Material Damage from Impacts of Lunar Soil Particles Ejected by the Rocket Exhaust of Landing Spacecraft

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Abstract. *This paper details the experimentation of lunar stimulant sandblasting. This was done to understand the damage that landing spacecraft on the moon will have to a permanent lunar outpost. The sandblasting was done with JSC-1A onto glass coupons. Correlations between the velocity and the damage done to the glass were not found. Reasons for this and future analyses are discussed.*

I. Introduction

One of the lesser known problems associated with establishing a lunar outpost has to do with the plume effects of Lunar Landers. We experience these plume effects here on earth every time we launch something into space. The launch pads go through tremendous strain as the rocket plumes push with enough force to accelerate themselves into orbit. Bricks from the launch pad actually get hurled farther than half a mile away and have enough momentum to break through chain-linked fence, (Image 1). This violence is not that big of a problem on earth where we can rebuild the pad and replace the fence, but on the moon, where supplies are limited, the problem becomes evident.

Image 1. Shuttle Plume Effects. *This fence is located half a mile away from the launch pad. The hole in the fence was caused by a piece of the launch pad being ejected at very high speeds during liftoff.*

When Lunar Modules land on the moon, lunar regolith gets ejected at very high speeds. There is evidence that these particles move at speeds between 1.5 and 2 kilometers per second. Compared with the escape velocity of 2.7 kilometers per second at the surface of the moon, these particles are moving extremely quickly. Add this to the fact that since there is no atmosphere on the moon, there is no air resistance to slow these particles down, and you find that the particles could potentially circle the moon and land at the feet of the Lander. The particles will end up sandblasting anything in their way. During the Apollo missions to the moon, the plume effects did not pose much of a problem. What makes this research relevant now for the Constellation Program is that we want to establish a lunar outpost. The last thing we want to do when we put hundreds of millions of dollars worth of technology on the moon is to sandblast it every time we land there.

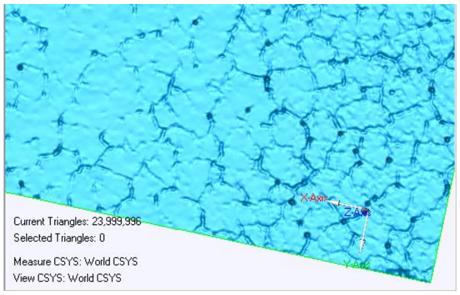

Image 2. Surveyor 3 Scanning. *This is a portion of the scanning done to one of the Surveyor 3 coupons. The little impacts were caused by lunar regolith being ejected from the Apollo 12 Lunar Module plume.*

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Evidence that this sandblasting is a reality can be found from Apollo 12 mission. The Apollo 12 Lunar Module landed on the moon about 155 meters away from Surveyor 3 and collected samples off the surveyor. Analysis of these coupons revealed that the side of the Surveyor facing the Lunar Module was pitted with hundreds of tiny holes thought to be caused by lunar dust ejected from the Apollo 12 Lunar Module plume [3]. (Image 2.) This is evidence that a lunar landing is quite violent. The purpose of our experimentation is to show how abrasive lunar regolith is and how destructive it will be if we do not account for the problem on the moon.

Our experiment consisted of using a sandblaster to shoot lunar stimulant at different materials to try to associate particle velocity and the damage the particles cause. Along the way we also wanted some information about sandblasting, namely using the different sandblasting pressures to estimate the velocity of particles of different sizes. We sandblasted glass with JSC-1A, a lunar regolith simulator. This stimulant is highly cohesive, just like lunar regolith. The particle size distribution of JSC-1A matches very closely to the particle size distribution of lunar regolith samples.

II. Velocity Tracking

For our experiment to work, we needed a way to track the velocity of individual particles accurately and efficiently. This is important for directly comparing the velocity of the particle to the damage of the particle. We needed something that would be quick, so that we could perform many tests, something accurate, so we could get the best possible data, and something efficient, so that it would be worthwhile to use it.

A. Laser-Sensor Design

To track the velocity of the particle, we used a set of two high-speed, large active area FDS 100 Si Photodiodes across from two line generating lasers. The particle would pass through each laser light sheet and make a shadow upon the photodiodes. The voltage emitted by the photodiodes would be tracked through the use of an oscilloscope. We set up the photodiode circuit (Fig. 1) so that the output voltage would show the change in light to the sensors. In this way, the voltage peak across one sensor would correspond to the voltage peak of the second sensor, and we could use the time delay to calculate the velocity of the particles. This would also cause the amount of light used or the amount of background light to affect only the amplitude of the peak and not the vertical position of the steady state.

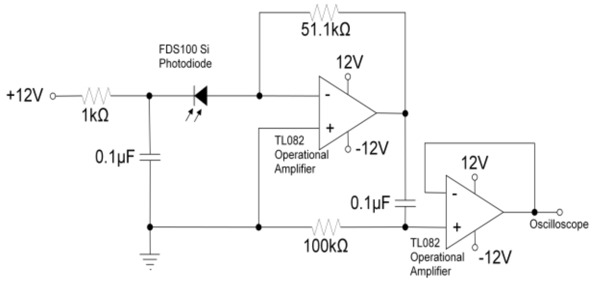

Figure 1. Photodiode Circuit. *This is how we set up the circuit for each photodiode.*

B. Laser-Sensor Housing

In order to hold the sensors, the circuit, and the lasers, we built an adjustable housing for it (Image 3a, 3b). The design we chose sits on the sandblasting platform independent of the gun. This allows for vertical and rotational adjustments on the gun relative to the laser sensor unit. The lasers are mounted on one side with the ability to rotate for adjustment. They also have minimal freedom in the side to side, up and down direction for fine adjustments. Opposite the lasers, the sensors are mounted onto a rotating disk. The rotating disk has its axis of rotation directly opposite the first laser. In this way, we could align the first sensor horizontally into the beam of the first laser and vertically across from the stream of particles. The horizontal placement of the second laser would automatically be taken care of since the sensors and lasers are at a fixed distance from each other. The rotation of the disk would facilitate the vertical adjustment of the second laser without excessively changing the first sensor's alignment. This makes for quick and accurate alignment of the sensors and lasers.

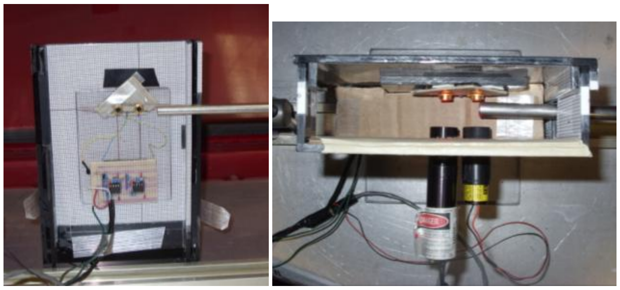

Image 3a, 3b. Laser-Sensor Housing. *These images show the side view and the top view of the Laser Sensor Housing. The lasers are opposite the sensors with the path of the particles out of the gun directly between them.*

Other features of the laser-sensor housing include the removable sides. The laser portion of the housing can be removed to allow a level look at the sensors relative to the gun. This makes vertically adjusting the sensors with relation to the gun accurate on the first try.

III. Adjustments to the Laser Velocity Tracker

In order for the sensors to track the shadow of the particles, we chose to use line generating lasers instead of point lasers. This way, the particle can be shot out of the gun a little higher or lower than center and still cast a shadow on the sensor. If we used a focused point laser, the particle would have to pass that particular spot for each laser. This is highly improbable. By turning the line generating lasers so they make a sheet orthogonal to the barrel of the gun, all the particles will pass through the sheet and make a shadow. One unavoidable disadvantage that we have to accommodate for is the size of the barrel of the gun compared to the size of the sensor. The barrel of the sandblasting gun is 6.4 mm in diameter, and the sensors are squares with about 4.50 mm edges. In order to make the most use of the sensors, we rotated the sensors 45^o so that we could increase the usable length of the sensor to about 6.36 mm. In addition, the laser line expands the farther out it goes. If the laser is too close to the gun, part of the nozzle of the gun may not have light for the particles to pass through. This would mean that the particles would not leave a shadow and we would not be able to track the velocity. Just as important, if the sensors are too far away from the gun, the shadows could be projected off the sensor as the laser light expands. Depending on where the particles come out and where the lasers and sensors must be placed in relation to the gun, it may not be possible to track enough velocities to make the apparatus worthwhile.

A. Laser Placement

To find out the minimum distance the lasers need to be from the gun so that all the particles leaving the gun would pass through the beam, we projected the lasers two different distances and then measured how long the laser line was. We assumed that the line was expanding at a constant rate and then we calculated how fast the laser was expanding. From that, we calculated how far away the laser would have to be from the barrel of the sandblaster to ensure that any particle leaving the gun will encounter the light sheet. The following results were found: The first laser must be placed at least .35 mm away from the nozzle, and the second laser must be placed at least 5.33 mm away from the path of the nozzle.

B. Analysis of Particle Paths with Application to Sensor Placement

The following experiment was designed to determine where particles of different sizes and velocities come out. In order to see where the particles come out of the sandblasting gun, we decided to utilize a high speed camera. The camera would be set up perpendicular to the vertical and to the barrel of the gun. We picked out 6 different particle sizes at 3 different sandblasting air pressures. We dropped these particles a pinch at a time into the sandblaster so that we could consolidate the different data set into a single video each. When we had collected the videos, we went through them frame by frame and recorded the position of every particle that showed up on the camera. This gave a general idea of where the particles tend to be when they are sandblasted. (Figure 2).

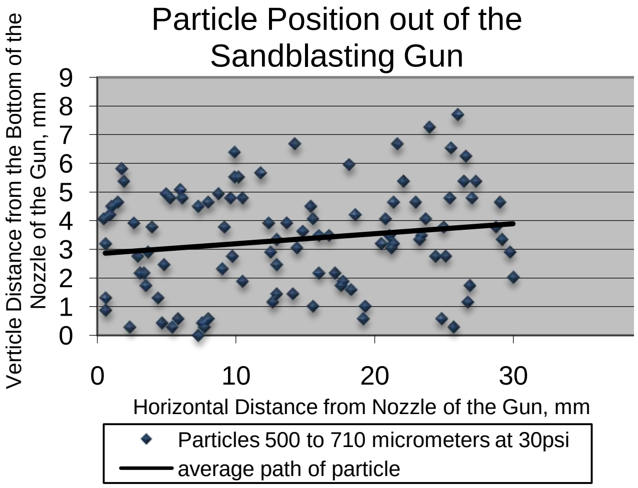

Figure 2. Particle Position. *This graph shows the position of the particles captured by high-speed camera coming out of the sandblasting gun at 30 psi. The particles range in size from 500 to 710 micrometers.*

We found that the smaller particles came out of the gun at all heights, but the larger particles mostly left the gun at least 1 mm from the bottom of the barrel. We also found out that by rotating the sensors 45^o so that the sensor would be taller vertically, we should be able to get velocity readings on 85% of the smaller particles and about 88% of the larger ones. Assuming the sensors are close to the gun, this predicts more than enough hits to make the apparatus worthwhile.

C. Oscilloscope Settings

To get the information we need, it was necessary to configure the oscilloscope. We accomplished this through trial and error. A complete set of instructions have been compiled as a manual to the laser sensor velocity tracker. One important oscilloscope setting to note is the acquisition mode. In order for the oscilloscope to display the quick voltage changes associated with the particle shadow, the oscilloscope must be in “Peak Mode”. This will pick out the distinct voltage peaks from each particle. Though no tests have been conducted, other acquisition modes may be beneficial with other particle sizes under other circumstances. For example, an average value acquisition mode may be ideal for clouds of very fine particles.

We find the time delay of the particle passing from one sensor to the next by measuring the change in time off the oscilloscope. We do this by moving the cursors to the peak of each wavelength and reading off the seconds in between (Image 4). When we have a time, we take the distance between the sensors and divide that by the time to get the average velocity of the particle as it passed the sensor.

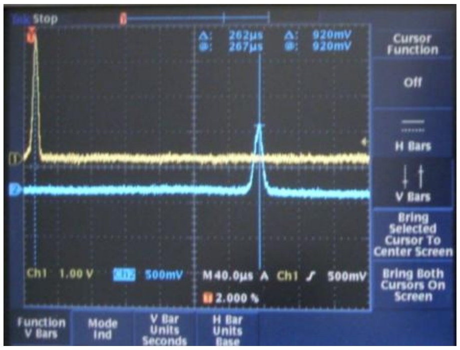

Image 4. Measuring Time off the Oscilloscope. *The vertical cursors are placed at the peak of each wave. These peaks indicate when the particle passed by each sensor. In this picture the time it took for the particle to move from one sensor to the next was 262 microseconds.*

D. Error Associated with the Laser Velocity Tracker

Some error is associated with the laser-sensor apparatus and it should be noted. The first type of error associated with the device has to do with the laser alignment. If the lasers are not directly opposite the sensors, the distance the particle travels from one recording to the other may be less or more depending on whether the lasers are slightly pointed inward or outward respectively. In addition, if the laser light sheets are not parallel, but tilt together one way or another, the distance the particle travels from one recording to the next will also change. This error should not have a huge effect on the velocity of the particles because we do not expect the misalignment to be too severe. The second type of error associated with the laser sensor velocity tracker has to do with the path of the particle. If the path of the particle is not completely straight, the distance from the first laser light sheet to the second would be greater than the recorded distance and would affect the velocity measurement. Though we cannot directly straighten out the path of the particles out of the gun, this problem is mitigated by the distance the sensors are from one another. We placed the sensors so they would be about 2 cm away from each other. If the path of a particle is angled more than minimally, the particle will not cast a shadow on the second sensor, and no data will be collected. Though some error is associated with this, the problem keeps itself in check.

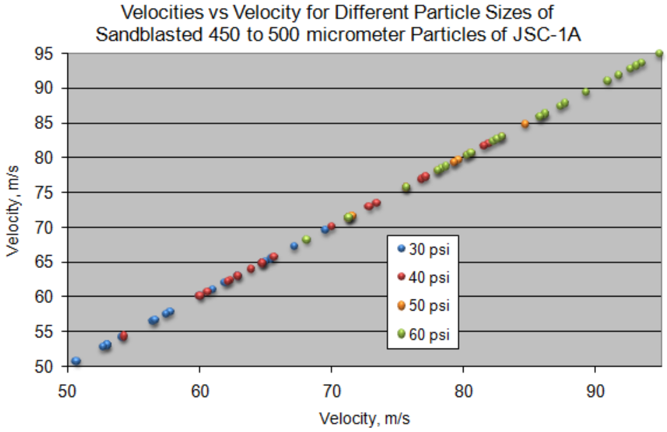

Figure 3. Visual Velocity Graph. *This graph shows exactly where there are gaps in the velocity data. Since we cannot pick and choose exactly what velocity to use, we reference this graph to see which velocities we should be going for to acquire a more complete data set.*

Other error associated with the device is that it gets the average velocity over the distance between the sensors and not the instantaneous velocity of the particle when it hits the material being sandblasted. No experimentation or analysis of the acceleration of the particle as it travels to the material has been conducted. The final source of error discussed here is the human error associated with manually finding the voltage peak of each sensor on the oscilloscope. The peak point is not always evident to an accuracy of more than 1 micrometer. There are also oscilloscope limitations that restrict the accuracy of the reading to greater than about 1 micrometer. This error could cause the time delay to be off by a couple microns which in turn would slightly affect the velocity reading of the device.

IV. Sandblasting

Sandblasting consisted of dropping one particle at a time into the sandblaster, recording the velocity measure, and labeling the impact. In this way we can compare the velocity directly to the amount of damage onto the material. Before testing began, we sieved the JSC-1A to different ranges of particle sizes and chose five different sizes to sandblast: 450 to 500 micrometers, 500 to 710 micrometers, 710 to 850 micrometers, 850 to 900 micrometers and 900 to 1000 micrometers. All these particles are relatively big for the average particle size of JSC-1A. The velocities at which we are able to sandblast particles is significantly lower than the velocities seen on the moon. Our velocities range from 50 to 90 meters per second. We got velocity measurements for about 260 impacts of the various particle sizes. We chose to sandblast glass.

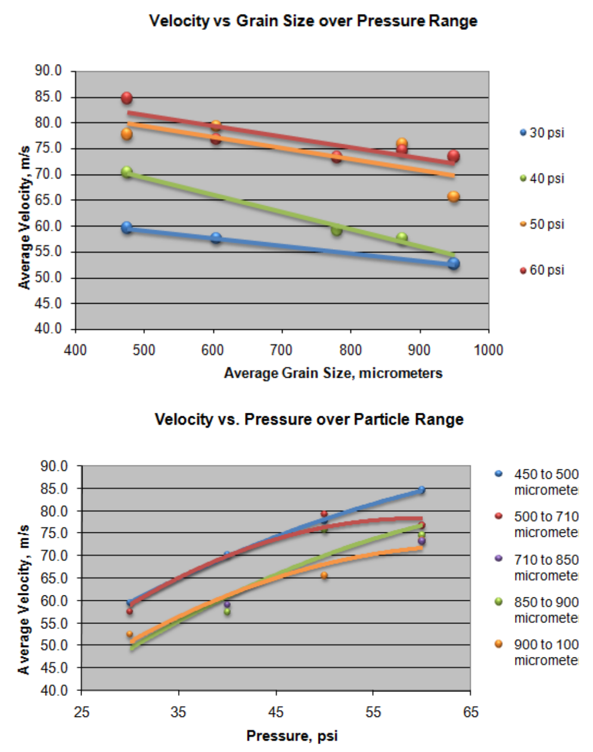

Figure 4a, 4b. Pressure Analysis. *These two charts show how as the sandblasting pressure increases, the velocity also increases, but as grain size increases, the velocity decreases.*

A. Pressure Analysis

For each particle size, we tried to get impacts for the whole range of particle sizes. We accomplished this by changing the sandblasting pressure. In order to ensure that we had enough particles at each given velocity, we made a chart of the number of particles we had for different ranges of velocities. We also plotted the velocities we obtained against themselves to visually see where we had gaps in the velocity data. (Fig. 3.) To continue a pressure analysis, we plotted a couple more graphs based on particle size, average velocities, and pressure. (Fig. 4a, 4b.) We found that as the sandblasting pressure increased, the velocity of the particles also increased, but as the particle size increased, the velocity decreased. We noticed that as the grain size increased, the velocity seemed to decrease at a constant rate. When the pressure increased, we noticed that the velocity was increasing at an ever decreasing rate. We calculated the standard deviation for all of the different points, but we found that the more velocities we obtained from each sandblasting pressure, the greater the standard deviation. This is seen clearly in Fig. 3, where when we only had a few points for each pressure, the velocities were relatively close, but as we obtained more and more data, the velocities started to deviate significantly.

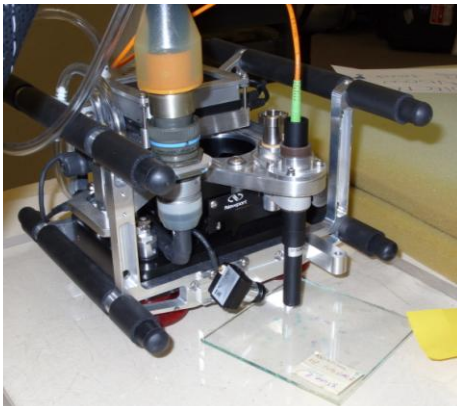

Image 5. The PHOWID. *The Portable Handheld Optical Window Inspection Device uses a white light interferometer pen to scan the depth of defects in glass.*

We expected the different pressures to be more specific in the velocity of the different sized particles, but this was not the case. Though the average velocity increased as you increased the pressure, and the velocity decreased for each given pressure as you increased the particle size, the range of velocities obtained was quite large. This may be due to the fact that within a given particle size there may be mass variation. When sieving particles, not all the smaller particles get through a given sieve, so though you will not get particles that are bigger than the size range, you will get particles that are smaller than the size range. In addition, some particles are not spherically shaped, and particles that have more mass but are egg-shaped, may filter down to a smaller particle size. This gives variation in mass that could directly affect the particle velocity at any given pressure.

V. Damage Analysis

The variation in damage from each particle was larger than expected. Some impacts chipped out a bit of glass. Other impacts crushed the glass at impact. Still other impacts had several individual impact points scattered in a couple millimeter diameter area. The unpredictability of the impacts made this kind of analysis near impossible. We did not know whether the particle velocity would affect the depth of the crater, the volume of glass removed, the area of damaged glass, etc. This required careful scanning of the glass impacts.

A. Scanning the Glass

We used the Portable Handheld Optical Window Inspection Device (the PHOWID) (Image 5) to scan the glass. This Device uses a White Light Interferometer Pen to scan a grid across the glass and measure depth. From there, a computer analyzes the data, makes a 3D image of the damage, calculates the volume of glass removed, the maximum depth, a de-spiked depth, a filtered depth, length of the crater, and width of the crater. (Image 6.) The damage we saw was surprising in the sense that no to impacts were very similar at all. Each impact was in its own group. We scanned about 65 impacts of the particle size 450 to 500 micrometers. This was as far as we got with scanning.

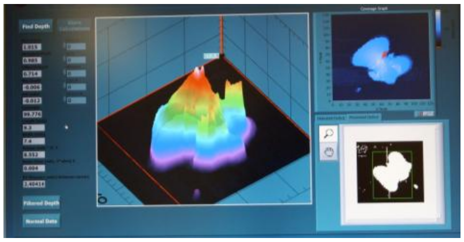

Image 6. Depth Analysis. *The PHOWID gives the scan information to this program to give detailed information about the impact such as maximum depth, volume, length and width.*

B. Analysis of the Data collected

Once we had entered all our data into a computer, we were able to make graphs and analyze what we did. The data we obtained was not as good as we expected. There did not to seem to be any correlation between velocity and impact size. (Fig. 5a, 5b.) This lack of correlation may be due to the fact that the velocity range is low. For instance, if the velocity to damage was a squared relationship, at small velocities the data would look nearly constant. Unfortunately due to limitations of the sandblasting method, higher velocities cannot be obtained in this way.

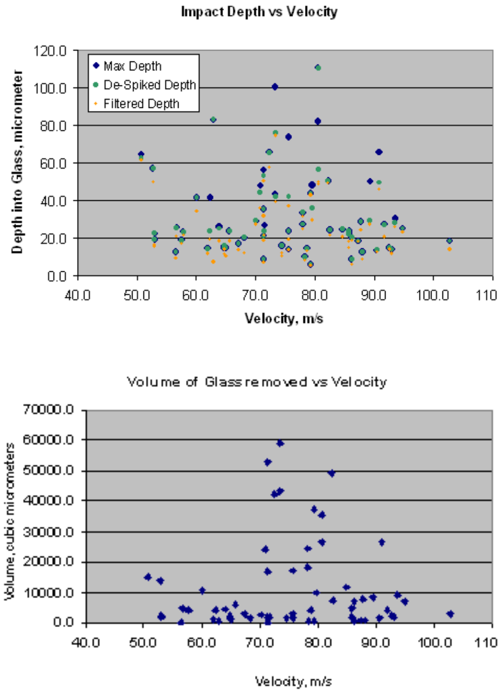

Figure 5a, 5b. Damage Analysis. *These graphs show plotted data of the impact depth vs. velocity, and the volume of glass removed vs. velocity. The two graphs do not show evidence of any correlation.*

There should be ways to organize the data to some sort of order, however. One way to gain some information about the impacts would be to split the impacts up into groups based on type of impact. The data from impacts which cut out a piece of glass may show a close correlation between particle velocity and damage. We can see that the impact size goes up when only looking at the large volume cut out, typical of an impact where a piece of glass got chipped out. Another idea is to compare the mass of the particle sizes to the damage. This mass could be estimated if it is assumed that the velocity of the particle out of the sandblasting gun has to do with the mass of the particle.

Reasons why the data may be so scattered include the fact that the velocity is so low. At these velocities, there is a lot of unpredictability. For instance, if the particles were moving much faster, the chances that all of them would crush into the glass would increase, whereas at these speeds, the particles could bounce off or break into a few pieces as they impact, etc, and the probability that they will all do the same thing is very low.

One thing we do expect to see is an impact size increase as the particle size increases. Though we have not collected scan data yet about the larger particle sizes, visual inspection of the glass shows larger impacts when larger particles are used and smaller impacts when smaller particles are used. Further analysis will show whether this hypothesis is correct or not.

VI. Conclusion

Our data did not turn out to contain as much information as we had initially hoped. Further testing, and additional different tests may prove to hold more valuable information.

A. Velocity Tracker

The velocity tracker proved to be one of the most important accomplishments of this experiment. With the velocity tracker we will be able to do future testing efficiently. Without this device, testing would take a really long time, longer than would be worthwhile, and we would have to settle for either less data, or less accurate data. We want to make the data as precise as possible, so as to eliminate any unnecessary uncertainty. The velocity tracker makes it possible to reduce the uncertainty of the velocity by quite a lot. The only other efficient way to track the velocity used to be by adjusting the pressure and estimating the average velocity that way. The testing done here has shown that estimating the velocity in this way is not very accurate. The range of velocities for each pressure is quite large, and overlaps considerably. By using the velocity tracker we are able to reduce this large uncertainty significantly.

B. Impact analysis

The impact analysis did not give the information we had wanted. The data was very scattered and there seemed to be no pattern or trend. Reasons for this and ideas about how to organize the data were discussed previously. The next step in analyzing the impacts would be to start scanning different particle sizes to get data to compare to the impact size already scanned. In addition, sorting the impacts into groups by visual type may lead to some conclusions about how the different velocities can impact the glass in different ways, and how each velocity affects the damage incurred. We did try to take high speed videos of the particles actually impacting the glass, but the camera resolution when zooming in to the glass was very low, and we were not able to see anything. This type of video could be very valuable in the impact analysis if a different camera made specifically for very small actions could be used. This way we would be able to see exactly what is happening when the different type of impacts happen. This would also give detailed information about the particle such as size, protrusions, and other properties. As of now, though, the data we have collected is inconclusive.

C. Sandblasting Metal

The future of this experiment would be to start sandblasting painted metal with lunar simulant. This would give us a basis of comparison for the Surveyor 3 coupons. There are several important things we can learn if we understand the impact analysis of the Surveyor 3. By doing experimental sandblasting onto painted metal, we can start to understand how abrasive lunar soil is, along with how much lunar regolith is displaced by a landing, and how much damage we can expect for future lunar missions.

Acknowledgments

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References

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