NASA BIG Idea Challenge:
Final Technical Paper and Verification Testing

TEST-RAD: Tufted Electrostatic Solution To Regolith Adhesion Dilemma

Brown Space Engineering (BSE) | RISD Space Design

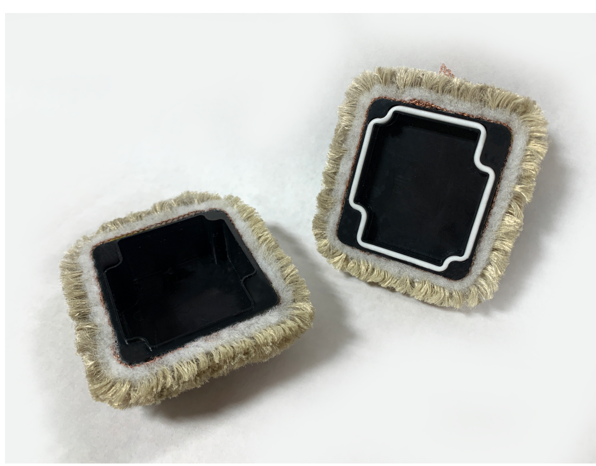
Team Members (16):

Brown University
Ian Bartlett: 2nd Year, Chemistry
Noah Bingham: 2nd Year, Biochemistry and Molecular Biology
Anthony Capobianco: Alumnus, Engineering Physics
Cameron Curney: 2nd Year, Mechanical Engineering
David Fang: 3rd Year, Astrophysics
Daniel Marella: 2nd Year, Mechanical Engineering and Applied Mathematics
Peyton Newman: 3rd Year, Mechanical Engineering
Luke Randall: 2nd Year, Geology-Chemistry
Justin Rhee: 3rd Year, Electrical Engineering

Rhode Island School of Design
Felix Arwen: 3rd Year, Industrial Design
Sebastian Boal: 4th Year, Industrial Design
Yizhou Tan: 3rd Year, Architecture
Avantika Velho: 4th Year, Industrial Design
Selena Yang: 3rd Year, Industrial Design
Bowen Zhou: 5th Year, Industrial Design and Sculpture

Brown | RISD Dual Degree
Hannah Skye Dunnigan: 4th Year, Industrial Design and Economics

Supporting Faculty & RISG Contacts:
Rick Fleeter (BSE Faculty Advisor): rick_fleeter@brown.edu
Christopher Bull (Principal Investigator): christopher_bull@brown.edu
Nancy Ciminelli (NASA RISG Program Manager): nancy_ciminelli@brown.edu
Peter Schultz (NASA RISG Director): peter_schultz@brown.edu



Team Photo

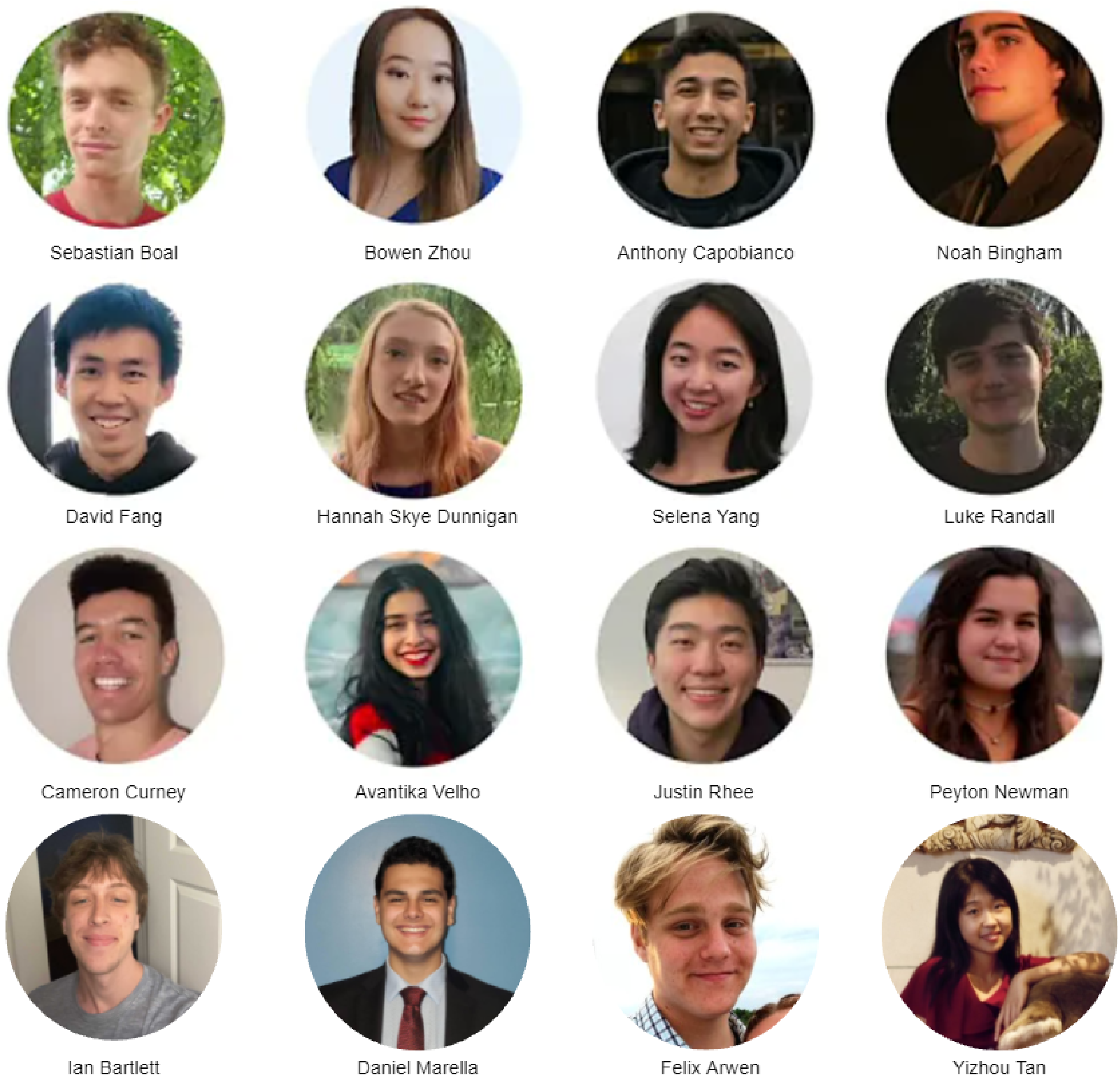
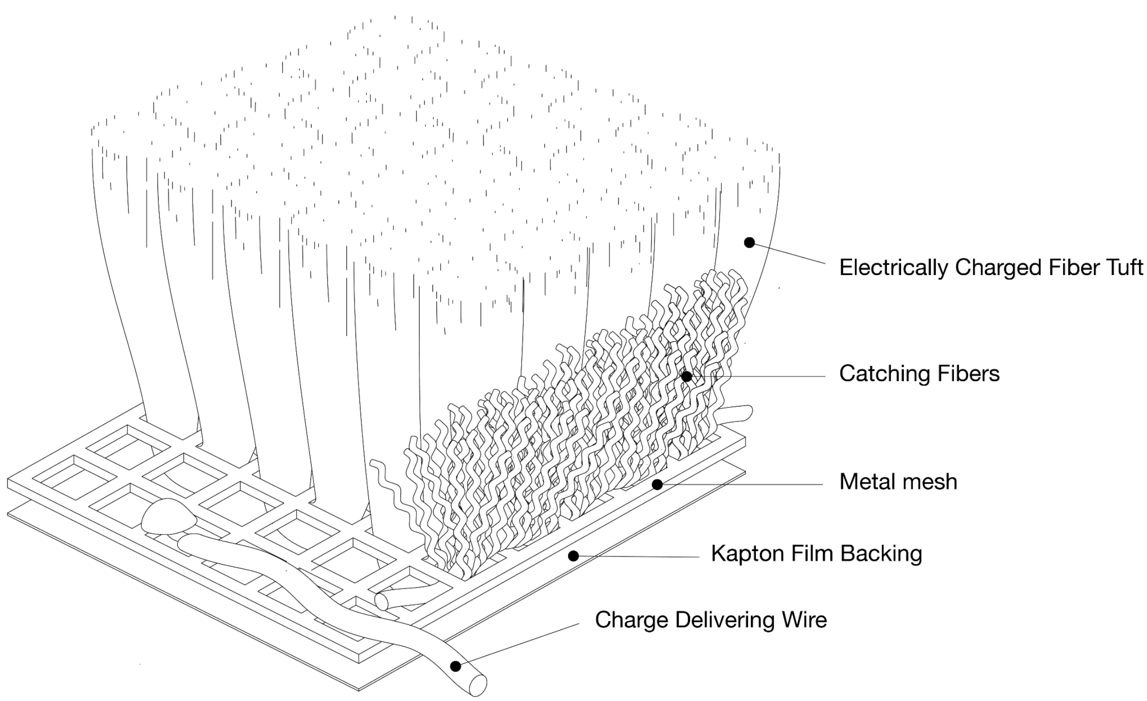

Sebastian Boal
Bowen Zhou
Anthony Capobianco
Noah Bingham
David Fang
Hannah Skye Dunnigan
Selena Yang
Luke Randall
Cameron Curney
Avantika Velho
Justin Rhee
Peyton Newman
Ian Bartlett
Daniel Marella
Felix Arwen
Yizhou Tan

Table of Contents

Team Photo	**2**
Table of Contents	**3**
Quad Chart	**4**
Executive Summary	**5**
Problem Statement and Background	**5**
Lunar Architecture	**7**
Alternative Applications	**7**
Project Description	**9**
Technology	**9**
Importance	**12**
Verification Testing on Earth	**13**
Simulant Generation	**13**
Laboratory Testing Environment	**14**
Stress Test	**15**
Testing Methodology	**16**
Results	**17**
Safety Plan and Protocols Followed	**20**
CONOPS & Project Management	**21**
Path To Flight	**24**
Results and Conclusions	**25**
Detailed Timeline	**27**
Detailed Budget	**29**
Acknowledgments	**29**
References	**30**



Quad Chart

Tufted Electrostatic Solution To Regolith Adhesion Dilemma
Brown & RISD

Concept Synopsis

TEST-RAD is a novel regolith mitigation technology intended for use on various systems deployed on the lunar surface, particularly junctures in apparatuses and moving components of spacesuits. Inspired by the dense fur of a chinchilla, our design utilizes biomimicry for passive protection and active same-charge repulsion of regolith. This hybrid passive-active system will reduce the penetration of regolith into closures or seals of a given apparatus by repulsion via conductive fibers and last-resort catching fibers.

Concept Depiction (Mark 4.1)

Innovations

- ➔ An outer layer of tufted charged fibers repels like-charged regolith using static electric technology
- ➔ Short catching fibers, placed along the internal edge and only exposed in the event of opening of the seal or closure act as a secondary layer of defense, catching regolith particles that get inside the seal or joint.
- ➔ Both types of fibers are tufted through a copper mesh with charging wires from the ionization device to provide the system with static charge. An adhesive backing connects TEST-RAD to the apparatus and insulates it from the protected equipment.

Verification Testing Results & Conclusions

- ➔ TEST-RAD achieved successful individual verification of both the fiber system and electrostatic generation assembly and partial verification of the hybrid mitigation approach.
- ➔ TEST-RAD's novel hybrid mitigation strategy warrants further research, specifically to delve deeper into its active repulsion capabilities.
- ➔ Testing conducted using charged highland simulant produced the best active repulsion results, which is especially useful for Artemis missions.

Executive Summary

TEST-RAD is a novel regolith mitigation technology intended for use on various systems deployed on the lunar surface, particularly junctures in apparatuses and moving components of spacesuits. Inspired by the dense fur of a chinchilla and incorporating preexisting electrostatic technologies, our design utilizes biomimicry for passive protection and active same-charge repulsion of regolith. This hybrid passive-active system will reduce the penetration of regolith into closures or seals of a given apparatus by repulsion via conductive fibers and last-resort catching fibers.

The system is composed of six parts: charged fibers, catching fibers, metal mesh, insulative backing, charging wires, and an ionization device. An outer layer of tufted charged fibers repels same-charged regolith. Short catching fibers, placed along the internal edge and only exposed in the event of opening of the seal or closure act as a secondary layer of defense, catching regolith particles that get near the surface of the seal or edge. Both fibers are tufted through a copper mesh with charging wires from the ionization device to provide the system with a static charge. An insulating backing connects TEST-RAD to the apparatus and insulates it from the protected equipment.

Using electrostatics for dust mitigation is proven to be effective (Calle, 2008; Manyapu, 2017), though this technology has not yet been combined with tufted fibers to repel lunar regolith. Verification of our technology was conducted within a glove-box inert gas chamber environment using high-fidelity simulants throughout the prototyping and testing processes. TEST-RAD was tested within the chamber and was subjected to various regolith mitigation tests. Tests on the system showed that the mean distance repelled was approximately 23 cm of particles in the 50 - 0.5 µm range. Additionally, testing showed that, at a distance of about 3 cm from simulant, TEST-RAD could repel a mean of approximately 30% of simulant in that same particle size range. These tests also had a maximum average value of 29 cm repelled, and an average maximum value of 66% repulsion at a distance of approximately 3 cm. The failed seal test, meant to illustrate a non-ideal seal, showed that TEST-RAD is more effective at keeping dust out of a seal area compared to no protection. We believe these results indicate that TEST-RAD is a versatile dust mitigation device, which can then be integrated into various Artemis instruments.

Overall, TEST-RAD aims to provide protection to lunar surface equipment and spacesuits. The use of TEST-RAD will reduce the risk of regolith adhesion to vulnerable areas, extending the life of the technology it is applied to, making maintenance easier, and reducing the amount of regolith which is brought into astronaut habitation areas.

Problem Statement and Background

The Big Idea Challenge tasks teams to find a range of lunar dust mitigation solutions, in the following areas: Landing Dust Prevention, Spacesuit Dust Tolerance and Mitigation, Exterior Dust Prevention, and Cabin Dust Tolerance and Mitigation. Lunar regolith can wear down components, infiltrate and disrupt electrical systems, and pose a threat to astronaut health. Our team derived a solution for Space Suit Dust Tolerance and Mitigation by researching natural solutions to dust mitigation and tufting techniques, as well as looking to past successful designs such as EDS Technology combining these concepts into a layered dust repulsion system with a tufted fiber and electrostatic component meant to maximize protection of the equipment and dust repulsion. The Artemis Program, NASA's current mission back to the Moon, will be implementing cutting-edge technologies, including a new spacesuit and the xEMU (Exploration Extravehicular Mobility Unit). There will inevitably be areas where regolith can cause abrasion and damage, given it has highly adhesive and infiltrative properties. In addition, regolith is electrostatically charged, making dust removal from surfaces challenging. These properties were damaging enough that an outer layer hole was formed above the boot of Harrison Schmitt's spacesuit during an Apollo 17 moonwalk (Manyapu, 2017). Further documented by other Apollo Missions, lunar dust affects all outer garments, especially lower limbs, seals, and bearings (Gaier, 2005). Extensive wear of these sensitive joints over long periods could potentially induce catastrophic failure. To understand how to best combat the issue of lunar dust, comprehensive studies were conducted on its geochemical properties.

Lunar regolith varies in definite mineral composition, ranging from mafic basalt in the mare to felsic feldspars in the highlands (McKay et al., 1991). 90% of soils are composed of silicate minerals, commonly plagioclase feldspar, olivine, and pyroxene, which are found in conjunction with ferrous oxides and glass particles (McKay et al., 1991; Christoffersen et al., 2009). Rock is freed from underlying bedrock by the mechanical weathering of meteoric bombardment and thus becomes fine dust. Upper regolith can be considered silty sand intermixed with some larger pebbles (Roberts, 2019). Low gravity combined with electrostatic forces can cause the levitation of small (<10 µm diameter) dust particles. The average dust grains found on Apollo spacesuits were these smaller particles, composed of plagioclase and glass grains. Lunar soil typically has a median size of around 60 µm due to the presence of much larger glass agglutinate (Colwell et al., 2007). Despite not being levitated, even soil grains up to 75 µm in size pose a potential threat to future astronauts (Manyapu, 2017).

The lunar surface experiences a relatively constant amount of ionizing radiation, which affects the geochemical properties of regolith. The lack of a strong planetary magnetic field and atmosphere facilitates the direct charging of lunar dust. Solar wind, cosmic rays, and solar radiation (ultraviolet and X-ray photons) all push a positive charge onto the particles of the lunar dayside (Manyapu, 2017). The "shadow" of solar wind on the nightside thus induces a negative charge due to the presence of plasma electrons (Stubbs et al., 2017). This specific distribution of charges leads to a sharp gradient across the boundary between the nightside and dayside, which can help to uplift clouds of electrostatically charged particles (McKay et al., 1991). Charged particles also tend to adhere to surfaces.

Previous attempts on the Apollo mission to regulate dust were somewhat unsuccessful. The previous methods of cleaning spacesuits: vacuuming, brushing, and wiping were all active methods to take off dust upon completing EVAs (Gaier, 2005; Wagner, 2006), and while somewhat effective in removing dust contamination, they were not methods intended to prevent the initial dust accumulation (Manyapu, 2017). Additionally, the mitigation methods employed on bearings and rotational hardware were "not totally effective" (Gaier, 2005). These rotational joints were more challenging to assemble and manage upon being clogged with dust. The previous passive mitigation methods (electrostatic work, function coatings, and lotus coatings) do not focus on sensitive joints and aim for overall protection. This oversight could lead to dust accumulation in areas not strongly protected by coatings, which ultimately may fail as the abrasion of joints and bearings becomes more intense.

Given these issues and gaps in dust mitigation technology, a new effort is needed to protect the Artemis xEMU and other sensitive technologies from regolith damage. Keeping in mind how small, abrasive, and electrostatically charged the regolith is, it becomes clear how dangerous it can be during lunar EVA. Dust accumulation problems for joints can range from difficulties in spacesuit management of bearings to tearing the outer layers. This coupled with longer EVA times drastically increases the risk for adverse consequences on all future lunar missions. Better solutions are needed to ensure the safety of the Artemis astronauts.

Lunar Architecture

One of the center points of the Artemis missions is the establishment of a long-duration crew presence on the Moon to conduct science and as testing ground for future missions further into space (NASA, 2020). TEST-RAD will be an essential aspect of the overall lunar plan, both in the initial crewed missions and the longer-duration missions to follow. As stated in the Artemis Plan, one of the significant aspects of the on-surface parts of the mission is the ability to traverse the Moon's surface on an unprecedented scale. TEST-RAD fits perfectly into this goal of the Artemis missions as this system will create opportunities for easier and safer travel, extending the life of suits and their components by limiting harmful interactions with regolith. This will be imperative to the success of the Lunar Terrain Vehicle, as this vehicle will be unpressurized and will require that pressure suits be worn for its operation. This will increase the astronaut's interaction with regolith and necessitate a technique for mitigating its effects on the condition of the suits and the health of the astronauts. Implementing protective measures like TEST-RAD fits the lunar plan. It will allow increased protection of crucial suit pieces and lower suit cleaning time, allowing for greater exploration.

The "Scientific Themes for Human Lunar Return" are the following: bombardment of the Earth-Moon system, lunar processes and history, scientific resources in the permanently shadowed polar environment, regolith as the recorder of the Sun's history, biomedicine, using the Moon's resources, and astronomy (ESAS, 2005). Upon further examination of these goals and the planned methodologies for achieving them, it is clear that five out of the seven goals present an immediate need for lunar contact and exploration outside of pressurized environments (such as the habitation area or the habitable mobility platform). With this much expected EVA time, technology for efficient and safe EVA will be of high priority. TEST-RAD will be one part of the EVA system, adding a meaningful contribution of safety and efficiency to the system overall.

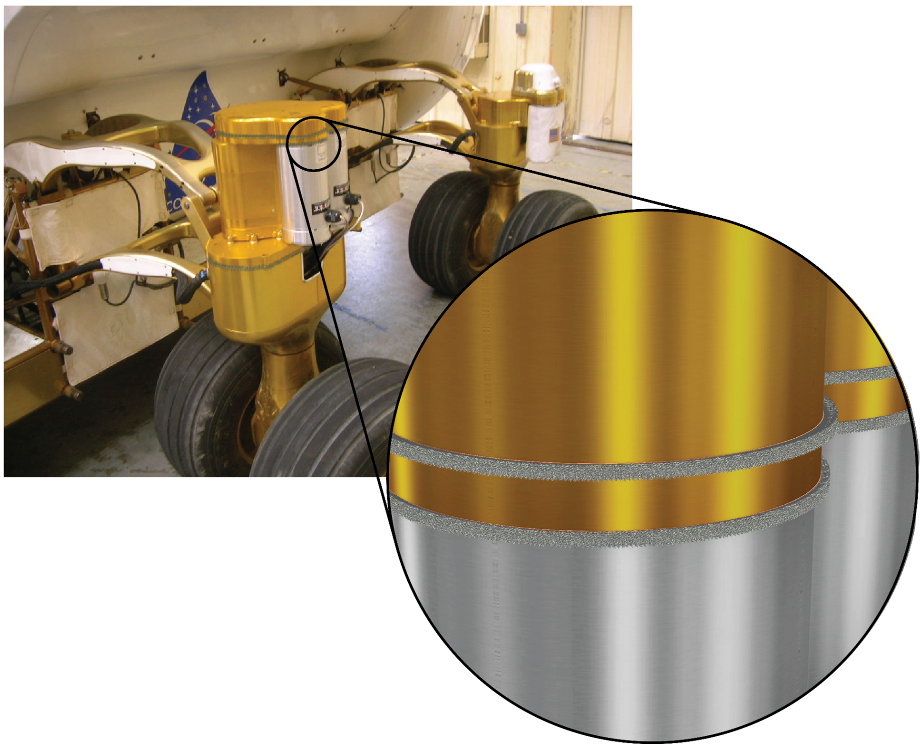
One of the advantages of TEST-RAD's size and lack of complexity is that many of the technologies and hardware that are going to be used throughout the mission are still in development and these features will lead to more seamless technological integration. This would create a higher level of ease of use for astronauts and ground team members as easy and simple technological integration would limit issues once the technology reaches the Moon.

Alternative Applications

Our team also sought to find potential applications of TEST-RAD outside of the initially designed use case. Our project was originally intended to be placed on the spacesuits of NASA's Artemis mission. However, if TEST-RAD cannot be put onto the xEMU suits or the commercial suits flown on early Artemis missions, we considered other applications where the use of the technology is appropriate and valuable. Some suggestions from the BIG Idea administration included gearbox covers and soft-wall habitats.

We also explored several other locations TEST-RAD could be useful: the VIPER battery cover, VIPER gearbox cover, and the mirror and lenses of mission cameras. The goal was to find closures, seals, and other appropriate edges and junctures on equipment that have an unresolved need for regolith mitigation. The decision was made to use TEST-RAD as a strip to ensure adhesion, coverage, and flexibility. This flexible tape-like format also allows versatility in application.

Figure 1. Rhino drawing of TEST-RAD applied to the VIPER Rover.



A promising alternative application of TEST-RAD is along the seam of the Volatiles Investigating Polar Exploration Rover (VIPER) battery cover. Regolith has the possibility of causing the battery to overheat either through permeation through junctions, or creating a film over surfaces, causing a larger system failure. Previously, there were no specific dust mitigation protocols, meaning astronauts had to manually brush regolith off the radiators. TEST-RAD would be applied as a dust mitigation strategy and would line vulnerable seams and junctions of the battery cover, preventing dust permeation and potentially the formation of a regolith film over battery surfaces. The wiring would also be connected to a central control board on a control panel within the astronauts reach.

TEST-RAD could also be applied to gearbox covers on the VIPER to prevent regolith-induced wear and tear. All junctures on the gearbox used for service access, or areas with vulnerable edges, could benefit from this application. Our Mark 4.1, which reaches an IP 67 rating, junction box test approximates the scale and application type to be used on the VIPER.

TEST-RAD can also be applied at the cameras monitoring crater formation below the lunar lander. After researching many different lunar camera systems, the SCALPSS Camera appeared to be the most at risk. These cameras, designed to film the lander crater and landing thrusters during landing, are bombarded with regolith. Thrusters launch particulates off the Moon's surface making these cameras particularly at risk. In addition, their data is internally stored and only physically accessed after landing.

Project Description

Technology

TEST-RAD's technology acts as a hybrid mitigation device providing both a passive barrier to lunar regolith, as well as an active electrostatic component that assists in repelling any charged lunar regolith. TEST-RAD aims to increase astronaut health and safety, decrease cleaning time, and reduce the harm done to equipment by regolith.

TEST-RAD is a layered defense system, combining two technologies intended to stop the penetration of regolith into fabric, seals, and internal surfaces. It uses electrostatic shielding combined with a novel bio-inspired tufted fiber to repel same-charge particles. Electrostatic shielding had already been proven for the repulsion of lunar dust (Calle et al., 2008). However, due to the variation in regolith size and shape, this mitigation technique alone is not enough to fully protect the joints and moving mechanisms, seals, edges, and openings of devices from being compromised by regolith. Our addition of densely packed fibers to block out sharp dust particles, within the given size range, aims to provide a complete solution. Inspired by the densely packed fur of the chinchilla, the tufted fibers will provide a physical barrier between the electrostatic generation assembly (EGA) and the regolith. This hybrid approach to mitigating regolith proliferation results in TEST-RAD being cost-effective and easy to implement on both established and future technologies. Adhering TEST-RAD to the outside surfaces of equipment requires little to no design modification.

Figure 2. The multi-layered system of TEST-RAD. Mark 2.3 labeled with each layer.

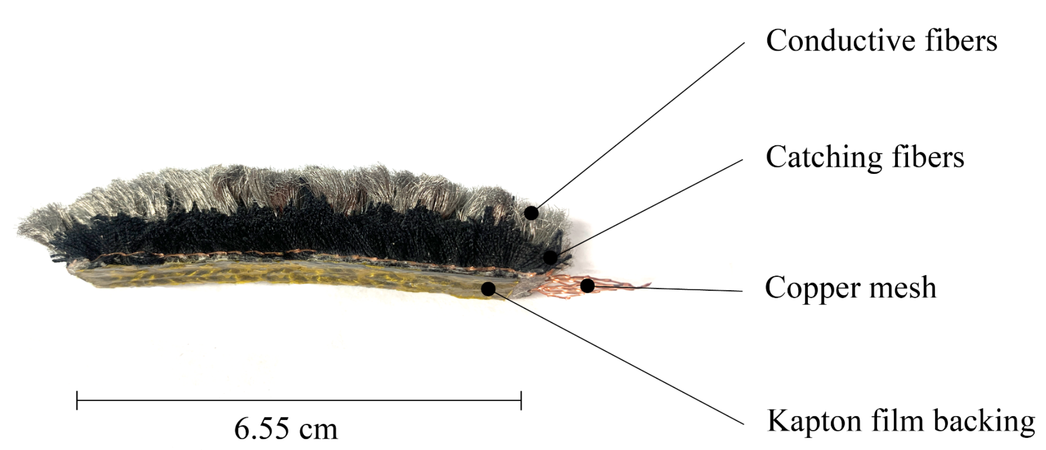
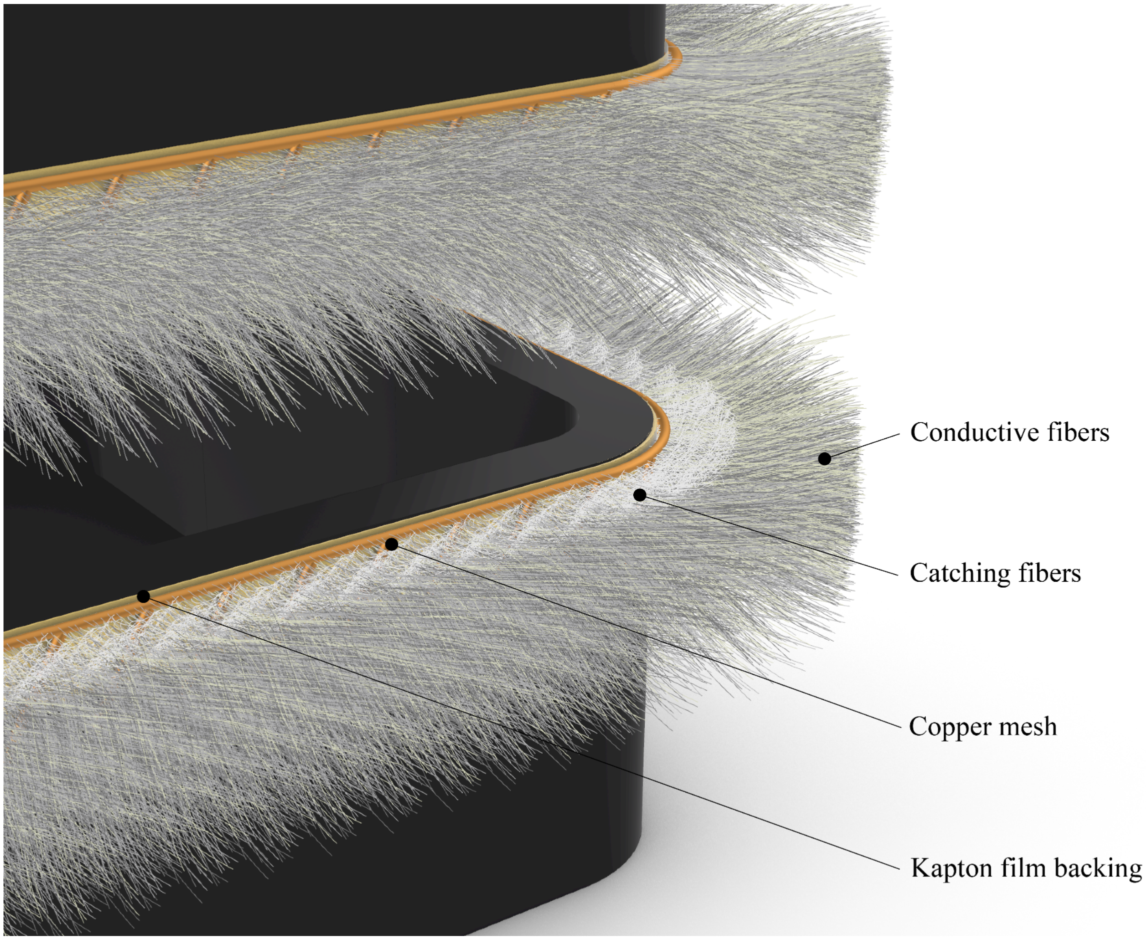


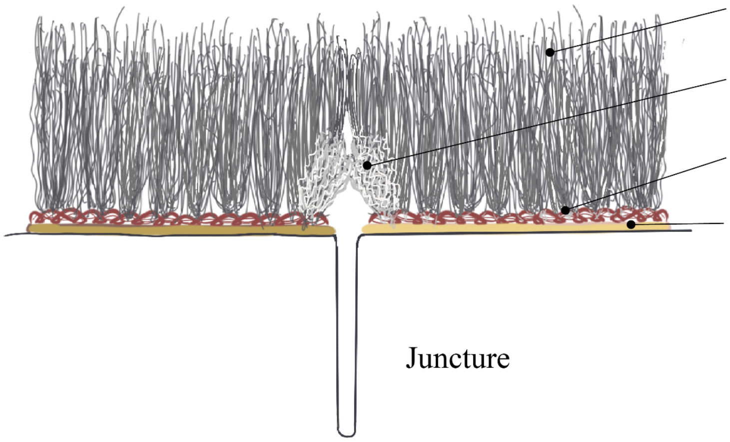
Figure 3. CAD drawing of TEST-RAD integrated with an apparatus. Shows how the multilayered system can be applied to a junction box (Mark 4.1).



The conductive tufted fibers are made from Liberator®, Vectran™ by Kuraray, a multifilament yarn spun from liquid crystal polymer (LCP). The tufting process creates an array of dense, durable fibers carrying the same charge as the regolith, extending the electrostatic field, and decreasing the rate of dust accumulation. Regolith adhesion to exposed seal surfaces is greatly reduced by the application of the charged fiber system. If the fibers become saturated with dust, it will not cause the system to fail and occasional brushing of the fibers will provide sufficient cleaning to improve the longevity of the system.

Shorter catching fibers are arranged in a single row along the seal abutting edge (Figure 4). These catching fibers are only exposed during seal opening and closing and act as a secondary layer of defense, catching the regolith particles that get near the surface of the seal or edge. However, during donning and doffing of the EVA suit, regolith particles will be shaken loose, potentially bypassing our charged solution, but not the catching fibers. Other opening and closing operations for alternative applications will present similar risks, but any regolith particles that land along the seal-abutting edge of TEST-RAD will be caught by the row of catching fibers. These catching fibers are composed of polyester, commercially used in fish tanks or woodshop filters.

Figure 4. TEST-RAD as applied on the sensitive area of an apparatus.

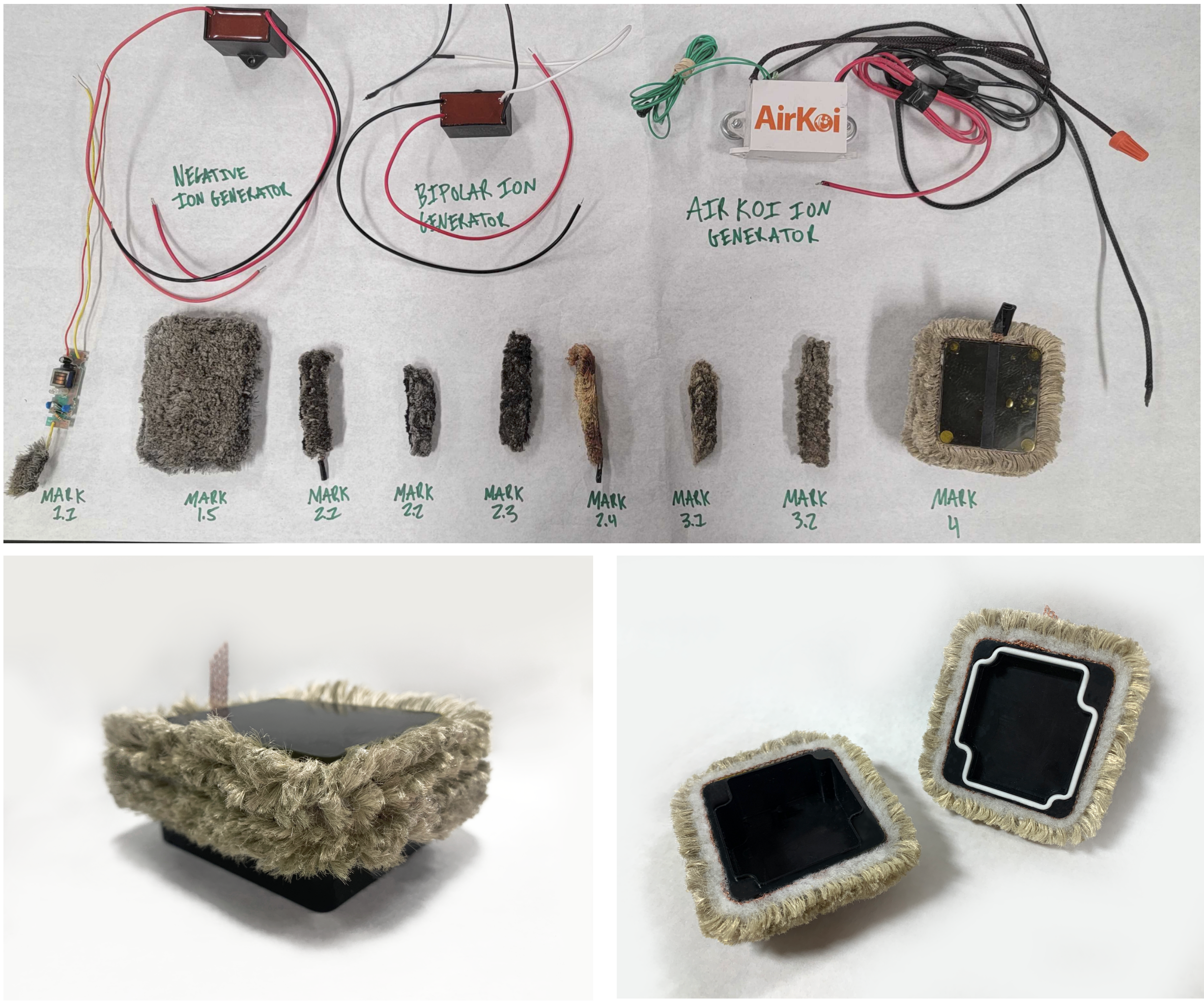


Both fibers are tufted through a copper mesh with charging wires from the ionization device attached to provide the system with static electricity. This serves as a medium for the electrostatic charge to pass through, as well as providing the necessary structure for fiber tufting. Prototypes used a copper expanded mesh with 3.2 mm holes. This mesh is one of the three major components of the EGA, with the other being an ion generator connected to the power supply of the life support system and a delivery wire. The power system supplies TEST-RAD with the required electrostatic charge to functionally operate. TEST-RAD is insulated and attached to equipment via a Kapton film backing.

TEST-RAD meets specifications for temperature tolerances and is non-toxic and non-out-gassing. Per 1 cm length test rad has a linear density of 1.45 ± 0.01 g/cm. Conductive fibers have a height of 1.30 cm ± 0.01 cm and catching fibers have a height of 0.50 cm ± 0.01 cm. Per 1 cm of width, or 5 rows, TEST-RAD fibers spread out to 2.25 ± 0.01 cm width at its height. At its current state of development, the material costs to prototype the first 10 cm TEST-RAD amount to $528.74 and each additional centimeter costs $0.24.

At the initiation of the EVA, the life support system is activated, causing an electrostatic charge to be applied to TEST-RAD and maintained, resulting in the repulsion of regolith from sensitive areas. One concern of the Artemis mission, and longer duration EVAs, is the variation in regolith charge depending on whether it is lunar day or lunar night. The system is effective in either of these situations, as the electrostatic field generated by TEST-RAD is large enough to repel dust particles independent of regolith polarity. This concept has been proved by the NASA Electrostatics and Surface Physics Laboratory and TEST-RAD will be developed to reproduce a similar level of success (Calle et al., 2008).

Figure 5. The evolution of TEST-RAD. Top row: All Marks of TEST-RAD lined up along with the bipolar generator iterations. Bottom row: The final Mark of our system, applied to a junction box.



Importance

TEST-RAD will improve the safety of astronauts on extended moonwalks through the deflection of regolith. Specifically, it aims to optimize the durability and functionality of key sections of the suit, such as joints, bearings, and seals. It will also lessen the amount of regolith in habitation modules as dust particles are actively repelled from the fabric. Lastly, it should decrease the time needed for overall suit cleaning which should help the crew focus on more significant tasks.

Christoffersen et al. recommended a limitation on the use of woven fabrics as they have a tendency to induce frictional regolith damage (2009). TEST-RAD does not use woven fabric; instead, the system employs a tufted design to account for fine regolith that will interact with the fabric. The outermost fibers being packed at such a high density (coupled with electrostatic forces) prevents the penetration of regolith onto the exterior fabric. Therefore the system helps to eliminate the possibility of damage to sensitive areas of the EVA suit, reducing the risk of catastrophic failure. Overall, extra protection and reduction of risk will greatly extend the life of Artemis generation spacesuits.

Astronauts from Apollo Missions noted mild lung discomfort due to inhaled regolith particles that were brought into habitable areas (James and Kahn-Mayberry, 2011). The system will decrease the amount of airborne regolith in two ways. The first involves the repulsion of lunar dust, fewer particles on the suit will result in fewer particles in habitation areas. The second involves dust that penetrated into the fabrics. Instead of becoming trapped during EVA and then released into habitation areas after doffing of suits, regolith would remain trapped underneath the electrostatic layer, bound by filtration media, unable to affect astronauts' respiratory health and comfort.

Cleaning time is also improved compared to the Apollo Missions. During previous EVAs, astronauts used brushes to remove large pieces of regolith from afflicted spacesuit areas. However, this was inefficient as there were still particles stuck in the woven parts of the suit (Christoffersen et al., 2009). This process was also highly time-consuming for crew members. TEST-RAD leads to faster and more effective cleaning due to decreased regolith adhesion. Additionally, TEST-RAD requires less maintenance as the most sensitive parts of the suit are already protected by the system.

As previously mentioned, lunar dust mitigation has not focused on the sensitive junctures of the suit or vulnerable areas of other mission systems. Instead it aimed for overall protection or limitation of deterioration after exposure. With the longer duration missions of Artemis, is it imperative that the dust mitigation systems used are intended to protect from exposure, and TEST-RAD has that primary purpose.

The mitigation of lunar dust abrasion and adhesion to spacesuits is of critical importance to the Artemis missions. Regolith, being small, glassy, and electrostatically charged, poses various issues for extended moonwalks. Thus, a solution is needed to ensure the safety of the Artemis astronauts. TEST-RAD provides the solution the space industry desperately needs for dust mitigation both on the spacesuits and other potential areas. It creates a thorough coverage that prevents regolith from getting in even the often overlooked areas of the spacesuits while also providing an easy way for astronauts to clean and restore the technology itself by controlling the electric charges on TEST-RAD. For this and many other reasons, TEST-RAD is worth further research and investments.

Verification Testing on Earth

Testing of TEST-RAD primarily assessed its ability to repel charged lunar regolith simulant which serves as a proxy for how much protection the prototype would provide on the Moon. To reach a Technology Readiness Level (TRL) of 4, a regolith simulant with similar size, electrostatic nature, and abrasive characteristics as lunar dust was used in a laboratory simulated environment.

Simulant Generation

The abrasive nature and size of lunar dust can be matched by regolith simulants. Based on the Design Specification for Natural Environments (DSNE), we decided to use the high fidelity simulants OPRL2W30 and OPRH2W30, which were manufactured by Off Planet Research, LLC. Both of these simulants contain particles in the required size range (50 to .50 μm), but they also contain much larger particles that impeded initial testing. Due to these large particles, our team filtered the simulant to create general-use mare simulant from the former and general-use highland simulant from the latter. The filtering process consisted of adding water to the simulant, passing the mixture through a fabric filter, and boiling off the water at the end. These simulants were used for all high fidelity testing, while our remaining unfiltered simulant used for initial experiments and testing various experimental procedures. This simulant generation process was necessary because TEST-RAD is designed to prevent the accumulation of small dust grains in sensitive areas and not to block the largest particles.

To simulate the charged characteristics of lunar regolith, we used an IONFIX Static Generator from TAKK Industries to generate a static charge on our lunar simulant. During verification testing, the static charge was transferred to the lunar simulant by spreading a thin layer of the lunar simulant over a metal plate charged to 30 kV by a TAKK generator. Our team purchased two such generators of opposite polarities so that we could measure TEST-RAD's repulsion capabilities during simulated lunar day and lunar night. The simulant charging apparatus was constructed with close proximity to each testing apparatus to ensure that charge was not lost when transferring simulant between charging and testing apparatuses. Tests with a faraday cup confirmed that simulant charge rapidly dissipates on Earth, so building the apparatuses together was required.

A variety of personal protective equipment was used throughout the testing process to minimize hazards in the laboratory environment. To minimize the risk of inhalation of the lunar simulant, KN-95 masks were worn at all times during verification testing. Insulative gloves rated for high voltages were worn to prevent the risk of electric shock when working with charged materials.

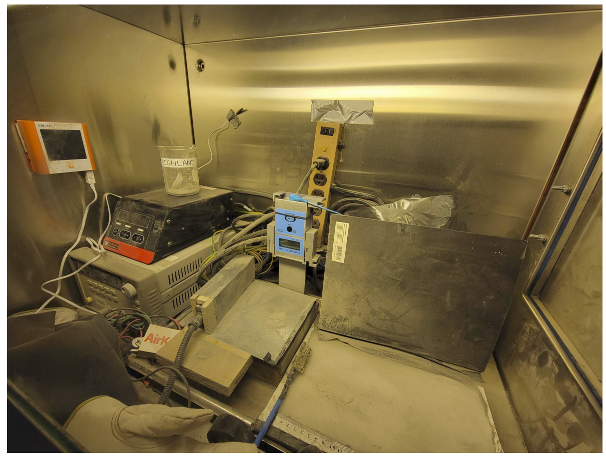
Laboratory Testing Environment

Ultimately, we used a glove box chamber manufactured by Terra Universal, Inc. (TUGB; Figure 6) instead of a proposed vacuum chamber for our laboratory environment. This decision was due to faults in the construction of the Cleatech 2700 Series Vacuum Glove Box (VGB; Figure 8) and its incompatibility with electrostatic systems. TUGB was unable to achieve a proper vacuum, but after using inert N_2 gas to push out ambient air, we were able to achieve an isolated environment for the majority of verification testing. This glove box was also equipped with outlets allowing us to charge both the prototype and the lunar simulant simultaneously. VGB did not have such a power supply, so we had to acknowledge the tradeoff between testing with charged simulant and testing with lunar atmospheric conditions, as the vacuum chamber could achieve a vacuum of 0.01 atm. Due to the construction faults, however, it was inoperable with a vacuum, so the pressure was brought back up to 1.00 atm with N_2 gas.

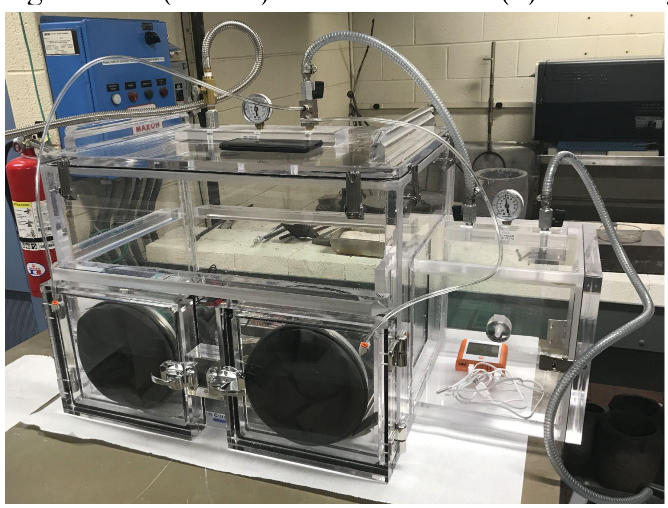
These chambers provided the necessary laboratory environment to reach TRL 4 because they provided an isolated environment with charged lunar simulant and lower humidity. Preliminary testing showed humidity (measured with an Elitech GSP-8 dry probe) had a large impact on simulant-charge retention. Low humidity levels were achieved with partial flooding of N_2 in TUGB and complete flooding in the vacuum chamber. From an ambient partial pressure of water vapor of 1.87 kPa, TUGB and VGB were able to lower this value to 1.57 kPa and .297 kPa, respectively. If the project continued over a larger time frame, we would have performed additional testing in a vacuum chamber in order to demonstrate TEST-RAD's performance under conditions more closely resembling the lunar environment.

Figures 6-8. Laboratory testing environments. (A) Inert gas glove box chamber partially flooded with N_2 during testing. (B) Practical test set-up for push test experiments. Apparatuses from left to right in TUGB: humidity and temperature sensor, ion generator for simulant, voltage source with ion generator for the prototype, simulant charging plate, and TEST-RAD on a blank sheet for measuring data. (C) Vacuum chamber flooded with N_2 during testing.

(6) Terra Universal glove box (TUGB)



(7) Inside of glove box



(8) Vacuum glove box (VGB)

Stress Test

From stress testing done under standard Earth conditions, TEST-RAD can handle stretching stresses up to 164 N before breaking. As it will be unlikely for TEST-RAD to experience these forces in the lunar environment, the integrity of TEST-RAD would most likely be maintained. Also, the prototypes made for testing have undergone over 350 trials without noticeable deterioration, proving its durability for prolonged usage in a simulant-laden environment.

Testing Methodology

Three tests referred to as the pass-over test, push test, and saturation test were performed in TUGB and two tests referred to as the junction box test and failed seal test were performed in VGB. Before all active repulsion tests, we used the same procedure to apply a charge to the simulant. This procedure consisted of applying a ± 30 kV charge to a metal plate via a TAKK Generator, where we spread a thin layer of simulant. Initially we used variable amounts of simulant charging time to check how repulsion varies with voltage, but preliminary tests showed this had almost no effect (all R^2 values were less than 0.042) so we generally waited for less than 30 seconds. The output voltage from TEST-RAD attached to a remote ion generator Jackson Control's AIRKOI-30M was 7.0 ± 0.5 kV for both positive and negative charges. We assumed that TEST-RAD maintained this charge for all tests, not including controls where there was no charge on the prototype.

The pass-over test involved passing TEST-RAD approximately 3 cm over a simulant-covered charged plate, with both the same electric charge sign (Figures 9 and 10). We repeated this pass-over, moving TEST-RAD across the simulant covered surface, five times. After the completion of the fifth, we would calculate the amount of simulant that was repelled by the system by mass. The purpose of this test was to determine if TEST-RAD was effective at repelling dust that did not come in direct contact with the system. This test is intended to model how the apparatus TEST-RAD is attached to will interact with levitating, charged clouds of regolith on the Moon. This levitation occurs due to same-charge repulsion coupled with low gravity across the lunar surface as well as astronaut activity (EVA, use of a rover, etc; Manyapu, 2017).

The push test consisted of pushing positively and negatively charged simulant directly from the simulant charging apparatus onto TEST-RAD, with the distance of the furthest particles recorded (Figures 12 and 13). This test simulated the regolith coming into direct contact with TEST-RAD and showed how the system is capable of repelling dust a significant distance away from a given apparatus. This would be a common occurrence on the lunar surface, especially if TEST-RAD is used on something near the ground.

The saturation test measured the limit of how much dust particle mass can be retained by TEST-RAD (Figure 11). The fibers were detached from the electrostatic system and their mass was recorded, before being placed in a container of simulant. The container was then shaken to simulate rough impacts to the system. The fibers were then taken out and their mass recorded again to calculate how much simulant was picked up. This is meant to give an upper bound of the regolith holding capacity that might limit TEST-RAD's mitigation capabilities.

The junction box test was designed to check if TEST-RAD can prevent dust from accumulating in sensitive areas of a given apparatus (Figure 14). Our team utilized Tulead IP67 rated waterproof and dustproof ABS junction boxes for this experiment, where one was treated as a control and one was outfitted with Mark 4.1. It was performed in the vacuum chamber flooded completely with N_2, and by placing the two boxes in a shallow tray with the top and bottom lids of Mark 4.1 charged by two nearby bipolar ion generators. Approximately 400 mL of highland stimulant total was then poured over both boxes (Figure 19). Each junction box lid was lifted vertically and placed back down 20 times (40 lifts between the two). Lastly the boxes were removed and the rims of the two boxes were compared qualitatively. This test is meant to demonstrate TEST-RAD's capabilities on the edge of an opening piece of equipment or cover such as the VIPER gearbox.

The last experiment is the failed seal test which has the same setup as the aforementioned test, except there are small balls of tape on the four corners of the inside of each junction box (Figure 21). This was done to create a small gap in each of the boxes that they would each have a small opening around their perimeter, to simulate a sensitive area or a seal that has "failed" and has begun to open. In the vacuum chamber flooded with N_2, we took the two boxes and rotated them on all four sides while pushing them into the simulant. We then removed the boxes from the chamber and checked the interior to assess how much simulant had gotten in through the openings.

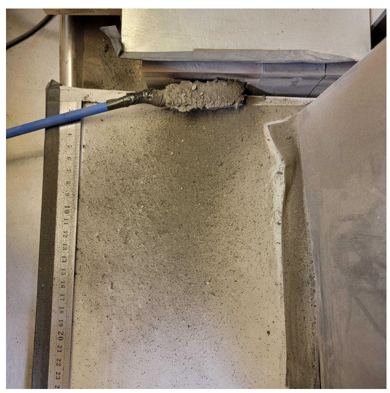
Figures 9-14. Several experimental tests performed on TEST-RAD.

(9) Pass-over test before

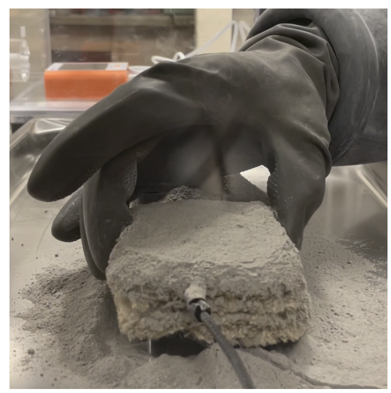
(10) Pass-over test after

(11) Saturation test

(12) Push test before



(13) Push test after



(14) Junction box test

Results

From the 186 pass-over tests conducted, the combination that repelled the greatest fraction of simulant was the negatively charged highland simulant with negatively charged TEST-RAD (Figure 15). This combination had a mean repulsion of 48.7 ± 0.88% of the simulant. There was an average repulsion of 28.8 ± 0.52% across all simulants and polarities with an average maximum of 65.7 ± 1.2%. The test was also conducted with the prototype being turned off as a control, which resulted in minimal repulsion, as evident by the plots extending down to 0.00% in Figure 15. This test gave us the best idea of how TEST-RAD can repel a significant percentage of lunar dust from a distance, and as a result shows using TEST-RAD as an active form of dust mitigation is viable as opposed to a solely passive solution.

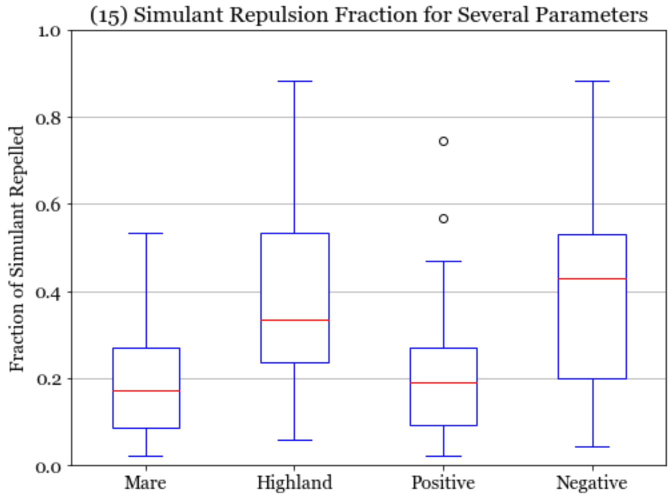
From the 186 push tests conducted, the simulant that was repelled the farthest was the positively charged highland simulant with positively charged TEST-RAD (Figure 16). Highland, positive-positive repulsion had a mean maximum repulsion distance of 26.62 ± 0.013 cm, though the overall mean for all tests was 22.99 ± 0.012 cm. The furthest particles were determined by the largest visible particle to the naked eye, as repulsion of smaller particles produced a dust cloud which did not settle until they reached the side of the chamber. All push tests resulted in greater than 8.50 ± 0.0043 cm repulsion, and the average minimum for repulsion distances was 14.78 ± 0.0075 cm across all simulants and polarities. Although using positive charges resulted in further distances, the data showed little correlation between the type of simulant and maximum repulsion distance. Furthermore, push tests showed that as the simulant is repelled, it forms a gradient of dust that tapers off as distance from TEST-RAD increases (Figure 13). This observation is indicative of an inverse square law which likely comes from an electrostatic field that the prototype maintains.

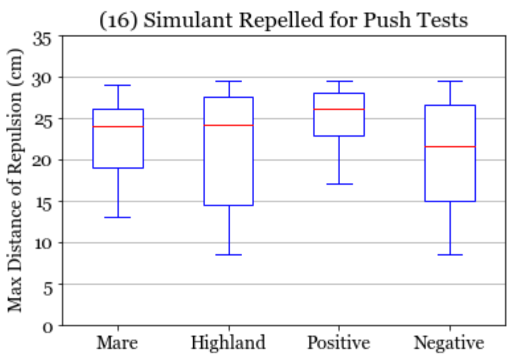
From the 10 saturation tests conducted, an average ratio of 0.549 ± 0.0037 of TEST-RAD's mass worth of simulant was picked up (Figure 17). Overall the prototype was able to hold more highland simulant than mare simulant. Considering the linear density of the prototype is 1.45 ± 0.01 g/cm, a mean 0.796 ± 0.001 g of simulant can be picked up per centimeter of TEST-RAD. This gives an estimate of TEST-RAD's mechanical ability to hold the simulant in a final line of defense to prevent regolith from entering and degrading sensitive areas.

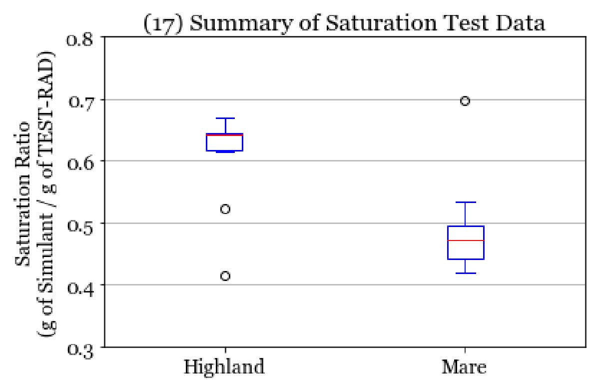
Furthermore, the materials chosen for the fibers and electrical system were done so considering their application in a lunar environment with cryogenic temperatures and a vacuum. Due to time constraints, we have not tested the temperature limit of TEST-RAD, but in theory, each part of TEST-RAD should maintain its integrity at low temperatures. Given more time, and access to other technology this can be verified as more rigorous testing and additional testing is carried out in environments beyond the laboratory setting.

In theory, the core function of TEST-RAD is utilizing an electric field to repel regolith particles by taking advantage of their charged nature. In practice, we have observed that the charged simulant does interact with an electric field, with the best results from using a negatively charged TEST-RAD and highland simulant. Also, from the numerous trials conducted, it was observed that the majority of simulant accumulation occurs at the outermost edges of the fibers where the catching fibers are located. Simulant rarely penetrated through the thick layer of fibers in the center, such that the electrostatic system of TEST-RAD was only slightly affected by repeated use in a regolith-laden environment and still functions as designed. In the event that the EGA of TEST-RAD fails, the fibers still provide a layer of protection with its catching fibers.

Figures 15-17. Key quantitative data from laboratory experiments.







The junction box test showed the Mark 4.1 lined junction box had significantly less dust accumulated on its rim than the control (Figure 20). This indicates successful verification of the fiber systems, specifically the catching fibers lining the inside edge. The control's accumulation of simulant around the rim simulates how any sealed device on the Moon would experience similar regolith accumulation upon opening and closing. Prevention of this accumulation would block both short-term damage to internal components of the apparatus as well as long-term damage to the seal itself.

The failed joint test directly displayed the Mark 4.1 lined junction box had less simulant buildup on the inside of the box (Figure 21). In the event of an exposed seal for any extended period of time, as simulated by the repeated contact with the pile of highland simulant, the expanded tufted and catching fibers prevented a majority of simulant from reaching the inside of the box, thus protecting the contents inside.

Both of the tests with the junction box were conducted once each, and while no quantitative measurements were taken for either, the qualitative results found in conjunction with our repulsion tests verify both our active and passive objectives. The limitation of VGB necessitated the use of uncharged simulant which reduced the amount of active repulsion that occurred. Despite successful active repulsion in the pass-over and push testing scenarios, it is not possible in the junction box testing as they were unable to use electrostatically charged simulant.

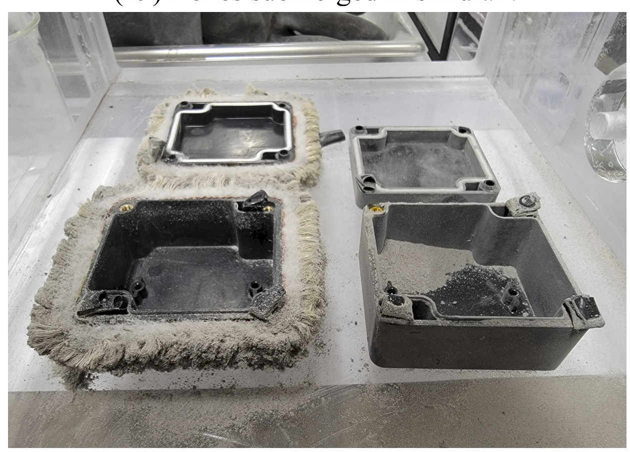
However, the passive system made up for this shortcoming and verified that, in the event of an EGA failure, TEST-RAD still maintains the majority of its dust mitigation capabilities. Future tests would be conducted in a laboratory environment with a power supply to charge the simulant, in which case it is probable there would be virtually no simulant in the Mark 4.1 junction box.

Figures 18-21. Junction box test qualitative data.

(18) Mark 4.1 and control junction boxes before test

(19) Boxes submerged in simulant

(20) Boxes after junction box test



(21) Boxes after failed seal test

Safety Plan and Protocols Followed

Brown Environmental, Health, and Safety (EHS) provided the necessary guidance to ensure engineering controls, administrative controls, and PPE were used to mitigate risks associated with the lunar simulants. Simulants were handled inside an engineering control at all times or while wearing respiratory protection. The primary engineering control used was the chemical fume hood located in our laboratory space. Given the current circumstances with COVID-19, face coverings were required at all times. Training included how to use each instrument properly and not waste materials, such as lunar regolith simulant. All members working in the laboratory received information and training on general laboratory safety procedures, including Laboratory Safety and Hazardous Waste Training and laboratory-specific training on hazardous materials, equipment, and procedures related to this project.

Standard Operating Procedures (SOP) were written for work with hazardous materials and processes, and laboratory-specific training was provided to each member on the SOPs. SOPs included details on PPE requirements, engineering controls, and other administrative controls, such as general housekeeping and disposal procedures. Baseline PPE requirements for working in a laboratory include impact safety glasses, laboratory coats, and gloves. While the voltages for simulants ranged between approximately -2 to +2 volts, voltages produced from the static generators from TAKK can reach up to 30kV and thus require additional control for potential electrical hazards that arise from this. We purchased antistatic and UV-safe gloves when directly handling potentially charged surfaces/materials. Work with UVA radiation was assessed by the University Radiation Safety Officer to determine PPE requirements. Cleaning procedures dealing with charging the simulant and the glovebox were taught as well.

With the spread of the Delta Variant, our team has been taking increased precautions to prevent infections and the spread of the virus. Our team committed to standard COVID-19 safety, such as wearing masks and socially distancing at all times. We strived to keep our spaces clean at all times, with no food or drink present. In addition, participants attending Brown were the only ones allowed to enter rooms on Brown's campus used for this challenge. Only a select number of students were allowed to use laboratory facilities. Each of these spaces also has a lab density requirement that we abided by; the appropriate department and facility managers approved these requirements. Both RISD and Brown students and faculty were required to participate in each school’s COVID testing program, the frequency of which was constantly updated as the COVID situation evolved. Therefore our team planned to be apprised of any breaches in our COVID safety plan. If a participant tested positive, their affiliated school would be notified, as well as our team. This participant would quarantine, as would any others who have recently shared space with them. Our team would also request university assistance in sanitizing any affected areas.

As for a final note, our team actively promoted a positive safety culture. During the project, if any member noticed an unsafe situation or practice, we encouraged them to discuss it with the team to make changes to our protocols when appropriate or if any university officials needed to be consulted. We recognize that this culture is imperative to maintain an adaptive and accurate set of protocols.

CONOPS & Project Management

Project Management

Project management was challenging, mainly due to circumstances relating to the pandemic and issues owing to delays that arose as a result. Maintaining COVID-19 safety was a priority for our team, and as a result, our lab and equipment access was bottlenecked by university and state health guidelines. Our entire team avoided the spread of the virus safely and maintained vaccine, mask, and social distancing guidelines for each of our schools. This focus was carefully balanced and prioritized against a compressed timeline due to the setbacks listed above.

Several budget delays prevented access to grant funding until late May, resulting in an accelerated but successfully executed schedule. These budget delays lengthened the timeline for producing prototypes, obtaining the correct testing equipment, and dispensing stipend payments. Some of the equipment affected by the delays included our testing chamber, high fidelity lunar regolith simulant, and electrostatic generators. The team was adaptive and dynamic in modifying testing schedules and prototype development to optimize time and minimize possible COVID-19 exposure.

This project was well-managed given these challenges. The team was cooperative throughout these milestones, adaptable to unforeseen changes to project timelines and scheduling, and vocal to leadership on how to best respond to these changes. Advisors were also of great help navigating these situations to maintain progress and keep to our projected timeline.

Design Assumptions

In the initial stages of prototyping and testing, we assumed regolith repulsion that occurs at low voltage levels would require some safety precautions, such as the use of rubber gloves. As we conducted more tests, it became clear that TEST-RAD needed a higher voltage for strong repulsion. As a result, we developed more robust protocols, including using additional grounding wires and gloves rated for high voltages. We also assumed that the charge field TEST-RAD used to repel dust would not affect other nearby systems, but after completing testing, we determined that this assumption needs reevaluation to develop a concrete answer. Furthermore, if testing were to occur at higher voltages than we currently employ, we would need to develop more robust safety protocols.

Unrelated to the charging of TEST-RAD, we also discovered that our work-time estimate was inaccurate when it came to tufting fibers. Due to the physical properties of the fibers and metal mesh, we were unable to use a tufting gun, requiring the work to be done by hand, causing this procedure to take more time than initially budgeted. A significant amount of this tufting work was also completed by one team member. In the future, we hope to train more people in tufting or find an automated way to assemble it to cut down on the number of person hours.

Key Design Decisions

Choosing an ionization device with a consistent output of both positive and negative ions was prioritized for the development of the EGA. While our team initially attempted to develop the ionization device, it became clear throughout the project that a higher grade device would be necessary to achieve our desired constraints above. As such, we chose commercially available bipolar generators to use in the EGA, making integration of the EGA with the fiber system of TEST-RAD a much simpler process overall. The tufted fiber arrangement was chosen to optimize charge delivery and repulsion surface area. A variety of fiber-based materials were explored to optimize performance, including stainless steel, nickel-plated stainless steel, silver, two different types of silver-coated nylon, three different types of copper fiber, and liquid crystal polymer.

Fabrication

Charged fibers were grouped in bundles and hand-tufted through expanded copper mesh holes in multiple rows. Catching fibers were similarly hand-tufted at a shorter length and in a single row. The backing was then glued to the Kapton film to secure both fiber types in place. Fibers were cut to respective lengths, and stray fibers were teased out. For the final iteration, Mark 4.1, the prototype was then applied to the exterior of a junction box with a certified waterproof and dustproof rating of IP67.

Prototype Operations

Day-to-day operations for prototype development and testing were impacted mainly by our access to facilities at each of our respective campuses. Over the course of the project, our team was reassigned laboratory space several times as a result of University guidelines resulting from the evolving COVID-19 situation as well as safety considerations and engineering controls required for work on TEST-RAD. Lab density requirements and limited access hindered progress initially, but as restrictions were lifted, the team accelerated our work on various prototype iterations. Collaboration between the teams at both schools meant that the development of the prototype often occurred simultaneously in several different locations. Constant communication among all working parties ensured that we met essential timeline requirements. The effective collaboration resulted in a pattern of prototype development, testing, and subsequent redesigns that informed future prototype Marks.

Budget Management

Our team coordinated with advisors, faculty, and challenge organizers to develop a cohesive budget: itemizing materials, administrative, and labor costs. This budget is updated for accuracy and subtle changes in material costs throughout the project. Leadership was responsible for developing the budget, receiving approval from our universities, and overseeing hours worked and materials relevant to TEST-RAD development. Our schedule was developed by leadership and approved by the team; after approval by the team, faculty advisers critiqued our timelines to help evaluate if they were reasonable and thorough enough.

Team Management

Our team made communication with our team, advisers, and campaign organizers a top priority to expedite all processes. Our team efficiently adjusted budgets and timelines to meet project deadlines. We were quick to consult with various technical experts, our advisors, and our team to overcome challenges faced by our team. This led to the creation of weekly meetings with our faculty advisor and principal investigator, where we discussed a variety of things, including testing and our progress. We also sought advice in these meetings regarding pandemic safety, pandemic-related supply chain and quality issues, and budget delays.

Potential Funders

Due to NASA's increased partnership with industry as a part of Artemis, many more doors are open for funding due to the planned increased use of commercially built technologies, both related to spacesuit technologies and other lunar surface technologies. This would allow for additional flight verification even before integrated into the xEMU suits. One of the features of TEST-RAD that would make it appealing to the industry is its versatility in use while maintaining the critical feature of protecting vulnerable areas from detrimental regolith interactions.

Path To Flight

To reach the lunar surface by the year 2026, a series of testing milestones and design changes would need to occur. The path to flight would involve the following development stages: an initial two-year implementation phase focused on testing and continued research in various relevant environments. Next, there will be a year-long integration and verification phase in which designs and systems are finalized, and testing of TEST-RAD fully integrated into its system would take place. Lastly, a year-long recombination and flight preparation would occur in which the technology would be prepared for launch and use on the Moon. We would develop methodologies and procedures to be used on the Moon to ensure TEST-RAD's safe and effective use and test the system for stresses faced during flight, transportation, and landing.

In the first stage of this development, we would continue to test the system to determine if critical design changes are necessary. For example, given the size of our prototypes, it was not essential to have multiple charge-producing units connected to TEST-RAD, but we would have to test the logistics of a larger prototype given possible applications requiring this as such. These tests may reveal that additional charge-generating devices may need to be added to sustain charge density. Furthermore, we would continue research into forms of bipolar charge generation to determine if there is a more efficient charging or charge proliferation method. However, this would require a revision of our testing protocol, as the voltages would be higher than what we can currently safely test with our equipment. In order to continue to determine the level of effectiveness of the system, we would conduct testing in a high vacuum 10^{-6} mmHg (3^{-15} bar; Beale and Bonometti, 2008) and temperature conditions (-49℃ to -243℃) which replicate that of the lunar surface. We would also conduct higher and more refined levels of long-duration testing to guarantee TEST-RAD's effectiveness throughout an extensive mission and advanced safety analysis. At the end of this implementation stage, a critical design review would take place to evaluate the quantitative data gained from the system and TEST-RAD's possible role in the lunar missions.

After the design review, if it is determined that there is a concrete and mission advantageous place for TEST-RAD in the Artemis missions, we would specifically tailor our design to that best-use case. At this point, it would be evaluated if any of the design changes investigated in phase one would need to occur to fit the new application, such as length and charge inputs. If so, those modifications would be made. Then the new model would be tested along with similar parameters as before, analyzing if the changes impact TEST-RAD's capability to repel dust and mitigate other regolith-associated problems. After, application-specific testing with a fully integrated model would be done to analyze TEST-RAD's mitigation properties in a simulated lunar environment, complete with low pressure (high vacuum) and temperature ranges reflective of the Moon's polar regions. We currently do not have access to such facilities but would spend the first testing phase developing a plan to complete this high fidelity testing. Following this year-long integration and implementation phase, we would conduct a complete analysis of our data and the position of the system in the lunar architecture. This is where we would determine if it was worth sending the system into space to be tested and used in the lunar environment; this analysis would consist of effectiveness analysis, safety considerations, and value-added to the mission. We would consider data generated from previous phases of testing and analysis of the Artemis missions that had already taken place to evaluate the need for TEST-RAD.

If our team and Artemis personnel see TEST-RAD's benefit and guaranteed success in the lunar environment, we would move into the recombination and flight readiness phase. In this phase of the process, we would conduct continued analysis of the system with a focus on the stresses it would face during launch and landing, the sequence of operations for the installation of the system, and a baseline level of tests to ensure the safety and effectiveness of the system after installation on the Moon's surface.

Results and Conclusions

- ➔ TEST-RAD achieved successful individual verification of both the fiber system and electrostatic generation assembly and partial verification of the hybrid mitigation approach.
- ➔ TEST-RAD's novel hybrid mitigation strategy warrants further research, specifically to delve deeper into its active repulsion capabilities.
- ➔ Testing conducted using charged highland simulant produced the best active repulsion results, which is especially useful for Artemis missions.

The proposed objective of our project was to produce a hybrid mitigation device that provides both a passive barrier to the lunar regolith and an active electrostatic component that repels charged regolith from the surroundings. Through our verification testing, we successfully validated the use of the fiber system's passive blocking abilities. This passive mitigation is an effective strategy that can be used on various applications that utilize seals. This was shown through the failed seal test. That test was designed to emulate a less than ideal seal between two sections of an apparatus and TEST-RAD's succeeded at blocking simulant from getting into the box. This shows TEST-RAD's ability to stop regolith from entering seals, and other like areas. Additionally, we achieved our Electrostatic Generation Assembly's (EGA) proof of concept for active repulsion cases, as shown in the data from the push test and the pass-over test. However, we believe further research is required into the active repulsion of charged particles, primarily due to limitations to the electrostatic charging method employed to charge the simulant.

Simulant charging, while effective, was only achieved under specific setups, which ultimately limited our ability to conduct testing efficiently. Using the conductive plate to ionize the simulant directly, we defined a series of experimental designs in which TEST-RAD's active repulsion is proven and effective at mitigating dust. The pass-over test, which was meant to show the long-range repulsion ability of TEST-RAD, successfully demonstrated that. Even though the mean repulsion was slightly under 30%, this overall repulsion was due to the field generated 3 centimeters from the system. At that range, the ability to repel 30% of regolith shows the effectiveness of the system. The push test simulates the interactions that happen when regolith comes into contact with TEST-RAD, particles are repelled, some at a very great distance, which is another success. Looking at this data, we can conclude that our design makes a low-cost mitigation solution possible. While sacrificing the efficiency of a comparable electrodynamic repulsion system, the low cost of fibers and ionization devices allows for a cost-effective approach that is easy to replicate and replace. Moreover, versatility in the integration process and the simplicity of attaching TEST-RAD externally to devices can keep implementation into established applications simple, shortening the time required. In addition to that, the active repulsion properties of TEST-RAD from the tufted fibers are more remarkable than initially anticipated. We hope that combining this with the electrodynamic system would provide a solid level of protection for vulnerable areas on lunar technologies.

Future research into a higher quality EGA that can safely utilize higher voltages is necessary for the electrostatic approach to be completely viable as a lunar regolith mitigation strategy. Additionally, both passive and active systems must be verified in conjunction to deem TEST-RAD's hybrid approach entirely successful. Beyond the scope of our project, functional repulsive capabilities using the EGA were not proposed initially but were found to be quite effective throughout our testing. If researched further, the use of a high voltage static generator with the EGA can provide further regolith mitigation and cleaning strategies that were not explored through the use of TEST-RAD.

Numerous consecutive trials necessitated constant cleaning of the prototype in a similar manner that would occur on the Moon. We found that frequent and thorough cleaning was easily achieved, and therefore TEST-RAD could present a potential pathway to decrease overall equipment cleaning time. In the long run, these strategies should reduce the harm done to equipment and astronauts by regolith.

Another advantage of our system is that the best performance of TEST-RAD in our verification tests occurred with the conditions that will be the most similar to the lunar landing locations chosen for the Artemis missions. The extremely consistent results found in trials using the highland simulant lend credence to its success for an eventual use case in the highlands of the lunar South Pole.

As humanity begins to establish their permanent presence on the Moon there will be many problems unthought of that we will need to solve together, technical and otherwise. We hope that TEST-RAD and the spirit of innovation and collaboration behind it, Brown and RISD, nature and engineering, and even passive and active dust repulsion, can continue as we travel further and further away from the small blue dot we call home.

Detailed Timeline

Matlab Modeling

Matlab Workshop	2/12/21 - 2/12/21
Develop Modeling Framework	2/13/21 - 3/7/21
Derive Fundamental Equations	3/8/21 - 3/27/21
Implement Differential Equations	3/28/21 - 4/15/21
Run Code with Realistic Variables	4/16/21 - 5/8/21

Alternative Applications

Exploratory Research	2/27/21 - 3/6/21
Research into Seals and Hatch	2/27/21 - 3/6/21
Research Mylar Heat Insulation	3/6/21 - 5/15/21
Research Camera Applications	3/6/21 - 5/15/21
Research Battery Cover	3/6/21 - 5/15/21
Research Gear Box	3/6/21 - 5/15/21
Research On Earth Possibilities	4/1/21 - 5/15/21
Select Primary and Featured Applications	5/15/21 - 5/22/21

Static Generator Prototyping

Initial Electrostatic Development	2/7/21 - 3/31/21
Initial Static Generator Research	2/7/21 - 3/31/21
USB Ionizer Development	4/1/21 - 4/30/21
USB Ionizer Reproduction	4/1/21 - 4/30/21
USB Ionizer Testing	5/1/21 - 5/31/21
Prototype Electrostatic Testing (USB Ionizer)	6/1/21 - 6/30/21
IONFIX Static Generator Prep	6/10/21 - 6/18/21
IONFIX Static Generator Testing	7/1/21 - 7/21/21
AIRKOI Ionizer Testing	8/1/21 - 10/20/21

Fibers Prototyping

Mark 1

Fiber Material Exploration	3/11/21 - 5/1/21
Backing Material Exploration	3/11/21 - 5/1/21
Practice Assemblies	5/2/21 - 5/8/21
Mark 1.1	5/9/21 - 5/14/21
Mark 1.2	5/15/21 - 5/19/21
Assembly 1.3	5/5/21 - 5/12/21
Assembly 1.4	5/13/21 - 5/18/21
Mark 1.5	5/19/21 - 6/28/21
Assembly 1.6	6/29/21 - 7/12/21

Mark 2

Mark 2.1	7/13/21 - 7/23/21
Mark 2.2	7/24/21 - 7/27/21
Mark 2.3	7/28/21 - 8/2/21
Mark 2.4	8/3/21 - 8/24/21

Mark 3

Mark 3.1	9/3/21 - 10/2/21
Mark 3.2	9/3/21 - 10/4/21

Mark 4

Mark 4.1	10/5/21 - 10/25/21

Prototype Integration

Mark 1			
1 Piece Prototype Assembly (USB Ionizer)	5/1/21	-	5/20/21
USB Ionizer Integration	5/21/21	-	6/10/21
1 Piece Prototype Pre-Testing (IONFIX Generator)	5/21/21	-	6/30/21
Mark 1.5			
1 Piece Prototype Assembly (USB Ionizer)	6/20/21	-	6/26/21
USB Ionizer Integration	6/26/21	-	7/1/21
1 Piece Prototype Pre-Testing (IONFIX Generator)	7/1/21	-	7/10/21
Mark 2			
2 Piece Prototype Assembly (USB Ionizer)	6/30/21	-	7/10/21
IONFIX Static Generator Integration	7/10/21	-	7/21/21
2 Piece Prototype Pre-Testing	7/22/21	-	8/1/21
Final Prototype Assembly (AIRKOI Ionizer)	8/2/21	-	8/24/21
Mark 3			
AIRKOI Static Generator Integration	8/25/21	-	9/1/21
Final Prototype Pre-Testing	9/2/21	-	9/30/21
Mark 4			
AIRKOI Static Generator Integration	10/25/21	-	10/26/21
Final Prototype Pre-Testing	10/26/21	-	10/26/21

Testing

Mark 1			
Testing Protocol Development	6/1/21	-	6/15/21
Testing Equipment Installation	6/1/21	-	6/14/21
Homemade Regolith Simulant	6/14/21	-	6/20/21
Static Testing	6/16/21	-	7/16/21
Physical Testing	6/16/21	-	7/16/21
Charge Testing	6/16/21	-	7/16/21
Static Repulsion Testing	6/16/21	-	7/16/21
Environment Testing	6/16/21	-	7/16/21
Dynamic Regolith Testing	6/16/21	-	7/16/21
Refine Model	7/17/21	-	7/24/21
Mark 2			
Updated Testing Protocol Development	7/13/21	-	7/23/21
Static Testing	7/24/21	-	7/27/21
Physical Testing	7/28/21	-	8/2/21
Charge Testing	8/3/21	-	8/24/21
Static Repulsion Testing	8/25/21	-	8/27/21
Environment Testing	8/28/21	-	8/30/21
Dynamic Regolith Testing	8/31/21	-	9/2/21
Refine Model	9/3/21		9/7/21
Mark 3			
Updated Testing Protocol Development	8/28/21	-	9/1/21
Static Testing	9/3/21	-	9/5/21
Physical Testing	9/6/21	-	9/11/21
Charge Testing	9/12/21	-	9/12/21
Static Repulsion Testing	9/13/21	-	9/18/21
Environment Testing	9/19/21	-	9/24/21
Dynamic Regolith Testing	9/25/21	-	9/30/21
Finalize Testing Results	10/1/21	-	10/15/21
Mark 4			
Updated Testing Protocol Development	10/16/21	-	10/26/21
Integrated System Testing	10/26/21	-	10/27/21
Junction Box Testing	10/26/21	-	10/27/21

Detailed Budget

Direct Labor included the direct labor costs of seven Brown University undergraduate students, one recent Brown graduate and one Brown | RISD Dual Degree undergraduate student for the total Direct Labor cost of $19,172.20 in Phase I and $29,021.00 in Phase II. Other Direct Costs included Materials and Supplies, totalling $16,540.39 for Phase I and $10,961.89 for Phase II. The RISD Subcontract included the direct labor costs of Rhode Island School of Design students for the amounts of $5,186.50 in Phase I and $8,097.00 in Phase II. Brown Space Engineering Club provided $391.77 of funding for materials before Phase I funding was accessible.

Budget Breakdown	**Phase I**	**Phase II**	**Total**
A. Direct Labor			
Stipends - 7 Brown Undergrad students (22 weeks each Phase 1 and 17 weeks each Phase II)	$7,820.00	$13,685.00	$21,505.00
Stipends - 1 Brown | RISD Dual Degree Undergrad student (22 weeks Phase 1 and 17 weeks Phase II)	$4,025.00	$6,210.00	$10,235.00
Stipends - 1 Brown Undergrad Senior (13 weeks Phase 1)	$2,967.00	$0.00	$2,967.00
1 Brown Recent Graduate (9 weeks Phase 1 and 17 weeks Phase II)	$4,360.20	$9,126.00	$13,486.20
Subtotal Direct Labor	***$19,172.20***	***$29,021.00***	***$48,193.20***
B. Other Direct Costs			
Materials and Supplies	*$16,540.39*	$10,961.89	$27,502.28
C. RISD Subcontract			
RISD Subcontract	$5,186.50	$8,097.00	$13,283.50
D. Total Direct Costs (A+B+C)			
	$40,899.09	**$48,079.89**	**$88,978.98**

Acknowledgments

We would like to thank everyone who helped us throughout the duration of this project. We could not have gotten to the place we did without the immense amount of support we received from both Brown and RISD. We would specifically like to thank Derek Stein Ph.D. for physics and electrostatics consultation. Nancy Ciminelli specifically and all of RISG for their support throughout the entire process, especially with funding. We would also like to thank John Shilko for allowing us to use his lab space, and Paul Waltz for guiding us through the process of securing research space in the midst of the pandemic. Lastly, we would like to thank Jackson Control for generously providing us with one of their AIRKOI-30M bipolar ionizers free of charge.

References

Beale, D., & Bonometti, J. (2008). Chapter 5: The Lunar Environment and Issues for Engineering Design.

Calle, C. I., McFall, J. L., Buhler, C. R., Snyder, S. J., Arens, E. E., Chen, A., . . . Trigwell, S. (2008). Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions. Proc. ESA Annual Meeting on Electrostatics, 1. Retrieved from https://www.researchgate.net/publication/235655144_Dust_Particle_Removal_by_Electrostatic_and_Dielectrophoretic_Forces_with_Applications_to_NASA_Exploration_Missions

Center for Lunar and Asteroid Surface Science. (CLASS). High-fidelity Regolith Simulants. Retrieved from https://sciences.ucf.edu/class/exolithlab/

Christoffersen, R., Lindsay, J. F., Noble, S. K., Meador, M. A., Kosmo, J. J., Lawrence, A., . . . McCue, T. (2009). Lunar Dust Effects on Spacesuit Systems: Insights from the Apollo Spacesuits Retrieved from https://www.lpi.usra.edu/lunar/strategies/ChristoffersenEtAl_NASA-TP-2009-214786_LunarDustEffectsSpacesuitSystems.pdf

Colwell, J. E., Batiste, S., Horányi, M., Robertson, S., & Sture, S. (2007). Lunar surface: Dust dynamics and regolith mechanics. Reviews of Geophysics. doi: https://doi.org/10.1029/2005RG000184

ESAS. (2005). Lunar Architecture. Retrieved from https://www.nasa.gov/pdf/140635main_ESAS_04.pdf

Gaier, J. R. (2005). The Effects of Lunar Dust on EVA Systems During the Apollo Missions. Retrieved from https://history.nasa.gov/alsj/TM-2005-213610.pdf

International Agency Working Group. (2016). Dust Mitigation Gap Assessment Report. Retrieved from https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

James, J. T., & Kahn-Mayberry, N. (2011). Risk of Adverse Health Effects from Lunar Dust Exposure. Retrieved from https://www.semanticscholar.org/paper/318-Risk-of-Adverse-Health-Effects-from-Lunar-Dust-James-Kahn-Mayberry/3859acca756fe4af9d674ac0f2751d6597f08e20

Jones, E. M. (2005). Apollo Dust Brush. Apollo Lunar Surface. Retrieved from https://www.hq.nasa.gov/alsj/alsj-dustbrush.html

Manyapu, K. K. (2017). Spacesuit Integrated Carbon Nanotube Dust Mitigation System For Lunar Exploration Theses and Dissertations. Retrieved from https://commons.und.edu/theses/2278

McKay, D. S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., . . . Papike, J. (1991). The Lunar Regolith. In Lunar Sourcebook: A user's guide to the Moon (D. T. V. Grant H. Heiken, Bevan M. French Ed.). New York: Cambridge University Press.

NASA. (2020). Lunar Exploration Program Overview. Artemis Plan. Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

Roberts, B. C. (2019). Cross-Program Design Specification for Natural Environments. Retrieved from https://ntrs.nasa.gov/citations/20200000867

Sternovsky, Z., Robertson, S., Sickafoose, A., Colwell, J., & Horanyi, M. (2002). Contact charging of lunar and Martian dust simulants. Journal of Geophysical Research, 107. doi:10.1029/2002JE001897

Stubbs, T. J., Halekas, J. S., Farrell, W. M., & Vondrak, R. R. (2007). Lunar Surface Charging: A Global Perspective Using Lunar Prospector Data. Retrieved from https://www.nasa.gov/centers/johnson/pdf/486015main_StubbsSurfaceCharging.4070.pdf

Sunpower. The CryoTel Family of Cryocoolers. In Ametek (Ed.).

Taylor, L. A., Pieters, C. M., & Britt, D. (2016). Evaluations of lunar regolith simulants,. Planetary and Space Science, 126, 1-7. doi:https://doi.org/10.1016/j.pss.2016.04.005

Thomas Scientific. (2020). Acrylic Vacuum Glove Box. Retrieved from https://www.thomassci.com/Equipment/Glove-Boxes/_/Acrylic-Vacuum-Glove-Box?q=Vacuum%20Glove%20Box

Wagner, S. A. (2006). The Apollo Experience Lessons Learned for Constellation Lunar Dust Management Retrieved from https://www.hq.nasa.gov/alsj/TP-2006-213726.pdf