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Abstract

Descent engine plumes interact with the lunar surface and accelerate regolith particles to potentially high velocities. These ejecta create risks to surface assets that have yet to be fully assessed. To better understand these risks, plume surface interactions can be simulated on the ground by firing a test engine plume into a bin of lunar regolith simulant under vacuum conditions. The dynamics of the resultant ejecta can then be recorded. In this technical memorandum we discuss the processes used in preparing a 150 kg bin of lunar regolith simulant for plume surface interaction ground tests under vacuum conditions for the NASA STMD Plume Surface Interaction project[1]. We present our approach to mitigating regolith simulant eruptions during pump-down, the methods used to fill and reset the regolith simulant bin for each test, and the techniques used to characterize the consistency of regolith simulant geotechnical properties before each new firing. The challenges of preparing a regolith simulant test bin below an ambient pressure of one atmosphere, particularly on the large scale, could largely be overcome with a system that could fill the test bin with simulant inside the chamber and under vacuum conditions.

1 Introduction

Landing videos taken from within the NASA Apollo lunar modules have demonstrated that descent engine plumes interact with regolith and cause it to be ejected from the impingement region at significant velocities [1]. The effects of plume surface interactions (PSI) consequently pose some risk to the sustained human exploration of the lunar surface as high velocity particles may damage the landers themselves and surrounding surface assets such as habitats, power systems, communication systems, and rovers. The efficiency of radiators and solar panels will also be significantly reduced by a coating of particles. In addition, PSI ejecta could contaminate regions of historical and scientific significance such as the Apollo landing sites and areas of interest for in-situ resource utilization like permanently shadowed regions.

Knowledge of ejecta velocities is required to assess the risks from PSI accelerated regolith. Attempts to determine these velocities have included analyses of the Apollo landing videos [2], unified flow solvers [3], and lagrangian simulations [4,5]. However, these results have produced a wide range of potential velocities that include particles that may be traveling at more than 2 km/s. Consequently, additional efforts are needed if improved constraints on PSI risks can be established.

Regolith simulants, simulated lunar lander engines (hot/cold gas thrusters), and appropriate vacuum chambers can be used to generate lunar relevant PSI events. And while the lower gravitational acceleration on the moon cannot be easily reproduced here on Earth, ground tests can still provide valuable information on the possible velocities particles can reach due to a PSI. By measuring initial particle velocities at an impingement point during a ground-test, trajectory calculations can then be performed to predict when and where ejecta would impact the lunar surface following a lunar PSI [6].

[1] https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/PSI

Ground tests can be engineered to control the height of the engine above the surface, the thrust of the engine (flow rate), and the nozzle design. However, comparative testing can only be accomplished with regolith simulants that can be regularly prepared with consistent initial conditions. Consequently, ground tests require regolith tests bins and techniques that can – under vacuum – consistently reproduce geotechnical charateristics before each simulated PSI test run. In addition, the ability to produce geotechnically relevant regolith simulants provides valuable insight for developing test bins for other applications, including excavation, drilling, and other lunar surface activities at larger scales.

Here we report on regolith simulant preparation and geotechnical characterization for PSI testing under vacuum conditions developed at NASA Kennedy Space Center. These procedures were developed to support the PSI physics focused ground-test (PFGT-1) that took place in 2021 at the 15-ft vacuum chamber at NASA Marshall Space Flight Center (Test Stand 300; TS300 [7]). The objectives of these first PSI ground-tests were to provide imaging data of crater and ejecta dynamics as a result of a Mach 5.3 500 K GN2 jet impinging into a bin of lunar regolith simulant, and for that data to provide comparisons to computational models [8]. TS300 can achieve 2.67 Pa (0.02 Torr) and was equipped with an array of synchronized FLIR and high-speed cameras to capture the crater evolution and ejecta dynamics [9]. The regolith test bin included a transparent side plate, with a knife edge, that split the jet in half. This splitter plate enabled a view of the crater evolution in profile. Various mass flow rates, environmental pressures, nozzle heights and regolith simulants were all determined to influence cratering behavior [10].

The preliminary findings from these first PSI ground-tests highlight the importance of controlling, or accurately measuring, the geotechnical properties of regolith simulants. Without this understanding the relative importance of environmental and plume parameters cannot be determined. As future PSI testing is being planned at larger scales, further regolith simulant preparation and characterization will be needed. That need provides the motivation for this technical memorandum so that the lessons learned from preparing regolith simulants for the first PSI ground-tests can be shared with the community. In §2 we provide details on the regolith simulants used and the known issues with testing these materials under vacuum. The geotechnical characterization of regolith simulants is presented in §3, and §4 describes the regolith simulant preparation procedures for PSI testing. The regolith test bin is described in §5. Conclusions and lessons learned are summarized in §6.

2 Regolith Simulants

Large volumes of regolith simulants are needed for the ground-test scales necessary to improve our understanding of PSI effects. This can only be achieved with regolith simulants that can be acquired en-masse. Readily available regolith simulants range in complexity from simple glass beads of one size, to sand, to course simulants that are similar to some properties of lunar regolith itself [11].

Lunar regolith is largely a result of eons of bombardment from solar system debris. It therefore is a crushed and course substance with a size distribution that

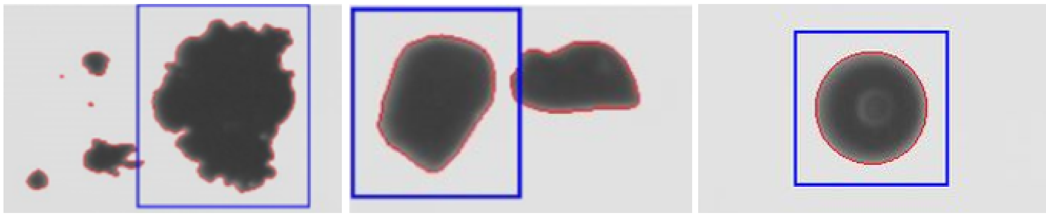

Figure 1. Comparison Fine Particle Analyzer images of three example regolith simulants. [left] Irregularly shaped coarse BP-1. [middle] Relatively smooth silica sand. [right] Spherical glass beads.

averages between 60 and 80 µm [12]. The particle size distribution is largely replicated by regolith simulants, but the shapes and mineralogy of the particles have some variations. However, for these ground-tests it was the particle shapes and sizes that were of primary interest. Spherical particles with a singular size are frequently used in computational models, and so mono-dispersed glass beads (between 125 and 177 µm) were the most appropriate simulants for comparisons to computational models. The simulant used that was most similar to lunar regolith was Black Point 1 (BP-1), which is a finely crushed basalt from the Black Point lava flow field in northern Arizona, approximately 60 km north of Flagstaff along SR 89 [13]. BP-1 was chosen due to its mechanical similarities to lunar regolith, i.e., it is an adequate simulant to reproduce regolith dynamics as a result of PSI. It should be noted that high-fidelity lunar regolith simulants require particular care in handling compared to coarser simulants that have been sieved to sizes larger than 60 µm. Mechanical analog simulants, such as BP-1, consist of crushed mineral particulates with the fines posing a breathing and eye hazard. Such materials require use of suitable personal protection equipment (PPE) including gloves, eye protection, and a suitable NIOSH-approved respirator with a protection factor appropriate for the level of exposure. The use of lunar simulant materials makes it challenging to maintain general cleanliness and difficult to compact the simulant in a soil bin under an ambient atmosphere while trying to avoid moisture adsorption.

A range of other regolith simulants were used during these ground-tests that filled the size and shape parameter space between the mono-dispersed glass beads and BP-1. A fine particle analyzer was used to determine the size distributions and representative shapes of particles from a sample of each simulant tested (Figure 1). The range of simulants used increased the value of these ground-tests as size and shape characteristics may influence regolith simulant dynamics as a result of PSI events. Figure 2 highlights the differences in geomechanical behavior from two of the regolith simulants shown in Figure 1. The rough surfaces of coarse particles (BP-1) can cause significant mechanical interlocking, unlike particles with smooth surfaces (silica sand, glass beads). Therefore, small samples of simulants like BP-1 can hold their shapes when tipped on their side.

Soil and regolith behavior under vacuum conditions has been studied in the past [14–16]. Without careful handling and preparation simulants may experience eruptions when a trigger pressure is reached, with eruption characteristics varying

Figure 2. Comparing the behavior of regolith simulants. [left] BP-1. [right] Silica sand. In both cases the samples where lightly compacted by tapping prior to being laid flat. The interlocking (or bridging) behavior of course BP-1 is demonstrated.

Figure 3. [left] BP-1 regolith simulant before vacuum pump-down. [right] BP-1 after pump-down. The surface of the simulant has been significantly altered due to vacuum eruptions.

between different simulant types. Due to void gaps between particles, and pores within particles themselves, simulants can trap gases that can be suddenly released at low pressures. In addition, any volatiles contained within or around particles can sublimate at trigger pressures and cause other sudden outbursts. Regolith simulant vacuum eruption mitigation techniques have been explored previously, such as controlling the pump-down rate, baking the simulants, and manipulation of the simulant when at operating pressures, but these techniques are highly dependent on the volumes of simulants being used and the times available to use certain test facilities [17]. Regardless, these eruptions disturb the simulant and renders any geotechnical characterizations before vacuum pump-down invalid (Figure 3). Regolith simulant vacuum preparation procedures are therefore required to mitigate against these eruptions.

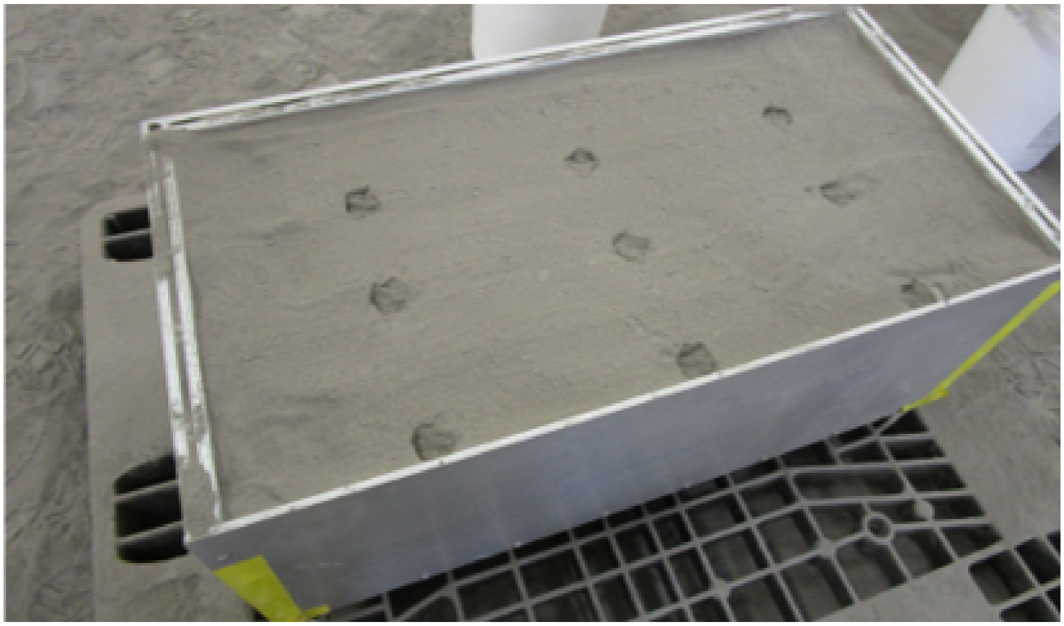

Figure 4. Shear vane testing locations for geotechnical characterizations.

3 Geotechnical Characterization

Geotechnical characterization enables the initial conditions of a regolith simulant to be determined before pump-down. This is important when using multiple PSI tests to investigate the effects of mass flow rate, environmental pressure, and nozzle height. Some properties typically measured in soil mechanics include the void ratio, porosity, and permeability, which are all important factors when it comes to the potential for vacuum eruptions. However, the objectives of these ground-tests were to study crater evolution and regolith dynamics. Therefore, the property of particular interest when preparing a regolith simulant test bin is the shear strength, i.e., the shear stress that a simulant can experience before shear failure. The void ratio, particle size, and particle shape all play a role in the determination of shear strength, so this parameter includes the major factors that drive the differences between the lunar regolith simulants tested.

Previous geotechnical testing studies have found that the typical instruments used in soil mechanics are not adequate for characterizing regolith simulants [18]. This is because standard geotechnical instruments have been designed for use in saturated clays and silts (ASTM-D2573). However, with care a shear vane tester does still enable a measurement of shear stress. A shear vane tester is also easy to use and simple from which to derive shear strength measurements. Therefore, this is the geotechnical characterization method used once a regolith test bin had been prepared. The vanes are pushed a predetermined depth into the test bin. As the device is twisted the applied torque is reported until shear failure occurs, i.e., the vanes rotate. It is then trivial to calculate the shear stress in terms of force per unit area.

Shear vane testing is a destructive process. Consequently, to determine the variations in shear strength at multiple locations within a sample, appropriate spacing between each test region must be used while also having enough testing locations to gather usable statistics (Figure 4). In addition, when measuring shear strength in a sample contained in a bin, test locations must be chosen to appropriately consider the edge effects of the container itself. In this case the location of the simulated PSI was at a transparent edge of the simulant bin so the crater evolution could be observed in profile. It was therefore important to determine if there is a change in shear strength as the edge of the regolith simulant bin was approached.

4 Regolith Simulant Vacuum Preparation Procedures

Vacuum eruption prevention is a requirement for regolith simulant preparation due to the geotechnical disturbance it creates. As the causes of eruptions stem from voids and volatiles, compaction and drying are two methods that could mitigate eruptions, as well as careful control of the pump-down procedure. In addition, lunar regolith can also be compacted, particularly at depths of 10 cm or more, due to densification as a result of lunar quakes and ongoing meteoroid bombardment [19].

4.1 Compaction

Compaction reduces void spaces that may mitigate vacuum eruption and better represents the geotechnical state of the lunar surface. In developing regolith simulant preparation procedures at KSC, compaction was achieved using a motor driven vibrating top plate. In this scenario, the weight and vibration of the top plate caused the depth of the simulant to reduce, thus increasing the density as a result of reduced void ratios.

Scale testing of the vibrating plate technique demonstrated that if the plate weight to motor force ratio was too low, compaction did not occur. The motor force needs to be greater than the plate weight in order to overcome the inertia of the plate and drive it into the surface of the regolith simulants. Consequently, a 130 lb. plate was driven by a 200 lb. force vibration motor operating at 60 rpm (Figure 5). Vibration continued for a set amount of time and the top plate was carefully removed to avoid any suction effects from disturbing the simulant.

As a baseline, the shear strength of BP-1 was first measured without any compaction. The shear vane method was used at evenly spaced locations across the top of regolith simulant. Each of the locations were repeatedly measured with the regolith simulant bin being reset between each new set. These measurements were also recorded at three different depths. At a depth of 7.6 cm the shear strength was 1.7 +/- 0.06 kPa, at 12.7 cm is was 2.1+/-0.1 kPA, and at a depth of 17.8 cm it was 2.2 kPa without any significant deviation.

Shear vane testing was repeated after the BP-1 regolith simulant had been top-plate vibration compacted over increasingly long periods. The results are summarized in Table 1 and demonstrate that the average shear strength increases after compaction. However, there is a significant increase in the variability of the shear

Figure 5. Top plate vibration setup for regolith simulant compaction testing.

strength after compaction. The top-plate vibration method of compaction produces less consistent geotechnical characteristics.

Compaction (mins)	Shear Strength (kPa)	
	μ	σ
0	1.70	0.06
1	2.3	0.3
3	2.3	0.5
5	2.2	0.5
10	2.1	0.4

Table 1. Results of shear vane testing as a function of the duration of top plate compaction for vibration compacted regolith simulant BP-1 at a vane depth of 7.6 cm.

Top-plate vibration compaction also resulted in an inverse density profile, i.e., the upper regions of the BP-1 had higher shear strength than deeper. In addition, compacting the BP-1 in layers, i.e., compacting a small depth first before adding more BP-1 and compacting again, still resulted in significant variations in shear strength. Variations in compacted shear strength also occurred when using different methods to fill the test bin. For example, a quick fill from a large bucket produced more significant variations in post-compacted shear strength measurements compared to a slow fill using small scoops.

The most consistent shear strength measurements resulted from slowly filling the test bin by gently shaking ("snowing") BP-1 evenly across the area from a metal scoop, followed by leveling the simulant with a straight edge and paint brush (Figure 6). Without any top-plate vibration compaction shear values remained con-

Figure 6. [left] "Snowing" technique for producing most consistent geotechnical characterizations, and [right] using a paint brush to level the surface.

sistent when measured at three different depths. This also resulted in the smoothest starting surface that required the least effort to set up and reset.

Compacted BP-1 was also tested under vacuum conditions and compared to the geotechnical and eruption behavior of uncompacted BP-1. Despite compaction being expected to reduce the void ratio, vacuum eruptions were still observed in compacted BP-1 at similar pressures to uncompacted BP-1 (~ 2 Torr). The geotechnical modifications of an eruption were also measured in the regolith simulant before and after vacuum testing. For uncompacted BP-1, the shear strength dropped by 5% pre- and post-vacuum.

It was found that the compaction method used here did not produce consistent geotechnical characteristics. However, with further study more consistent compaction methods could be developed using a vibration table with variable amplitude and frequency. Nevertheless, this study has demonstrated that compacted regolith simulant still produces eruptions when the soil bin is filled in an ambient atmosphere. Top-plate vibration compaction at 60 rpm does not mitigate vacuum eruptions.

Furthermore, vibration compaction resulted in particle size segregation through the depth of the test bin, and some level of compaction at the base of the test bin takes place simply from the force of the regolith simulant placed on top. Therefore, until further studies on compaction methods can be investigated there is not a reliable method for producing geotechnically consistent compacted regolith simulant for PSI testing.

4.2 Drying

To prevent the sublimation of volatiles within the simulant from creating vacuum eruptions, the regolith simulants can be dried out. In order to minimize moisture content before being placed in vacuum, BP-1 was transferred into baking pans up to 4 inches in depth. These samples were then baked at 250 F for 2 hours in an oven. Due to the oven volume limitations and the size of the regolith test bin for the PSI

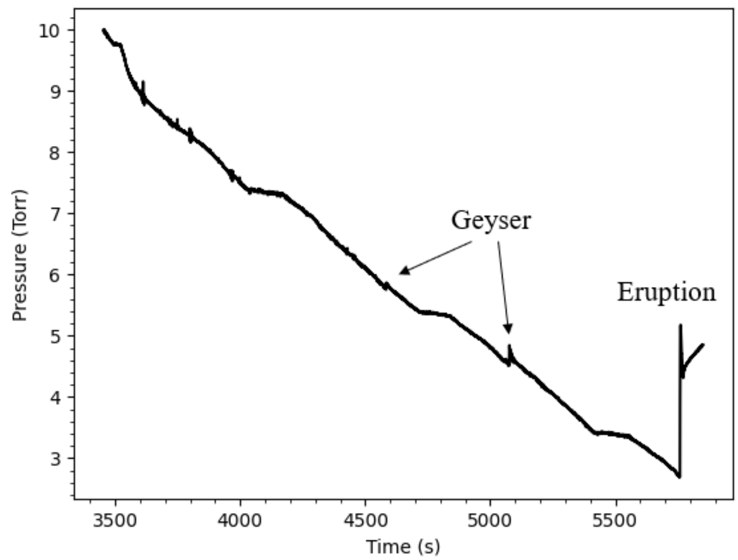

Figure 7. Pump down of undried BP-1 in a one-gallon soil mold. The rate was ∼0.2 Torr/min. The small spikes in pressure indicate micro-eruptions, or geysers, that are not visibly noticeable. Large spikes in pressure indicate a vacuum eruption that results in a visible change in the regolith simulant bed.

ground-tests, the maximum length of time dried regolith simulant could be stored for (before the moisture content increased) needed to be determined. Consequently, measurements were performed on dried regolith simulant that was stored in open containers at 50% relative humidity for 2 and 8 hours. In addition, dried regolith simulant was stored in 5-gallon sealed containers with plastic liners and desiccant packs.

By reducing the pump down rate, it was found that by baking out moisture and minimizing the exposure to ambient humidity vacuum eruptions were mitigated. Vacuum eruptions continued to be mitigated in dried regolith samples 2 hours old and samples stored for up to 1-month in sealed containers. Samples exposed to ambient humidity for 8 hours resulted in vacuum eruptions again. Consequently, samples left in unsealed ambient conditions for more than 2 hours should be redried before vacuum testing to avoid eruptions.

It must also be noted that by using the snowing technique to fill a regolith test bin, regolith simulants are exposed to atmosphere such that as they fall they may once again increase their moisture content due to water adsorption on particle surfaces. Therefore, one should use the lowest humidity environment possible when employing the snowing technique on dried simulants to fill a regolith test bin (including filling the soil bin under vacuum conditions, if possible).

4.3 Pump Down

When pumping down unprepared regolith simulants in a vacuum chamber, fewer disturbances were recorded when the pump down rate was carefully controlled. However, an eruption can occur without any visual indication on the surface of the simulant. These micro-eruptions (geysers) are manifested by small spikes in the pressure pump down curve (Figure 7). The slower rate of change provides an opportunity for air and volatiles to slowly diffuse through the simulants, rather than gather up in pockets leading to a catastrophic eruption.

Pump down rates were investigated using a small-scale soil mold 6 inches in diameter. Despite slowing the pump-down rate below 7 Torr, undried BP-1 still erupted below 2 Torr. However, dried BP-1 could be reliably brought down to 0.5 Torr without soil disturbance in approximately 15 minutes. Dried BP-1 that sat for 2 hours at 70° F and 47% RH showed no surface disturbance with a 50-minute pump down to 0.5 Torr. However, the dried sample left for 8 hours exposure showed significant surface disturbance and would not pump past 0.5 Torr.

5 Regolith Simulant Bin Design

The design of the regolith simulant bin was driven by the requirements to image crater evolution, conduct geotechnical characterization, and mitigate vacuum eruptions. These requirements were met by one side of the bin having a transparent splitter plate, with dimension large enough to minimize edge effects, and with sides that consisted of a fine wire mesh applied across a plate perforated with regularly gridded holes (Figure 8).

The splitter plate was constructed from a half inch thick plate of transparent acrylic. The plate needed to withstand a Mach 5.3 500 K jet of GN2, therefore the leading edge was beveled to 38 degrees and fitted with an aluminum knife-edge. The dimensions of the bin were 80 (W) x 40 (D) x 30 (H) cm. These dimensions were large enough to visualize the expected crater sizes, avoid geotechnical edge effects, and contain 150 kg of BP-1 and other simulants.

The wire mesh covered the sides and bottom of the bin, excluding the splitter plate side. It consisted of a 10-micron stainless steel wire mesh with pores that were small enough to minimize loss of simulant particles but large enough to allow escaping air and volatiles to exit the bin to reduce the risk of a vacuum eruption. The sides themselves were gridded with 1 inch diameter holes so that the sides would both support the wire mesh and maintain a solid structure for the bin.

The low end of the particle size distribution of regolith simulants creates some mechanical issues for the bin, as would be the case for flight hardware operating on the lunar surface. For example, fine particles easily bound up bolt threads causing them to become easily stripped. Therefore, it is best practice to cover or seal any bolt holes or exposed threads that could be subjected to regolith simulants.

During pump down tests, it was noted that eruptions in undried simulants increased with the total depth of the simulant. Where there were only thin layers of regolith simulant eruptions were not observed.

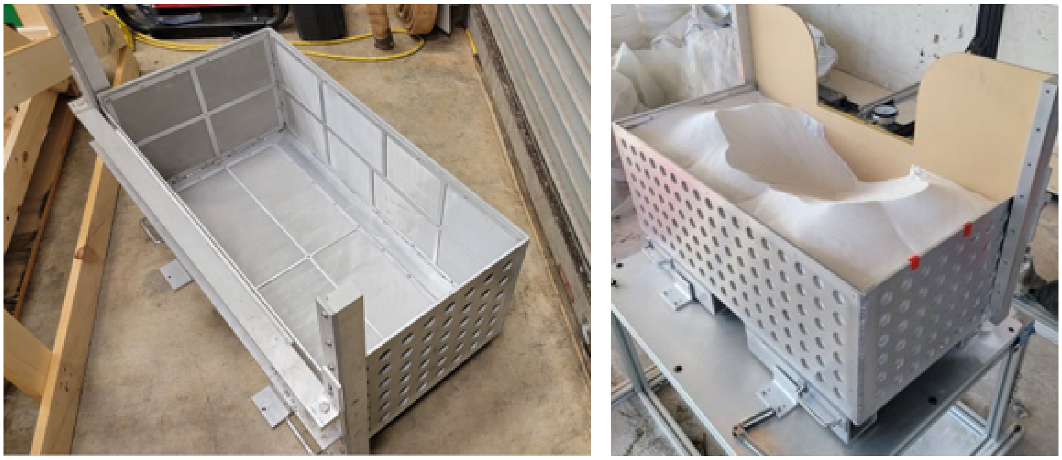

Figure 8. [left] Empty regolith simulant test bin demonstrating the wire mesh interior wall design to prevent particles spilling through the gas escape holes. [right] Testing of the bin with silica sand and a dummy splitter plate.

It has also been noted that scaling from one-gallon sized soil molds to the 150 kg regolith simulant test bin presented a significant increase in complexity. Handling, manipulating, and testing simulant samples a half gallon at a time presented few issues aside from the need for appropriate PPE. However, following the same processes established at smaller scales at the scale of the test bin used here presented a few technical challenges. Such challenges will only increase as ground-tests are further scaled up in the future.

5.1 Scaling up

In these ground tests 150 kg of BP-1 (and other simulants) were used in a regolith test bin 30 cm deep. Future ground tests may need to use up to 15,000 kg of BP-1, and so the challenges of scaling up the regolith simulant test bin must be considered. For example, if 15,000 kg of BP-1 were distributed uniformly to a depth of 30 cm, the area of the scaled-up test bin would be approximately 43 m^2. This kind of area creates logistical challenges to simply moving the simulants into the bin, drying and storing such a large volume, and geotechnically testing the regolith simulants at appropriate locations throughout the bin.

To apply any of the eruption mitigation techniques described here on 15,000 kg of BP-1 simulant will be a significant challenge. This mass of simulant requires a large bin. A large bin - if choosing to compact the regolith simulant via vibration - will need to be floating and driven by appropriate motors. Such a large volume will take a significant amount of time to dry out in ovens. A large bin will take a significant amount of time to fill, especially by hand when adhering to OSHA lifting limits. Hand filling will also require significant physical exertion that will increase humidity in the filling area. And reaching across the regolith simulant surface to make consistent geotechnical measurements with hand tools will create risk, limit the locations that can be tested, and will introduce errors as it will become increasingly difficult for the geotechnical test instrument to be inserted perpendicular to the surface.

One method that will mitigate vacuum eruptions and will avoid the challenges identified above, would be to fill (or reset) the regolith test bin when simulants are already at vacuum. While this approach will also present significant challenges, the regolith simulant could be introduced to the test bin after already experiencing eruptions (slowly poured in). Alternatively, the regolith simulants could be geotechnically reset after they have been subjected to vacuum while in the test bin (stirred). A small-scale study of both of these methods is being considered and will be of great value to scaling up the soil test bin for future large scale ground tests.

6 Conclusions

Regolith simulant preparation for vacuum-based ground tests is required to produce consistent geotechnical conditions before each new test run. However, voids and volatiles within regolith simulants can alter the geotechnical properties of the simulant bed during pump down as the trapped gasses outgas through the test surface. It is therefore important to develop techniques for mitigating these vacuum eruptions.

Voids can be reduced through compaction. However, the compaction technique used here does not produce consistent geotechnical conditions throughout the simulant volume. The most consistent geotechnical results were recorded after regolith simulant was slowly "snowed" into the test bin using small scoops. The surface was then flattened off with a straight edge and finished with a paint brush.

Baking batches of regolith simulants at 250 F for 2 hours in 4-inch-deep baking sheets removed enough volatiles, primarily water molecules, to reduce eruption events. Once dried, simulants must be used within 2 hours or be sealed in dry and tight containers. Outside of these conditions, simulants will need to be rebaked in order to again remove adsorbed water. However, if the environment where the test bin is being filled is at high humidity, water adsorption could result during the filling.

Even if pump down can be carefully controlled to minimize geysers and eruptions, the regolith simulant test bin must be designed to allow trapped gasses to escape through its surfaces. A wire mesh covering a holed-out container has demonstrated success in mitigating eruptions in combination with dried simulants, limiting exposure to humidity after drying, and careful pump down rates.

While top-plate vibration showed no success in producing consistent geotechnical conditions, the effects of amplitude and frequency were not explored. This warrants further study as compacted regolith is a feature of the lunar surface. However, vibration compaction leads to particle size segregation and can occur naturally when the upper layers of a simulant push down on lower layers.

The scaling up of PSI soil test bins from 150 kg to 15,000 kg presents significant logistical and operational challenges, both in terms of physically filling a soil test bed with dried simulant and in testing its geotechnical characteristics. It will be valuable to conduct small-scale tests in which regolith simulant is prepared under vacuum conditions after air and volatile containing void spaces have been mitigated.

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14. ABSTRACT
Descent engine plumes interact with the lunar surface and accelerate regolith particles to potentially high velocities. These ejecta create risks to surface assets that have yet to be fully assessed. To better understand these risks, plume surface interactions can be simulated on the ground by firing a test engine plume into a bin of lunar regolith simulant under vacuum conditions. The dynamics of the resultant ejecta can then be recorded. In this technical memorandum we discuss the processes used in preparing a 150 kg bin of lunar regolith simulant for plume surface interaction ground tests under vacuum conditions for the NASA STMD Plume Surface Interaction project[2]. We present our approach to mitigating regolith simulant eruptions during pump-down, the methods used to fill and reset the regolith simulant bin for each test, and the techniques used to characterize the consistency of regolith simulant geotechnical properties before each new firing. The challenges of preparing a regolith simulant test bin below an ambient pressure of one atmosphere, particularly on the large scale, could largely be overcome with a system that could fill the test bin with simulant inside the chamber and under vacuum conditions.

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