

Large Vehicle Lunar Landing Surface Interaction and In-Situ Resource Based Risk Mitigation: Landing & Launch Pads

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A key capability required for the exploration of planetary bodies is the ability to land on the surface. Previous work performed by NASA and other institutions has primarily focused on landing small spacecraft on planetary surfaces and the associated small-to-medium thrusters required for the soft landing. In the case of human exploration—particularly the establishment of long duration exploration and habitation outposts—the ability to land large landers, such as the SpaceX Starship, is necessary.

These larger landing systems require the use of more powerful engines, with higher engine exhaust temperatures and higher landing loads. Understanding the excavation of material by the engines, as well as the potential for the landing legs to sink into the subsurface, is key in ensuring reliable and safe landings. A further

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improvement in landing reliability can be achieved by constructing landing / launch pads, especially with in-situ resources.

Some material excavation by the plume is inevitable, leaving at least a portion of the surface scoured and uneven under the lander and ejecting regolith particles and rocks at very high velocities. One possible solution would be to robotically build landing / launch pads (ideally autonomously) at the destination using in-situ materials. In this case, the first one or few landers will need to land on unimproved surfaces at higher risk; however, they would bring the required equipment to build the landing pads with mostly local resources, thus increasing the reliability of safe landing for subsequent larger landers. A number of methods to build in-situ landing and launch pads have already been developed. These methods include no, or some, addition of required binder additives to the local regolith material, different processing approaches and result in varying landing pad strengths.

A sub-scale rocket engine plume, was used to simulate some of the conditions of a landing on the Moon to assess the effectiveness of various materials for an in-situ built landing pad, The GO_2/GCH_4 rocket engine fired on a 1 m^2 area coupons of representative pad materials. The results will allow continued development towards materials that satisfy the landing pad properties required for the effective risk reduction and increased reliability for landing people and equipment on the lunar surface.

This work contained two parts: (1) computer modeling of a large rocket engine plume interacting with regolith on the Moon, using the Granular Gas Flow Solver (GGFS) provided by CFD Research Corporation as well as other computational fluid dynamics codes (CFD) such as Loci/CHEM. (2) Developing landing/launch pad materials that could be used for in-situ construction on the lunar surface in the future, to mitigate the calculated effects of a large vehicle rocket engine landing and launching on the Moon.

I. Nomenclature

<i>ACO</i>	=	Announcement of Collaborative Opportunity
<i>BP-1</i>	=	Black Point – 1 Lunar Mare Regolith Simulant
<i>CFD</i>	=	Computational Fluid Dynamics
<i>DAQ</i>	=	Data Acquisition
<i>G</i>	=	gravity
<i>GGFS</i>	=	Granular Gas Fluid Solver
<i>GMRO</i>	=	Granular Mechanics & Regolith Operations
<i>KSC</i>	=	Kennedy Space Center
<i>NASA</i>	=	National Aeronautics & Space Administration
<i>PSI</i>	=	plume surface impingement
<i>RTV</i>	=	Room Temperature Vulcanization
<i>SBIR</i>	=	Small Business Innovative Research
<i>STTR</i>	=	Small Business Technology Transfer

II. Introduction

On July 30, 2019, NASA announced that SpaceX had been selected for a collaboration under an Announcement of Collaborative Opportunity (ACO): “SpaceX of Hawthorne, California, will work with NASA’s Kennedy Space Center (KSC) in Florida to advance their technology to vertically land large rockets on the Moon. This includes advancing models to assess engine plume interaction with lunar regolith.”

This effort consisted of two phases:

- 1) Model Starship landing plume surface impingement (PSI) on the Moon with an under-expanded nozzle and resultant rarified hot exhaust plume using the NASA / CFD Corp. Granular Gas Fluid Solver (GGFS) and other computational fluid dynamics (CFD) software, to understand plume effects on lunar surface materials. Extend work to relevant landing/launch pad construction materials models.
- 2) Design and construct landing/launch pad materials proof of concept test articles. Conduct landing/launch pad materials testing. Perform strength of materials characterization lab tests and compare to computer model predicted forces. Test the pad materials test articles performance with Oxygen/Methane rocket engine hot firings.

The landing/launch pad materials for the test articles were developed and fabricated at the KSC Granular Mechanics & Regolith Operations (GMRO) laboratory and were subsequently tested by Masten Space Systems under contract with NASA.

NASA's modeling work of Starship PSI with CFD Corp. GGFS software and the PSI effects were quantified to determine whether a lunar landing could be safely accomplished using one throttling Raptor rocket engine. The GGFS code is under development and the latest version was used to predict the regolith behavior under the rocket engine exhaust flow. Five candidate lunar landing and launch pad candidate materials were evaluated in exposure tests to a relevant Oxygen/Methane rocket engine plume environment. The performance trends were observed, modeled, measured (to the extent possible), and the testing results were evaluated. A total of fifteen high temperature plume tests were performed in two test campaigns: five in December 2020 and ten in March 2021. The results indicate that the several selected materials are promising for future consideration in designing and building lunar landing and launch pads, although further development work is needed for all of them.

Overall, this collaboration with SpaceX advanced the understanding of Starship lunar landing requirements and advanced the technology readiness level of the tested materials from 4 to 5.

III. Raptor Engine Plume Surface Interaction (PSI) Modeling

The Raptor rocket engine plume surface interaction (PSI) was simulated with computer modeling, using a modified version of the Gas Granular Flow Solver (GGFS). This code was developed under several collaborative projects between NASA KSC, MSFC, CFD Research Corporation and the University of Florida. The projects were funded by NASA Small Business Innovative Research (SBIR) / Small Business Technology Transfer (STTR) contracts to create a uniquely capable simulation framework that solves the gas and granular phase interaction in a coupled manner with high fidelity granular phase particle physics modeling.

The purpose of the PSI simulations was to understand the regolith particle flow induced by Starship landing on the unprepared surface of Moon. The code was customized for extreme space environments that combine low gravity, reduced atmosphere or vacuum, with Raptor rocket exhaust gas flow that is supersonic and partially rarefied, and unusual mechanical properties of the regolith. The goal was to predict surface impingement pressure and temperature environments and the resulting topology alterations which may range from shallow erosion to cratering. The original GGFS and Loci/GGFS simulation tools were used to predict landing surface damage resulting from Raptor engine impingement on the landing surface. The results are proprietary to SpaceX and therefore are not reported here. Table 1 shows the various cases that were modeled to inform PSI characterization.

Table 1. Parametric simulations with varying thrust level and nozzle location with respect to the regolith surface.

Thrust Level	Location from Surface (m)	Simulation Time (s)	Simulation Cost (CPU-hr)
25%	1	1	19,000
	25	1	24,000
	75	1	25,000
50%	1	1	19,000
	25	1	24,000
	75	1	25,000
100%	1	2	38,000
	25	5	96,000
	75	2	48,000

IV. Design of the Test Campaign: Differences between 1G Terrestrial Test and a 1/6 G Lunar Vacuum Test

The reproduction of conditions created by a rocket plume in lunar vacuum is not physically possible by a rocket engine test run in atmospheric conditions. However, this project aimed at identifying certain characteristics of the Raptor rocket plume that could be approximated by an O₂/CH₄ engine to create similar challenges for the materials being tested in atmospheric conditions.

In a lunar environment the plume of the engine used for landing would be under expanded due to the nozzle exit pressure being greater than the surrounding vacuum. This results in a plume impinging the surface or test article that is distributed over a wide area and not focused (as is the case in Earth's atmosphere). Due to engine characteristics and atmospheric pressure in Mojave, CA the plume of the O₂/CH₄ engine used for testing was anticipated to be over expanded i.e. collimated or closer to a small disk footprint, several centimeters (cm) in diameter. In order to minimize the effects of having a focused area of high pressure and temperature on the test article caused by a concentrated plume at the point of impingement, a descent profile was chosen to allow the cross section of the plume impinging on the test article to vary as the nozzle approached the test article, giving a more distributed heat and pressure zone. The selected approach was to approximate Raptor environmental conditions on the surface of the test article to achieve the best case and the worst case, "bracketed" as the nozzle approached the test article with a collimated plume.

The test campaign managed differences between under-expanded and over-expanded plumes of the same engine by using the following approach:

- The high temperatures of the Raptor engine impinging on the pad material in a lunar environment can be approximated by bringing the Masten 444 N rocket engine closer to the surface, but then the pressure will be too high, and gas velocities will also be high.
- The low pressures of an under expanded plume can be approximated by raising the rocket engine, but then the temperatures will be too low, and the gas velocities will also be low.
- To achieve both conditions, two sets of tests were run.
- The first test campaign parked the nozzle exit plane at 19 cm height to achieve high impingement temperatures.
- The second test campaign had a controlled descent of the rocket engine from 1.02 m to 60 cm height to simulate the descent of a lander more accurately and to position the test article in the far field region of the plume. This configuration approximates an under expanded plume, with lower maximum temperatures, but more realistic impingement pressures and gas velocities.
- These compromises were designed to gain an understanding of materials performance. The tests were not designed to accurately replicate the Raptor engine lunar environment because this would require a far more elaborate test configuration of a rocket engine in a very large vacuum chamber, which was beyond the scope of this project.

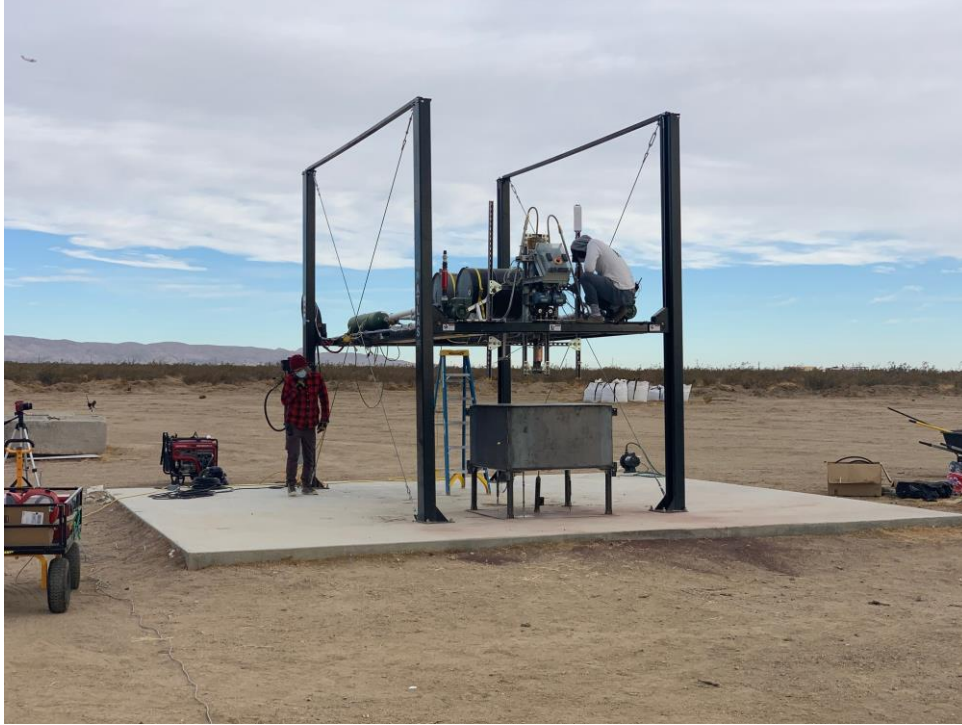


Figure 1. Masten Vertical Descent Rocket Engine Test Stand in Mojave, California.

V. Selection of Medium TRL Landing/Launch Pad Candidate Materials

The project team reviewed and evaluated a wide range of materials and associated construction techniques for lunar landing and launch pads (LLP) during a trade study to determine their level of readiness and suitability to perform the functions of a LLP. The scope and number of engine tests was constrained by the project budget and limited the number of candidate materials to be tested. The selection of materials to be tested was guided by the following criteria:

- The minimum TRL of the candidate material should be 3-4
- Near term availability of the components to make the candidate material
- The feasibility of completing a design, manufacturing the material, and assembling by the test date

The trade study produced the following short list of candidate materials concepts that were deemed worthy of testing to observe their performance under engine exhaust plumes (Table 2).

The selection of LLP concepts and materials led to the design and fabrication of test articles according to the specifications of the test facility at Masten and the data sought by the NASA team. The test articles were designed to fit at the top surface of a 1 m x 1 m surface area steel bin filled with regolith placed under the rocket engine as shown in Figure 2.

Table 2. Candidate Materials for a LLP

Pad Material Concept	TRL	Test Feasibility Decision
Prepared Regolith Surface (leveled, compacted, and cleared)	5	Previously tested in terrestrial atmosphere under Masten rocket engine plumes by Small Business Innovative Research Contracts (SBIR)
Bedrock Surface	3	Availability of large lunar simulant rock uncertain. Not testable at present.
Rock Piles	3	Anorthosite rocks were available and on site at KSC
Regolith bags (Basalt fiber, carbon fiber, Nomex, glass fiber)	3	Materials were available. Low difficulty in design and manufacturing.
Metallic plates	5	Tested during Morpheus test campaign at KSC
Sulfur concrete	4	Not available to project due to schedule constraints.

Synthetic biology concrete	3	Not available to project due to schedule constraints.
Thermally Sintered regolith	4	Available through Hawaiian Pacific International Space Center for Exploration Systems (PISCES) partnership
Thermoset polymer binder with regolith	4	Available at KSC Granular Mechanics and Regolith Operations (GMRO) lab with current capabilities
Deployable mat of basalt or carbon fiber textile layers	3	Available commercial off the shelf (COTS) materials and feasible manufacturing
Sintered regolith by metal powder combustion	3	Not available to project due to schedule constraints



Figure 2. Regolith-filled steel box used under engine for landing pad materials test showing instrumentation as it is being installed

VI. Oxygen/Methane Rocket Engine Plume Impingement Testing of Landing / Launch Pad materials

Rocket engine firing tests were performed by Masten Space Systems, inc. under contract to NASA (NASA SBIR 20-1, Topic Z7.04-3871, Contract No.80NSSC20C0230, MSS-ENG-1810-009). Testing took place in two separate campaigns. There were an initial five tests performed during December 2020 and another 10 tests were completed during March 2021. Masten undertook the following tasks to accomplish these tests:

- Utilized Variable Geometry Research (VGR) engine technology to meet NASA testing performance requirements
- Procured, modified, and operated a hydraulic vehicle lift to provide vertical descent movement during engine testing
- Worked with NASA to provide the appropriate data and test points to meet customer objectives

This included:

- Building a test stand filled with regolith simulant to integrate with test articles
- Integrating a data acquisition system (DAQ) for collecting sensor data

The rocket engine test stand included a welded steel box container filled with basalt regolith simulant to simulate a lunar surface. The box had a top surface area slightly larger than 1 m x 1 m on which the materials test articles were installed for rocket engine firing tests, as shown in Figure 4. Control of the engine test stand was executed via hardline commands from a control room located 65' from the test stand. Data from the test stand was routed to the control room via Data Acquisition (DAQ) hardware. High speed, real time and infrared cameras were mounted on and in the vicinity of the test stand to capture events during firing.

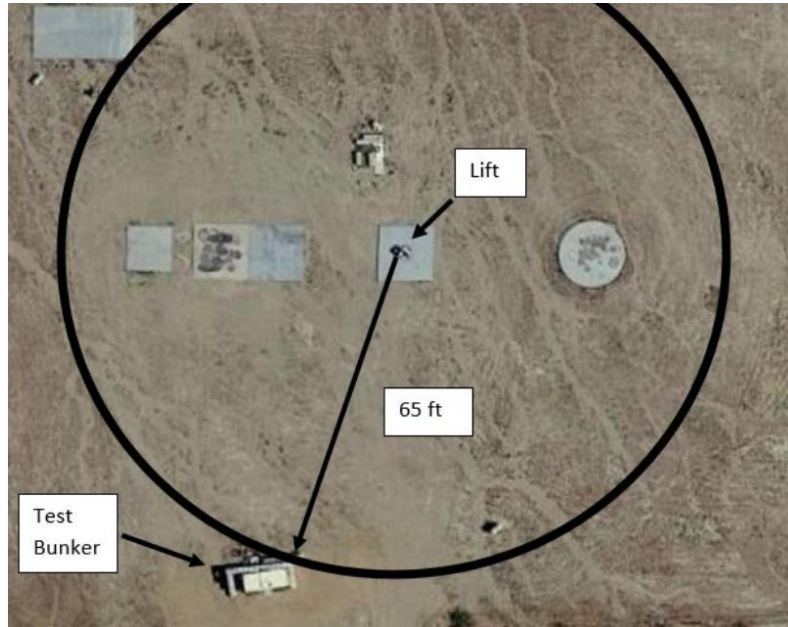


Figure 3. Control Room bunker location.



Figure 4. Test stand regolith container with a test material installed.

A. Test Instrumentation: Design and Implementation

The evaluation of the performance of the test materials under rocket engine plume impingement require a suite of measurements obtained both in-situ and from remote observation. 2 displays the type of measurements being sought, the instrumentation selected and notes on implementation.

Table 2. Rocket Engine Test Measurements

Measurement	Sensor	Test Campaign 1	Test Campaign 2	Notes
Test Material Temperature	C-Type Thermocouples	x	x	Fast response eroding thermocouples (Nanmac)
Regolith Temperature	K-Type thermocouples	x	x	Buried at 2 and 5 cm in regolith under test article near the plume area
Vertical loading of test article	Load cells	x	x	Attached to test articles from below
Surface velocity of engine gas	Aluminum tracer balls and pebbles inserted in plume. High speed video recording.	x	x	Device provides a flow of Al. tracers on test article near impingement point. High speed video recordings of tracers in motion.
Surface damage to test material	3D scanning tool, photography, high speed video recording	x	x*	*3D scanning was not obtained in Campaign 2.

1. Temperature Measurements

The rocket engine conditions predicted by modeling at the surface of the test materials in Section 3 indicate a rapid rise of temperature to values near 2966 °C within a few milliseconds. The NASA team selected a custom-made design of the E-12 C-Type fast response thermocouple commercially available from Nanmac, Inc. C-Type thermocouples (TCs) are made of Tungsten 5% / Tungsten 26% Rhenium and are rated to measure temperatures up to 2320 °C, but will measure higher temperatures while melting. The Nanmac E-12 was selected based on its design and ruggedness in rocket nozzle environments. The alloys of the thermocouple junction are juxtaposed in long parallel ribbons that are encased in a tantalum probe sheath. The configuration allows the device to operate even while the tip of the junction is eroded by flowing high temperature gases in the test environments. In addition to an increased longevity, the ribbon configuration provides fast response time on the order of microseconds. The NASA team worked with Nanmac engineers to design two types of E-12 units with two different probe lengths customized to operate in the test articles and survive the test environment.

Figure 5 displays a schematic of a custom E-12 unit used inside all the test articles. The primary objective of the in-situ temperature measurement of the materials being tested is to gather sufficient data to define the thermal conditions at the surface of the material and the response of the material to these conditions at various depths. The maximum number of C-type thermocouples inside each test article was limited to 3, due to the thickness of the test materials and the budget for instrumentation for the total number of tests to be conducted.

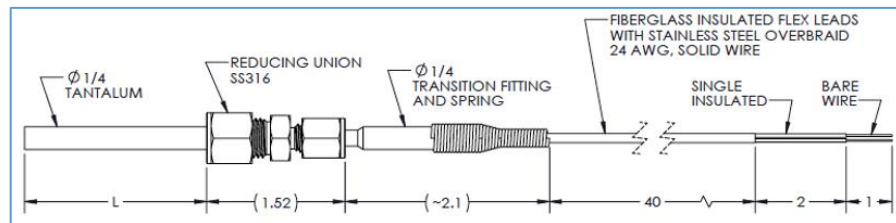


Figure 5. Nanmac E-12 C-type thermocouple assembly designed for materials temperature measurements.

The temperature of the surface regolith below each test article was measured for each test with 4 K-type thermocouples at two different depths (2 cm and 5 cm) and 2 different distances from the engine centerline (10 cm and 25 cm).

2. Vertical load measurements

The Masten test stand provided an interface to three tension/compression measuring load cells to record any compressive pressure or uplift exerted on the test articles. The load cells were Omega Engineering LC703-100. They were connected to Omega Engineering DRC-4710 signal conditioners. A National Instruments PXIe-1082 Data Acquisition (DAQ) unit was used to collect data from the load cells. A threaded rod interface was provided for each load cell at the regolith surface. The threaded rods were attached to linear bearing rods that were configured to transmit vertical loads through the regolith box to the load cells positioned below. The threaded rod heights and initial loading conditions could be adjusted via turnbuckle connections below the regolith box. Figure 6 shows the threaded rod interface to the load cells at the top of the regolith surface and the configuration of the turnbuckles and load cells below the regolith box alongside the DAQ enclosure.



Figure 6. Threaded rod interfaces to the load cells at the top of the regolith surface (left). Configuration of the turnbuckles and load cells below the regolith box alongside the DAQ enclosure (right)

3. Gas surface velocity measurements

A method was devised to dispense tracers into the horizontally accelerated gas to provide a measurement of surface gas velocity. The measurements were made by examining the distance the tracers traveled in time stamped high-speed footage after the tests. In some tests, pebbles were placed on the surface of the test article to serve the same purpose. Figure 7 shows a diagram of the tracer dispenser system. The tracers were 0.125" hardened aluminum ball bearings. The dispenser is a stainless-steel tube bent at one end into a rounded 90 degree angle. Tracers were loaded into the tube and attached to a spring mounted pivot. At the beginning of a test, the tube was held in sloped configuration by a monofilament trigger line that ran directly below the engine. The slope allowed the tracers to be stored against a stop in the straight end of the tube. Upon igniter firing, the trigger line melted and the spring in the pivot lowered the angled side of the tube so that the slope caused the tracers to roll out. The tracers were then transported by the hot gas.

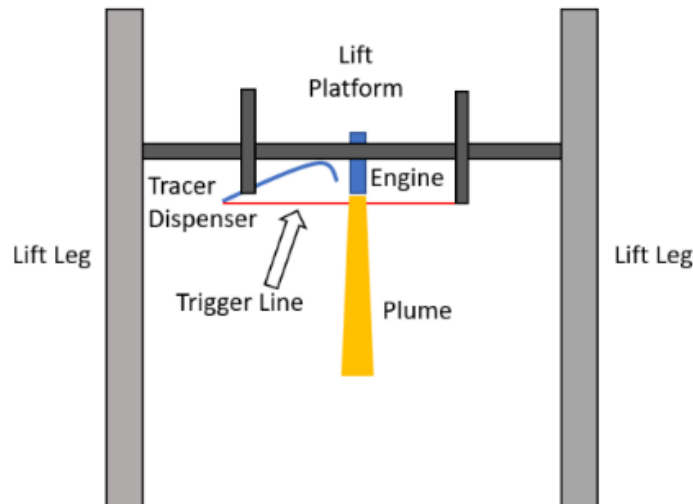


Figure 7. Diagram of the tracer dispenser system

4. Surface damage measurements

The NASA team used a hand-held Creaform Go Scan 50 3D scanner with VX Elements software to capture before and after images of the test articles topography in order to derive material volume loss and therefore mass loss due to plume effects. The scanner system has a resolution of 0.500 mm (0.0197 in.) and a volumetric accuracy of 0.300 mm/m (0.0036 in./ft.) with positioning targets installed. The system uses reflections of transmitted LED white light from positioning targets (small reflective stick-on discs) applied to the test article and natural light reflections that enable the software to determine relative distances and build a 3D image based on the returned light. All test articles were scanned with varying success. Bright sunlight (common in the high desert), certain textures and matte surfaces are limiting factors to capturing a good scan. More sophisticated metrology-grade units on the market now appear to overcome these issues.

VII. Test Results

A. Test Campaign 1 & 2

A trade study had been previously performed to investigate materials and construction techniques for a LLP which identified over 30 concepts. These concepts were reduced to 11 promising concepts as previously stated in Table 2. Then a further down selection was made to 5 feasible materials test articles that could be created with the schedule and budget available. These concepts are listed in Table 3 below.

Table 3. Concepts chosen for Test Campaign #1 rocket engine testing

Material Test Article	444 N Rocket Engine Test Static Height (cm)	Test Campaign #1 December 2020 Number of Tests
RTV Regolith Paver	19	1
Sintered Basalt Regolith Pavers with Grout	19	1
In-Situ Rocks in Gabion Cages	19	1
Regolith Filled Carbon Fiber Textile Bags	19	1
Carbon Textile Blanket – Woven with Non-Woven	19	1

Table 4. Concepts chosen for Test Campaign #2 rocket engine testing

Material Test Article	Descending 444 N Rocket Engine Test Final Height (cm)	Test Campaign #2 March 2021 Number of Tests
Sintered Basalt Regolith Pavers with Grout	60	2
20% RTV Regolith Paver	60	1
11% RTV Regolith Paver	60	1
Anorthosite Rocks in Gabion Cages	60	1
Carbon Textile Blanket: Woven with Non-Woven	60	5

B. Discussion of Test Results

1. Engine Plume Environment – Modeling

Although the Masten testing campaigns did not accurately mimic the environmental conditions during Starship landing on the Moon, valuable information was gained from these tests.

Plume surface interaction is one of the major phenomena of interest. The tests were conducted in Earth's atmosphere while Lunar pressure is close to vacuum. However, regardless of the ambient conditions, within the plume regions the flow is still continuum. Therefore, all the flow dynamics such as shock expansion/compression, plume reflection and propagation can be correlated to the Raptor engine rocket exhaust.

The plume temperature during testing was measured using an infrared technique, which had temperature range limitations. The actual plume temperature as predicted by CFD exceeded this measurement capability. However, the trend and profile of temperature contours can be observed and extrapolated to the case of Lunar landing.

The major difference from lunar conditions, is an over-expanded plume in the tests due to nozzle exit pressure being lower than ambient pressure. The velocity contours in CFD showed this over-expansion, which is also confirmed by the photos captured during the tests. For Starship landing the plume is under-expanded in the vacuum, so the testing results should be used with care, especially near the nozzle exit.

The surface pressure is valid in the plume surface interaction region. This information can be used for the design of landing pads and evaluation of different materials to withstand the high pressures.

2. Thermoset RTV-Regolith Pavers

The RTV-BP-1 paver tests demonstrated that the materials could be a viable solution for LLPs. The pavers were able to withstand the harsh conditions of the December test campaign with a small amount of erosion. The erosion that took place occurred in a controlled ablative manner with minimal debris liberation as opposed to the spalling that occurred with the gabion cage tests. The pavers were virtually unaffected by the less demanding test conditions of the March test campaign.

3. Sintered Pavers

The sintered paver tests demonstrated that the materials could be a viable solution for LLPs. The pavers were able to withstand the harsh conditions of the December test campaign with a small amount of erosion. The erosion that took place occurred in a controlled ablative manner with minimal debris liberation as opposed to the spalling that occurred with the gabion cage tests. The pavers were virtually unaffected by the less demanding test conditions of the March test campaign. In addition, grouting the sintered pavers with RTV-Regolith proved to be a viable method to join pavers and prevent gasses from penetrating the seams.

4. Gabion Cages filled with Anorthosite Rocks

The gabion cage test demonstrated that the concept could be viable as a potential lunar LLP. Anorthosite rock will tolerate the simulated conditions imposed by the thruster used in this testing. Spalling of the face of the rock directly impinged upon by the engine plume was evident however the overall integrity of impinged rock did not appear to be affected. Beyond scorching, little to no damage of the adjacent rocks was noted. The cages did not sustain any damage likely due to their distance from the impingement point. Further work must be performed to understand the nature of the how the anorthosite or any other proposed media is degraded by the plume environment from repeated exposure or longer durations as well as alternate, lighter weight, in-situ derived material for the cages, for example anorthosite glass rods could be wired or fused together and assembled into a gabion cage structure.

5. Carbon Fiber Textile Regolith Bags

The regolith bags were challenging in many ways. First, the fabrication by sewing was difficult to accomplish. High temperature carbon fiber thread is not available for sewing machines due to its brittle nature, which breaks at the tight bend radius of the needle. This project resorted to hand sewing the bags with rolled seams, and carbon strands taken from the fabric itself. While the method was successful, the sewn seams present a risk to the integrity of the bags. The bags were also not heavy enough to withstand the PSI forces and they were dislodged. The carbon fiber textile combusted, which is discussed below. The team decided that the regolith bags was not an easily feasible option and

eliminate them from the testing after test campaign 1 in December 2020, to dedicate resources to more promising concepts.

6. *High Temperature Carbon Fiber Textile Blankets*

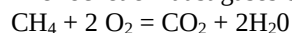
The basic concept being tested was the feasibility of a blanket made of various textile woven and non-woven fabric materials in a layup that was joined by needle punching them together throughout the blanket. The attraction of this materials concept is that a relatively lightweight textile blanket could be rolled up and transported to the Moon and then be deployed robotically. The textiles chosen were all made of high temperature fibers – carbon, Pre-Ox Carbon and silica. These materials exhibit extraordinary resistance to high temperatures and carbon fiber has a very high strength to mass ratio.

The initial test of the prototype blanket resulted in a rapid failure. Even though the carbon fiber textile used is very strong, the exposure to the rocket engine CH₄/O₂ combustion products and the high temperature flame in Earth's oxygen environment caused a degradation of the carbon fiber textile to the point where its strength was compromised enough to fail.

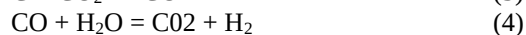
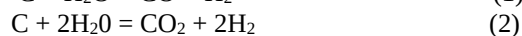
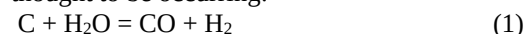
This failure was seen as an opportunity to learn quickly and iterate to new solution concepts in subsequent testing. The next 5 new textile blanket design tests were conducted with a new test procedure where a positive GN₂ purge was introduced under a plastic film into the test box cavity in order to eliminate the presence of oxygen as much as possible, and to avoid any oxygen or fuel saturation during rocket engine startup and shutdown procedures. The plastic film was instantly burned off during rocket engine ignition, so that atmospheric oxygen intrusion was very limited.

The purge did not solve the combustion issue as observed in high speed video of the tests, so it is postulated that oxygen causing carbon burning was not the only factor in the carbon fiber combustion process.

The rocket exhaust gases contain water (in the form of steam) and carbon dioxide:



An investigation into the rocket engine exhaust plume constituent hot gases revealed the following reactions are thought to be occurring:



Reaction 4 may occur either as a gas phase reaction or as a heterogeneous reaction at the solid-gas interface. All the other reactions must take place at the solid-gas interface. The presence of hydrogen in the reaction products creates a safety concern since hydrogen will react with oxygen to burn and create a fire. On Earth this could be an issue during testing due to the presence of oxygen in the atmosphere, but on the Moon, there will be no atmospheric oxygen so the danger will be eliminated. However, the chemistry predicts that the carbon material will be consumed, so further work is required to find a coating for the carbon fibers that will isolate them from the superheated steam in the very short landing and launch environments (estimated to be 1 to 5 seconds). The NASA Space Shuttle used carbon-carbon material for the thermal protection system on the leading edge of the orbiter wings and on the chin panel. To withstand reaction the Earth's atmosphere in a hot plasma environment, these parts were coated with silicon carbide and then with an additional layer of tetraethyl orthosilicate and a subsequent sodium silicate sealant. In order to mitigate the effects of superheated steam, a similar coating may need to be applied to the carbon fibers before weaving them into a textile or needle punching them into a non-woven textile.

Since the test was only 2 seconds in duration, the remaining blanket prototypes survived the PSI event. The textile blanket did not burn all the way through all layers, and therefore no regolith was ejected, so these tests were considered promising since no regolith dust was ejected. However, reusability of such a LLP blanket would not be possible without repairs. Further work is needed to develop the textile materials, based on the data from these test campaigns, but preliminary test data indicated that a feasible layup may be possible. A blanket made purely of basalt materials is also an option, since the basalt textile would likely melt into a glassy material which might then become an ablator.

7. *Test Instrumentation*

The selection of test instrumentation proved adequate and worked well in the field overall. The C-type fast response thermocouples proved to be very resilient and effective even during materials failures. The K-type thermocouples in the regolith provided the ambient reference needed to verify the pre-test conditions. The data obtained with the C-type units is under careful analysis to understand the range of values obtained which is lower than expected. The units and the data acquisition system worked properly during each test.

The load cell configuration worked well overall but proved cumbersome in its installation and calibration. Occasionally, one load cell would not register data.

The 3D scanner tool is of high sensitivity while its operation in the field is challenging. The placement of the targets, the illumination conditions, and the scanning time proved to be difficult to manage during field operations under windy and cold conditions. The data obtained is being analyzed at the time of the writing of the report.

The addition of tracer balls in the plume field was an innovation that worked well since several of the balls were seen in high-speed videos. The analysis of the video frames is underway to obtain estimates of gas velocities near the surface of the materials.

VIII. Conclusions

The testing conducted under this project occurred in a terrestrial environment under atmospheric pressure in Mojave, California. However, in lunar conditions the environment will be different due to the high vacuum conditions at the Moon. In the vacuum, a rocket engine plume will rapidly spread out causing a low gas density and low impingement pressures on the LLP, while on Earth the rocket engine plume remains collimated with higher gas densities and pressure. Testing a rocket engine in a vacuum chamber on Earth is extremely difficult and expensive, since the gas from the plume rapidly eliminates the vacuum conditions, therefore providing limited vacuum data. In addition, the rocket engine plume environments change depending on whether the rocket is in the descent, landing, launch or ascent phases.

In order to gain an understanding of the materials behavior of various candidate LLP materials, this test program attempted to create a relevant plume environment by using the same propellants as the SpaceX Starship (O_2 / CH_4), and then the height of a 444 N thrust engine was varied. The test conditions were identified by using Computational Fluid Dynamics (CFD) computer modeling corresponding to the engine height. At the lowest engine height, the test conditions approximated the most severe expected Raptor engine temperatures and gas velocities, while pressure and gas densities were too high. At the highest engine level, the test conditions more accurately matched Raptor engine gas densities and impingement pressures. These two conditions bound the expected LLP environments that the materials are expected to experience in a SpaceX Starship lunar landing using one Raptor engine and provided an indication of the materials' viability for LLP construction. Nevertheless, these tests could not accurately re-create a lunar landing with Raptor engine plume surface impingement environment, so the results can only be interpreted as trends and approximations of the materials' performance. This points to further testing, more specific to lunar conditions with combinations of materials that offer optimal solutions.

However, the testing was able to show the promise of various materials which have now become candidates for LLP design and construction utilization. The materials were evaluated with the emphasis on the following observations to judge viability:

- Penetration of the rocket engine plume into the materials test articles
- Presence and extent of excavation and ejection of regolith
- Mechanical behavior under the plume
- Thermal behavior under the plume
- Extent of materials damage
- Feasibility of in-situ construction of the LLP using these materials

Five materials were tested in suitable configurations for LLP construction. The thermally sintered regolith pavers with a RTV / regolith mix ablative grouting showed a high degree of promise and a high degree of ISRU with good performance and high feasibility of construction. The same RTV /regolith mixture that was used for the grouting was also used to cast a LLP slab test article. It performed well as an ablator and could be used to pour a LLP horizontal structure, but had a lower degree of ISRU due to the larger quantities (11%) of RTV thermoset polymers that must be brought from Earth. Anorthosite rocks that were captured in stainless steel Gabion cages to avoid rock ejecta from the rocket engine plume also performed well by withstanding the rocket engine plume with some minimal rock spalling evident. The textile woven with non-woven layups had an interaction with the plume combustion products that caused the materials to degrade, but some of the textile layups did survive the test, although they all sustained some damage. Further textile materials development work is needed to make the high temperature blanket materials viable, but they showed promise and could provide a way of rapidly deploying a lightweight horizontal LLP structure brought from Earth.

In conclusion, this test program established that there are materials that showed promise, for LLP construction, under terrestrial rocket engine plume impingement testing, which created a relevant environment. Further development work is necessary for all the materials, but potential feasibility of these materials for LLP construction was established. Overall, this collaboration with SpaceX advanced the understanding of Starship lunar landing requirements and advanced the technology readiness level of the tested materials from 4 to 5.

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