
<tr>
<td>30 to 60</td>
<td>3.0</td>
<td>2.4 to 3.8</td>
</tr>
<tr>
<td>0 to 60</td>
<td>1.6</td>
<td>1.3 to 1.9</td>
</tr>
</tbody>
</table>

\( c \) = cohesion (kPa), \( \phi \) = friction angle.
Figure A.15.—Compressibility of lunar soils from Apollo 12 and Luna 16 and 20 missions. Void ratio as function of applied stress is shown, with compression index as slope of curves. Adapted from Carrier, Olhoeft, & Mendell (1991).

A.7.9 Slope Stability

The slope stability of a soil is the ability of a slope to stand without support. Slope stability can be modeled with the equation

\[ FS = N \frac{\rho g h}{c} \]  

(A.3)

where \( FS \) is the desired factor of safety, \( N \) is the stability number, which is a function of internal friction angle and slope angle, \( \rho \) is the bulk density, \( g \) is gravitational acceleration on the Moon, \( h \) is the height of the slope, and \( c \) is cohesion of the soil. This equation demonstrates that for a typical lunar soil, a vertical cut could be made to a depth of 3 m with an adequate degree of safety. See Carrier, Olhoeft, and Mendell (1991) for a more in-depth discussion of slope stability.

A.7.10 Trafficability

Firsthand observations of the trafficability of the lunar regolith were obtained from performance analyses of the LRV, utilized on Apollo 15, 16, and 17. On average, the wheels of the LRV only sank 1 to 1.25 cm into the surface of the regolith, with a maximum depth of 5 cm recorded near crater rims and, at times, no noticeable sinkage. The wheel of the LRV was constructed of wire mesh partially covered by titanium chevrons. Most of the time, impressions of the chevrons were clearly visible in the lunar soil, indicating very little wheel slippage. Indeed, wheel slip was measured to be only 2 to 3 percent for the LRV. The maximum speed of the LRV was 13 km/h on a level surface, but operating speed was restricted to 6 to 7 km/h in order to successfully navigate the irregular, cratered lunar terrain. Thus, it was other terrain features, not the lunar soil, that proved to be the limiting factor in most cases. When making sharp turns at over 5 km/h, the LRV tended to skid. The primary difficulty with operating the LRV in the regolith was the tendency for material to rooster-tail behind the rover when acceleration was too quick. Without proper fenders covering the wheels, the astronauts and critical rover components were coated with dust, as on Apollo 17, when a fender was damaged.

Analysis of the Modularized Equipment Transporter tracks from Apollo 14, rover tracks from Apollo 15, 16, and 17, and the Lunokhod 1 tracks from Luna 17 yielded no perceptible difference in the trafficability of lunar regolith across sites. However, pyroclastic deposits primarily composed of glass spherules could reduce the trafficability of soils. Significant pyroclastic deposits were not traversed by any of the lunar rovers.

A.8 Conclusion

The Apollo missions demonstrated that lunar dust poses a significant challenge to habitation of the lunar surface. While observations of lunar dust have attested to the hazards of
operating in the lunar environment, these observations are also useful resources for developing mitigation strategies to overcome this obstacle. Samples returned by Apollo have been invaluable in analyzing the specific properties of lunar dust and soil. However, the Apollo landing sites were all concentrated in the lower latitudes of the lunar nearside. There is uncertainty about how the properties of the regolith might differ in the polar regions or on the lunar far side. Recent remote observations have demonstrated increased porosity of the lunar soil near the poles, indicating a less consolidated material that might be more prone to transport. Additionally, the presence of water ice and other frozen volatiles in the polar regions could alter the electric or geotechnical properties of soil. With the lunar south pole targeted as the site for a potential Moon base for a long-term human presence on the Moon, further investigation of polar regolith should be a priority.
Appendix B.—Measuring Lunar Dust and Simulants

B.1 Introduction/Background

For dust mitigation techniques to be evaluated and compared, quantification of how much particulate matter has been accumulated, removed, or avoided must be done, which can be exceedingly difficult with microscopic particles. What to measure, how to measure, and limits of detectability are critical concerns depending on the sensitivity of the specific application to particulates.

B.1.1 What Needs To Be Measured

The measurement techniques presented in this section are intended to address two specific applications: (1) the characterization of regolith and simulant materials, and (2) the quantification of volumetric and surface concentrations. The first is important in ensuring the availability of appropriate and reproducible materials for testing, whereas the latter is necessary to specify exposure conditions used in testing and evaluating various components and systems, and to standardize and replicate exposure and test conditions among investigators.

An immediate consideration is the size range of interest. The lunar surface presents a continuum of sizes, the largest extent being literally represented by massive rocks and boulders. The nature of the smallest sizes present is not yet fully understood, in part due to aspects of the collection, transfer, and storage of Apollo sample materials. Independent measurements of both Apollo samples and associated simulant materials establishes a lower size bound on the order of 20 nm (Liu & Taylor, 2011; Greenberg, Chen, & Smith, 2007). NASA has not established a formal definition for the upper size limit constituting the dust fraction, but for the present purposes, this is taken to be 10 to 20 μm. Above this level, (1) sedimentation forces begin to dominate convection, (2) particle mass affords removal by virtue of inertial forces dominating surface adhesion, (3) relevance to human respiratory health diminishes by virtue of uptake mechanisms, and (4) imaging techniques become increasingly practical relative to aerosol and scattering methods.

B.1.2 Units, Equivalent Diameters, and Moment Quantities

The amount or concentration of particles can be specified using a variety of units. Those most commonly utilized are number, surface, and volume (or mass for fixed density). Given the respective quadratic and cubic dependence on particle diameter, the distribution of surface area and volume (or mass) is strongly influenced by the underlying particle size distribution. Units of interest vary between applications, in part due to fundamental physical considerations, but in some cases due to compliance specifications (e.g., permissible concentrations for respiratory exposure continue to be expressed on the basis of mass).

As will be discussed further, some instruments can resolve details of the distribution, whereas others provide what are known as integrated moment quantities. Examples of moment quantities are total number (zeroth moment), total surface area (second moment), and total volume or mass (third moment). In some instances, additional statistical information can be derived. Examples include the location of the peak in the distribution as well as the width of the distribution. The former is typically expressed in terms of the count median diameter (CMD), and the latter in terms of the geometric standard deviation (σg). For distributions that can be effectively modeled as lognormal (reasonably common for many aerosols), conversions between moment quantities can be easily calculated using the Hatch–Choate relations. For more details on the mathematical details of moment quantities and their calculation, the reader is directed to Hinds (1999).

In general, the techniques described here provide information only about concentration and size distributions. For those cases where shape information is available, the method and formulation of this information will be described. Because differing techniques are based on different physical principles, the issue of what particle size is being measured must be approached with some care. This introduces the concept of equivalent diameters. These will be discussed in the context of individual instruments, noting that numerous and more thorough discussions are available (DeCarlo et al., 2004). These distinctions become important when the equivalent diameters involve dependence on density or composition. The subject of equivalent diameters becomes increasingly complicated for nonspherical particles, and methods for correcting for asphericity vary with differing measurement techniques. This aspect has been extensively investigated, and the reader is directed to the indicated reference for more details.

With the exception of diagnostics supporting electron microscopy, compositional information is not provided. The techniques described also do not afford the direct measurement of particle charge state but can in some cases be combined with field plates or other potential surfaces to determine charge state indirectly.

Overviews on the subject of particle measurements often provide a graphical illustration of the size range provided by various instruments, and in some cases concentration as well. While at face value this would appear useful, a simple pictorial description of performance of this type is not included here. This has been avoided due to fundamental differences in what individual types of instruments physically measure as well as the pitfalls of attempts at direct comparison. For example,
describing the minimum size particle that can be resolved by a device based on ensemble light scattering can only result in misleading interpretations. Similarly, statements about particle size or concentration cannot be meaningfully offered for a direct mass-reading instrument, such as a tapered element oscillating microbalance (TEOM).

It is emphasized that various characteristics of both regolith and simulants affect different components and systems to significantly differing degrees. For example, transmissive optical surfaces, solar collectors, and thermal radiators are principally affected by larger particles by virtue of their larger radiative and absorptive cross sections. In contrast, the design of mechanisms and seals may involve smaller penetrating sizes and their associated abrasive properties. The point here is that no single measurement technique is optimal for all applications; the issue at hand is to aid in determining the optimal choice for each situation.

The material presented here is limited to a description of measurement instruments but does not address the related and important aspect of sampling and transport. Among other features, this includes the topic of size biasing and losses resulting from sedimentation, impaction, diffusion, and non-isokinetic sampling. For more details on the subject, the reader is referred to Baron and Willeke (2001).

B.1.3 Limitations of Measuring the Weight of Particle Samples

Using a simple spherical approximation, particle mass scales roughly as $1/r^3$. This strong dependence influences what concentrations of what sized particles can be measured by weight.

In the following, the particles are assumed to be lognormally distributed, with CMD ranging from 1.0 to 40 µm and geometric standard deviation of 2, values representative of both simulants and actual regolith. Measurements are assumed to be made with a state-of-the-art analytical balance having a resolution of 0.0001 grams. Dust is defined as sizes occurring at or below 10 µm, with the ultrafine population defined as at or below 0.1 µm.

Figure B.1 shows the cumulative mass of ultrafines contained in a 1-gram sample, illustrating only the limiting cases of CMD = 1 and 40 µm. It is seen that weight measurements are ineffective for assessing the mitigation of ultrafine particles, or even considerably larger sizes.

We next calculate $d_{min}$ for four size distributions. In Figure B.2, $d_{min}$ is defined such that the combined mass of all the particles in the blue shaded region below $d_{min}$ is just below the resolution of the weighing instrument. More simply, if all particles smaller than $d_{min}$ are removed, the balance would not be able to tell.
Table B.1 also refers to a 1-gram sample. The Threshold column defines the value of $d_{\text{min}}$ corresponding to the detection resolution of the balance. The Measurement column is the corresponding value of $d_{\text{min}}$ for ±10 percent accuracy (i.e., 0.001 gram).

The following can be seen from Table B.1:

1. The analytical balance cannot detect the presence of ultrafines ($\leq 0.1 \mu m$) for any sample, even at threshold.
2. For the samples with the three largest CMDs, the balance cannot detect the presence of PM2.5 or smaller.
3. For the largest CMD, the balance cannot measure to 10 percent accuracy the presence of dust at all.

These results are used to illustrate the implications for a typical experiment assessing mitigation efficiency. The quantity of interest is remaining deposited mass after mitigation treatment, $M_{\text{residual}} = M_{\text{initial}} - M_{\text{removed}}$, where in practice, $M_{\text{residual}}$ is typically less than 1 gram (or in most cases, considerably less). The trend in $d_{\text{min}}$ for a residual mass less than an initially deposited 1 gram due to particulate removal methods is observed in Figure B.3:

1. For the two samples with larger CMDs shown, the balance cannot detect the presence of PM2.5 or smaller particles. This detection insensitivity is true even if none of the original 1 gram of particulates is removed by the mitigation method being tested.
2. Measuring the presence of dust to 10 percent accuracy requires $M_{\text{residual}} \geq 80 \text{ mg}$ for CMD = 10 $\mu m$ and $M_{\text{residual}} \geq 820 \text{ mg}$ for CMD = 20 $\mu m$.
3. The entire dust fraction cannot be measured for the case of CMD = 40 $\mu m$.

### B.2 Measurement of Volume Concentrations

The characterization of volume concentrations relates principally to the quantification of exposure conditions. This contrasts with surface measurements, which describe the portion of material that has been deposited, or conversely assess the efficacy of a mitigation strategy by virtue of the material that subsequently remains. As previously noted, the measurement of volumetric concentrations is also applicable to the characterization of simulant materials themselves.

The associated instrumentation has largely emerged from the field of aerosol science and technology and is also widely utilized in the related fields of atmospheric sciences. Considerable applications are also identified in the areas of soil characterization and powder technology. In the case of powder technology, the evolutionary processes of terrestrial soils do not result in the abundance of nanoscale particles notable in lunar regolith, and thus this aspect is relatively underemphasized in the associated instrumentation. In terms of soil characterization, the more recent interest in nanomaterials technology is driving an increased interest in instrumentation of utility in characterizing lunar simulants.

Methods for aerosolizing materials are equally important and will also be discussed. In the case of laser diffraction techniques, liquid suspension is also commonly utilized and will be briefly reviewed.

#### B.2.1 Differential Mobility Analyzers

Differential mobility analyzers (DMAs) are widely utilized for aerosol measurements and occupy a unique instrument niche with their ability to resolve particles in the nanometer and submicron range (Baron & Wileke, 2001). The analyzer or classifier discriminates particle sizes on the basis of electrical mobility.
where \( Z_p \) is the particle mobility, \( n_e \) is the electrical charge on the particle, \( C_c \) is the Cunningham slip correction factor, \( \eta \) is the dynamic viscosity of the surrounding medium (typically air), and \( D_p \) is the particle diameter. The electrical mobility is the ratio of electrostatic to viscous forces acting on a particle and is the equilibrium velocity exhibited by a particle of diameter \( D_p \) in a gas of viscosity \( \eta \) under the presence of a unit electric field. For spherical particles, the measured mobility diameter \( D_m \) is equivalent to the actual diameter \( D_p \).

The classifier itself functions as an electrical capacitor, typically in the form of a pair of long, concentric cylindrical tubes. A radial electric field is established by applying a voltage across the inner and outer tubes. Particles are entrained in a flow and introduced into the volume between the concentric tubes. This applied field induces a radial drift in the particles as they travel down the tube. Viscous forces act in opposition to this drift, and because viscous drag is a function of particle diameter, each size exhibits a unique trajectory. These differing spatial trajectories can be exploited to sort particles on the basis of size, most commonly by sequentially scanning the magnitude of the applied field. This arrangement requires that the incoming particles be electrically charged, which is accomplished by bipolar diffusion charging, unipolar field charging, or more recently by ionization via soft x rays. The classifier itself serves only as a size separator. The concentration of particles of a selected size exiting the column must be counted or detected, most commonly using either a charge-sensitive electrometer or condensation particle counter (CPC) (Baron & Willeke, 2001). A CPC is a counter only and inherently insensitive to particle size but can be used independently to measure total number concentration within its capture range. Typical CPCs provide a range extending from roughly 5 to 7 nm to 1 to 3 \( \mu m \), with a maximum concentration limit of \( 10^5 \) to \( 10^6/cm^3 \).

Differential mobility analyzers offer a number of useful features, resulting in their extensive use in a broad range of applications. In particular, the high resolution affords the ability to resolve particles on nanometer-size scales. By virtue of operating in a scanning fashion, no a priori assumptions are required about the shape or modality of the particle size distribution, and smaller size particles are not masked or biased by the presence of larger ones. Further, they provide unequaled dynamic range in concentration, spanning from single particles (using CPC detection and neglecting losses), to \( 10^5/cm^3 \) in an individual-size bin (typically 128 bins/decade). A disadvantage is temporal response, requiring 1 to 2 min for a single scanning measurement. An additional disadvantage is the upper limit on particle size, typically on the order of 1 \( \mu m \). As such, measuring broad distributions requires an additional instrument. As will be discussed, this is most often accomplished with either an optical particle counter (OPC) or aerodynamic particle sizer (APS).

DMS are useful in the ability to function as independent size classifiers, or in essence as a tunable size-selective filter. In this fashion, the applied voltage can be set to a fixed value, allowing only one extremely narrow size range of particles to exit the analyzer. These particles can then be used to characterize and calibrate other aerosol sensors, or in some cases used to accommodate specialized exposure requirements.

### B.2.2 Optical Particle Counters

Optical particle counters (OPCs) detect or count individual particles and provide sizing based on elastic light scattering. The basic principle of operation is straightforward, wherein the amount of light scattered by a particle is a function of its size. In practice, the instrumental response function is somewhat more complicated (Szymanski, Nagy, & Czitrovszky, 2009). A variety of factors come into play, including the inherent nonlinearity of the scattering process itself, the optical collection geometry, dependence on particle composition (refractive index), and the temporal response of the electronics and associated signal processing.

The angular distribution of light by particles is described by Mie theory and is a highly nonlinear function of particle size with respect to both total magnitude and its spatial distribution (Van de Hulst, 1957; Bohren & Huffman, 1983). This behavior is strongly influenced by the illumination wavelength and particle refractive index, such that the response of individual instruments varies with the details of their construction, in particular with the geometry of the collection optics. The use of monochromatic sources (i.e., lasers) can result in the response function becoming multivalued over selective size intervals, restricting the associated measurement resolution.

The notion of an equivalent optical scattering diameter does appear in the literature (Buettner, 1990, p. 414):

\[
R = \frac{n_e C_c (D_p)}{3 \pi \eta} \tag{B.1}
\]

Because of the influences of size, shape, and refractive index, this normalized equivalent light-scattering diameter gives by no means a statement about an unique, geometrical measure or about a relationship to other important equivalent diameters.

The absence of a formal definition is attributable to the fact that, unlike other equivalent diameters, there is no direct analytical formula available to correct for density or refractive index. The exact form of the response function, \( R \), or the amount of light scattered and detected from a particle of diameter \( d_p \) is given by
Aerodynamic Particle Sizers

As the name implies, an aerodynamic particle sizer (APS) derives size information based on a particle’s aerodynamic or Stokes drag, and departs from this limiting behavior. The basic operation consists of sampling the aerosol at a relatively high volumetric rate (typically on the order of 5 L/min), directing the sample through an accelerating nozzle, and splitting off and filtering roughly 80 percent of the sampled flow to create a sheath flow to surround the nozzle. Pressure and flow transducers are used to determine the gas velocity at the nozzle exit, and a multiple-beam optical time-of-flight arrangement measures the velocity of the exiting particles. Size information is obtained by virtue of the size-dependent nature of a particle’s ability to accelerate in the entrained flow. Some more recent instruments include an optical scattering detector intended to reduce coincidence events; this is required because, by definition, the transit time through the measurement volume is size dependent. However, for nonspherical particles this can result in an associated reduction in detection efficiency for particles below roughly 7 μm in size (Baron, 1986).

Particle size is reported in terms of the equivalent aerodynamic diameter, \(d_a\), which is the diameter of a unit density sphere having the same settling velocity as the particle in question, \(d_p\):

\[
d_a = \alpha \frac{d_p}{\rho_0}
\]

Here \(\rho_0\) is the density of the particle in question, \(\rho_0 = 1 \text{ g/cm}^3\), and \(\alpha\) is the ratio of the corresponding Cunningham slip corrections for \(d_a\) and \(d_p\), which is close to unity for typical departures of \(\rho_0\) from unity. The quantification of various loss mechanisms within the APS is documented in the literature. Small corrections for particle density are required for departures from the Stokes regime, that is, for larger particles (Baron & Willeke, 2001). The nominal size range of an APS typically spans from approximately 0.5 to 20 μm, noting that entraining the largest sizes in tubing of any considerable length or containing sharp bends must be considered. The upper limit of particle concentration is on the order of \(10^3/\text{cm}^3\) and therefore requires dilution for values exceeding this value. The APS is often paired with a DMA to extend the size range of the latter. This can also be accomplished with an OPC, but the APS is sometimes viewed as preferable due to previously noted issues relating to the assignment of an equivalent optical scattering diameter.

B.2.4 Laser Diffractometers and Scattering Photometers

This classification includes a broad variety of instruments that differ considerably in their construction and application. They share a basic measurement concept: the use of one or more wavelengths and fixed optical detectors that characterize the light scattered from an ensemble of particles. The analysis and interpretation of ensemble scattering data differs considerably from single-particle detection, which has been the case for the instruments described to this point.

The embodiment of these instruments represents a wide range of complexity and sophistication. On one end of the spectrum are comparatively simple devices often referred to as “dust monitors” or “dust photometers.” These generally take the form of a single laser source (most often a relatively low-power laser diode) and a single, fixed optical detector. Extremely

\[
R = \frac{\lambda^2}{4\pi^2} \int_{\theta_1, \phi_1}^{\theta_2, \phi_2} \left( I_1(x, m, \theta, \phi) + I_2(x, m, \theta, \phi) \right) G(\theta, \phi) d\theta d\phi \quad (B.2)
\]

where \(\lambda\) is the illumination wavelength, \(I_1\) and \(I_2\) are the scattered light intensities polarized parallel and perpendicular relative to the plane of oscillation of the electric field vector of the incoming radiation, \(m\) is the complex refractive index, \(x\) is the dimensionless particle size parameter defined by \(\pi d_p/\lambda\), \(G(\theta, \phi)\) is a geometrical factor specifying the collection efficiency of the optical design, and \(\theta_1\) and \(\theta_2\) together with \(\phi_1\) and \(\phi_2\) are truncation angles limiting the solid angle in which the scattered light is collected. In this expression, \(I_1\) and \(I_2\) specify the size-dependent angular scattering behavior described by Mie theory.

The complexities in the response function, most notably in the dependence on particle refractive index, require OPCs to be calibrated relative to a standard reference material. Application to other particle types is at best difficult to do analytically, and corrections of this type are generally not provided by the manufacturers. This can be accomplished experimentally, although the availability of monodisperse reference materials with varying values of refractive index is severely limited. As previously noted, a DMA can be used to sequentially size select nearly monodisperse particles from a more broadly polydisperse sample, but due to the nonlinearity of the OPC response function, this calibration must be performed at multiple particle sizes throughout the measurement range.

The size range of typical commercial instruments typically spans from 0.2 to 0.3 μm to a maximum on the order of 10 to 20 μm. In principle, an OPC provides a measurement of the geometric particle diameter. This is essentially correct for spherical particles, with the aforementioned dependence on refractive index being noted. The upper concentration limit for OPCs is largely determined by the occurrence of processing deadtimes and sample volume coincidence errors (Walser et al., 2017), and is generally on the order of \(10^3\) to \(10^4\) particles/cm³.

B.2.3 Aerodynamic Particle Sizers

The embodiment of these instruments represents a wide range of complexity and sophistication. On one end of the spectrum are comparatively simple devices often referred to as “dust monitors” or “dust photometers.” These generally take the form of a single laser source (most often a relatively low-power laser diode) and a single, fixed optical detector. Extremely
compact and inexpensive integrated sensors of this type are commercially available for a variety of monitoring applications. Numerous dust monitors are produced commercially and are typically compact enough to be handheld. In virtually all cases, measurements are reported in units of mass, traceable in large part to the historic use of mass for studies of human respiratory effects and related issues of regulatory compliance.

Empirical studies have been performed, but because the instrument response depends on (1) particle shape and composition, (2) the particle size distribution, and (3) the wavelength and optical collection geometry of individual instruments, the ensuing accuracy for aerosols other than the aerosol used for calibration is generally difficult to evaluate precisely (Patts et al., 2019). In practice, the preferable option (if available) for characterizing accuracy in reported mass units is through the use of reference, direct mass reading instruments such as TEOMs or quartz crystal microbalances (QCMs), as will be presented later. This having been said, it is important to recognize that various transport and loss mechanisms invariably alter the aerosol size distribution as it evolves spatially and temporally; these variations affect the accuracy of all scattering instruments, and in particular simple, fixed-angle instruments. If the optical geometry is known, corrections can be modeled and estimated under the assumption that the size-dependent transport and losses can also be estimated.

The instrumental response function, $R_{ens}$, is dependent on both the particle properties (individually and of the distribution as a whole) and the optical geometry, and it is essentially the same as indicated above for OPCs, with the addition of a third integral over the ensemble:

$$R_{ens} = \int_{d_{\text{min}}}^{d_{\text{max}}} R(d_p) \rho(d_p) dd_p$$

(B.4)

where $R(d_p)$ is the response function for a single particle of diameter ($d_p$), and $\rho(d_p)$ is the probability density function for the particle size distribution. Simulants vary in terms of the largest sizes that are sieved out, but at a minimum, the ratio of $d_{\text{max}}/d_{\text{min}}$ spans three orders of magnitude or more. It is possible to optimize the optical geometry to minimize and bound the dependence of the response relative to variations in the size distribution $\rho(d_p)$ as well as variations in the particle refractive index (Greenberg & Fischer, 2015).

Laser diffraction instruments differ principally in employing a number of fixed detectors and, in some cases, a number of sources emitting at different wavelengths. In turn, more sophisticated algorithms are used to analyze this additional information. Many diffractometers include provisions for processing both dry powder and liquid-phase particle suspensions. The advertised size range spans from 10 nm to several millimeters, but because these instruments are based on ensemble scattering, this specification is not of practical utility in the context of measuring broadly polydisperse materials such as lunar simulants. The scattering efficiency for small particles scales as $d_p^6$, and for most materials (lunar simulants among them) the concentration continuously falls with decreasing size. In combination, this renders it difficult to resolve the presence of the small particles in the presence of larger ones (Xu, 2000). The situation is further complicated because ensemble scattering data cannot be uniquely decomposed, and as a result, some form of distribution model must be assumed in the inversion process.

A more recent development concerns the addition of detectors that resolve the polarization of the scattered light, a technique called polarization intensity differential scattering, or PIDS (Xu, 2000). This development purports to extend the lower size limit, as well as enhance the ability to discriminate multimodal distributions. While encouraging, at present the peer-reviewed literature does not provide descriptions of the quantitative accuracy that may be achievable.

In common with any optical scattering technique, the measured quantity corresponds to an equivalent optical diameter, with the considerations noted in the preceding section on OPCs. The situation here is somewhat more complicated in that the scattering occurs from an ensemble, and as such, individual equivalent diameters are not accessible. More formally, the result corresponds to an optically equivalent distribution that best fits the observed angular scattering data. The mathematics of the inversion process have been widely pursued to the extent that a bibliographic listing is beyond the scope here. For a number of applications, more generalized knowledge of the distribution parameters or, in some cases, the concentration of larger sizes, is sufficient, the point being that the utility of ensemble scattering measurements needs to be evaluated on a case-by-case basis.

B.2.5 Tapered Element Oscillatory and Quartz Crystal Microbalances

Tapered Element Oscillatory Microbalances (TEOM) and Quartz Crystal Microbalances (QCM) form the two principal types of direct-reading mass instruments. A simultaneous pro and con, these devices report the deposition of total sampled mass and are therefore insensitive to particle size, shape, density, or composition. By definition, this is useful when total mass is the measurement objective, but this feature is also useful in serving as a reference for calibrating other instruments. A good example is dust photometers, where the output is generally reported in mass units and a variety of particle characteristics affect the instrumental response function.

Both TEOMs and QCMs are resonant mechanical devices, in essence highly sensitive tuning forks. A feedback and drive circuit is coupled to the vibrating tine and also precisely
measures the oscillating frequency. Particles deposited on the tine increase its effective mass and therefore decrease its resonant frequency, and this frequency shift can be detected with suitably sensitive electronics. QCMs generally employ a pair of matched resonators, one being a clean reference that is compared with the frequency of the resonator on which particles are deposited. Provisions are often included to heat the incoming aerosol to drive off moisture that would otherwise be detected and bias the mass reading.

In a TEOM, the mechanical tine is a hollow, tapered tube. A porous filter is installed on the end of the tube and the sampled flow is drawn through the tube, resulting in particle deposition on the filter (Wang, Patashnick, & Rupprecht, 1980). The filter can be removed and replaced and is often made of a material compatible with analysis by electron microscopy. This affords the ability to interrogate other properties, such as shape and composition. The particles can also be washed off the filter and retained for additional analyses. Due to mass variations of the filter elements, a calibration procedure is required when a new filter is installed. Although the dynamic range or saturation point of the instrument is usually limited by the amount of deposited mass, certain circumstances can result in an excessive pressure drop across the filter, and a differential pressure transducer is used to alert for this occurrence. In QCMs, a piezoelectric quartz crystal serves as the resonant structure. Particles are deposited by inertial impaction or electrostatic precipitation onto the surface (Olin & Sem, 1971; Ho, 1984). In some cases, a low-volatility grease is applied to the surface to reduce particle bounce. In contrast to the replaceable filters used in TEOMs, QCMs must be periodically cleaned. For both types of devices, commercially available instruments provide sensitivities on the order of 10 µg/m³. The dynamic range, or maximum permissible deposited mass, typically occurs at a value of a few hundred milligrams for a TEOM, and roughly 150 µg for a QCM.

B.2.6 Cascade Impactors

Impactors are commonly used devices for separating aerosolized particles on the basis of size and are members of a broad class of devices called inertial separators. The basic principle of operation is straightforward: classification is achieved by entraining the particles in a gas flow and then subjecting this flow to an abrupt turn. For particles below a critical diameter, the ratio of drag forces to inertial forces is sufficient for the particles to remain entrained. As particle size increases, inertial forces dominate, entrainment can no longer be maintained, and particles impact on some physical surface within the body of the device (Marple, Rubow, & Behm, 1991). Because the classification process is determined by the relative influence of aerodynamic and inertial contributions, the response is expressed in terms of aerodynamic diameter. The resulting size cutoff is not an idealized, infinitely steep function but has a more gradual rolloff dependent on details of the design, the nominal size cutoff, and the flow rate. Impactors are described by \( d_{50} \), the size at which particles are impacted at 50 percent efficiency.

A series of impactors of decreasing \( d_{50} \) can be arranged or cascaded. The maximum number of stages found in commercial devices is typically on the order of 10 to 12. The associated \( d_{50} \) for each stage ranges from roughly 50 nm to 10 to 20 µm, a comparatively large dynamic range relative to other aerosol instruments.

The resulting size-classified materials can be utilized in a variety of ways. One obvious consequence is the ability to estimate the overall size distribution of the parent material in terms of the percentage of material collected in each stage. This is typically done on the basis of mass, in contrast to the difficulty in determining the total number collected in each stage. For mass measurements, the radius-cubed dependence of mass with particle size combined with the falloff in the tails of the size distribution for simulant materials must be considered. For example, for 1 gram of simulant with a CMD of 1 µm and a geometric standard deviation of 2.5 (reasonably typical values), the combined mass of all particles 0.27 µm and below amounts to \( 10^{-4} \) grams. Collecting the same \( 10^{-4} \) grams in a stage with a cutoff of 50 nm would require processing a total of roughly 3 kg of simulant. The samples in each collected stage can also be used for more refined analyses of particle properties occurring in specific size ranges or used for re-aerosolizing and creating controlled exposures based on size.

The cumbersome aspect of weighing individual stages has led to the development of real-time cascades that measure the deposited mass as it accumulates. This is accomplished in two ways. One configuration incorporates a QCM into each stage, with achievable sensitivities on the order of 10 ng. In electrical impactors, the incoming particles are electrically charged, then detected at each stage using sensitive electrometers. A downside of both QCM and electrical cascade impactors is the flow rate required to support adequate detection sensitivity, which for commercially available devices is on the order of 10 L/min.

B.3 Aerosolization Techniques

All of the instrumental techniques described for the measurement of volume concentrations rely on aerosolizing powder or granular materials. The resulting aerosols are then collected and analyzed by sampling the gaseous medium in which the particles are entrained. From a separate perspective, aerosolization is used to disperse materials in a controlled fashion into test facilities, glove boxes, or other contained environments where components and systems are being purposefully exposed. Clearly entrainment is not possible in the
vacuum environment of the lunar surface or in terrestrial facilities emulating the vacuum environment, but this operational scenario lies outside the scope presented here.

This discussion will focus on techniques for aerosolizing materials such as regolith or simulant, but it should be noted that a wide variety of techniques also exist for generating reference aerosols. This separate but important class of aerosols is required for calibration of the measurement instruments themselves. A number of references on this topic are based on the generation of controlled droplets, whereas others are based on the aerosolization of precisely manufactured solid particles or the evaporation of salts or other reproducible materials from solutions. For a detailed description, the reader is directed to (Baron & Willeke, 2001).

In general terms, techniques and associated apparatus for aerosolizing dry powder materials fall into three basic categories: (1) fluidized beds, (2) conveyors or brushes that deliver material to the exit of an impinging jet, and (3) venturi entrainment. A fourth category involves preparing and aerosolizing from a liquid suspension. The selection of an aerosolizer involves a number of factors, requiring careful examination of the specific devices being considered. These factors include (but are not limited to) the concentrations that can be achieved and the volumetric output of the medium in which the particles are entrained.

A fluidized bed consists of a relatively large, contained volume of the sample material, generally in the form of a cylindrical tube for convenience in both manufacturing and cleaning. The bottom surface of the bed is constructed from a porous material, which must be of suitably fine mesh to contain the smallest particles present. A pressurized source of either dry air or nitrogen is introduced into the chamber through this porous surface. As the supply pressure is increased, a condition is established where the Stokes drag on the particles equals the weight of the material. The velocity at which this balance occurs is called the minimum fluidization velocity (MFV), and is typically on the order of 10 cm/sec. The motion of the powder has been described as resembling a boiling liquid, and the constant relative motion serves to deagglomerate the material. In a two-component fluidized bed, the sample is mixed with larger beads such as bronze. The collision process provides mixing and deagglomeration, but because the process results in significant tribocharging the exiting aerosol must be electrically neutralized to prevent losses (generally size dependent) with subsequent transport.

Conveyor or brush-based aerosolizers are relatively simple devices that employ a mechanism to continuously transport and present the sample to the exit of a pressurized nozzle. From the user perspective, certain configurations are more problematic than others by virtue of clogging and/or seizing of the delivery mechanism itself. While often underappreciated, a more significant issue is the temporal consistency of both the concentration and size distribution of the delivered aerosol. This feature arises from the fundamental nature of granular materials, specifically preferential settling and redistribution from cyclic mixing. In an effort to overcome this some devices utilize arrangements of rotating paddles or employ mechanical or acoustic vibrators. There are no identifiable references in the literature describing the general and comparative performance of these generators insofar as the temporal stability of their respective outputs.

Venturi atomizers are particularly useful when dealing with samples that are only available in sparse quantities. The sample is typically preloaded onto a rotating turntable or conveyor, above which is positioned a small-diameter capillary tube. The other end of the tube is placed in a venturi throat such that suction transmitted through the capillary tube removes the powder from the surface. Because the air velocity in the venturi throat greatly exceeds that in the capillary tube, shear forces are created where the two flows meet, causing the powder to deagglomerate. The powder then enters an expansion cone, from which it exits the generator assembly. The suction entrainment and deagglomeration process is extremely efficient, allowing the aerosolization of samples consisting of only fractions of a gram.

The preparation and dispersion of powders from liquid phase suspensions represents a useful class of techniques, both from the standpoint of generating stable and reproducible aerosols, but also from the practical considerations of avoiding the mechanical assemblies previously described. However, it is noted that creating stable suspensions generally involves rather nuanced surface chemistry to balance surface wetting with agglomeration mechanisms. Establishing a suitable suspension generally involves the proper selection of a suitable solvent or surfactant system (Lu, Pugh, & Forssberg, 2005), as well as mixing to avoid the sedimentation of larger particles. Principles and techniques for establishing and characterizing liquid suspensions are also described in ISO 14887 (Sample Preparation—Dispersing Procedures for Powders in Liquids). Some techniques, such as laser diffraction, can measure particles in a liquid suspension directly; alternatively, the resulting suspension can be atomized and the associated liquid phase either evaporated or removed with a diffusion dryer.

**B.4 Measurement of Surface Concentrations**

Another modality for quantitative measurement of particulates is optical imaging. Often, the particulates lie on surfaces, either through direct sample preparation (on a microscope slide, for example) or through in situ deposition.

Conventional optical imaging is fundamentally limited in spatial resolution to about half the wavelength (200 nm at the lower end of the visible spectrum), so imaging of individual dust
particles is practically limited to particles larger than about 2 µm. For dust particles smaller than 2 µm, electron microscopy can be quite useful due to its nanometer resolution (see Figure B.4).

Despite that limitation, optical imaging can be quite useful for performing statistical size (clump) analysis, as well as measurements of surface occlusion, over an extended field of view (FOV). In order to appreciate the capabilities and limitations of optical imaging for dust analysis, a deeper look at the optical imaging chain is needed.

An optical imaging system relays a two-dimensional (2D) rendering of an object onto a photosensitive sensor array. When specifying an optical imaging system for a specific task, the two most important figures of merit are the spatial resolution and the FOV. Two additional figures of merit, which are particularly important when imaging surface dust due to its variable topography, are working distance (WD) and depth of field (DOF). These four quantities are not independent, however, and compromises must be reached for a given application.

An optical imaging system can be decomposed into three subsystems: illumination, imaging, and detection. Sources of illumination include ambient sunlight, incandescent lamps, light-emitting diodes (LEDs), and laser light. Generally speaking, the first three sources of illumination are incoherent and the latter is coherent, although an incoherent source can produce locally coherent light under certain conditions. Incoherent light is typically desired for full-field imaging so that coherent artifacts such as speckle are minimized. Coherent light is necessary, however, for certain forms of microscopy, such as differential interference contrast (DIC) and confocal microscopy.

The imaging subsystem consists of reflective elements (mirrors) and/or refractive elements (lenses) to faithfully reproduce a 2D representation of the object. In a perfect world, each point on the object would map to a unique point in the image plane. That is, assuming for the moment that the object is 2D, the image would ideally be a scaled exact copy of the object. In practice, this is not possible due to diffraction, which is a fundamental limitation, as well as geometric aberrations, which are constrained by manufacturing precision and economics as well as size, weight, and power (SWaP) allowance limitations.

All optical imaging systems possess geometrical aberrations. That is, light rays that leave a given object point will not simultaneously converge at a point in image space. This is due primarily to the curvature of the optical surfaces as well as the index of refraction (and its dependence on wavelength, i.e., dispersion) of the refractive optical elements. In general, aberrations increase with the diameter of the element and with increasing distance of the object point from the optical axis, so, in addition to optimizing the optical design, certain corrective measures include limiting the aperture and FOV.

In addition to geometric aberrations, the finite size of optical elements introduces diffraction, which spreads the light from a single object point over a finite region of the image plane. The function describing the mapping of a given object point to the image plane is known as the point spread function (PSF). This is analogous, in linear systems theory, to the impulse response function for a 2D delta excitation. The PSF limits the detail in the object that can be faithfully reproduced. In general, it depends on the location of the object point, although for object points close to the optical axis, it is linear shift invariant. For incoherent illumination, the PSFs of neighboring image points add in intensity, whereas for coherent illumination, they add in amplitude. In the latter case, this leads to interference effects in the image (i.e., speckle). For incoherent imaging, the PSF is equal to the squared modulus of the Fourier transform of the function describing the exit pupil of the system. All imaging
systems have a limiting aperture; the exit pupil is the image of that aperture as formed by it and all of the elements between it and the image plane. Conversely, the entrance pupil is the image of that aperture as formed by it and all of the elements between it and the object plane. For a circular pupil, the PSF is known as the Airy disk. In contrast to geometric aberrations, diffraction dominates as element size decreases, as it depends on the ratio of the wavelength to the extent of the limiting aperture. An imaging system where geometric aberrations are negligible compared to diffraction is typically called diffraction-limited.

The spatial resolution of a conventional diffraction-limited imaging system in air is approximately given by

\[ \Delta x = \frac{\lambda}{2NA} \]  

where \( \lambda \) is the nominal wavelength and \( NA \) is the object-space numerical aperture. The object-space numerical aperture, in turn, has the form

\[ NA = n \sin(\theta) \]

where \( n \) is the index of refraction and \( \theta \) is the half angle subtended by the entrance pupil at the object. The numerical aperture represents the angular collection efficiency of the imaging system. When the entrance pupil is coincident with the first optical element, the numerical aperture will approximately equal the radius of the entrance pupil divided by the WD. The spatial resolution can be improved by employing a shorter wavelength (via filtering), immersing the object space in a liquid (with index of refraction >1), moving closer to the object, or increasing the aperture size. Increasing the resolution in this way has its limits, however, as geometric aberrations will worsen. Spatial resolution can also be increased by utilizing evanescent waves (near-field imaging) or exploiting material nonlinearities, but these techniques are specialized. The DOF is inversely proportional to the square of the numerical aperture, so spatial resolution and DOF are orthogonal trade-space variables. When imaging surface dust, the spatial resolution must be relaxed to a certain extent in order to achieve a reasonable WD and DOF.

The FOV is dependent on both the system focal length and the sensor size. Decreasing the focal length for a given sensor size results in an increased FOV, as does increasing the sensor size for a given focal length.

The sensor array also affects the effective resolution of the imaging system. It must have enough elements (pixels) to adequately sample the image or it will ultimately limit the resolution of the system. In addition, undersampling can lead to an image artifact known as aliasing, in which real high-spatial-frequency components in the image manifest themselves as spurious low-frequency components in the recorded image. According to Nyquist, for a signal (or image) to be accurately represented, it must be sampled at a frequency that is at least twice that of the highest frequency it contains. In the spatial domain, this means that the smallest detail in an image must be sampled at least twice, so the size and pitch of the array elements must be such that two of them fit within the main lobe of the PSF.

As such, having an optical system with high spatial resolution and large FOV is not achievable in practice unless the sensor pixel density is high enough to adequately sample the image. If the sensor pixel density is not sufficient, then it will ultimately limit the spatial resolution of the system, and the inherent (or native) resolution of the optics will be wasted. Oversampling the PSF can be equally problematic, as it does not increase the effective resolution and comes at the expense of lower sensitivity and dynamic range due to the smaller pixel size. Balancing native optical performance and sensor pixel density is the foremost issue in designing an imaging system. Typically, a good balance can be achieved, as sensor arrays come in a variety of sizes and pixel densities, as well as detection mechanism (charge-coupled device (CCD), complementary metal-oxide semiconductor (CMOS), etc.). Sizes range from 35 mm to 1 to 2 mm, pixel sizes range from 20 to 1 µm, and pixel numbers range from 1 million to 50 million. Many sensors used for scientific imaging have a pixel size of 6 µm, as this strikes a nice balance between resolution and sensitivity.

In addition to optimizing the native optical and sensor resolution of the imaging system, deconvolution methods can be applied to sharpen a given image and minimize the blurring effects of the PSF, especially in the case of incoherent imaging systems. These methods are particularly useful when the particle size is close to the resolution limit of the system. For example, the image of a round 1-µm particle with an imaging system having a native resolution of 1 µm will have a diameter of 2 µm. If one were attempting to estimate surface occlusion from a discrete group of such particles, the estimate would be off by 300 percent. For a discrete group of 10-µm particles, the error would only be 20 percent. Consequently, the measured statistical distribution will be biased to larger sizes at the low end without correction.

A digital single-lens reflex (DSLR) camera fitted with a macro lens having a magnification of 1 can be useful for detecting particles of a certain size. If the DSLR has a 45-megapixel full-frame sensor (36- by 24-mm area), each pixel will have a linear dimension of 4 µm. Assuming that the image is properly sampled according to Nyquist, the recorded image will have a resolution of 8 µm. This camera will therefore be useful for detecting individual particles down to 8 µm in size as well as imaging groups or clusters of particles. Individual particles smaller than 8 µm will appear as 8-µm particles in the image, only weaker in intensity.
For magnifications higher than 1 that allow finer detail to be observed, one must turn to optical microscopy. Due to the inverse relationship between resolution and FOV, increases in spatial resolution will result in a reduced FOV. As mentioned earlier, however, one must be careful not to increase spatial resolution to the point that WD and DOF are compromised.

Defining “dust” as particles smaller than 20 µm in diameter, it is clear that conventional photography is limited to imaging individual dust particles at the upper end of the range, although it can be useful for wide FOV measurements of dust deposition and surface occlusion. Optical microscopy, however, can be used to image individual particles in the 2- to 20-µm size range. Optical microscopy is also useful for studies of dust deposition and measurements of dust clump size distributions, with the caveat that measurements will be biased to larger sizes without correction (i.e., deconvolution). Imaging of dust particles smaller than 2 µm is best left to electron microscopy, as seen previously.

An example of an instrument that strikes a good balance between competing design constraints is the Foldable Optical Confocal Microscope (FOCµS) optical microscope (see Figure B.5). FOCµS is a rugged, long-WD microscope that was designed and constructed at the NASA Glenn Research Center specifically for monitoring lunar dust. It has an ultracompact footprint and employs matched incoherent Köhler illumination. It also allows easy access to the Fourier plane for implementation of enhanced contrast techniques.

FOCµS was utilized in a radiant emission study involving a Z93 thermal radiator coating exposed to JSC–1A simulant. With a diffraction-limited spatial resolution of 0.9 µm, FOCµS was able to resolve >97 percent of the area covered by the simulant material. The raw dust image (see Figure B.6) was thresholded using the Ohtsu method, yielding a binarized image with an occluded area of 25.8 percent (see Figure B.7). Clump area size statistics were also derived from the binarized image (see Figure B.8).
Appendix C.—Inertial Particle Removal

C.1 Mechanical Agitation Methods

Particulate removal via mechanical agitation can be one of the most straightforward approaches, although more complex processes can also be leveraged. One common feature for all mechanical agitation approaches is that energy is transferred to the article being cleaned, resulting in finite material displacement. That can be realized in a single energy transfer event (e.g., tapping or striking) as well as in a series of energy transfer events (e.g., vibratory motion). Identifying the ideal mechanical agitation approach will depend on the size of the article to be cleaned, the sensitivity of the article, the level of contamination, the dust clearance frequency, the requisite level of cleaning, and the available energy budget for cleaning processes. Excavation tools, lunar terrain vehicle tires, and other robust articles will likely be amenable to controlled-force, impact-event cleaning techniques to remove bulk particulate contamination. This approach will leave at least a monolayer of very fine particles on the surface. However, the needed level of cleaning for these surfaces is likely to be low, given that retention of fine particles will likely not impact subsequent use of these robust mechanical articles.

Other surfaces of greater sensitivity (e.g., solar arrays, instrument windows, etc.) will require techniques with greater precision and dust removal efficacy. Many approaches have been demonstrated to remove some particulate contaminants for either terrestrial or extraterrestrial applications, including periodic mechanical agitation, piezoelectric actuators, acoustic excitation, and laser-induced acoustic waves. A demonstration of mechanical agitation was described by Attia et al. (2019) where energy was translated from a rotating gear to a vertically oriented steel pipe through interactions with cams. A nylon stinger was used to dissipate the impact force. Using this setup, the authors were able to demonstrate a dust clearance parameter value of 0.7 (1.0 would represent complete clearance) for surfaces tilted at 15° that were contaminated with undefined particulates ranging in size from 75 to 150 µm. Although several mechanisms would need to be protected to realize this approach, the simple purely mechanical systems used to impart this cleaning process may make it appealing in some instances.

One of the most promising periodic energy transfer approaches at the time of writing this document is the use of piezoelectric materials. In this approach, piezoelectric materials are utilized to translate electrical energy into mechanical energy, which is imparted into the article of interest as acoustic waves. One of the great benefits of this approach is that, by changing amplitude and frequency, the cleaning efficacy can be tuned. It is important to consider how the article to be protected will respond to the vibrational energy when evaluating these techniques. The imparted acoustic waves will dissipate due to the transfer of energy to heat and sound, and also due to interaction with any damping materials or structures. Additionally, Alagoz and Apak (2020) determined that the angle of inclination of a surface was insignificant for particles smaller than 200 µm based on calculated Hamaker constants for silica particles interacting with silica surfaces. This is particularly relevant, as it indicates that the nature of the acoustic mode being excited in the article of interest is critical. Williams et al. (2007) observed martian simulant migration from regions of high surface velocity to regions of low surface velocity, which they attributed to standing waves. These experimental results were correlated with simulated vibrational modes of the experimental setup. At higher frequencies, standing waves were no longer observed; instead, traveling waves were detected. Although the absolute magnitude of surface displacement was not as large as it was for frequencies that imparted standing waves, the traveling waves imparted in the surface at higher frequencies resulted in better surface clearance. The density of the interacting medium immediately above the article to be cleaned will also play a role, as was shown by Vasiljev et al. (2013), which may complicate analysis of this approach in terrestrial settings for extraterrestrial applications.

Surface acoustic waves can be generated using other approaches as well. Application of laser-generated surface acoustic waves to remove particulate contamination was investigated by Kolomenskii et al. (1998). In this work, a nanosecond laser was focused on a silicon wafer. Particles as small as 50 nm were calculated to be removable from the surface based on calculated surface acceleration values, the limit of which is influenced by the fracture energy of the substrate. For this approach, it is important to optimize the surface acoustic wave generation without imparting substrate damage by remaining in the nondestructive thermoelastic regime of the material. The use of a speaker located at a defined separation distance from a polyvinyl chloride surface to remove particulate contaminants was investigated by Abubakar et al. (2020). Although it is unlikely that this approach will be of much use on the lunar surface due to lack of atmosphere to carry acoustic energy from the speaker to the specimen, the specimen surface response was unique relative to the other literature. Given that the specimen was a symmetric disc, the greatest cleaning efficacy was observed when excitation resulted in activation of the fundamental vibrational mode of the material. Higher excitation frequencies, activating higher vibrational modes, resulted in diminished particulate vertical and horizontal displacement, possibly due to reduced acoustic coupling efficiency.
C.2 Analysis for Dislodging Surface Particulates Using Vibration

In considering mechanical agitation techniques to remove lunar particulates from the surface of an object, acceleration forces developed from resonant structural vibration could potentially be an efficient approach. If the developed acceleration force (inertial load) on the debris particle results in a force that exceeds the adhesive force, the debris will be removed. The underlying physics of this technique comes from Newton’s second law of motion:

\[ F = ma \]  \hspace{1cm} (C.1)

where \( F \) is adhering force (combination of surface adhesion forces acting on the debris particle), \( m \) is mass of the debris particle, and \( a \) is acceleration resulting from surface vibrational motion.

If the debris particle acceleration force \((ma)\) is greater than the adhesion term \((F)\), the debris particle can be removed from the surface of an object.

To develop acceleration, surface motion at a given frequency will determine the resultant magnitude. At any point on the surface of an object, the motion can be modeled by the following equation, assuming the structure is excited with simple harmonic motion:

\[ x(t) = X_0 \sin(\omega t) \]  \hspace{1cm} (C.2)

where \( x(t) \) is surface position as a function of time (motion), \( X_0 \) is maximum surface amplitude, \( \omega \) is angular vibration frequency (rad/s), and \( t \) is time (s).

The surface velocity of that same point can be determined from the first derivative of the motion equation:

\[ v(t) = X_0 \omega \cos(\omega t) \]  \hspace{1cm} (C.3)

and the surface acceleration can be determined from the second derivative of the motion equation:

\[ a(t) = -X_0 \omega^2 \sin(\omega t) \]  \hspace{1cm} (C.4)

What is interesting about these equations is that the \( \sin(\omega t) \) and \( \cos(\omega t) \) terms will oscillate between the values of –1 and 1. Thus the maximum magnitude of the motion, \( x(t) \), is determined by the \( X_0 \) term; the maximum velocity, \( v_{\text{max}} \), magnitude is determined by the \( X_0 \omega \) term; and the maximum surface acceleration, \( a_{\text{max}} \), magnitude is determined by the \( X_0 \omega^2 \) term.

Using this information, we see that the following relationship develops for the surface acceleration:

\[ a_{\text{max}} = \pm X_0 \omega^2 \]  \hspace{1cm} (C.5)

Also note that

\[ \frac{\omega}{2\pi} = \nu \text{ (Hz)} \text{ and we call } \frac{a}{9.81} = g \text{ (m/s}\text{)}^2 \]  \hspace{1cm} (C.6)

The interesting part of this equation is that the angular frequency term \((\omega)\) is raised to the second power. This means that very high surface accelerations can be achieved through high frequency while allowing small surface motions to be present. This is important given that surface motions develop strain in the object material and, if these strains are high enough, material fatigue will result over a predictable time due to stress cycling. Fortunately, in many materials, the numbers of cycles until fatigue are very large, or the material will have some endurance limit where if material strains are kept below some maximum value, the material will have effectively infinite fatigue life.

As an example, assume the maximum surface motion is set to be no more than \(2.54 \times 10^{-5} \text{ m (0.001 in.)}\). The resulting surface acceleration as a function of frequency is shown in Figure C.1.

![Figure C.1.—Surface acceleration shown as a function of frequency; maximum surface motion = \(2.54 \times 10^{-5} \text{ m (0.001 in.)}\).](image-url)
Figure C.1 shows that for very small surface motion, accelerations on the order of 10,000g are achievable at a frequency of 20,000 Hz. If this acceleration is applied to surface debris and the particle mass is large enough, then the adhesive force can be exceeded by the acceleration term (ma), and the surface debris will be ejected, as illustrated in Figure C.2.

Achieving this vibrational surface motion is most efficiently achieved by exciting a selected structural mode at its natural frequency. This condition will set up resonance in the structure, and the desired surface displacement can be achieved with minimum input energy.

Figure C.2.—Acceleration applied to surface debris resulting in debris ejection.

The general equation of motion of any structural system can be modeled by Equations (C.7) and (C.8):

\[ u(x, t) = \sum_{i=1}^{\infty} [\varphi_i(x)q_i(t)] \]  

where \( u(x,t) \) is physical motion at position \( x \) and time \( t \), \( \varphi_i(x) \) is mode shape \( i \) coefficient value at position \( x \), and \( q_i(t) \) is modal response \( i \) at time \( t \) due to an external force.

The real challenge in solving for the motion \( u(x,t) \) due to an external force lies in calculating the modal response value \( q_i(t) \) given that the mode shape \( \varphi_i(x) \) is only a function of position and not of the time-dependent external force. It is beyond the scope of this guidebook, but the mathematics used for solving the modal response, \( q_i(t) \), is identical to that of a single-degree-of-freedom oscillator and takes the form

\[ \frac{\partial^2 q_i(t)}{\partial t^2} + 2\zeta\omega_i \frac{\partial q_i(t)}{\partial t} + \omega_i^2 q_i(t) = Q_i \]  

where \( q_i(t) \) is modal response \( i \) at time \( t \), \( 2\zeta\omega_i \) is damping coefficient for mode \( i \), \( \omega_i \) is angular frequency for mode \( i \), \( Q_i \) is time-dependent external force applied to the system, and \( t \) is time.

In practice, these mathematical equations for a structure are modeled and solved in finite element analysis (FEA) computer codes. By understanding and then strategically exciting one or several of the material’s high-frequency structural mode shapes at resonance, the required amount of interface acceleration acting on the debris particle mass can produce a force sufficient to break the adhesive bond while not damaging the underlying structural material, if the two have not become chemically bound.

This technique has been used and proven in a laboratory environment and shown to effectively remove ice, water, dirt, and other contaminants from the surface of aluminum structures. The primary focus of the work was to remove ice buildup from the leading edge of aircraft wings and windshields. In these experiments, a modal analysis was performed for the leading-edge structure, which provided the information on mode shape and natural frequency. To date, all targeted mode shapes have been in-plane shear modes of the structure given that adhesive tests showed that the force required to remove ice from a material surface was lower in shear than in tension. An example of a targeted in-plane mode shape of an aircraft leading edge is shown in Figure C.3.

Once a mode shape and associated frequency are identified, the challenge becomes how to excite this mode. Although there are several ways to excite structural modes, experimentation found that piezo patches were effective to excite these high-frequency modes (15,000 Hz and above) to resonance with the structural damping limiting the maximum surface motion. The piezo patches were placed at the target mode’s nodal points and operated in synchronous fashion so that as they expanded and contracted, the natural structural modal motion was excited. An example of piezo patch placement on an aircraft leading edge is shown in Figure C.4.

This technique has been applied to composite as well as glass material with success similar to that seen for aluminum. If the operational surface motion keeps the material strain below the allowables for the substrate material, the substrate will not be damaged while the loose debris is removed. Notably, during the experiments the debris was nearly instantaneously removed if sufficient surface acceleration was achieved, and the excitation system needed to be run for only short periods of time. Also, high levels of heat could be created due to internal structural energy dissipation and friction if the system were to be run for long periods of time (Ludwiczak, 2012).
This approach also allows an assessment of the smallest particles reasonably expected to be removable via shaking, tapping, or vibrational excitation (inertial accelerations). For dependence of the effectiveness of regolith removal techniques on particle size generally, generic physics of scaling considerations come into play. Specifically, for any inertial removal approach, the mass of a roughly spherical particle decreases with the cube of the radius, while the effective contact area only decreases with the square of the particle radius (i.e., surface area in contact). So the removal force due to acceleration decreases faster than any adhesion forces that scale with contact area as the effective particle radius decreases, which provides a rough lower bound on the size of particles that will not be readily removed by acceleration. Irregular or jagged particles may present only small contact points to a surface, but nonweathered fracture particles may present relatively flat facets to a surface for enhanced adhesion (larger contact area relative to particle size). Further, if lunar dust particle surfaces are chemically reactive, the adhesion force per unit area can approach or exceed the substrate material strength (Israelachvili, 2011). Chemically bonded lunar regolith particles could then result in damage to an engineering surface however the particle is removed.
Appendix D.—Terrestrial Dust Mitigation Best Practices

Terrestrial dust mitigation draws inspiration from many different fields and industries. A common way to investigate terrestrial dust mitigation is to separate indoor dust mitigation from outdoor dust mitigation. In general, indoor dust mitigation will focus on removing dust from the air, whereas outdoor dust mitigation will focus on preventing the dust from becoming airborne. It is also worthwhile to investigate different industries that rely on dust mitigation. Among those highly interested in controlling dust are the pharmaceutical industry, the grain and sugar processing industries, and the mining industry. Each sector has techniques best suited to its needs and those of the stakeholders involved in the industry.

In enclosed spaces, terrestrial dust mitigation typically utilizes technology designed to remove dust from the air and other enclosed surfaces. Most commonly, air cleaning technology involves the use of filtration devices. Air filters can be further categorized as mechanical filtration through a fibrous media filter (panel, pleated, and high-efficiency particulate air (HEPA) filters), gas-phase filtration (sorption filters), and electronic filtration (electrostatic precipitators, ion generators, and ozone generators).

The most common type of air filters are mechanical air filters that draw air through a fibrous media. These types of air filters work by a mechanical process in which dust-laden air is drawn into a housing via low pressure and then forced through a medium that traps and contains dust particles, resulting in cleaner air being cycled into an enclosed space. Mechanical air filters are rated according to how much air they process in a given unit of time (e.g., cubic feet per minute) as well as how effective they are at removing airborne particles. The most common type of rating for mechanical filters is the minimum efficiency reporting value (MERV) rating scale (Table D.1).

Gas-phase filters work by removing gaseous pollutants through the process of adsorption or chemisorption. The principal difference between the two processes is physical bonding of pollutants to the substrate in the case of adsorption, and chemical bonding of pollutants to the substrate for chemisorption. Activated carbon is the most common filter used in adsorption-type gas-phase filters. It can potentially remove most hydrocarbons, ozone, aldehydes, and organic acids but is not effective against oxides like sulfur, nitrogen oxide, and ammonia. Gas-phase filters are rarely used as a stand-alone filter and are often designed for brief durations to filter a single type of pollutant.

Electronic filters use an electrostatic process to charge particles, which causes the particles to become “sticky” and attracted to opposite electrical charges. Electrostatic precipitators have charged plates, which collect the charged particles inside the filter unit. Ion generators release charged particles into the air, where they often stick to other pollutants in the air and settle onto walls or floors due to their increased mass or electrostatic attraction. A common drawback to electronic filters is the byproduct ozone, which is a respiratory irritant.

In open-air environments, terrestrial dust mitigation typically involves limiting the source of the dust and preventing materials from becoming airborne. The most common method involves wetting materials to prevent them from becoming airborne. Other methods include applying bonding agents and other techniques to bond materials together to increase cohesive strength, covering materials to reduce exposure to wind, and reducing wind speeds. The most common type of dust in open spaces is fugitive dust—a mineral dust most commonly derived from soil and transported primarily by wind. In open-air environments, the focus is on preventing material from becoming an airborne dust, which in the “avoid, remove, tolerate” framework is an example of avoiding dust.

### Table D.1.—Minimum Efficiency Reporting Value (MERV) Ratings for Woven Material Mechanical Air Filters

<table>
<thead>
<tr>
<th>MERV rating</th>
<th>Particle size range, µm</th>
<th>Efficiency</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 4</td>
<td>3.0 to 10.0</td>
<td>&lt;20%</td>
<td>Minimum equipment protection</td>
</tr>
<tr>
<td>5 to 8</td>
<td>3.0 to 10.0</td>
<td>≥20 to &lt;85%</td>
<td>Minimum particulate protection Residential homes Commercial buildings</td>
</tr>
<tr>
<td>9 to 12</td>
<td>3.0 to 10.0 1.0 to 3.0</td>
<td>≥85%</td>
<td>Improved particulate protection Industrial buildings Commercial buildings Residential buildings</td>
</tr>
<tr>
<td>13 to 16</td>
<td>3.0 to 10.0 1.0 to 3.0 0.30 to 1.0</td>
<td>≥90% &gt;90% &lt;70 to ≥95</td>
<td>Superior particulate protection Smoke removal Healthcare facilities General surgery</td>
</tr>
</tbody>
</table>

*Minimum efficiency reporting value.
D.1 Fugitive Dust (Unpaved Roadways and Agriculture)

Control techniques for fugitive dust sources generally involve watering, chemical stabilization, or reduction of surface wind speed with windbreaks or source enclosures. Watering, the most common and, generally, least expensive method, provides only temporary dust control. The use of chemicals to treat exposed surfaces provides longer dust suppression, but this may be costly, have adverse effects on plant and animal life, or contaminate the treated material. Windbreaks and source enclosures are often impractical because of the size of fugitive dust sources. Table D.2 describes common fugitive dust sources and common methods to prevent the source from becoming fugitive dust.

There are several soil modification techniques that can be effective at reducing fugitive dust by consolidating dust-sized particles into larger masses that are not as easily eroded by wind. Many commercial products are available in the construction and agriculture industry that improve soil strength and particle cohesion, which helps to reduce dust. For example:

- Chlorides spread over a layer of granular material form a crust that holds moisture and bonds to the granular material, increasing the particle mass and allowing water to weakly bond to dust-sized material.
  - Calcium chloride (Jones, 2019)
  - Magnesium chloride (Bustos, Girardi, & Pereyra, 2015)
- Chemical-based adhesive-like materials form a glue-like bond between granular aggregates, increasing mass and reducing freely transported dust-sized grains.
  - Isoalkane and binder system (Midwest Industrial Supply, Inc., 2021)
  - Latex-based rock dust binder (Zircon Industries, Inc., 2021)
  - DirtGlue® industrial polymer (Global Environmental Solutions, LLC, 2022)

Specific industries have a vested interest in controlling dust, and each has its own best practices for avoiding, removing, and tolerating dust. The following sections examine how the pharmaceutical, grain processing, and mining industries apply dust mitigation to suit their needs.

D.1.1 Pharmaceuticals (Handling and Contamination Controls)

Many of the products used and produced in pharmaceutical production contain hazardous ingredients that can be toxic because of the quantities being processed. In certain circumstances, some of these products are also potentially explosive, posing hazards to personnel and the plant in which they are being processed (Whitaker, 2005). Keeping airborne dust at a minimum is therefore crucial. Typically, this is done via a combination of air filters near sources of airborne dust and a central vacuum to ensure clean facilities are maintained. In addition, to reduce workers’ exposure to airborne dust, personal protective equipment is worn by employees. To reduce dust contamination on clothing, some manufacturing facilities have “de-dusting” booths that spray compressed air over employees’ clothing upon exiting a designated contamination area. These de-dusting booths also have air filters to remove any dust particles liberated from the employees’ clothing. Avoiding and removing dust is highly important for the safety of workers.

<table>
<thead>
<tr>
<th>Source</th>
<th>Fugitive dust prevention strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paved roads</td>
<td>Improvements in sanding/salting, truck covering, prevention of track-on/wash-on including construction site measures, curb installation, shoulder stabilization, and storm water drainage</td>
</tr>
<tr>
<td>Unpaved roads</td>
<td>Paving, chemical stabilization, surface improvement (graveling), vehicle speed reduction</td>
</tr>
<tr>
<td>Storage piles</td>
<td>Wet suppression</td>
</tr>
<tr>
<td>Construction/demolition</td>
<td>Paving permanent roads early in project, truck covering, access apron construction and cleaning, watering of graveled travel surfaces</td>
</tr>
<tr>
<td>Open area wind erosion</td>
<td>Revegetation, limitation of off-road vehicle traffic</td>
</tr>
<tr>
<td>Agricultural tilling</td>
<td>Land conservation practices under Food Security Act</td>
</tr>
</tbody>
</table>
TABLE D.3.—MINING INDUSTRY DUST CONTROL METHODS: EFFECTIVENESS, COST, AND DRAWBACKS
[Table reproduced from Kissell (2003).]

<table>
<thead>
<tr>
<th>Dust control method</th>
<th>Effectivenessa</th>
<th>Cost and drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust ventilation</td>
<td>Moderate</td>
<td>High – more air may not be feasible</td>
</tr>
<tr>
<td>Displacement ventilation, including enclosure with extraction of dusty air</td>
<td>Moderate to high</td>
<td>Moderate – can be difficult to implement well</td>
</tr>
<tr>
<td>Wetting by sprays</td>
<td>Moderate</td>
<td>Low – too much water can be a problem</td>
</tr>
<tr>
<td>Airborne capture by sprays</td>
<td>Low</td>
<td>Low – too much water can be a problem</td>
</tr>
<tr>
<td>Airborne capture by high pressure sprays</td>
<td>Moderate</td>
<td>Moderate – can only be used in enclosed spaces</td>
</tr>
<tr>
<td>Foam</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Wetting agents</td>
<td>Zero to low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Dust collectors</td>
<td>Moderate to high</td>
<td>Moderate to high – possible noise problems</td>
</tr>
<tr>
<td>Reducing generated dust</td>
<td>Low to moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Enclosure with sprays</td>
<td>Low to moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Dust avoidance</td>
<td>Moderate</td>
<td>Low to moderate</td>
</tr>
</tbody>
</table>

*aLow is 10 to 30 percent, moderate is 30 to 50 percent, high is 50 to 75 percent.

D.1.2 Grain and Sugar Processing

In grain and sugar processing facilities, it is vital to keep the levels of airborne dust low because of the risk of combustion. Typical approaches used to achieve this goal include limiting airborne dust, removing dust from surfaces, and minimizing dust generated at transfer points. Transfer points and conveyors can be enclosed and isolated from any spark-generating machinery. Equipment must be maintained and cleaned to avoid dust buildup, and machinery speeds should be limited to minimize dust generation. Depending on the end use of the grains, edible oils can be applied in a manner similar to wetting. Filters, differential pressures, and pneumatic dust collection systems can all be effective at removing dust from the air (Occupational Safety and Health Administration, 2022). When workers must be present, mitigation via dust tolerance is vital; for example, bakery employees might wear personal protective respirators to reduce the amount of inhaled dust.

D.1.3 Coal and Other Mining Industry

The mining industry must control several types of dust that can endanger workers and equipment. Combustible dust and gas can accumulate in coal mines and must be controlled and/or vented. Ventilation in mines is carefully planned to vent combustible gas and to ensure adequate oxygen is available for respiration. Airborne dust is best controlled via wetting, which is the most effective method to control rock dust. Table D.3 describes the most common methods for controlling dust in the mining industry, estimates their effectiveness at reducing airborne dust, and describes some potential drawbacks to each method.

D.2 Application of Terrestrial Dust Mitigation to the Lunar Environment (Commentary)

Terrestrial dust mitigation techniques can inform best practices in the lunar environment if considered in context. Ballistic dust particle trajectories potentially altered by electrostatic fields in low gravity are outside the common experience of most people, so dust behavior in the lunar surface environment and mitigation techniques may not be intuitive for many. Early endeavors in the lunar environment will encounter dust during landing and the initial brief excursions on the lunar surface. Equipment and human habitat systems will need to be dust tolerant until strategies to avoid dust can be determined. Techniques for reducing fugitive dust in a terrestrial application rely on binding dust-sized particles together in order to increase effective particle mass and/or soil cohesion. Although techniques that rely on water use, such as wetting, will not work in a lunar surface environment, the goal of binding lunar regolith to reduce the free transportation of dust-sized particles should be pursued in high-traffic areas. High-traffic areas on the lunar surface will need to be evaluated to determine if some form of paving, rolling, chemical sprays, or melting would be practical to reduce fugitive lunar regolith-derived dust. Human-inhabited spaces will need a method of removing dust from suits (such as a de-dusting booth) as well as highly effective internal air filters to minimize airborne dust. It may be prudent to plan long-term human habitats away from the dusty lunar surface, such as on an elevated platform, buried beneath lunar regolith, or in lava tubes, in an effort to avoid the lunar dust and the harsh lunar environment.
Appendix E.—Nomenclature

E.1 Acronyms

2D two-dimensional
AC alternating current
AIAA American Institute of Aeronautics and Astronautics
APS aerodynamic particle sizer
ART avoid, remove, or tolerate
BP bundle protocol
CCD charge-coupled device
CLPS Commercial Lunar Payload Services
CMD count median diameter
CMOS complementary metal-oxide semiconductor
ConOps concept of operations
CPC condensation particle counter
CSM Command and Service Module
CVCVM collected volatile condensable material
DC direct current
DCN Document Change Notice
DIC differential interference contrast
DMA differential mobility analyzer
DOF depth of field
DSLR digital single-lens reflex
DTN Delay/Disruption Tolerant Networking
ECLSS Environmental Control Life Support System
EDS electrodynamic dust shield
EMS extravehicular mobility suit
EM–X Exploration Module—undetermined
EPA Environmental Protection Agency
ESD electrostatic discharge
ESTL European Space Tribology Laboratory
EVA extravehicular activity
FEA finite element analysis
FEP fluorinated ethylene propylene
FOCμS Foldable Optical Confocal Microscope
FOV field of view
FPGA field-programmable gate array
GCR galactic cosmic ray
GI gastrointestinal
HEPA high-efficiency particulate air
IAWG International Architecture Working Group
IR infrared
ISO International Organization for Standardization
ISRU in situ resource utilization
ITI intratracheal instillation
ITO indium tin oxide
IVA intravehicular activity
JSC Johnson Space Center
KREEP potassium (K), rare-earth elements (REE), and phosphorus (P)
LADEE Lunar Atmosphere and Dust Environment Explorer
LADTAG Lunar Airborne Dust Toxicity Advisory Group
LCROSS Lunar Crater Observation and Sensing Satellite
LDAB lunar dust adhesion bell jar
LDEX Lunar Dust Experiment
LEAM Lunar Ejecta and Meteorites
LED light-emitting diode
LIDS Low Impact Docking System
LRO Lunar Reconnaissance Orbiter
LRV Lunar Roving Vehicle
LTP Licklinder transmission protocol
MAC multiply alkylated cyclopentane
MERV minimum efficiency reporting value
MFV minimum fluidization velocity
MISSE Materials International Space Station Experiment
MLI multilayer insulation
MOC mission operation center
NESC NASA Engineering and Safety Center
OCHMO Office of Chief Health and Medical Officer
OECD Organization for Economic Cooperation and Development
OPC optical particle counter
OSHA Occupational Safety and Health Administration
PAO polyalphaolefin
PEL permissible exposure limit
PET polyethylene terephthalate
PFPE perfluoropolyether
PIDS polarization intensity differential scattering
PLSS Portable Life Support System
PM particulate matter
PMMA polymethyl methacrylate
POSS polyhedral oligomeric silsesquioxane
PPTA polyparaphenylene terephthalamide
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSF</td>
<td>point spread function</td>
<td>STD</td>
<td>standard</td>
</tr>
<tr>
<td>PSR</td>
<td>permanently shadowed region</td>
<td>SWaP</td>
<td>size, weight, and power</td>
</tr>
<tr>
<td>PTFE</td>
<td>polytetrafluoroethylene</td>
<td>TEM</td>
<td>transmission electron microscopy</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
<td>TEOM</td>
<td>tapered element oscillating microbalance</td>
</tr>
<tr>
<td>PVF</td>
<td>polyvinyl fluoride</td>
<td>TRL</td>
<td>Technology Readiness Level</td>
</tr>
<tr>
<td>QCM</td>
<td>quartz crystal microbalance</td>
<td>TSP</td>
<td>total suspended particle</td>
</tr>
<tr>
<td>RAC</td>
<td>Regolith Adherence Characterization</td>
<td>UHV</td>
<td>ultra-high vacuum</td>
</tr>
<tr>
<td>RF</td>
<td>radiofrequency or radio frequency</td>
<td>USB</td>
<td>unifying S-band</td>
</tr>
<tr>
<td>SCALPSS</td>
<td>Stereo Cameras for Lunar Plume-Surface Studies</td>
<td>USLP</td>
<td>Unified Space Link Protocol</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>SEP</td>
<td>solar energetic particle</td>
<td>VHF</td>
<td>very high frequency</td>
</tr>
<tr>
<td>SPARCLE</td>
<td>Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment</td>
<td>VIS</td>
<td>visible radiation</td>
</tr>
<tr>
<td>SSA</td>
<td>specific surface area</td>
<td>W–LAN</td>
<td>wireless local area network</td>
</tr>
<tr>
<td>SSP</td>
<td>Space Station Program</td>
<td>WD</td>
<td>working distance</td>
</tr>
<tr>
<td>xEMU</td>
<td>Exploration Extravehicular Mobility Unit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
E.2 Symbols

\( A \)  contacting solids' conductive contribution to thermal conductivity (A.6.1)
\( a \)  acceleration
\( d_{\text{max}} \)  maximum surface acceleration
\( B \)  radiative contribution to thermal conductivity
\( C_c \)  Cunningham slip correction factor
\( C_p \)  specific heat
\( CC \)  compressibility (A.7.7)
\( c \)  cohesion
\( D_m \)  particle differential mobility equivalent diameter
\( D_p \)  actual particle diameter
\( D_R \)  relative density
\( d_{50} \)  size at which particles are impacted at 50 percent efficiency (B.2.6)
\( d_a \)  particle aerodynamic equivalent diameter
\( d_{\text{all}} \)  allowable sinkage depth into soil
\( d_p \)  particle optical equivalent diameter
\( d_{\text{min}} \)  minimum detectability-by-mass particle diameter
\( e \)  average void ratio (Table A.4, Fig. A.15)
\( e \)  electron charge (A.5.2.2)
\( F \)  force
\( F_I \)  inertial load
\( F_A \)  adhesion force
\( G(\theta, \phi) \)  geometric factor specifying collection efficiency of optical design
\( g \)  gravitational acceleration
\( h \)  slope height
\( I-V \)  current–voltage
\( I_1, I_2 \)  scattered polarized light intensities
\( J_e \)  plasma electron current
\( J_p \)  photoemission current
\( K \)  thermal conductivity
\( K_s \)  subsurface thermal conductivity
\( k \)  subgrade reaction modulus (A.7.8)
\( k_B \)  Boltzmann constant
\( M \)  deposited mass (B.1.3)
\( M_{\text{initial}} \)  initial deposited mass (B.1.3)
\( M_{\text{removed}} \)  deposited mass removed by mitigation treatment (B.1.3)
\( M_{\text{residual}} \)  residual deposited mass after mitigation treatment (B.1.3)
\( m \)  complex refractive index (B.2.2)
\( m \)  mass (C.2)
\( N \)  slope stability number (A.7.9)
\( N_{\text{4}} \)  object space numerical aperture (B.4)
\( n \)  index of refraction (B.4)
\( n \)  porosity (A.7)
\( n_e \)  electrical charge on particle (B.2.1)
\( n_{\text{max}} \)  highest possible porosity (A.7)
\( n_{\text{min}} \)  lowest possible porosity (A.7)
\( p \)  probability
\( Q \)  time-dependent external force applied to system
\( q \)  bearing capacity (A.7.8)
\( q_{\text{all}} \)  allowable bearing capacity (A.7.8)
\( q(i) \)  modal response i at time t due to an external force (C.2)
\( R \)  response function (B.2.2)
\( R_{\text{ins}} \)  instrumental response function (B.2.4)
\( T \)  temperature
\( T_p \)  photoelectron temperature (A.5.2.2)
\( t \)  time
\( \tan \delta \)  dielectric loss tangent (5.2.3)
\( u(x,t) \)  surface motion at position x and time t
\( v_{\text{max}} \)  maximum surface velocity
\( X_0 \)  maximum surface amplitude (C.2)
\( x \)  dimensionless particle size parameter (B.2.2)
\( x(t) \)  surface position as function of time (motion) (C.2)
\( Z_p \)  particle electrical mobility (B.2.1)
\( z \)  depth in regolith (A.7.4)
\( \alpha \)  wavelength dependent absorptivity (A.6.2)
\( \alpha \)  ratio of Cunningham slip corrections (B.2.1)
\( \varepsilon \)  permittivity
\( \varepsilon \)  wavelength-dependent emissivity (A.6.2)
\( \varepsilon_0 \)  vacuum permittivity
\( \varepsilon_r \)  relative permittivity (dielectric)
\( \zeta_{\text{damp}} \)  damping coefficient for mode i (C.2)
\( \eta \)  photovoltaic efficiency (Fig. 6)
\( \eta \)  dynamic viscosity of embedding medium (B.2.1)
\( \theta \)  numerical aperture half angle (B.4)
\( \theta_1, \theta_2 \)  truncation angles limiting solid angle of collected light (B.2.2)
\( \lambda \)  wavelength
\( \rho \)  bulk density
\( \rho \)  reflectance (A.6.2)
\( \rho_p \)  particle density
\( \rho_s \) specific density
\( \sigma \) conductivity
\( \sigma \) normal stress (A.7.6)
\( \sigma_g \) geometric standard deviation (B.1.2)
\( T \) transmittance
\( \tau \) shear strength (A.7.6)
\( \phi \) internal friction angle (A.7.6)
\( \phi_1, \phi_2 \) truncation angles limiting solid angle of collected light (B.2.2)
\( \phi_i(x) \) mode shape \( i \) coefficient value at position \( x \) (C.2)
\( \psi \) electron flux (A.5.2.2)
\( \omega \) angular vibration frequency (C.2)
\( \omega_i \) angular frequency for mode \( i \)
References


