Experimental Investigation of Electric Fields for Dust Removal on Solar Panels

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Abstract

The key to future colonies on Mars lies in further exploration and the use of rovers to sustain future habitats. However, the Martian environment is known to be unforgiving and inhospitable. In fact, one of the main concerns in regards to future expansion on Mars is the effects of large scale dust storms. Sometimes these dust storms can encircle the entire planet in a haze of dust (Hille). Specifically, these dust storms pose a threat to a rover's ability to generate power and can be hazardous to any critical rover component. Even a smaller dust storm event can be enough to render a solar panel useless. In fact, both Spirit and Curiosity saw their missions severely affected by a global dust storm in 2007. This dust accumulates on the solar panels and other surfaces on the rover, reducing their effectiveness over time. What makes this dust especially problematic is the fact that Martian dust tends to be electrostatically charged (Hille). These charged dust particles are harder to remove due to the electrostatic attraction forces that occur on surfaces of the rover and solar panels, making them "stickier" than regular dust particles. Overall, it is important to note that the key to sustaining a human presence on Mars is developing a reliable and efficient dust mitigation system. Such a system could help extend the life span of the solar panels and increase the amount of energy generated tenfold. This in turn ultimately extends the life span of the rover. Thus, for future habitats relying on solar energy creation, methods for dust mitigation need to be further explored.

Introduction

Past work with dust mitigation techniques has largely explored the realm of mechanical methods, with the simplest solution being a brush. However, a brush can often scratch the surface of a solar panel and cause more permanent damage over time. Other methods such as vibrating or flipping the panel are potential options, but may not be effective at removing the "sticky" dust particles. We decided to take a less explored avenue and research the use of electrodynamic methods and their effectiveness in dust mitigation. Revisiting the fact that Martian dust tends to be electrostatically charged and understanding that mechanical methods have known to continuously leave dust residue motivated us to explore the use of an electric field. In summary, we set out to investigate whether an electric field could in fact remove a considerable amount of dust to be considered effective and have the potential for further discussion and development.

Problem & Objective

We came into this experiment attempting to analyze how the angle at which a solar panel is set impacts the removal of dust from the panels using an electric field. However, we determined that due to the effects of Earth's gravity already being an aid in removing the dust from the panel, standardizing the experiment with different panel angles would be difficult and not result in any beneficial conclusions. Given the diverse array of particle sizes present in Martian dust, we determined that assessing the impact of increasing particle size on dust removal by a traveling electric field would be more advantageous for the development of this technology. However, due to our lack of quantitative measurement methods in the short period of time we had to conduct the experiment, we ultimately decided that this experiment would be more like a proof of concept, laying the foundation for future experiments that will follow it. The experimental hypothesis posits that electric fields will be an effective method for removing fine dust particles, but larger dust particles are anticipated to present greater challenges in their removal from the solar panel.

Literature Review

We explored a variety of research articles pertaining to dust mitigation methods, and every article shared a common theme highlighting just how important dust mitigation is for the future of space exploration. Though we are focused specifically on Mars and Martian rovers, dust is an ongoing issue impacting optical systems like cameras, thermal surfaces, fabrics for space suits and habitats, valves and linkages, gaseous filtration, and a variety of other factors. Additionally, dust has always been an interference with lunar exploration, and astronauts have given accounts of the great inconveniences dust imposes on missions. Thus, reviewing dust mitigation-related literature helped us realize just how critical of a problem dust accumulation is and how important dust mitigation experiments are to the future of space travel. Conclusively, any gains we can make in dust mitigation technologies will not only aid the exploration of Mars via rovers, but also improve the future of space exploration as a whole.

We began by researching preexisting dust mitigation techniques, and we found these methods largely fell into three categories: mechanical methods, fluidal methods, and electrodynamic methods. Through our research, we found that mechanical methods like brushes and vibrating mechanisms are currently the most widely used approach for dust mitigation. In fact, several Mars rovers have already been equipped with and have used mechanical methods during their missions (Moskowitz). However, there are various drawbacks to these mechanisms including damage to surfaces and inability to remove the finer layers of dust. Pertaining to fluidal methods, using liquid jets, foam, and compressed gasses have been proposed in the past, however there is very little recent information available on this approach. After researching electrodynamic methods, we found experiments using electrodynamic methods were more successful and had more recent focus. Moreover, there seems to be the least amount of accompanying complications with electrodynamic methods. To better understand how to set up our experiment, we researched further into previously completed electrodynamic-related experiments.

We came across an extremely helpful study testing electrostatic dust removal via moisture-assisted charge induction. This experiment had a relatively simple setup that produced meaningful results which provided helpful insight for us while designing our own experiment. For example, this study was able to determine the electric potential difference needed to remove dust particles by balancing electrostatic, van der Waals, and gravitational adhesion forces. We consulted this result to determine what voltage we needed to complete our experiment successfully. Additionally, researchers were able to actively charge their dust particles to better replicate the behaviors of the dust particles that could be found on Mars. Though we ideally would have liked to do the same, due to complexity and limited resources, we were unable to determine a way to charge our dust particles similarly. This study notably did not distinguish between different particle sizes while conducting their experiment. We were particularly interested in dust particle size, so we were able to closely mirror their setup to test particle size. Moreover, this experiment based results off of a small lab-scale prototype that closely aligned with our target size. Thus, referencing their provided list of materials helped us determine what we needed to make our experiment successful (Sreedath). Therefore, this in-depth research into electrodynamic forces was highly valuable in aiding us to create a successful experiment.

Experimental Setup

Since the Martian environment has a low atmospheric pressure and temperature, we planned to use a vacuum chamber to ensure that all conditions stayed the same for each trial of the experiment while also simulating the Martian environment. However, after meeting with Dr. Graber, who is experienced with generating high voltage electric fields for experiments, we were able to determine that a vacuum chamber would not be possible in the time frame of a semester. Additionally, he mentioned that using such high voltages in a low pressure environment similar to Mars could potentially result in glow discharge, where the remaining particles in the atmosphere get charged and essentially “glow” like a lightbulb. This effect would render the electric field useless for the removal of dust, and should be something that is considered in future experiments with this methodology.

To simulate a solar panel, we used ITO coated glass panels that would be identical to the outer layer of the solar panel. To generate an electric field, we used a DC power supply to apply a 15kV voltage to the glass panel, then subsequently attached ground to a 152x127mm copper fiberglass electrode using an alligator clip. With this setup, shown in Figure 1, we were able to manually move the grounded electrode over the glass panel to generate the electric field.

In order to evenly distribute dust of varying particle sizes on the glass panel, we used a strainer with different micron meshes in order to filter out the desired particles as seen in Figures 2 and 3. For this experiment, we used 200µm, 400µm, and 600µm meshes. We also tested with unfiltered dust to analyze the impact that larger chunks of dust had on the effectiveness of this method. While holding the strainer over the glass panel, we filtered regolith by shaking the strainer 5 times to ensure our glass panel had a uniform distribution of regolith, which is shown in Figure 4. We set the glass panel on a blank white sheet of paper to take a “before” picture for qualitative results.

From there, we attached the copper fiberglass electrode to ground and connected our glass plate to a positive voltage. Water pump pliers were used to hold the electrode to assist in moving it over the glass. After turning on the DC power supply, we executed 2 back-and-forth sweeps over the glass panel. Once those had been completed, the DC regulator was turned off, and an "after" picture was taken on another blank white paper.

After each trial, all the equipment was wiped down with a microfiber towel to ensure that there was no excess dust that could impact the results of the experiment. Using the different filter meshes, we were able to successfully complete multiple trials for each particle size threshold.

Challenges and Iterations

We made numerous changes to the experiment, simply trying different approaches to see what would work. Testing showed that charging the glass resulted in a layer of dust tightly adhering to it. To remedy this issue, the glass was grounded and the electrode was charged. However, this caused the voltage to travel through the table, wires, and anything else that was remotely close to the ground. We determined that grounding the panel and charging the electrode would not be effective due to the risk of the charge accidentally making its way into other systems on the rover. Since most of the rover's systems, including the solar panel, will be grounded, our 15 kV charge might flow into other subsystems, posing a significant risk.

Initially, we experimented with a small aluminum electrode. While this electrode performed extremely well with our finer particle size of 200 μm, it had an immense amount of trouble picking up any larger particle size with great success. Another idea was the occasional usage of paper materials such as paper cups and paper to test the effectiveness of the electrode. There was an acknowledgement that the more dust present directly on the electrode, the less effective the electrode became throughout a trial. We believed using the paper materials might enhance the performance of the electrode if used in tandem. Regardless, the aluminum electrode only showed minimal improvement with the addition of paper materials and did not adequately justify the addition of another material into the experiment. One other iteration involved abandoning the electrode entirely in favor of a wire bent in a circular loop and attaching it to the ground alligator clip. Ultimately, we determined the size and material of the copper fiberglass electrode, with no additions, to be the most effective and leaned into its usage to produce our final results.

Results

Based on the data presented in Table 1, we made several key observations out of our experimental results. The copper fiberglass electrode exceeded expectations on its performance as is evidenced by the substantial reduction in regolith residue on the glass panels following each trial. This outcome suggests promising potential of electric fields for various dust removal applications on a rover. However, its limitation is still blatantly prominent as it struggled to produce perfect results on the 600 μm and the unfiltered particle sizes, as there were still splotches of dust left on the panel after these trials. This discrepancy emphasizes the need for further testing into the electrode's performance across varying particle sizes to enhance its overall effectiveness. Conversely, the remaining two trials at 200 μm and 400 μm showcased exceptional performance, leaving minimal traces of dust on the glass panels. These observations underscore both the strong and weak points of the copper fiberglass electrode, highlighting areas for further optimization in future iterations.

Conclusion

From the observations made during testing, we were able to conclude that an electric field is an effective method for removing dust from a surface. While the initial prediction was that the largest particles would be the most difficult to remove, there actually ended up being an extremely fine layer of dust on the glass after every trial. This fine layer tends to be the "stickiest" and thereby the most important to remove using the electric field method. Because the testing showed that the electrode's effectiveness significantly diminishes after it is covered in a layer of dust, combining the electric field method to remove the fine particles with a mechanical method to get rid of the larger dust particles would likely be the most effective way to clean the solar panel.

Testing also revealed some potential pitfalls to the electric field method regarding the longevity of the solar panel itself. In particular, electric arcing happened quite often, especially when the electrode was brought too close to the glass. Prior testing concludes that electric arcing will eventually damage a solar panel, so arcing happening as often as it did during the experiment would significantly impact the lifetime of the solar panel. To remedy this issue, further testing would have to be done to find the "sweet spot" for distance between the glass and the electrode where arcing would rarely occur, but dust would still be effectively removed. An additional factor that needs to be taken into account is whether or not a solar panel can actually be charged with 15 kV without damaging it. While the glass remained unaffected during testing, it would require testing with a solar panel to determine whether or not such a high voltage would truly affect its ability to capture solar energy.

Finally, the practical application of this technology on a rover must also be considered. It is important to note that in low pressure and partial vacuum environments, utilizing such high voltages could potentially result in glow discharge, where the few particles in the atmosphere get charged and render the generated electric field useless. Only further testing in a Martian simulated environment would truly prove whether this would happen on Mars, but it is something to consider when thinking about practical applications on a rover. Additionally, testing revealed that the 10x50mm aluminum electrode was not nearly as effective as the 152x127mm copper electrode, something that could be attributed to the mere size difference between the two. If the same size ratio between the glass panel and the copper electrode was maintained on the rover, a 1.3x.4m electrode would be needed to effectively clean a 425x165mm solar panel, which is the average size of solar panels on previous Martian rovers. An electrode of this size would add a lot of weight to the rover as well as be very impractical to even attach to the rover in the first place.

The science of tradeoffs is certainly something to consider with this dust mitigation method. Rovers are already pushing mass limits as it is, so determining whether this dust mitigation method is even worth it for a rover's lifetime is incredibly important. One way to solve this problem would be to design a secondary rover or probe that has the sole function of cleaning the solar panels on the primary rover. This rover could return back to "base" for charging and cleaning, and would completely eliminate the problem of designing a low mass mechanism to employ the electric field method on the primary rover.

Future Work

Overall, we are satisfied with the setup and results of our initial experiment, as it underscores the potential for further exploration of using electric fields as a viable dust mitigation technique. However, in the future, we hope to refine our experimental setup through iterative enhancements in future testing.

For instance, we want to ensure we have a method for uniform dust application onto the glass panel. While the filters we utilized were sufficient in filtering the regolith, it was difficult to ensure that the application of the filtered regolith on the glass was uniform across the glass and consistent over several trials. For the future, we are considering using a hyper-sensitive scale to ensure that an identical mass of dust is spread onto the panel for each trial.

Furthermore, we struggled with several instances of electric arcing throughout our trials, which we hypothesized could be due to the inconsistent distances from the glass to the electrode, given that we were holding the electrode by hand. To correct this in the future, we want to include a 3D- printed rail and computer controlled stepper motor system in our setup so that the electrode can smoothly glide over the glass at a fixed distance and speed. Further testing can be done to determine the ideal distance at which no electric arcing will occur, but dust removal will still occur effectively.

With regards to the data collection, we aim to integrate a more quantitative method of analyzing our results. Prior to our initial experiment, we had planned on using a scale underneath the glass plate to measure the mass of the plate with dust on it before and after each trial. However, given that we were unable to find a scale that would be sensitive enough for this task, we decided to switch to computer image processing. Using a MATLAB script, we plan to analyze photos of the plate with dust before and after each trial, count the pixels of dust using image processing software, and calculate a percentage of dust remaining on the panel compared to the initial amount of dust in order to further standardize results between trials.

Given that Mars has an average gravitational acceleration of about 3.71 m/s^2, about 38% of the gravity of Earth, we want to incorporate a vacuum chamber in our experimental setup to more accurately simulate the Martian environment and further investigate the effects of glow discharge on our experimental setup. Other minor adjustments that can be made include electrostatically charging the dust with UV light, using an AC wave (sine) as opposed to a DC wave, and using different surfaces on a rover, rather than just glass.

After refining our current experimental setup, we will be able to use a similar setup to explore other related research questions for this topic. For example, we can investigate how changing the size and material of the electrode will affect the amount of dust that is picked up. After initially playing around with our experimental setup, we noticed that the larger copper electrode picked up more dust than the small aluminum electrode. We are still unsure whether this was due to the size difference or material difference, so further testing of this discrepancy would be incredibly beneficial for the most optimal implementations of this methodology on a rover. To investigate this, we can run our experiment with the same dust particle size and a constant voltage with various electrode sizes. All of these are valid research questions that we hope to investigate in the future.

After iterating on our our experimental setup and researching all of these areas within the topic of dust mitigation, we plan to design a low-mass mechanism that will be able to effectively implement electric fields on a Martian rover, using our results and research to ensure the functionality of the rover is not affected by our mechanism.

Works Cited

Hille, Karl. "The Fact and Fiction of Martian Dust Storms." *NASA*, NASA, 26 July 2023, www.nasa.gov/solar-system/the-fact-and-fiction-of-martian-dust-storms/#:~:text=%E2%80%9COnce%20every%20three%20Mars%20years,an%20astronaut%20on%20Mars%2C%20however.

Moskowitz, Clara. "NASA's Curiosity Rover Brushes Mars Rock Clean, a First." Space.Com, Future US Inc., 8 Jan. 2013, www.space.com/19167-curiosity-rover-dusts-mars-rock.html.

Sreedath Panat, Kripa K. Varanasi, Electrostatic dust removal using adsorbed moisture–assisted charge induction for sustainable operation of solar panels.Sci. Adv.8,eabm0078(2022).

Appendix

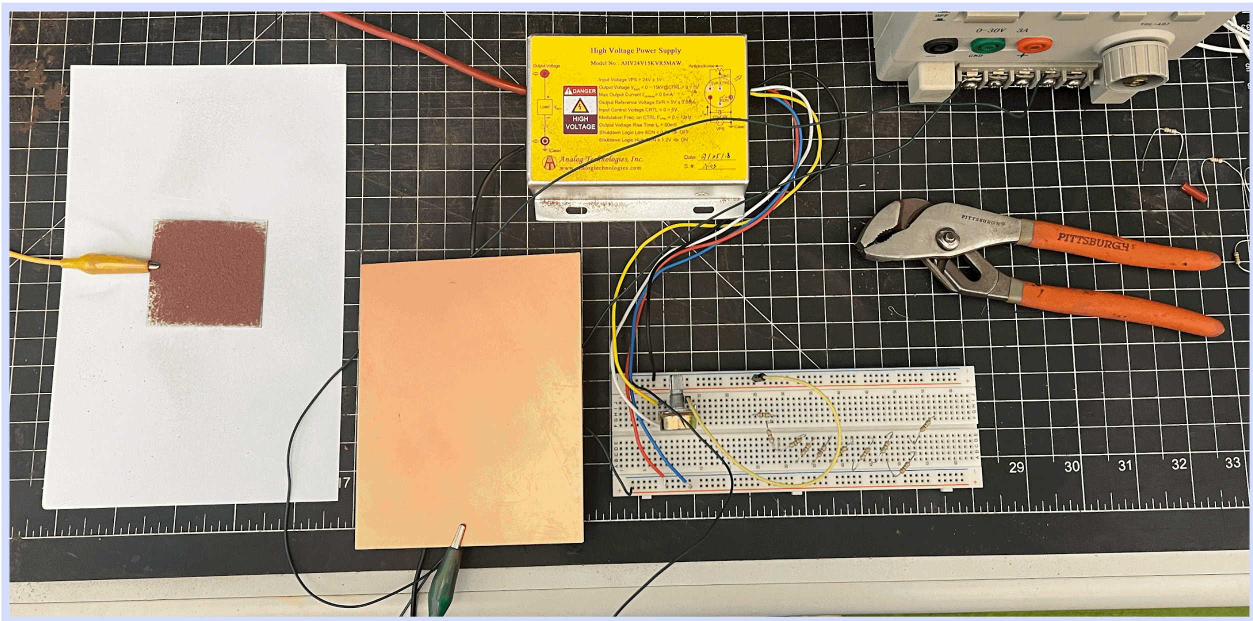


Figure 1: Final Experiment Set-Up

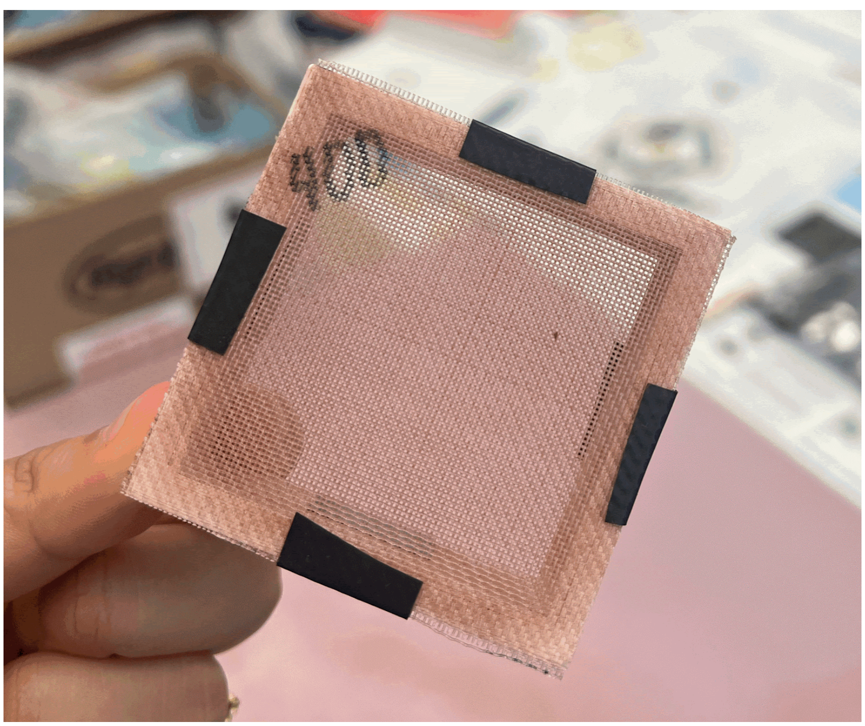


Figure 2: Front view of frame with attached strainer (400 µm)

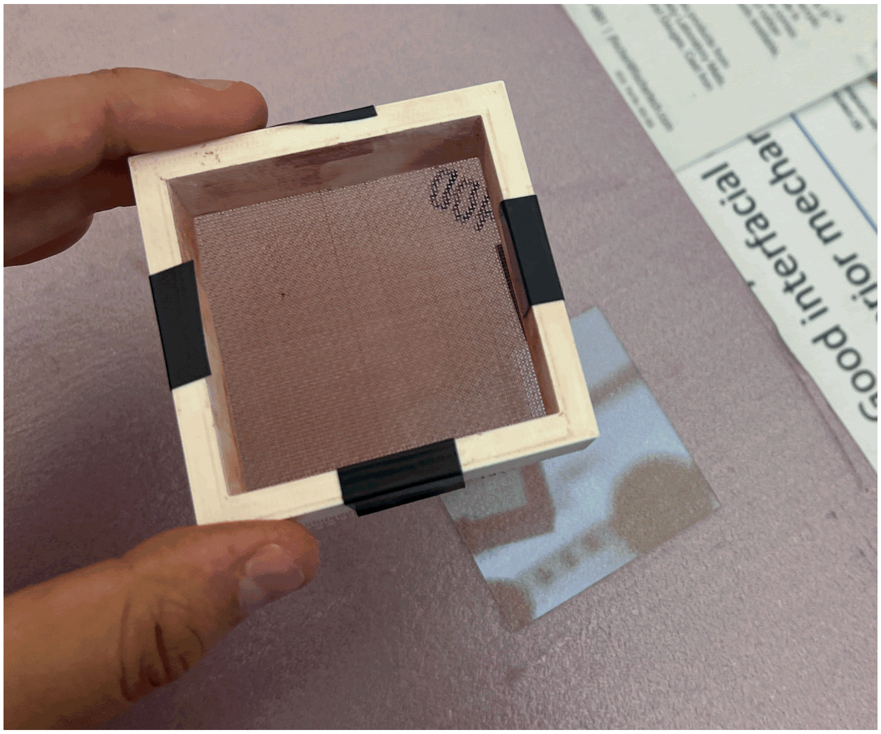


Figure 3: Back view of frame with attached strainer (400 µm)

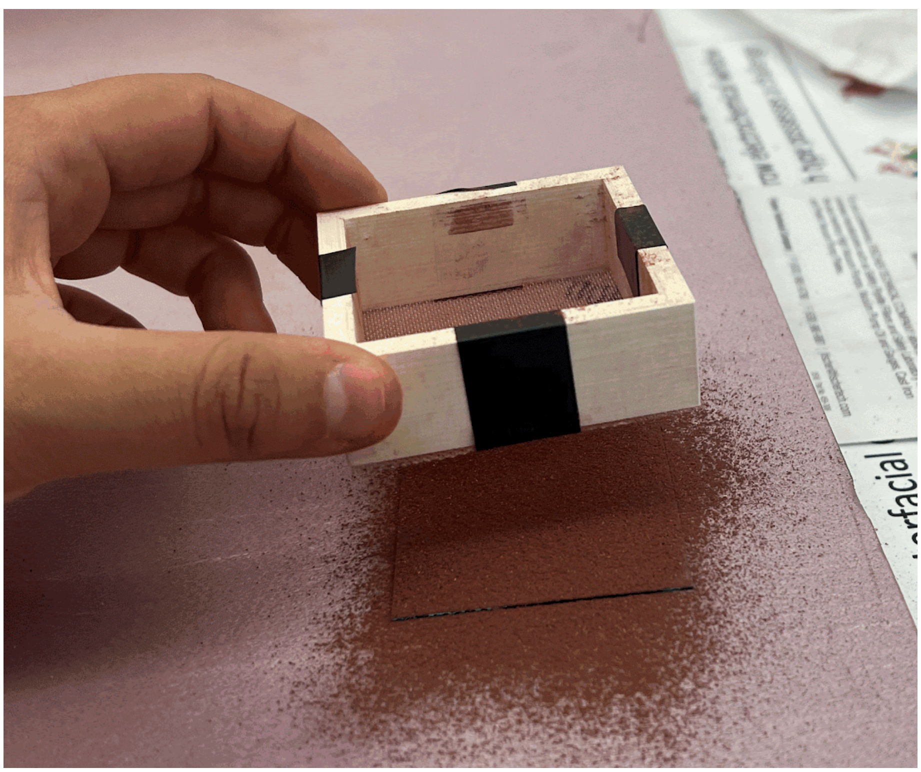
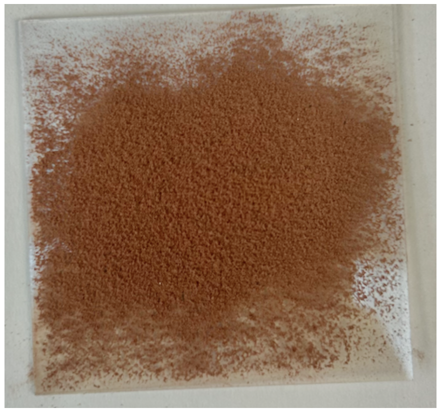
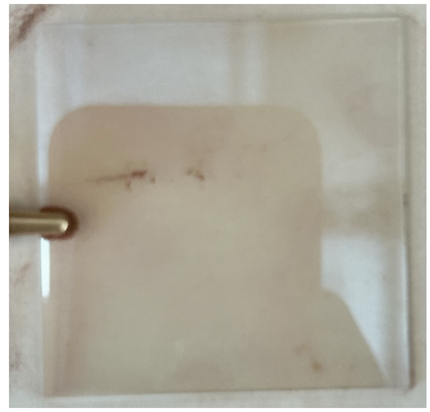
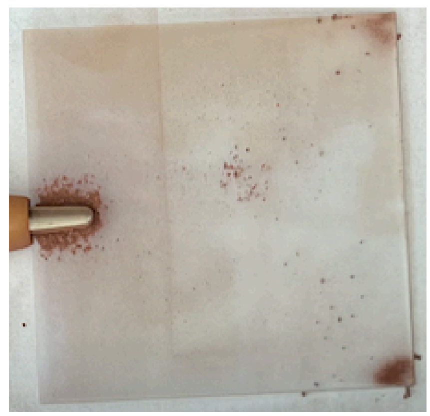
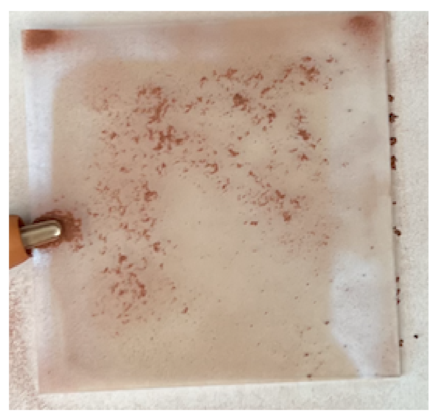


Figure 4: Application of regolith onto glass panel

Table 1: Varying particle sizes and their results after usage of our electrodynamic field.

Particle Size	Before	After
< 200 µm		
< 400 µm		
< 600 µm		

Unfiltered