Electrostatic dust remediation for future exploration of the Moon

M. Hirabayashi[a,b], C. M. Hartzell[c], P. M. Bellan[d], D. Bodewits[e], G. L. Delzanno[f], T. W. Hyde[g], U. Konopka[e], E. Thomas, Jr.[e], H. M. Thomas[h], I. Hahn[i], U. E. Israelsson[i]

[a]*Aerospace Engineering, Auburn University, Auburn, Alabama, 36849, USA*
[b]*Geosciences, Auburn University, Auburn, Alabama, 36849, USA*
[c]*Aerospace Engineering, University of Maryland, College Park, Maryland 20742*
[d]*Applied Physics and Materials Science, California Institute of Technology, Pasadena, CA 91125, USA*
[e]*Physics Department, Auburn University, Auburn, Alabama 36849, USA*
[f]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[g]*Center for Astrophysics, Space Physics, and Engineering Research (CASPER), Baylor University, Waco, Texas 76798-7310, USA*
[h]*Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), D-82234 Weßling, Germany*
[i]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*

Abstract

Dust accumulation is one of the critical issues that must be mitigated on in-situ lunar explorations because an in-situ probe is exposed to small dust particles, which are easily attached to it, during its operations. The Lunar Dust Science Definition Team is organized by the Jet Propulsion Lab/California Institute of Technology through NASA's Biological and Physical Sciences Division to define key science questions and assess dust remediation techniques. Here, we assess three electrostatic remediation technology concepts: electrostatic dust shield; surface electrostatically collecting dust, later called attractive surface; and electron beam - plasma jet inducing electrostatic dust lofting from a surface. We qualitatively investigate their maturity by defining six operational factors: Time and location; Amount of dust removal; Contamination of target surfaces; Operation duration; Installation; and Safety. In addition to these techniques, we discuss a supporting system that loads dust particles onto a test article to examine dust removal efficiency. The results show that further development increases the maturity of all the technologies. While laboratory and theoretical demonstrations reported whether each technology robustly work on the Moon, which hosts a complex, heterogeneous dust environment, we find that it is still uncertain if this is the case because none has been tested in the lunar environment. Particularly, operation duration and safety are critical to be addressed further on both laboratory and spaceflight scales.

Keywords: Space exploration, Lunar surface, In-site operations, Dust physics, Electrostatic charges, Dust mitigation

---

Email address: `thirabayashi@auburn.edu` (M. Hirabayashi)

1. Introduction

1.1. *Risks of dust*

On the Moon, dust covers a substantial part of its surface. Major dust particles are generated and sharpened by fragmentation of surface materials during meteoroid impact events [1]. Volcanic events have also contributed to the generation of dust particles and the evolution of the surface conditions, particularly within mare [1]. Furthermore, material mixing frequently occurs due to impacts [e.g., 2], leading to heterogenous dust distributions from one location to another [e.g., 3]. Because the size of such particles ranges from nm to μm, they are exposed to various physical forces. For example, during such mixing processes, gravity and electrostatic forces may cause dust lofting [4].

Dust is a contributor to contaminating spacecraft systems both naturally and anthropogenically [5]. Small dust particles can go through narrow parts of the systems, such as fabric, bearings, and moving parts. Although the Apollo missions in general controlled lunar dust, there are still unresolved issues [6]. For example, suit glove and helmet bearings experienced no significant effects on operations but had many scratches from dust. While the lunar rovers had their wheel bearings and electronics sealed against any penetration by dust, mirrors and thermal control surfaces suffered from dust accumulation and needed to be cleaned often. Suit visors were usually covered by electrostatically adhering dust, making dust removal challenging. The dust prevented the sample return containers from maintaining vacuum during storage in the spacecraft. These outcomes indicate that dust mitigation techniques are still immature and there is a need for further development [6].

Dust is also a critical issue for space exploration missions to Mars and airless bodies. On Mars, dust storms can cover onboard instruments with dust. For example, the Opportunity rover suffered dust covering on its solar panels, which resulted in mission termination [7]. Recent work studying dust mounting on instruments on the Curiosity rover shows that vertically mounted instruments experienced less dust covering than horizontally mounted ones, which possibly results from effective dust removal [8]. Recently, two space exploration missions explored different rubble pile asteroids. The OSIRIS-REx spacecraft visited 101955 Bennu to sample materials and successfully landed on its surface [9]. On the other hand, the Hayabusa2 spacecraft explored 162173 Ryugu and obtained samples at two different locations [10]. However, the Hayabusa2 spacecraft experienced contamination of its remote sensing instruments by dust particles ejected by chemical thrusters during landing operations. The attached dust reduced the instrument sensitivity at some levels [11]. Although efforts were made, none succeeded in removing dust particles from the instruments effectively [11].

1.2. *Dust Mitigation Efforts/Technologies*

Mitigation technologies can be categorized into passive and active technologies [12]. Passive technologies are those pre-treated physically or chemically in laboratories to mitigate dust attraction without using external forces. Active technologies, on the other hand, apply processes that remove dust on site and can be split into four major steps [13]:

1. Loosening the dust. This process breaks attractive bonds, which mainly result from van der Waals/electrostatic forces and hold dust particles on a given surface. Processes to break them may use mechanical, electrostatic, and chemical effects.

2. Removing the dust from the surface. This process pulls dust off a surface and can be achieved by applying mechanical force (e.g., removing dust particles with fluids or brushes), electrostatic forces, and chemical conditions (solutions to trap dust particles).
3. Transporting the dust away from the target surface.
4. Disposing of the dust (properly and safely placing the dust without contaminating critical areas such as probes and investigation sites).

Below, we discuss active technologies using fluid, mechanical, and electrostatic forces.

Fluid methods use compressible or incompressible fluids to remove dust from surfaces. Possible options may include using foams and gels, liquid solutions, and gas solutions [14]. Using fluids, however, may encounter some technical issues, especially in the zero-pressure environment on the Moon, which may cause immediate evaporation, preventing these solutions from working effectively [14]. On the other hand, experimental jetting tests have demonstrated that carbon dioxide gas jets might effectively remove dust even in such low-pressure environments [15]. Gaier et al. [16] used nitrogen gas pulses to quantify whether a thermally controlled surface enhances the puffs to remove dust; however, given environmental variations in their study, the results were not advisable.

Mechanical methods apply forces driven by equipment (for example, a brush) to remove dust particles. Reports have generally shown high dust removal performance. The use of lunar dust samples from the Apollo 12 program demonstrated that brushing (with nylon- or brass-bristle brush) eased removing dust from various materials [17]. Further analyses quantified brushing techniques, showing that it achieved high dust removal rates [18, 19]. However, it is also shown that using mechanical brushes usually scratches sensitive, delicate surfaces [14]. For example, during the Apollo 14 Thermal Degradation Sampling (TDS) experiments, when astronaut Alan Shepard dusted metal sample holders of the TDS, he found some brushes scratched the metal samples [20].

Electrostatic methods are generally preferred and explored, given the above limitations for the fluid and mechanical methods. The primary principle is that devices electrostatically charge dust particles, induce electrostatic forces, and move them from one place to another. By properly providing dust particles with electrostatic charges, this method can remove them from a target.

1.3. Electrostatic dust remediation technologies and supporting device

We focus on electrostatic dust remediation technologies for removing dust from a target surface effectively. In this study, we investigate the following three techniques:

- **Technique A. Electrostatic dust shield:** This technique consists of wires embedded below a target surface. When an alternating current is passed through the wires, dust lofting occurs, causing particles to hop off the treated surface. See Figure 1a.

- **Technique B. Attractive surface:** This is an early phase technology that dust lofting is prompted by passing an electrically biased plate or wand above a dusty surface, thereby attracting dust to the biased plate or wand. See Figure 1b.

- **Technique C. Electron-beam and plasma jets induced lofting:** This technique combines an electron beam and a plasma jet to enhance the dust removal process. This technique actively charges dust particles electrostatically, enabling dust lofting due to electrostatic forces and plasma jets. See Figure 1c.

1.4. Operational factors

To assess the remediation technologies discussed in Section 1.3, we define six operational factors that would impact the use of them in the lunar environment.

- **Factor 1. Timing and location:** This factor defines whether the remediation technique depends on the local time and location. A desired device's performance is independent of the environment. The Moon is rotating with a spin period of around 30 days. The lunar dayside may have an electrostatic potential of 5 V, while the night side may have -1000 V [21]. Solar energetic electron events could even induce stronger negative charging on the night side [22]. The variations in the lunar surface charge due to solar storms, as well as the Moon's passage through Earth's magnetotail, may influence the efficacy of the techniques discussed. The chemical compositions of regolith may also influence the charge state. The lunar surface mainly consists of two material conditions; one side is the mare, where volcanic materials are widely distributed, and the other side is the highlands, where major components consist of light materials. The mixing of these materials at local levels further makes the problem complex. The topographic features such as surface roughness control the sunlight condition at local scales, giving variations in the electrostatic properties. Also, potential sites affected by the lunar magnetic field may host unique dust particle conditions [23].

- **Factor 2. Amount of dust removal:** This factor specifies a technique's dust removal efficiency. An ideal device is independent of the constraints on the device size and the amount of dust removal. However, in general, if the technique's mass increases with the amount of dust, this factor becomes crucial to constrain the design. For example, if the method consumes materials, the device mass increases with the scale of dust removal. Also, if device components are continuously degraded during the operation, dust removal efficiency eventually becomes lower than the planned threshold.

- **Factor 3. Contamination of target surfaces:** This factor defines whether the remediation technique contaminates or damages a target surface. If a target surface (e.g., camera lenses) is sensitive, it is desirable to keep it clean and unaffected. This factor is crucial to determine if the considered technique can be applied to desired purposes regardless of the dust mitigation efficiency.

- **Factor 4. Operation duration:** This factor defines whether the operation duration is flexible or limited. A longer operation period (and repeatability) is suitable for the use of remediation techniques. A technique that can be active as long as a power source is available is preferable for exploration missions. This factor also accounts for whether the technique is robust when there is a malfunction of the remediation device.

- **Factor 5. Installation:** This factor defines how flexibly the remediation technique can be installed to onboard systems of spacecraft. If the technique is independent of other onboard systems, it is not necessary to account for potential issues with system integrations. When the technique requires a supporting system that needs to be embedded into other onboard systems, such as a target surface, there may be strong installation constraints.

- **Factor 6. Safety:** This factor describes how safely the remediation technique can be used during operation. The key issues include high electric potentials and UV light, which may potentially harm astronauts or system hardware. Any dust remediation technique for impacting spacecraft systems (including humans) negatively should be avoided.

1.5. Present scope and outline

As the Lunar Dust Science Definition Team established by the Jet Propulsion Lab/California Institute of Technology through NASA's Biological and Physical Sciences Division, we assess the mitigation technology concepts in Section 1.3 to identify remaining questions for them to be explored in the future. While our assessment is qualitative, this paper summarizes our findings of necessary development, especially for technology instrumentation for future lunar landed missions. Our discussions consist of simplified concept designs and assessments of the remaining elements that need to be developed. The present study is outlined as follows. Section 2 discusses the Electrostatic Dust Shielding technology (Figure 1a). Section 3 introduces the Attractive Surface technology (Figure 1b). Section 4 shows the UV/Electron-beam and Plasma Induced Lofting technology (Figure 1c). Section 5 argues the operation factors that may control the dust remediation efficiency and how each technique is ready to respond to each factor. In addition, in Section 5, we discuss a dust loading device that mounts dust on a target surface so that the techniques considered can demonstrate their dust remediation efficiencies on spaceflight missions (Figure 1d). The present paper is a companion study with Hartzell et al. [4].

2. Technique A: Electrostatic dust shield

This section discusses the electrostatic dust shield, or Technique A (see Figure 1a). The fundamental idea of this method is to embed parallel electrodes into a surface and generate electrodynamic forces controlled by AC signals [25, 26, 27, 28]. This technique consists of a series of parallel electrodes connected to a two-phase or multi-phase AC voltage that generates an electric field that oscillates as the polarity of the electrodes changes (Panel a in Figure 1). This creates a standing wave that produces electrostatic and dielectrophoretic forces on charged particles in a considered field. These charged particles move either with or against the wave, depending on polarity. This technique has also been shown to work on polarizable, uncharged particles [29].

Recent applications of this technique demonstrated high performance, giving the recovery of solar panel power generation to higher than 90% of its nominal condition [e.g., 30, 31, 32]. Manyapu et al. [33] demonstrated an application of this technique, as well as the Work Function Matching Coating passive technology and the Carbon Nanotube (CNT) flexible fibers, to remove 80-95% of dust on a spacesuit. This technique's removal efficiency depends on both device and dust conditions and properties. For example, the applied amplitude and frequency of the AC signals influence the removal efficiency [34]. Particle size distributions, material compositions, and charges also affect dust removal [35]. Higher voltage and vacuum

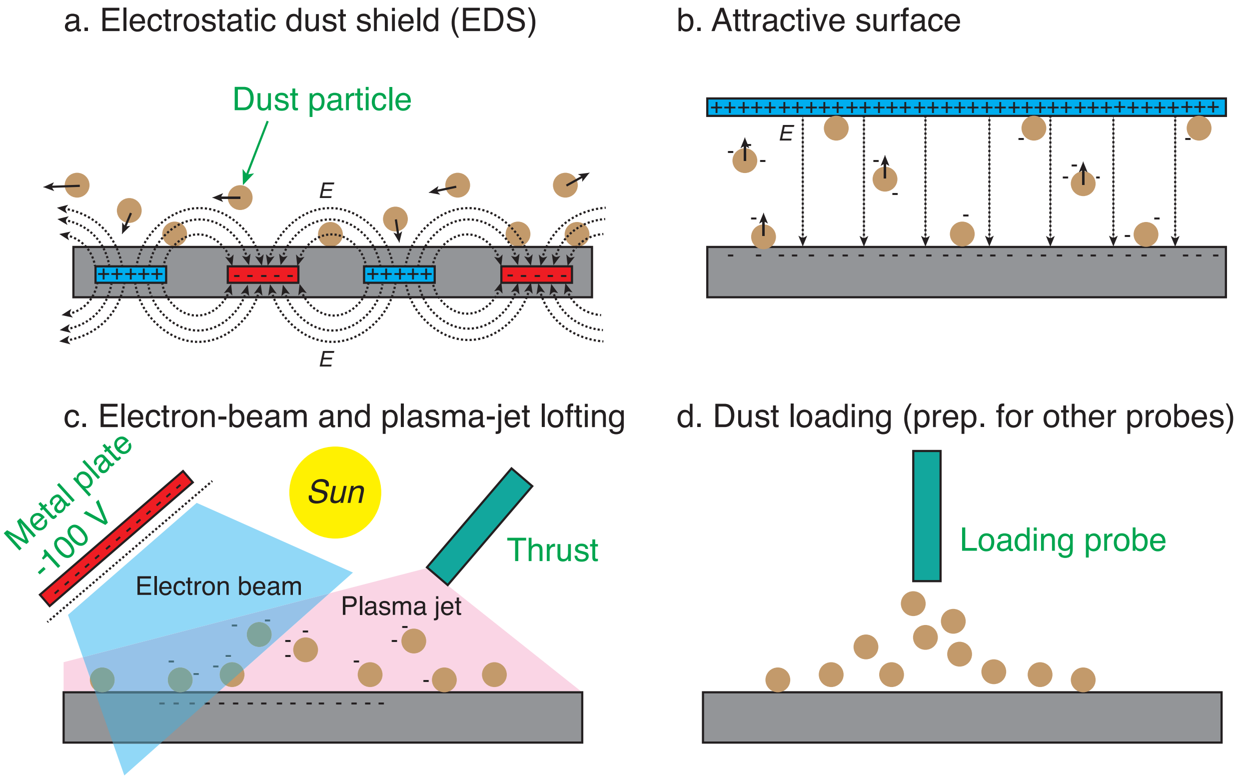

Figure 1: Dust mitigation concepts discussed in this study (a-c) and dust loading concept (d). a. Electrostatic dust shield. The illustration given is based on the 2-Phase electrostatic dust shield design introduced by Buhler et al. [24]. b. Attractive surface. c. Electron-beam and plasma-jet lofting. d. Dust loading device.

conditions may give higher dust removal performance [36] because these removal efficiencies correlate with the dust particles' hopping processes over an AC-controlled surface [37]. Applications to fabric materials (e.g., astronaut spacesuits) also confirmed high dust removal with vibrations enhancing the performance [38].

The use of this technique on the Earth has also been a key topic, such as cleaning solar panels covered by dust [39, 40, 41, 42]. While the mechanisms of these applications are similar, techniques behave quite differently in the lunar environment. The main reason is the environmental difference between the lunar surface and the Earth surface. First, the lunar surface has extremely low humidity compared to the Earth surface. This changes the electrostatic dust shield performance [e.g., 43, 44]. Second, on the Moon, the electrostatic environment is complex due to the interactions between solar winds and the lunar and Earth magnetic fields. This may also be due to variations in material compositions; regions are distinguished in mare or highlands [1], but material diversity at local scales has widely been reported in the literature [e.g., 45, 46, 47]. While the current version of this technology seems partially effective in removing deposited micron-size particles from target surfaces, it has not yet been fully tested under realistic lunar surface conditions.

2.1. Principles

We discuss approaches proposed by two groups: Calle et al. [29, 48] and Kawamoto and Hashime [49].

First, the device tested by Calle et al. [29, 48] includes a two-phase electrode design consisting of two sets of parallel copper electrodes interlaced in a comb configuration with each set connected to one of the signal inputs which have a 180 degree phase shift. The field strength varies proportionally due to the potential difference between the electrodes as dictated by the phase shift. Scaled versions include: (a) Transparent 20-cm-diameter electrostatic dust shield employing indium tin oxide electrodes on a polyethylene terephthalate film or (b) Copper electrodes on Kapton film (two with Lotus coating).

Successful demonstrations of a two-dimensional (2D) version of this electrostatic dust shield system have been reported in the literature on (1) solar panels [29, 32], (2) optical systems [32, 50], (3) viewports [48], (4) thermal radiators (for both AZ-93 thermal paint and Fluoro Ethylene Polypropylene coatings) [32], (5) spacesuit fabric (Mars and Lunar environments), and (6) both the Pressurized Excursion Module and the Lunar Habitat Demonstration Unit [48]. Also, the production process has recently been updated to apply photo-lithography which allows the production of larger panels with fewer defects at an increased production rate [50]. Solar panel dust clearing results to date show approximately up to 98 percent dust clearing after 30 minutes while this value was about 96% for thermal radiators [29, 32]. Buhler et al. [24] developed a three-dimensional (3D) version of the electrostatic dust shield.

Second, Kawamoto and Hashime [49] developed a similar system that uses a four-phase rectangular voltage and also showed that the cleaning process is improved by application of ultrasonic vibrations. This approach, allowing both positively and negatively charged dust particles to be cleared without changing the configuration of the system, has been tested using the lunar dust brought back by Apollo 11. Numerical models suggest that the cleaning performance of this technique should improve in the gravitational environment of the Moon. The system reportedly has no moving mechanical parts and consumes less power than the electrostatic dust shield by Calle et al. [29, 48].

2.2. Concept study for spaceflight

Here, we summarize the currently available size, mass, and power of the electrostatic dust shield system by referring to Kawamoto and Guo [49]. Their device consists of two components: a high voltage source and an electrostatic dust shield cleaner plate. That total mass is 210 g (180 g for the high voltage source and 30 g for the cleaner plate) and the required potential is ±6 kV (Table 1). The dimensions and used products are provided in Table 2. While the generated potential is up to 1 kV, the reported power is 0.5 W during operations and 0.3 W in the idling mode [49]. This specification promises the feasibility of this device for future spaceflight.

Table 1: Specification of the electrostatic dust shield system developed by Kawamoto and Guo [49].

	Mass (g)	Potential (V)
High Voltage Source	180	Positive/Negative 1 kV
Cleaner Plate	30	N/A

Table 2: Dimensions of the cleaner plate and electrodes as well as the substrate and amplifiers developed by Kawamoto and Guo [49].

	Dimensions (mm)
Prototype High Voltage Source	125(L) x 70(W) x 40(H)
Cleaner Plate	100(L) x 100(W) x 1.1(T)
Width and Pitch of Electrodes	0.3 / 0.6
Substrate	Borosilicate Glass
Substrate Covering	Borosilicate Glass (0.1)
Positive / Negative Amplifiers	Matsusada Precision - HVBT-1P-5 and 1N-5
Amplifiers Switching	Panasonic AQV258

2.3. Suggested areas of technology advancement

While the electrostatic dust shield technology has already demonstrated several promising outcomes, it requires further advancement to be flown. We summarize the areas needing technology development below.

- Further investigation of the scaling of these devices to larger surface areas is necessary. Tests to date have considered a small active area. Operational methods and efficiencies for larger active areas are currently unexplored.
- Power sources need to be optimized to ensure minimum size, weight and power consumption.
- Current systems still require testing at both the maximum and minimum temperatures observed in the lunar environment.
- The lunar plasma environment is complex under interactions with the Earth's magnetosphere, but the mechanism is poorly understood. Future assessment is necessary to make sure this technique robustly works on the Moon.

3. Technique B: Attractive surface

This section illustrates the attractive surface technique, or Technique B. This technique uses an electrically charged plate to attract charged dust particles and remove them from target surfaces. Dust particles are naturally electrically charged due to solar wind impingement, photoemission, and tribocharging. The electrostatic force produced by a charged plate can cause the dust to detach from surfaces. The addition of electrostatic charges to the plate induces a stronger electric field, enhancing the magnitude of the electrostatic forces acting on dust particles exposed to it. A series of dust hops can be used to electrostatically sweep dust off a surface, given fringing fields at the edges of the plate. We neglect the plasma environment near the lunar surface in our preliminary calculation, assuming that the attractor is within the Debye sheath of the dust-bearing surface (~ 1 m in the lunar environment [e.g., 4]).

3.1. Principles

To assess the efficiency of this technique, we compare the magnitude of forces acting on dust particles adhered to a plate. The main forces include the gravitational force, the attractive force that binds surface particles together, and the electrostatic force acting on the charged dust particles. The necessary condition to electrically remove dust particles from a surface is that an electrostatic force acting on a dust particle exceeds gravity and forces binding the dust particle to a dusty surface:

$$F_{es} > F_{grav} + F_{co} \tag{1}$$

where F_{es} is the electrostatic force driven by the attractor plate ($F_{es} = Q\Delta\phi/\Delta h$, where Q is the charge of the dust grain, Δh is the height of the attractor above the surface, and $\Delta\phi$ is the potential between the attractor and the target surface), F_{grav} is the gravitational force, and F_{co} is the force binding dust particles.

The above condition yields the electric potential of the attractor required to cause dust motion. We assume that the dust grains are spherical, with a material density of 2 g/cm^3, and that the lunar surface gravity is 1.625 m/s^2. We characterize the cohesive force, $F_{co} = \sigma_{co}\pi r_d^2$, where σ_{co} is the cohesive strength in Pa, and r_d is the radius of the dust grain. Substituting the definitions of the forces into Equation (1) gives:

$$Q\Delta\phi/\Delta h > 4/3\pi r_d^3\rho g + \sigma_{co}\pi r_d^2 \tag{2}$$

We consider Δh =10 cm, although this can be varied. The attractor must remain close to the surface ($<$ 30 cm) for the shield due to the near-surface plasma being negligible. Figure 2 shows predictions of the electric potential of the attractor required to cause particles lofting for a range of cohesive strengths and grain potentials. While lunar dust may be referred to as those less than 20 μm in size, the present analysis shows a broader range of lunar particle sizes to quantify the general trends. The grain charge is modeled using a spherical capacitor approach, which gives $Q = 4\pi\epsilon_0 r_d V$, where V is the grain potential, and ϵ_0 is the permittivity of free space.

While the amount and polarity of the charge on individual dust grains are not constrained, grains can be charged due to interactions with the solar wind plasma, UV-induced photoemission and tribocharging. Prior experimental work by Schwan et al. [51] has shown that electron emission can result in charges up to 10's of thousands of electrons for 40 micron-scale grains. Additionally, Carter and Hartzell [52] have shown that 200 micron-scale tribocharged silica-zirconia beads can support charges up to millions of electrons.

3.2. Concept study for spaceflight

To approximate the size, mass, and power requirements of the dust attractor device, we assume a hand-held plate-type attractor sized to be used by astronauts and robotic devices. This type of attractor should not be larger than 30 cm in size. Larger attractor plates require more power to operate, as increased surface area enables increased current to the plate from the ambient plasma. To calculate the mass of the attractor plate, we consider it to be made of aluminum (with a density of 2.7 g/cm^3). We estimate the power (P) required to hold the plate at the required electric potential from:

$$P = I\Delta\phi \tag{3}$$

$$I = n_e A_{plate} e v_{Te} \tag{4}$$

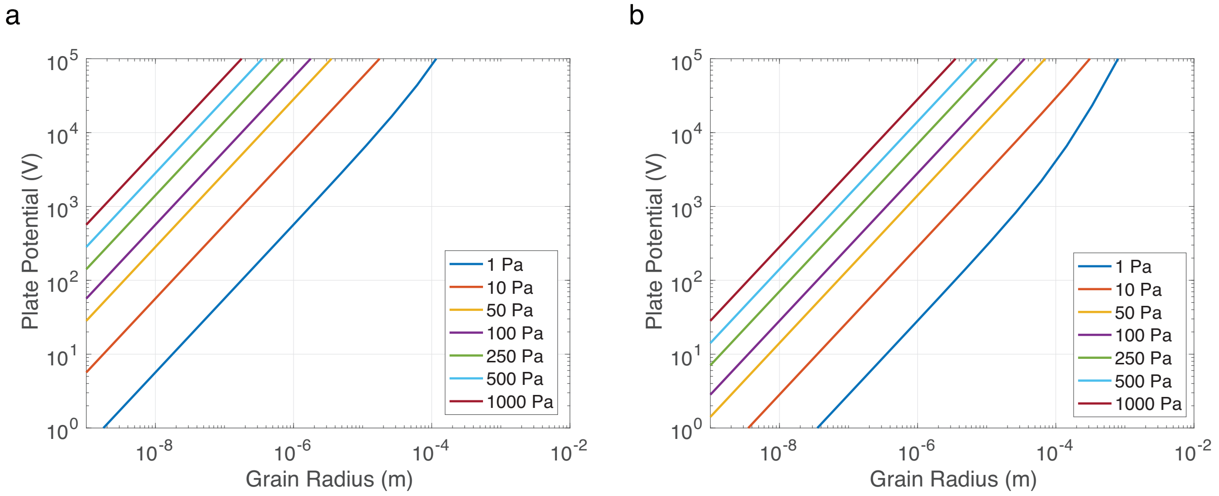

Figure 2: Electric potential of the attractor required to electrostatically loft dust with varying grain electric potential and cohesive strength. Panel a assumes a grain potential of 5 V, while Panel b illustrates results for 100 V. The legends in both panels show σ_{co}. The grain radius range is defined based on the particle size distribution in the Apollo samples [1].

where I is the electric current, n_e is the local plasma density (assumed to be 2.5×10^6 m^{-3}, half of the freestream ion density due to the local plasma sheath), A_{plate} is the cross sectional area of the plate, e is the charge of an electron, and v_{Te} is the thermal velocity of the electrons. n_e can range widely, depending on the lunar surface conditions, and is not well constrained. For example, Popel et al. [53] considered n_e to be 8.3×10^6 m^{-3}. The use of $n_e = 2.5 \times 10^6$ m^{-3} only provides a rough idea of this approach, and thus further analyses are necessary. Assuming an electron temperature of 15 eV, this zeroth order approximation leads to a required power of 8 mW for a 30 cm × 30 cm plate biased to 10^5 V (Table 3). Because the plate potential must remain constant (i.e., its functionality is based on its use at a potential not equal to the floating potential), the current to the plate from the local plasma environment must be balanced by a power supply attached to the plate. While 8 mW is a relatively small steady-state power draw, we note that this power evaluation does not account for the fact that the plate is at a high potential, and thus the current can be much larger than the thermal current.

The major operational constraint is that the dust must be charged to be affected by the dust attractor. Regolith on both the day and night is expected to be charged. However, charging may be quicker on the day-side, due to photoemission and the increased plasma density (as compared to the wake region on the nightside). It is possible that the dust attractor's performance will be enhanced by certain astronaut activities. Tribocharging of the substrate (e.g, astronaut or spacecraft) to which the dust adheres may influence the plasma environment near the surface, and, in turn, influence the nominal charge of the grains [54]. Additionally, changing the orientation of the dust covered surface with respect to the solar incidence angle may change the charge of the grains – a property that may be exploited during operations.

3.3. Suggested areas of technology advancement

Below is a list of necessary advancements for this technique.

Table 3: Estimated requirements for a dust attractor plate.

	Dimensions (cm)	Mass (g)	Power (W)
Attractor Plate	$30 \times 30 \times 0.5$	1,215	8 mW (baseline)

- The attractive surface format should be optimized. Fringing fields may be particularly effective at moving particles, which would suggest that a wand format may be more effective for remediation. However, because of the decreased size of the wand as compared to a plate, the wand may be more easily shielded by the near-surface plasma, thus requiring either higher voltages or positioning of the wand closer to the dust-covered surface. In contrast, a plate may more quickly remove dust from a larger area.
- The effect of operational changes such as different target surfaces and timing should be investigated to determine whether or not these significantly influence the efficacy of the device.
- Experiments are needed to quantify the efficacy of removing dust from a surface in the lunar environment.

4. Technique C: Electron-beam and plasma jet induced lofting

This section discusses a combination of plasma jets and electron beams to perform dust remediation (Figure 2c). This technology's uniqueness is to move dust by using plasma jets and enhance its performance by actively supplying electrostatic charges to dust particles using solar UV light.

4.1. Principle

Technique C may offer two versions. The first version combines an electron beam and a weak plasma, while the second version has plasma only but with higher density than in the first version. The first version exploits sunlight-instigated natural photo-emission to create the electron beam. Below, we introduce the principles of generating electron beams and plasma jets.

4.1.1. Electron beams

Flanagan and Goree [55] generated a 70-eV electron beam in a setup where a hot tungsten filament was used in conjunction with an applied 70 V bias with respect to ground walls. The resulting thermal electrons are characterized by two Maxwellian populations, one colder with temperature T_{cold} ~0.3-4 eV and one hotter with temperature 3-16 eV. The density could be varied between 2.4×10^6 cm^{-3} and 2.5×10^8 cm^{-3}. A 4.5 cm diameter glass sphere was coated with JSC-1 lunar dust simulant, with dust size distribution having a characteristic size less than 20 μm. The coated sample was then exposed to the thermal plasma or the electron beam or both. There are three key findings from Flanagan and Goree [55]. First, measurable dust release could only be obtained when the sample was exposed to both the thermal plasma and the electron beam. Second, significant dust release occurred only for plasma densities above 2.4×10^6 cm^{-3}, suggesting a density threshold for strong dust mobilization. Last, the release time-dependence followed an exponential decay with a release rate between 4 s and 25 s, with faster release rates associated with higher plasma densities.

Another set of experiments with similar conditions was performed by Schwan et al. [51]. In their experiments, the beam emitted by a hot filament had an energy of 120 eV. The thermal electron temperature was reported to be ∼2 eV [51], although no measurements of the plasma density were provided. Schwan et al. [51] confirmed the findings by Flanagan and Goree [55], who showed that dust could be mobilized when exposed to a plasma and an electron beam. Their focus may be slightly different from our interest in applying a combination of electron beams and plasma jets because they attempted to demonstrate the so-called 'Patched Charge Model,' which suggests that dust is mobilized by strong electrostatic forces building up in microcavities.

Farr et al. [56] later used a 1.5 μA cm^{-2}, 230 eV electron beam on a dust-coated flat target glass to observe dust shedding from the surface. The lofting of dust particles is mainly considered to result from secondary electrons that are created on the dusty surface exposed to the beam and become absorbed into microcavities between the dust grains. This process charges the dust grains negatively, causing them to repel each other and to be ejected from the surface.

4.1.2. Plasma jets

Ticos et al. [57] reported a technique for using plasma jets to clean surfaces, which they called the plasma broom technique. The reported plasma broom used a plasma jet produced in a pulsed discharge (pulse length of ~ 1 μs). The setup by Ticos et al. [57] was based on a coaxial plasma gun with the gap filled by CO2 gas with pressure of 670 Pa and an applied voltage between 1 kV and 2 kV. This plasma jet technique was applied to the cleanup of solar panels coated by a thick layer of JSC-1 martian simulant dust. During the operation of this technique, the plasma densities were extremely high, of the order of 10^{21} m^{-3}, and the dust particles were expelled from the surface simply by drag forces. Ticos et al. [57] demonstrated a high cleaning efficiency of $> 97\%$ after only a few shots at 2 kV voltage, and an energy consumption of about 250 J per pulse. The application of this technique to the lunar environment may be challenging because additional adjustments may be necessary to provide the required conditions; for instance, there may need to either (i) have a gas source that would puff in a cloud of 670 Pa gas just before the pulse or (ii) have a solid ablated by an arc to provide the mass for the plasma.

4.2. Concept study for spaceflight

Considering the first version of this technique, we propose an alternative approach that uses both electron beams (Section 4.1.1) and plasma jets (Section 4.1.2). This approach combines plasma jets and electron beams without the need for a hot filament providing electrons and a gas supply for the plasma mass. Electron beams are sourced by naturally provided photoelectrons (solar UV), and plasma jets come from another source. The proposed setup is sketched in Figure 3. The specification of this apparatus is provided in Table 4. The influence of the lunar plasma environment on this device concept may need to be quantified; however, it is likely negligible because the plasma density for this device may be as high as 10^{21} m^{-3}, while that in the lunar environment only may only reach 10^{6} m^{-3} with large uncertainties, as discussed above.

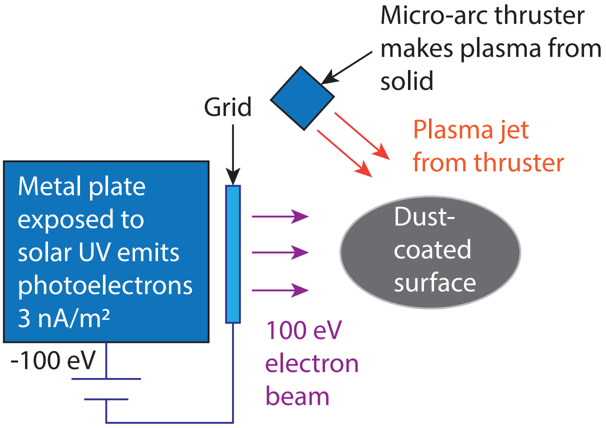

Figure 3: Sketch of proposed dust remediation scheme. This scheme is inspired by [55], who applied plasma and electron beams to enhance particle release. An electron beam created from accelerated photoelectrons is aimed at the region to be cleaned. This region is also sprayed with low density plasma coming from a continuously operating vacuum arc thruster.

Electron beams are generated by using a metal plate with nominal dimensions of 30 cm × 30 cm exposed to sunlight so that the plate emits photoelectrons. The plate is biased to -100 V so that the photoelectrons are ejected with 100 eV energy. A nearly transparent grid biased to 0 V is located just above the metal plate. Electrons are accelerated towards the grid but, because of the grid transparency, continue through the grid to form a beam. This process generates a directed 100 eV electron beam without the use of hot filaments. The electron beam is directed at the dusty surface to be cleaned. Assuming 3 nA/cm^2 photoemission as typical for space materials [58], a current of 3 μA is supplied from the metal plate.

A plasma micro-thruster is used to generate a continuous plasma jet. Microthrusters have widely been tested with emphasis placed on thrust, efficiency, and longevity, while there has also been first-principle modeling [e.g., 59]. This type of thruster is intended for small satellites such as CubeSats and so does not consume much power [60]. In this thruster, plasma is made from a solid material, and so no gas supply is needed. Two possible options are the vacuum arc thruster [61] and the Polytetrafluoroethylene (PTFE, known as Teflon) thruster [62, 63]. These small, light-weight, low-power thrusters are intended for quasi-continuous operation and provide a directed plasma jet. The vacuum arc thruster typically has a coaxial cathode (inner conductor) and anode (outer conductor) with vacuum in between. High voltage breaks down the anode-cathode gap and melts small quantities of cathode, which become plasma. The background is essentially vacuum so the plasma is fully ionized. Electromagnetic forces accelerate the plasma to produce a jet with velocity of tens of km/s.

On the other hand, the Teflon thruster ablates Teflon located between the cathode and anode to make a weakly ionized plasma from the ablated Teflon. A combination of thermal pressure gradient and electromagnetic forces accelerates the Teflon plasma out to form a jet. Depending on the design, the exhaust velocity of the Teflon thruster can range from ∼2 km/s to 50 km/s [62]. It has capacitor discharges lasting several μs, stored energy of tens of

Joules, and pulse repetition rate of 1 Hz [62]. The Teflon thruster differs from the plasma broom as the plasma broom involves a very high power transient pulse (order 1 μs) and would be fired using a large capacitor that is slowly charged and then quickly discharged.

Table 4: Categorization of microthrusters. We referred to Burton [62] for the pulsed plasma thruster and Kolbeck and Anders [61] for the vacuum arc thruster. *Values for the LES-8/9 PPT thruster, given in Table 2 in Burton [62]. **Values based on the thruster planned for the Illinois Observing Nanosatellite (ION), a 2U CubeSat from the University of Illinois at Urbana-Champaign [61].

		Pulsed plasma thruster	Vacuum arc thruster	
		Value	Value	Units
Operation	Mass	6.60*	0.15**	[kg]
	Pulse length	~ 20	> 250	[μs]
	Power	~ 100	$0.1 - 20$	W
	Repetition rate	1	1	[Hz]
Propellant		Teflon	Aluminum**	[-]
Plasma	Ionization	$10 - 40$	100	[%]
	Electron density	10^{16}	10^{14}	[cm^{-3}]
	Exhaust velocity	$10 - 50$	$20 - 40$	[km/s]

4.3. Suggested areas of technology advancement

We list necessary technology advancements below:

- The electron beam source using sunlight generates an electric current likely 3-4 orders of magnitude smaller than that used by Flanagan and Goree [55] and Schwan et al. [51]. This discrepancy can be reasonable because it only lengthens the exposure time for dust removal from seconds to hours and thus does not affect operations on the Moon. However, proper assessments are necessary.

- The dust removal efficiency of this technique has not been demonstrated well yet. It is necessary to conduct lab experiments using various types of microthrusters to determine whether high plasma momentum is critical or whether simple presence of low momentum plasma is sufficient when used with an electron beam.

- The plasma jets may contaminate sensitive surfaces. If this is the case, it is necessary to quantify how the plasma jets influence the surface conditions to reduce this risk.

5. Discussion

5.1. Dust mitigation performance

Based on the operational factors defined in the previous section, we assess the technology of each technique. Table 5 summarizes the rates for each technology. In this table, three categories ◯, △, and × mean that a considered factor is well characterized, less characterized, and not explored, respectively. If Sections 2 through 4 identify multiple studies to address a considered factor, we consider it to be well characterized. If there is limited work, and we

Table 5: Operational factor rates of each technology. The top row specifies techniques: A, Electrostatic dust shield; B, Attractive surface; C, Electron-beam, and plasma induced lofting. The first column shows the operational factors. ○, △, and × indicate the applicability levels, meaning *well characterized*, *less characterized*, and *not explored*, respectively.

	A	B	C
1. Location & timing	△	△	△
2. Amount of dust removal	○	×	△
3. Contamination	○	○	×
4. Operation duration	×	×	△
5. Installation	×	○	○
6. Safety	△	×	×

identify the need for additional investigations, we label it as less characterized. Finally, if we find necessary technologies (or processes), but there is no report discussing the factor, we define it as not explored. Overall, while each technology shows strong advantages, it needs additional investigations to mature.

5.1.1. Technique A: Electrostatic dust shield

This technique has been demonstrated in multiple studies, showing the highest maturity among the considered techniques. This technique continuously removes accumulated dust on a test surface as long as the device is active. This technique needs further investigations of the performance in the lunar environment, where dust's electrostatic properties likely change over time and location. The amount of dust removal was well characterized by earlier work. We identify no issues on the contamination of the target surface but consider some issues on the operational duration factor due to the necessity of its robust design. For example, if the device is embedded in other systems like spacecraft surfaces, a single cut of its electric circuit may lead to the termination of operation because there may be no way of replacing it. A possible mitigation of this issue may be to design backup systems. Also, for the installation factor, the flexibility of incorporating the dust shield into complex geometric components may be limited. Additive manufacturing may be a potential solution to this issue, although complex electrostatic force fields, possibly reducing the dust removal efficiency, may need to be quantified. Regarding the safety factor, Buhler et al. [24] demonstrated that the 3D version of the Electrodynamic Dust Shields developed a safe zone that prohibits the penetration of large electromagnetic fields. Therefore, we find that resolving this issue is in progress, and this factor is currently under investigation.

5.1.2. Technique B: Attractive surface

The performance of this technique is likely affected by the location and timing, i.e., the dust particle conditions in the lunar surface environment. How such variations control the dust remediation efficiency needs to be quantified. Also, how much dust it can remove is currently unknown. No contamination is expected for this technique. The operation duration needs to be quantified especially because the dust removal efficiency may change with time due to the attachment of dust particles to the attractive surface. This technique does not need to be incorporated into a target surface, i.e., no constraints on the installation factor. This trend allows users to apply this technique directly without any design changes in other systems. However, it may be necessary to bring the attractive surface close to a target surface that is hardly approachable. A key safety issue includes a high electric potential between the attractive plate and the target surface, which may increase the possibility of harming the system hardware and astronauts.

5.1.3. Technique C: Electron-beam and plasma jet induced lofting

Technique C uniquely uses electron beams and plasma jets to remove dust particles from a target surface. Again, electron beams are used to electrostatically charge dust particles, while plasma jets are applied to kinetically move dust particles. This technique enhances the mobility of dust particles. It can choose whether electron beams are necessary; even when electron beams are not available, plasma jets can still be used. Therefore, we consider this technique to perform at any location and timing, though it is necessary to quantify how this factor changes the performance. While Ticos et al. [57] reported a high efficiency of the plasma broom, it is still necessary to quantify its performance in various space environments. The contamination of a target surface may need to be quantified. Given the process considered, plasma jets generated by melting the cathode may affect the target surface. If the target surface is sensitive, like remote sensing instruments and other onboard systems, it is necessary to have proper mitigation processes. Also, because this technique consumes the cathode, the operation duration may be limited. Because this mitigation system is independent of other onboard systems, no interactions between them need to be considered. Regarding the safety issue, it is necessary to assess how electron beams and plasma jets affect the onboard systems and astronauts.

5.2. Dust loading device

This section discusses a dust loading device that can be used to load dust onto a coupon to test the efficacy of various remediation technologies (Figure 2d). The device is used for remediation technology demonstration. Once the remediation technology is established, the loading device is no longer necessary. The major purpose of this dust loading device is to quantify how efficiently each dust mitigation technique removes dust from a testbed. How much dust is naturally accumulated on the lunar surface is poorly understood and also strongly depends on the location. This issue likely challenges quantitative assessment. Cohesion/adhesion likely affects the efficiency of the sorting process using sieving. However, agitation is anticipated to break particle-particle/particle-surface interactions, leading to granular particle fluidization. Another concern may be how lower gravity affects this process; however, recent studies have shown higher fluidization in microgravity [64], giving the possibility that the lunar environment may be preferred for the dust sorting process compared to the Earth environment, regardless of the necessity of further investigation.

In this study, we assume that the dust samples are loaded onto the loading device by either a robotic device or an astronaut. Based on the Apollo lunar samples [1], we consider that target particles are tens of microns in size, and the necessary amount for one loading is small. Following the styles of Sections 2 through 4, we describe the device's principle, concept study for spaceflight, and suggested areas of technology advancement.

5.2.1. Principle

The main purpose of this device is to support loading dust particles on testbeds for experiments. While the probe's size may depend on the testbeds, we assume that the testbeds are a few cm in diameter. If the probe's size needs to be modified, proper resizing is still possible. Our straw-man design consists of three components: an electric agitator, sieves, and a glass funnel (Figure 4). An electric agitator will be used to help sort out dust particles by vibration in a vacuum.

Sieves are used to sort dust particles by size. There are commercially available sieves that sort out dust particles in this size range (down to 20 μm). A glass funnel is used to load the sorted dust particles on the testbeds. The funnel's internal diameter needs to be determined to avoid clogging based on the size of the testbeds and the necessary amount of dust particles. The solution to this issue may be to control the dust flow rate and design an appropriately sized funnel. Challenges may appear when we target smaller dust particles. The cohesive/adhesive forces influence small particles – thus, it is more difficult to predict the flow rate for small dust particles. Particularly, if electrostatic charges are added to the probe during operations, electrostatic forces enhance such forces. While using electrically insulated materials may be a possible solution, this issue needs to be resolved. However, cohesion-based clumps were observed to be a few mm in size from lunar dust observations on the Apollo mission [65]. For our target (lunar surface layers having particles with sizes of $\sim \mu$m), we consider that a funnel size larger than 1 cm would avoid this issue.

Figure 4 shows a schematic of the device seen from the side view and the top view. An electric agitator and sieves are fixed on a movable base. Multiple sieves with different mesh sizes are placed to make the sorting efficient (to prevent clogging). Once the agitator is on, the vibration allows dust particles to be granularly fluidized. Smaller particles can go through the mesh of Sieve 1. As they reach other sieves, the mesh sizes become finer. When dust particles pass through Sieve 4, they enter the glass funnel. The movable base is connected with the fixed base by vibration isolation pads that absorb the movable base's vibration. The fixed base can be connected with other hardware devices. Beneath the fixed base, a connector is placed to connect the fixed base and the glass funnel. The movable base, the fixed base, and the connector have wide holes so that dust particles sorted by the sieves can go through the system.

5.2.2. Concept study for spaceflight

To demonstrate the feasibility of the dust loading device, we need to show the availability of an electronic agitator. However, we could not find a space qualified product. Here, we use the Micro Series Electric Vibrators available by Martin Vibration Systems & Solutions [66] as a sample device. However, the specification of an agitator necessary for our mission should be similar to the cited product. Considering the NEA 504 series [66], we confirm that the agitator's size is as small as 0.1 m by 0.1 m by 0.1 m. The power input is around $\sim$ 30 W. The maximum force is 260 N. The vibrator's operating temperature range is 273 K - 310 K; therefore, thermal control is likely necessary. The process of shaking particles in sieves has been used in many terrestrial industries. However, the necessary devices and subsystems may not have been used or tested in the space environment. Considering two aluminum plates (0.3 m by 0.3 m by 0.005 m for each) for the bases, we estimate the device mass as $\sim$ 5 kg.

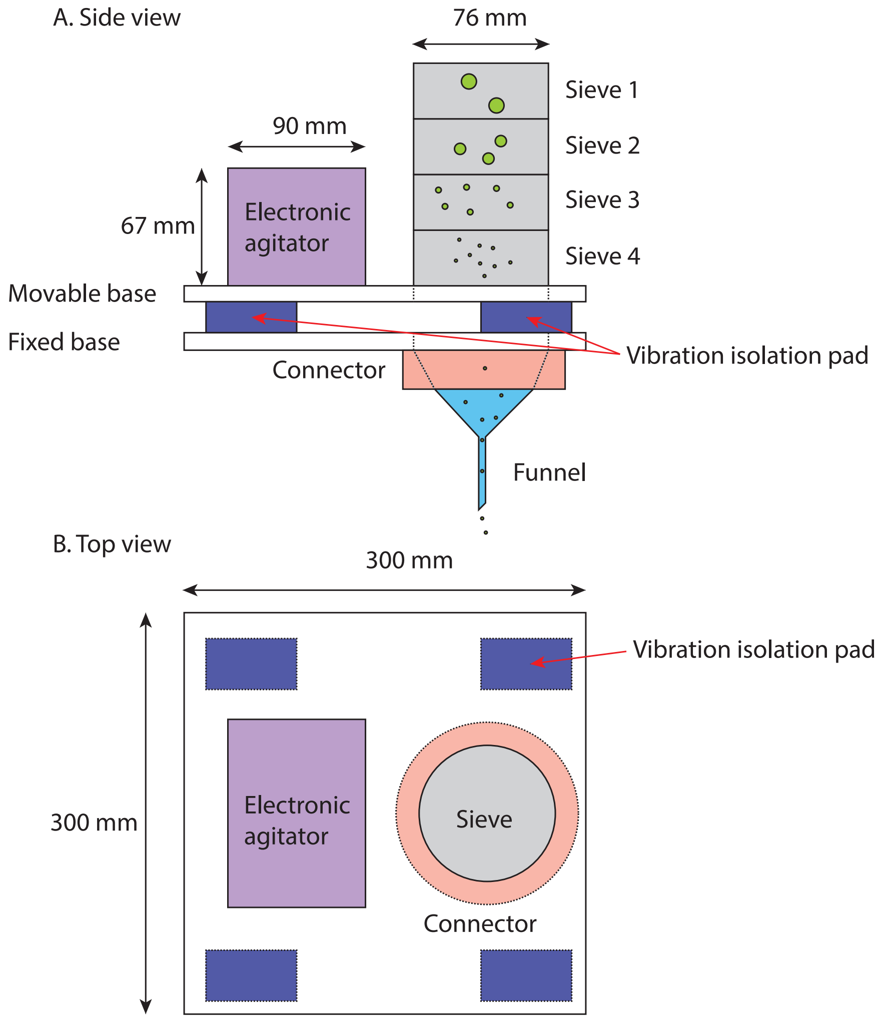

Figure 4: Schematic of dust loading device

Table 6: Estimated requirements for dust loading device.

Properties	Value	Units
Dimensions	$30 \times 30 \times 10.5$	[cm×cm×cm]
Mass	5	[kg]
Power	30	[W]
Temperature	$273 - 310$	[K]

5.2.3. Suggested areas of technology advancement

Below are potential issues to be mitigated.

- The sieving process in the lunar environment needs to be investigated to ensure the efficiency of the dust loading device. Particularly, the current sieving portion is a tentative solution, as there may be a risk that low gravity on the Moon may cause an enhanced influence of adhesive and cohesive forces on particles and the sieving grids. An alternative solution is necessary if low gravity tests are not conclusive for efficient particle flow through the sieve setup.

- The way of loading dust particles to the device (i.e., how to put dust particles into Sieve 1) needs to be specified. A possible design for this operation is using a scoop or a drilling system. However, for the use of a robotic system, it is likely that such an operation can draw heavily from the work of the Mars rovers.

- While we illustrated four sieves, it is unknown how many sieves are necessary. This depends on the desired particle sizes. However, adding additional sieves does not dramatically change the design (other than increasing the mass and changing the vibration frequency of the system).

- There is no active device that controls the amount of dust falling into the glass funnel. The main contributor to preventing granular flows of dust particles is cohesion and friction. If the funnel is sized close to the jamming limit (at which point the grains would clog the funnel and the flow would stop), changing the level of agitation may be able to control the amount of grains deposited on the desired coupon.

- As the device continues to sort out dust particles, particles that cannot go through the sieves are stuck and thus accumulated there. The easiest way may be that the loading device is just one-time use. The planned loading device can likely supply dust more than necessary for experiments and does not need to clean the sieves. If repeated cleaning processes are required, sophisticated mechanical systems are inevitable, which is out of our scope.

- Further concept design to reduce this device's size and mass is essential to make it fit future exploration missions.

6. Conclusion

This paper discussed three electrostatic dust remediation techniques for lunar exploration missions. We assessed electrostatic dust shielding, an attractive surface, and electron beams and plasma jets inducing dust lofting. We defined six operational factors to assess these techniques and necessary development to be completed. The operational factors included the timing and location, amount of dust removal, contamination of target surfaces, operational duration, installation, and safety. While our analyses were qualitative, we reached the following findings. First, the electrostatic dust shielding technology has demonstrated its high dust removal capability. This technique has been demonstrated to remove dust effectively and reduce its safety issues. Additional efforts may further overcome challenges in operational duration and installation. Second, in contrast to the electrostatic dust shielding technique, the attractive surface technique does not need installation and can flexibly be used to remove dust. This technique can be further improved by quantifying the amount of dust removal and operational duration. Finally, a combination of electron beams and plasma jets can enhance dust removal. This approach will improve its capability by adding further investigations for the contamination of target surfaces and safety. We also discussed a supporting system that loads dust particles so that the remediation techniques demonstrate dust removal efficiency. We conclude that further investigations on lab and spaceflight scales will advance dust remediation technologies for future lunar missions.

7. Acknowledgment

This work was supported by the Biological and Physical Science Division of NASA's Science Mission Directorate and by the Game Changing Development Program of NASA's Space Technology Mission Directorate through a contract with the Jet Propulsion Laboratory, California Institute of Technology.

References

[1] G. H. Heiken, et al., Lunar sourcebook (1991).

[2] M. Hirabayashi, et al., The Role of Breccia Lenses in Regolith GenerationFrom the Formation of Small, Simple Craters:Application to the Apollo 15 Landing Site, Journal of Geophysical Research: Planets 123 (2018) 527–543. doi:10.1002/2017JE005377.

[3] Y.-H. Huang, et al., Heterogeneous impact transport on the Moon, Journal of Geophysical Research: Planets (2017) 1,158–1,180doi:10.1002/2016JE005160.

[4] C. M. Hartzell, et al., Payload Concepts for Investigations of Electrostatic Dust Motion on the Lunar Surface, Acta Astronautica Under review (2021).

[5] S. A. Wagner, The Apollo Experience Lessons Learned for Constellation Lunar Dust Management, Tech. Rep. NASA/TP-2006-213726 (2006).

[6] H. H. Schmitt, Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space, Springer, 2006.

[7] A. Witze, Opportunity lost: NASA says goodbye to pioneering Mars rover, Nature (2019). doi:10.1038/d41586-019-00575-2.

[8] R. A. Yingst, et al., Dust cover on Curiosity's Mars Hand Lens Imager (MAHLI) calibration target: Implications for deposition and removal mechanisms, Icarus 351 (2020) 113872. doi:10.1016/j.icarus.2020.113872.

[9] D. S. Lauretta, et al., The unexpected surface of asteroid (101955) Bennu, Nature 568 (7750) (2019) 55–60. doi:10.1038/s41586-019-1033-6.

[10] S. Watanabe, et al., Hayabusa2 arrives at the carbonaceous asteroid 162173 Ryugu-A spinning top-shaped rubble pile, Science 364 (6437) (2019) 268–272. doi:10.1126/science.aav8032.

[11] T. Morota, et al., Sample collection from asteroid (162173) Ryugu by Hayabusa2: Implications for surface evolution, Science 368 (2020) 654–659. doi:10.1126/science.aaz6306.

[12] N. Afshar-Mohajer, et al., Review of dust transport and mitigation technologies in lunar and Martian atmospheres, Advances in Space Research 56 (6) (2015) 1222–1241. doi:10.1016/j.asr.2015.06.007.
URL `http://dx.doi.org/10.1016/j.asr.2015.06.007`

[13] J. Aliberti, Design of a Device to Remove Lunar Dust from Space Suits for the Proposed Lunar Base, Tech. rep. (1990).

[14] K. Wood, Design of equipment for lunar dust removal, Tech. rep. (1991). doi:10.12681/eadd/1834.

[15] R. V. Peterson, C. W. Bowers, Contamination removal by CO2 jet spray, in: Opt/ca/System Contamination: Effects, Measurement, Control 11, no. 1329, 1990, pp. 72–85. doi:10.1117/12.22599.

[16] J. R. Gaier, et al., Evaluation of Surface Modification as a Lunar Dust Mitigation Strategy for Thermal Control Surfaces, in: 41st International Conference on Environmental Systems, 17-21 July 2011, Portland, Oregon, Vol. AIAA 2011-5183, 2011. doi:10.2514/6.2011-5183.

[17] S. Jacobs, et al., Lunar dust depostiion effects on the solar absorptance of thermal control materials, in: AIAA 6th Thermophysics Conferences, no. 71-459, 1971, pp. 0–7.

[18] J. R. Gaier, The Effects of Lunar Dust on EVA Systems During the Apollo Missions, Nasa/Tm-2005-213610/Rev1 (March) (2007) 1–16.

[19] J. R. Gaier, et al., Evaluation of surface modification as a lunar dust mitigation strategy for thermal control surfaces, 41st International Conference on Environmental Systems 2011, ICES 2011 (December) (2011). doi:10.2514/6.2011-5183.

[20] J. R. Gaier, Interpretation of the Apollo 14 Thermal Degradation Sample experiment, Icarus 221 (1) (2012) 167–173. doi:10.1016/j.icarus.2012.07.002.
URL `http://dx.doi.org/10.1016/j.icarus.2012.07.002`

[21] J. S. Halekas, et al., Lunar Prospector observations of the electrostatic potential of the lunar surface and its response to incident currents, Journal of Geophysical Research: Space Physics 113 (2008) A09102. doi:10.1029/2008JA013194.

[22] J. E. Borovsky, G. Delzanno, Do Impulsive Solar-Energetic-Electron (SEE) Events Drive High-Voltage Charging Events on the Nightside of the Moon?, frontiers in Astronomy and Space Sciences 8 655333. doi:10.3389/fspas.2021.655333.

[23] T. D. Glotch, et al., Formation of lunar swirls by magnetic field standoff of the solar wind, Nature Communications 6 (2015) 6,189. doi:10.1038/ncomms7189.

[24] C. Buhler, et al., Current state of the electrodynamic dust shield for mitigation, in: Lunar and Planetary Science Conference, no. 5027, 2020.

[25] S. Masuda, et al., Confinement and Transportation of Charged Aerosol Clouds via Electric Curtain, Electrical Engineering in Japan 92 (1) (1972) 9–18. doi:10.1002/eej.4390920106.

[26] S. Masuda, Y. Matsumoto, Theoretical characteristics of standing-wave electric curtains, Electrical Engineering in Japan 93 (1) (1973) 41–53. doi:10.1002/eej.4390930110.

[27] S. Masuda, T. Kamimura, Approximate methods for calculating a non-uniform traveling field, Journal of Electrostatics 1 (1975) 351–370. doi:10.1016/0304-3886(75)90030-3.

[28] F. B. Tatom, et al., Lunar dust degradation effects and remove/prevention concepts, in: NASA Technical Report, 1967, pp. TR–792–7–207A.

[29] C. Calle, et al., Dust particle removal by electrostatic and dielectrophoretic forces with applications to nasa exploration missions, in: Proceedings of the ESA Annual Meeting on Electrostatics 2008, 2008.

[30] C. I. Calle, et al., Electrodynamic dust shield for surface exploration activities on the moon and Mars, AIAA 57th International Astronautical Congress, IAC 2006 3 (2006) 1851–1861. doi:10.2514/6.iac-06-a5.2.07.

[31] C. I. Calle, et al., Particle removal by electrostatic and dielectrophoretic forces for dust control during lunar exploration missions, Journal of Electrostatics 67 (2-3) (2009) 89–92. doi:10.1016/j.elstat.2009.02.012.

[32] C. I. Calle, et al., Active dust control and mitigation technology for lunar and Martian exploration, Acta Astronautica 69 (11-12) (2011) 1082–1088. doi:10.1016/j.actaastro.2011.06.010.

[33] K. K. Manyapu, et al., Proof of concept demonstration of novel technologies for lunar spacesuit dust mitigation, Acta Astronautica 137 (2017) 472–481. doi:10.1016/j.actaastro.2017.05.005.

[34] R. A. Sims, et al., Development of a transparent self-cleaning dust shield for solar panels, Proceedings ESA-IEEE joint meeting on electrostatics (1) (2003) 814–821.

[35] C. E. Johnson, et al., Effect of particle size distribution on the performance of electrodynamic screens, Conference Record - IAS Annual Meeting (IEEE Industry Applications Society) 1 (2005) 341–345. doi:10.1109/IAS.2005.1518330.

[36] H. Kawamoto, T. Miwa, Mitigation of lunar dust adhered to mechanical parts of equipment used for lunar exploration, Journal of Electrostatics 69 (4) (2011) 365–369. doi:10.1016/j.elstat.2011.04.015.

[37] Q. X. Sun, et al., Mechanism of dust removal by a standing wave electric curtain, Science China: Physics, Mechanics and Astronomy 55 (6) (2012) 1018–1025. doi:10.1007/s11433-012-4722-9.

[38] H. Kawamoto, N. Hara, Electrostatic Cleaning System for Removing Lunar Dust Adhering to Space Suits, Journal of Aerospace Engineering 24 (4) (2011) 442–444. doi:10.1061/(asce)as.1943-5525.0000084.

[39] B. Guo, et al., Electrodynamic dust shield performance under simulated operating conditions for solar energy applications, Solar Energy Materials and Solar Cells 185 (2018) 80–85. doi:10.1016/j.solmat.2018.05.021.

[40] B. Guo, et al., Solar pv soiling mitigation by electrodynamic dust shield in field conditions, Solar Energy 188 (2019) 271–277. doi:10.1063/5.0053866.

[41] H. Kawamoto, B. Guo, Improvement of an electrostatic cleaning system for removal of dust from solar panels, Journal of Electrostatics 91 (2018) 28–33. doi:10.1016/j.elstat.2017.12.002.

[42] J. K. W. Chesnutt, et al., Numerical analysis of the effects of particle-particle interactions and particle size on the performance of an electrodynamic dust shield, Journal of Electrostatics 98 (2019) 58–68. doi:10.1016/j.elstat.2019.02.005.

[43] A. Sayyah, et al., An experimental study on the characterization of electric charge in electrostatic dust removal, Journal of Electrostatics 87 (2017) 173–179. doi:10.1016/j.elstat.2017.04.001.

[44] W. Javed, B. Guo, Effect of relative humidity on dust removal performance of electrodynamic dust field, Journal of Electrostatics 105 (2020) 103434. doi:10.1016/j.elstat.2020.103434.

[45] G. Y. Kramer, et al., M^3 spectral analysis of lunar swirls and the link between optical maturation and surface hydroxyl formation at magnetic anomalies, Journal of Geophysical Research: Planets (116) (2011) E00G18. doi:10.1029/2010JE003729.

[46] L. C. Cheek, et al., The distribution and purity of anorthosite across the Orientale basin: New perspectives from MoonMineralogy Mapper data, Journal of Geophysical Research: Planets (118) (2013) 1,805–1,820. doi:10.1002/jgre.20126.2013.

[47] D. P. Moriarty, C. M. Pieters, The Character of South Pole-Aitken Basin: Patterns of Surface and Subsurface Composition, Journal of Geophysical Research: Planets (123) (2018) 729–747. doi:10.1002/2017/JE005364.

[48] C. Calle, et al., Integration of the electrodynamic dust shield on a lunar habitat demonstration unit, in: Proceedings of the ESA Annual Meeting on Electrostatics 2010, 2010.

[49] H. Kawamoto, S. Hashime, Practical performance of an electrostatic cleaning system for removal of lunar dust from optical elements utilizing electrostatic traveling wave, Journal of Electrostatics 94 (2018) 38–43. doi:10.1016/j.elstat.2018.05.004.

[50] P. Mackey, et al., Electrodynamic dust shield for space applications, in: Proceedings of the ASCE Conference on Engineering, Science, Construction and Operations in Challenging Environments, 2016, pp. 539–545.

[51] J. Schwan, et al., The charge state of electrostatically transported dust on regolith surfaces, Geophysical Research Letters 44 (2017) 2017GL072909. doi:10.1002/2017GL072909.

[52] D. Carter, C. Hartzell, Experimental methodology for measuring in-vacuum granular tribocharging, Review of Scientific Instruments 90 (2019) 125105. doi:10.1063/1.5111983.

[53] S. I. Popel, et al., Dusty Plasma at the Surface of the Moon, Solar System Research 47 (2013) 419–429. doi:10.1134/S0038094613060063.

[54] T. Jackson, et al., Discharging of roving objects in the lunar polar regions, Journal of Spacecraft and Rockets 48 (4) (2011) 700–703.

[55] T. M. Flanagan, J. Goree, Dust release from surfaces exposed to plasma, Physics of Plasmas 13 (12) (2006) 123504. doi:10.1063/1.2401155.
URL `http://aip.scitation.org/doi/10.1063/1.2401155`

[56] B. Farr, et al., Dust mitigation technology for lunar exploration utilizing an electron beam, Acta Astronautica 177 (2020) 405–409. doi:10.1016/j.actaastro.2020.08.003.
URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576520304902`

[57] C. M. Ticos, et al., A pulsed ‘plasma broom’ for dusting off surfaces on Mars, New Journal of Physics 19 (6) (2017) 063006. doi:10.1088/1367-2630/aa60e5.
URL `https://iopscience.iop.org/article/10.1088/1367-2630/aa60e5`

[58] E. C. Whipple, Potentials of surfaces in space, Reports on Progress in Physics 44 (11) (1981) 1197–1250. doi:10.1088/0034-4885/44/11/002.

[59] M. Keidar, et al., Electrical discharge in the Teflon cavity of a coaxial pulsed plasma thruster, IEEE Transactions on Plasma Science 28 (2) (2000) 376–385. doi:10.1109/27.848096.
URL `http://ieeexplore.ieee.org/document/848096/`

[60] S. Mazouffre, Electric propulsion for satellites and spacecraft: established technologies and novel approaches, Plasma Sources Science and Technology 25 (3) (2016) 033002. doi:10.1088/0963-0252/25/3/033002.
URL `https://iopscience.iop.org/article/10.1088/0963-0252/25/3/033002`

[61] J. Kolbeck, A. Anders, I. I. Beilis, M. Keidar, Micro-propulsion based on vacuum arcs, Journal of Applied Physics 125 (22) (2019) 220902. doi:10.1063/1.5081096.
URL `http://aip.scitation.org/doi/10.1063/1.5081096`

[62] R. L. Burton, P. J. Turchi, Pulsed Plasma Thruster, Journal of Propulsion and Power 14 (5) (1998) 716–735. doi:10.2514/2.5334.
URL `https://arc.aiaa.org/doi/10.2514/2.5334`

[63] C. D. Rayburn, et al., Pulsed Plasma Thruster System for Microsatellites, Journal of Spacecraft and Rockets 42 (1) (2005) 161–170. doi:10.2514/1.15422.
URL `https://arc.aiaa.org/doi/10.2514/1.15422`

[64] N. Murdoch, I. Avila Martinez, C. Sunday, E. Zenou, O. Cherrier, A. Cadu, Y. Gourinat, An experimental study of low-velocity impacts into granular material in reduced gravity, Monthly Notices of the Royal Astronomical Society 468 (2) 1259–1272. doi:10.1093/mnras/stw3391.

[65] B. J. O'Brien, M. Hollick, Sunrise-driven movements of dust on the moon: Apollo 12 ground-truth measurements, Planetary and Space Science 119 (2015) 194–199. doi:https://doi.org/10.1016/j.pss.2015.09.018.

[66] Martin Vibration Systems and Solutions, Catalog for Micro Series Electric Vibrators, `https://www.shake-it.com/app/uploads/2013/02/MicroSeries-2-1-unlocked.pdf`.

Highlights

Electrostatic dust remediation for future exploration of the Moon

M. Hirabayashi, C. M. Hartzell, P. M. Bellan, D. Bodewits, G. L. Delzanno, T. W. Hyde, U. Konopka, E. Thomas, Jr., H. M. Thomas, I. Hahn, U. E. Israelsson

- We assess three dust mitigation technologies for in-situ lunar explorations.
- Six operational factors are considered to qualitatively assess their maturity.
- Further assessment sheds light on how mitigation technologies work on the Moon.
- Operation duration and safety are key to improving dust mitigation technologies.
- We also introduce a dust loading device that supplies dust to a testbed in situ.