# DESIGN AND TESTING OF A DEVICE FOR MOON DUST DEPOSITION ON TEST ARTICLES/SYSTEMS


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## ABSTRACT

During this decade, NASA is charged to return humans to the surface of the Moon. One of the most challenging aspects to operating on the lunar surface is the regolith present, which is pervasive and damaging. To support systems design and validation for this environment, the handling and application of lunar simulants onto test articles or systems becomes important, albeit difficult. A device to apply the same amount of dust uniformly was developed in a previous study but was only utilized with Mars dust simulant during that previous project. The current work provides evaluation of this device with multiple lunar simulants, each representing different composition as found at various locations on the Moon's surface. Enhancements to the design and operation of the dust distributor are also described, along with a new digital imaging technique to calculate the percent surface coverage of the dust after deposition. The results support the use of the distributor and improved techniques to provide a uniform coating of dust on test articles and systems.


## NOMENCLATURE, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| ARES | Astromaterials Research and Exploration Science |
| AVG. | average |
| CLAHE | Contrast Limited Adaptive Histogram Equalization |
| cm | centimeters |
| EHP | EVA and Human Surface Mobility Program |
| est. | estimated |

| | |
|---|---|
| g | grams |
| mg | milligrams |
| PLA | Polylactic Acid |
| TDW | total dust weight |
| tsp | teaspoon |
| WG | weight gained |

## INTRODUCTION

With the imminent return of humans to the surface of the Moon, research is underway to evaluate one of the most challenging aspects to establishing a permanent presence. Lunar regolith is damaging to space vehicles and systems, and also poses significant risk to human health. For design and validation in this environment, the handling and application of lunar simulants onto test articles or systems becomes important, albeit difficult. This paper describes a device to apply lunar dust uniformly as was demonstrated in a previous study with Mars dust simulant, including enhancements to the design and operation of the dust distributor. An overview of the early testing is presented along with representative data with multiple lunar simulants. Also, a new digital imaging technique is presented to allow determination of the percent surface coverage of the dust after deposition. The early test results support the use of the distributor to provide a uniform coating of dust on test articles and systems.

## SYSTEM DESCRIPTION

### Dust Distributor Operational Concept

The dust distributor was repurposed from the device developed for the original Mars dust study described in Hollingsworth et. al.[1] The purpose of the unit was to apply an amount of dust uniformly to all test articles. Dust is loaded into a central reservoir and an impeller at the base of the reservoir creates an air/dust suspension. The suspension spreads radially at the chamber top and settles on the test articles below. A second impeller at the base of the tube containing the reservoir can be used to create a co-flow of air to assist in moving the dust suspension into the chamber. Experience in the Mars study indicates this option is not required in practice but may still enhance the uniformity of the distribution. A conceptual image of the distributor design is shown in Figure 1. As in the previous testing, visual inspection of samples showed that dust was distributed with acceptable uniformity and that a single dusting deposits a nearly equal amount of dust by mass on to test articles located circumferentially around the chamber. Again as in the previous testing, it was shown that the deposited dust weight varied almost linearly with the activation time for the impeller given the same initial dust volume in the reservoir.

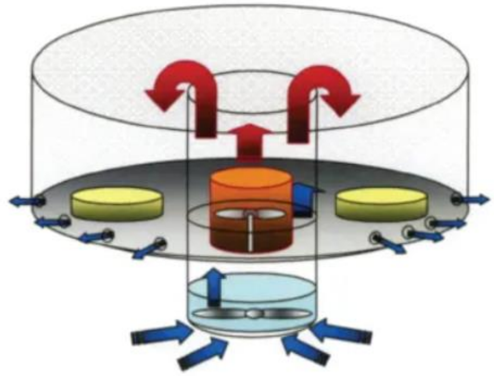

**Figure 1. Schematic depiction of the dusting apparatus is shown from a published NASA Tech Brief[2].**

Dust Distributor Experiment Hardware

This test project began with intent to use equipment inherited from the previous Mars dust study without modification. However, some of the original hardware was damaged and therefore modifications were needed to repair and/or alter the apparatus for the current work. Most of the alterations were focused on ensuring consistency in the dust distribution, such that there would be homogeneous layering of the Moon dust simulants onto the test articles/components placed within the chamber. Evaluation from the work of Hollingsworth et. al. [1] using Mars simulant showed spatial variations ranging from ±4% at best to ±14% at worst for the highest dust loadings by mass.

The original hardware is also described in a NASA Tech Brief[2] with the major pieces being an aluminum platform on which test articles are placed, a central Plexiglas aerator tube with fans to setup convective flow and allow for dust aeration, and a chamber for containment. Because the original containment chamber was damaged, a new one was 3D-printed out of Polylactic Acid (i.e., PLA). This chamber is 2 ½' tall with a 2' diameter, open-ended "barrel" and a lid made of clear acrylic. The lid has a 6" hole in the center where a 3D-printed cone is inserted upside-down; this acts as a diverter for dust propelled into the container from the fan system, creating a vortex flow and distributing the dust. For the current evaluation of dust uniformity, the actual test articles were replaced with 2.5" diameter cardboard disks suspended above the platform by plastic tripods. Overall these test tables looked like "pizza tables" used to prevent the lid on pizza boxes from caving in or touching the surface of the pizza inside.

While the hardware was successful in the past studies using uniform fine-grain Mars simulant, issues were identified in preliminary testing with the current Moon dust simulants, including a lack of consistency in setting up the system for each test, an air leak in the barrel lid that disrupted the distribution flow, loose-fit of the diverter cone into the lid, and consistency of the airflow pattern created by the fan system. Hardware changes were made to address consistency issues in the system, and images of the modifications are shown in Figure 2. First, a new diverter cone was 3D-printed to fit exactly in the lid opening and eliminate 2 ½ inches of possible play. Additionally, registration markers (i.e., yellow stickers) were attached to the topside of the diverter and lid, and on the sides of the lid and barrel. These registration marks were used to ensure consistent orientation of the removable parts of the system. Also in early testing, a bias in the distribution of Moon regolith was noticed. Examination of the lid led to a discovery of an air leak in the acrylic lip seated in the barrel. This was rectified by lining the inside of the acrylic lip with standard silicone rubber weatherstripping. The final modification to the testing system was an added 1½" tall ring with the same radius of the barrel, printed out of PLA and placed at the bottom. This vent ring had ¼" holes equally spaced around its circumference to equalize the pressure gradient in the airflow from the center to the outer barrel wall, thus supporting distribution of the dust prior to its deposition onto the test articles below.

**Figure 2. Images show the dust distributor component modifications.**

One final hardware addition was made to mitigate test operator issues. The test tables were light and difficult to handle, and it was not uncommon to drop at least one while the tables were being extracted for weighing during a testing series. To remedy this, a hand-held device (a curved spatula with end resembling a spork, also shown in Figure 2) was developed to aid in removing and transporting the test tables. Its flat grab-end was designed to mate exactly with the underside of the test tables, and the curved handle allowed easy insertion and removal from both the barrel and from the enclosed weight balance that was used for mass measurements.

Digital Imaging System for Percent Coverage Measurement

A new system for the measurement of dust coverage, as a percentage of surface area covered/obscured, is in development. The current configuration uses an XIMEA XiC camera with a resolution of 12 megapixels, a custom LED lighting arrangement, and a custom 3D-printed acrylic enclosure. The samples are presented on standard 2.53 cm by 7.62 cm microscope slides that have been placed in the dust distributor apparatus alongside other test articles. Each slide is removed from the dusting apparatus after coverage and imaged. The pictures are then processed using Python and OpenCV and passed through a Contrast Limited Adaptive Histogram Equalization (CLAHE) routine. Typically, in global thresholding, an arbitrary value is used as a threshold. Here Otsu's Binarization method is used to automatically determine the threshold value. Figure 3 shows a sample image of a dusted slide.

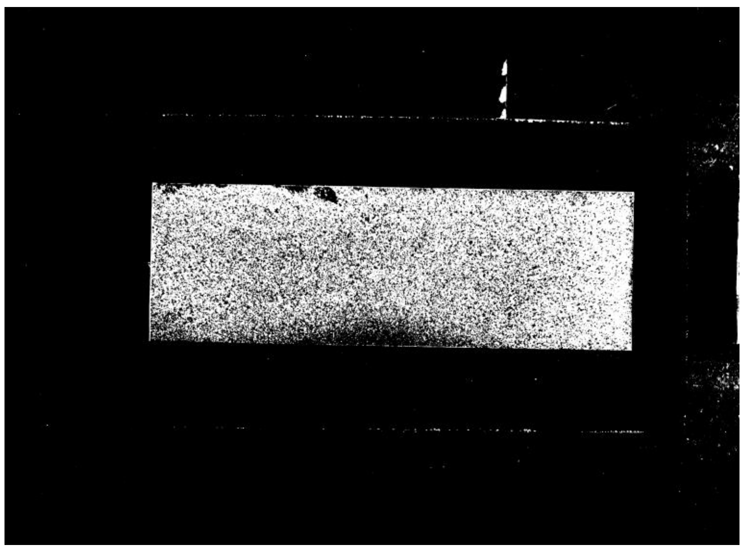

**Figure 3. Sample image after passing through the CLAHE algorithm.**

**TEST PROGRAM OVERVIEW**

While the dust distributor hardware was shown to provide reasonable results during the former study, it was never tried with Moon dust simulant(s) until the current work. The original hardware was repaired/modified as described and then tested with variations, such as different amounts of dust loading in the aeration tube, use of different lunar simulants with varied composition, and modified/altered procedures as the testing progressed based on lessons learned. The hardware was also modified to reduce the bias created by the influence of leaks in the chamber. As an example, initially the lower fan was not activated and only the aeration fan was energized. It was determined that both fans should be used to support the injection of the dust into the distributor containment, which is especially helpful for simulant with larger particulates. Furthermore, steps were added to ensure a proper seal and alignment of the acrylic lid. The general procedure based on early testing includes steps to ensure the distributor hardware is clean and dry, measurement of the simulant to the selected loading mass, weighing the “pizza tables” prior to testing and after each dusting increment, operation of the fans to loft the dust and then waiting for its natural deposition onto the test articles below. Various increments of dust settling time were tested to determine what the minimum required time was for most of the dust to settle.

## TESTING RESULTS

### Controlled Simulant Mass Deposition onto Test Articles

The primary object of the dust distributor is to uniformly coat test articles with a selected simulant. Visible inspection can be used to coarsely assess the uniformity, as seen in Figure 4. While visual inspection shows acceptable uniformity, quantification of the amount of dust deposited on to a surface of interest is needed to analyze/correlate degradation effects. Use of the dust distributor as described allows for measurement of the dust accumulated via the total mass gained per test cycle. For test articles placed at an equal distance circumferentially around the aluminum platform, the increase in mass with each dust cycle should be equivalent if there is ideal dust distribution without influences from external factors.

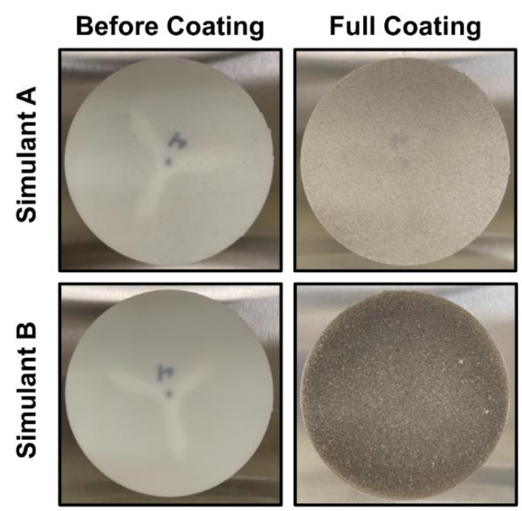


**Figure 4. Images shown of test surfaces before and after coating with two different lunar dust simulants.**

Testing was completed over periods of weeks and some representative initial results are shown in Figure 5. This data was collected using the same initial mass loading (est. 1 tsp/0.298 mg) of simulant placed into the aerator tube for each of 30 loading cycles. Two test runs composed of 30 cycles each were executed with two different lunar dust simulants, NU-LHT-4M and LHS-1D. Both simulants are general use, lunar highlands simulants meant to represent the Moon’s South Pole region. Additional information on the simulant sources, composition, recommended usage, etc. can be found via NASA[3].

The results in Figure 5 show the average dust distribution by mass (in mg) per loading cycle over 30 cycles per test (i.e., the test tables each have an assigned number based on location relative to the distributor system). In addition, the averaged total dust weight (TDW) gained (in g), across all eight test tables, per each test cycle is plotted.

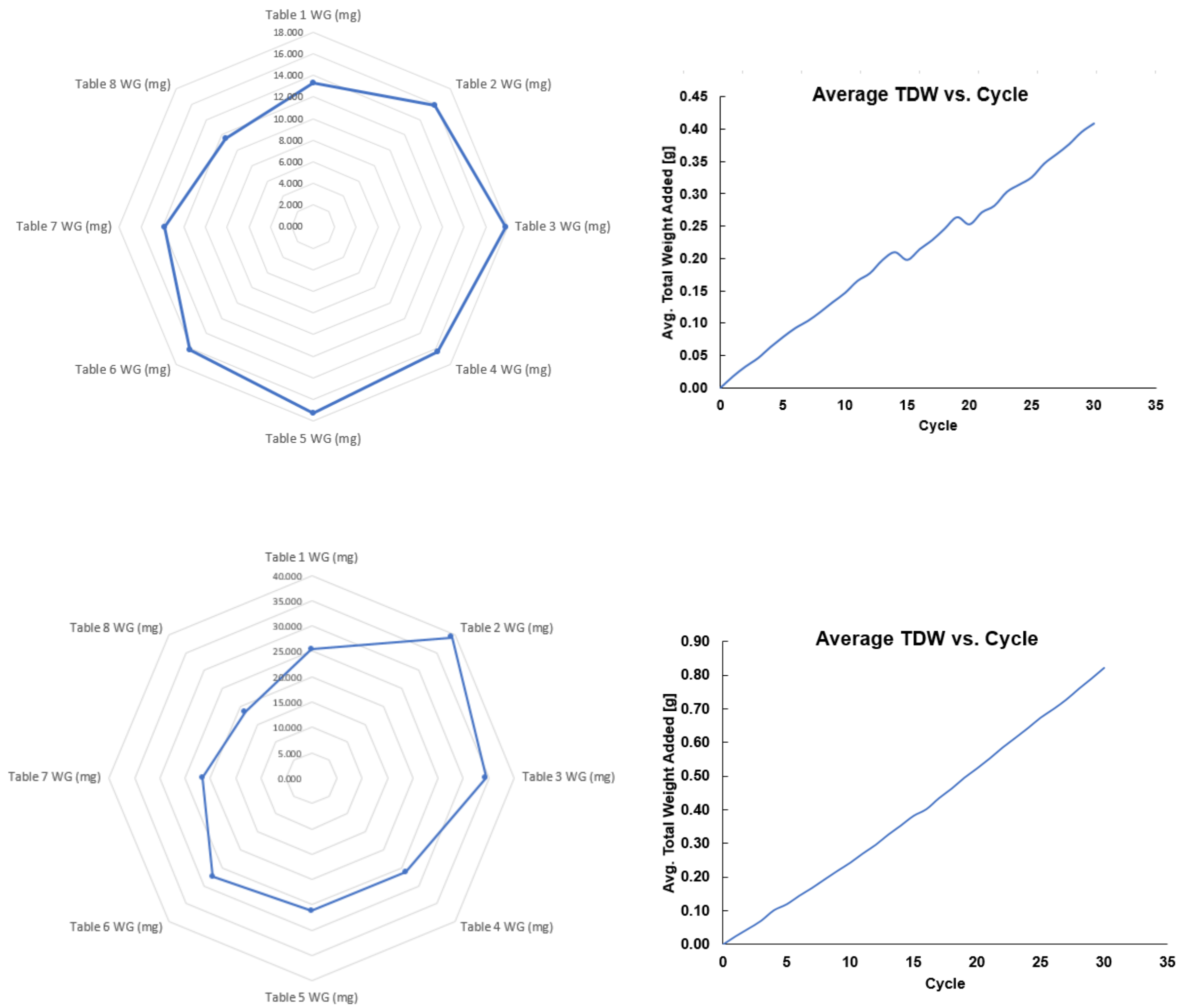


**Figure 5. Graphs of average dust distribution by mass per dust loading/test cycle based on orientation/location on the test platform and averaged total dust weight (TDW) gained per test cycle/operation for two lunar simulants: LHS-1D (top) and NU-LHT-4M (bottom).**

These initial test results provide some key insights, including that the distributor will perform differently for various simulants which can be attributed to varying simulant properties. This is largely due to composition. The LHS-1D is a fine dust whereas the NU-LHT-4M has texture similar to sand or finely ground rock. When testing the NU-LHT-4M, larger solid particulates did not exit the aerator/fan containment immediately on activation but were visualized “sliding” up the side/wall and then ejecting with help of the lower fan airflow (i.e., the aeration fan was not powerful enough alone to loft the larger particulates). Another difference is that more mass was deposited on average per test cycle for the NU-LHT-4M. This is attributed again to composition of the simulant, where not only is there a density difference, but the very fine LHS-1D created a disperse dust “cloud” in the containment and took a longer time for fine dust deposition onto the test tables below. Another finding of early testing is that there seems to be bias in the deposition of the dust, seen in both the LHS-1D and NU-LHT-4M concentric graphs in Figure 6. This representative data suggests the bias is more pronounced in the rougher simulant, although there is not enough data to be definitive on the primary cause for bias. Some contributing factors though are likely the air flow pattern out of the aerator tube, the larger particles in a simulant that would not disperse uniformly, leaks or lack of sealing of the distributor containment/lid, and/or test operator error. During many test runs as mentioned previously, a significant source of error occurred when the test stands (i.e., “pizza tables”) were tipped or dropped during transfer to/from the weight scale. For the very small amount of dust being measured, loss of any quantity can significantly skew the averaged data, and hence the development of the “sporkatula” as described before.

Another significant finding of early testing is seen in graphs of average total weight added with each test cycle. Preliminary results show that the deposited dust weight varies linearly with additional dust loading/distributor operations given the same initial dust volume in the reservoir. The two perturbations in the LHS-1D TDW graph shown in Figure 5 correlate directly to a “pizza table” being tipped/dropped. Table 4 was tipped over after cycle 14 and Table 8 was tipped after cycle 19, affecting the averaged overall weight gain calculated at that point. However, the linearity resumed after those perturbations. The distributor exhibits an average dust distribution deposition control of 1.352 $mg/cm^2$ and 0.764 $mg/cm^2$ (measured for the surface area of the test tables) for NU-LHT-4M and LHS-1D, respectively. These graphs are significant as they serve as course calibration curves for the specific simulant in the dust distribution system, where a specific amount of dust deposition might be selected for coating/loading on to surfaces/components on the platform. While there is limited data from early testing, a more rigorous study can be undertaken to refine the dusting hardware, procedures, etc. to obtain more accurate calibration data in support of future testing.

Simulant properties, such as grain size and density, heavily influence the overall dust distribution. Simulants with larger grains present tend to have increased outliers and, therefore, decreased dusting control due to the inconsistent distribution of those larger particles. Meanwhile, simulants with a smaller average particle size and a tighter particle size distribution tend to result in more consistent dust distribution. Consistent dust distribution is measured in dust mass gained per table per dusting cycle. Testing with LHS-1D yielded a much smaller error when measuring dust mass gained cycle to cycle when compared to the latest data collected for NU-LHT-4M (average standard deviation and standard error were nearly double for NU-LHT-4M). Refer to the radar graphs below in Figure 6 which show a greater dust distribution bias and increased number of outliers for NU-LHT-4M (left) when compared to LHS-1D (right). Each colored polygon on the graphs represents distribution across the tables (numbered according to relative position in the system) during one cycle of dusting (both graphs consist of data from 30 cycles of dusting).

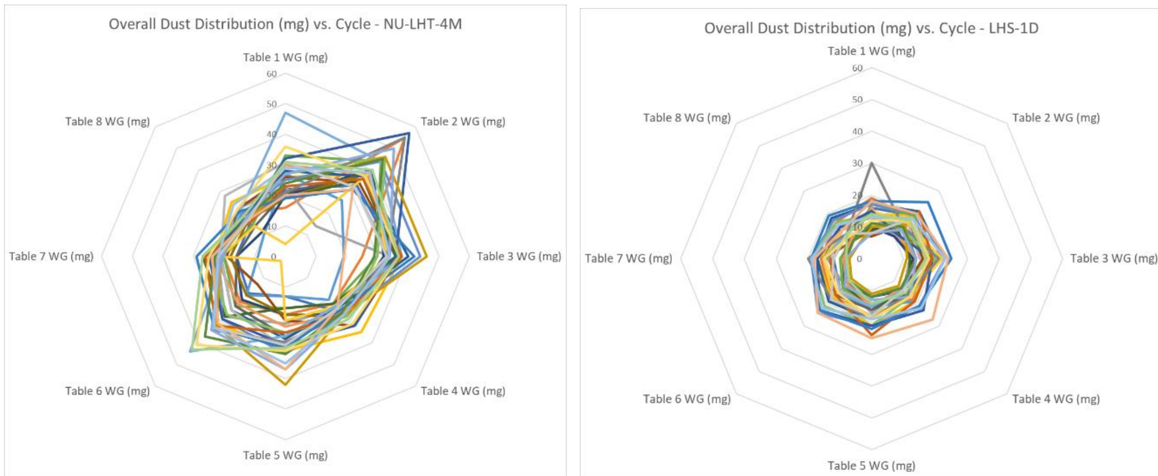


**Figure 6. Radar graphs display the dust distribution across all 8 test tables for each cycle of dusting. Measurements are in mg and each graph contains 30 cycles worth of data.**

Digital Imaging Technique to Estimate Percent Dust Coverage

After the CLAHE processing described previously is completed, the images are evaluated by cropping to a region of relatively uniform dust coverage and then highlighting the dust and background (by coloring it blue). A sample is shown below in Figure 7. For the selected area of coverage, the pixels of dust are counted and compared to the total pixels.

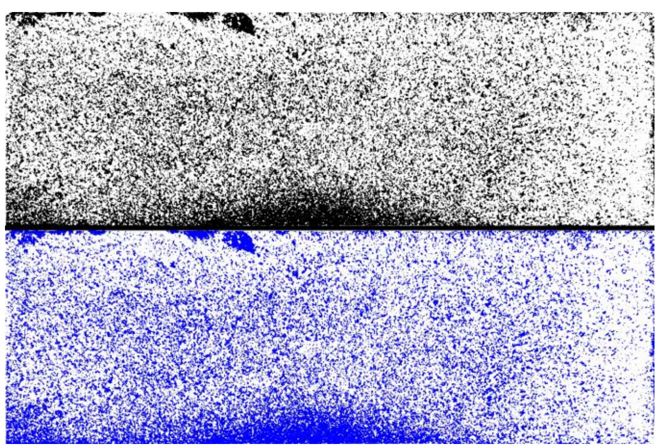

**Figure 7: A cropped image after the CLAHE Algorithm is applied (top), with dust (white) highlighted on the glass surface (blue).**

Early results are provided for seven dusted slides, with the algorithm run based on different crop regions. Multiple cropped images were evaluated due to sample handling and other issues that may have led to non-uniform coverage on the glass slides. A full image shown in Figure 7, a large crop that is approximately ~50-70% of the total surface area, and a small cropping that is approximately ~20-25% of the total area were all evaluated for the seven samples. The results can be seen in Figure 8. There is increasing coverage area with the sample number. This corresponds to increase dust loading as the samples gathered more dust with each dusting cycle completed. For the initial loading values, 1 to 3, the full image over-predicts the amount of dust loading. The lighting and possibly the arrangement of the slides played a role in this result likely because the right side of the images have more dust than the left due to a gradient produced from the dust distributor. The large and small crops were near the left side of each slide, and these match well across all loading values. Another interesting result is for loadings 6 and 7, the coverage does not significantly vary indicating that the increased loading of dust may be building vertically as the coverage approaches 100 percent.

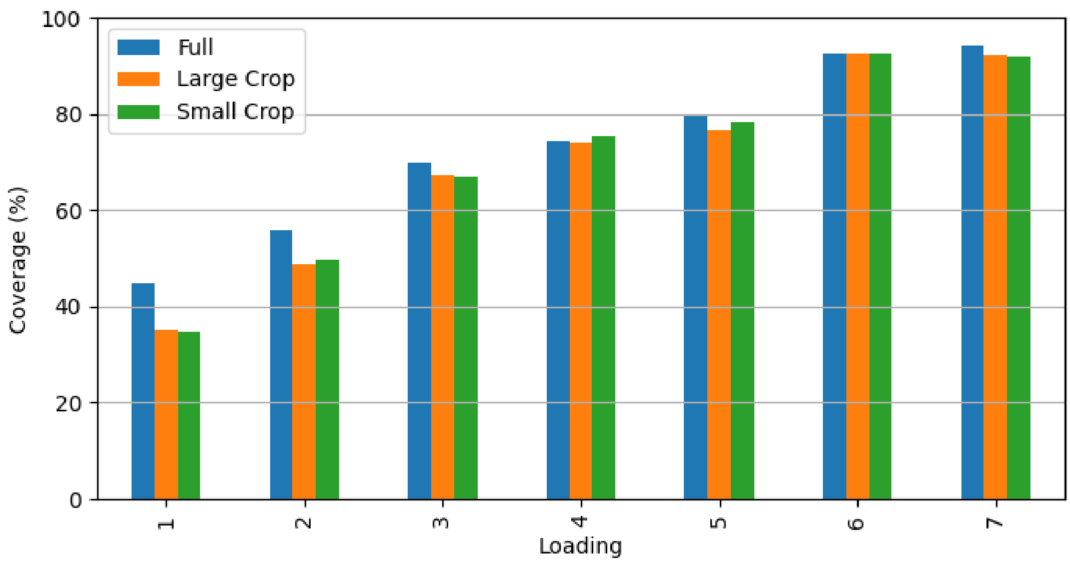


**Figure 8: Dust loading versus coverage for various crop sizes are shown for dusted samples, with increasing dust loading.**

## CONCLUSIONS

Techniques to apply lunar regolith uniformly on test articles and quantify the associated dust coverage have been presented. Representative early results support the use of the dust distributor device to provide uniform coating onto test articles and systems. Sample results using the digital imaging hardware and processing steps also show promise to quantify dust coverage as a percent of total surface area. Further development and validation testing of the hardware and techniques described are recommended to support future space missions to planetary bodies where surface regolith is present.

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