

## **Planetary Basalt Field Project: Construction of a Lunar Launch/Landing Pad, PISCES and NASA Kennedy Space Center Project Update**

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### **ABSTRACT**

Recently, NASA Headquarters invited the Pacific International Space Center for Exploration Systems (PISCES) to become a strategic partner in a new project called “Additive Construction with Mobile Emplacement (ACME)”. The goal of this project is to investigate technologies and methodologies for constructing facilities and surface systems infrastructure on the Moon and Mars using planetary basalt and other in-situ materials. The first phase of this project was to robotically-build a 20 meter (66-ft) diameter vertical takeoff, vertical landing (VTVL) prototype pad out of local basalt material on the Big Island of Hawaii. This VTVL pad is a technology “proof of concept” demonstration project to show how a robotic precursor mission could viably construct a VTVL pad on a planetary surface. Such VTVL pads can mitigate the effects of a lander rocket engine exhaust plume impinging on the regolith surface, which can cause cratering and high speed ejecta. In March, 2015 a “lunar sidewalk” construction was first completed in Hilo, Hawaii, which proved that raw crushed Hawaiian basalt could be sintered into modular paver elements. The Hawaiian basalt is very similar to granular materials found on Mars and the Moon. Subsequently, PISCES and the NASA Kennedy Space Center (KSC) Swamp Works team completed the basalt construction of a tele-operated, robotically-built basalt VTVL pad. Construction was started in October, 2015 and successfully completed by the end of December, 2015.

PISCES and NASA KSC assessed various in-situ construction methodologies for the 2015 VTVL pad deployment demonstration using additive construction with Hawaiian basalt regolith.

Using the PISCES robotic rover (named “Helelani”) as the central platform for construction, the team evaluated a variety of technologies for stabilizing the basalt surface, and then selected a sintered inter-locking paver system to meet the requirements. New methods for sintered basalt regolith paver production were developed and a tele-operated paver deployment mechanism (PDM) was developed and installed on the PISCES rover to simulate VTVL pad construction operations during an actual space mission. The rover was tele-operated locally in Hilo, Hawaii and also from NASA KSC in Florida, which created valuable lessons learned for future space missions requiring a VTVL pad capability.

## **INTRODUCTION**

PISCES and the NASA Kennedy Space Center (KSC) Swamp Works completed the execution of an innovative planetary robotic construction-demonstration project in the State of Hawaii in December, 2015. This task is part of a larger NASA effort called “Additive Construction with Mobile Emplacement (ACME)”. The goal of the ACME project is to investigate technologies and methodologies for constructing infrastructure and facilities on the Moon and Mars using in situ materials such as planetary basalt material. By using the indigenous regolith materials on extra-terrestrial bodies, then the high mass and corresponding high cost of transporting construction materials (e.g. concrete) can be avoided. At approximately \$4,000 to \$10,000 per kg launched to Low Earth Orbit (LEO), depending on the launch provider used, this is a significant cost savings which will make the future expansion of human civilization into space more achievable. Part of the first phase of the ACME project was to robotically-build a 20 meter (66-ft) diameter VTVL pad out of crushed basalt granular material on the Big Island of Hawaii. This field demonstration showed that two dimensional (2D) horizontal planetary construction is feasible with tele-operated robots, using only in-situ materials. In addition, a VTVL pad can solve rocket plume regolith surface erosion issues and prevent lofted dust and ejecta, which would otherwise cause a large dust cloud and high velocity regolith debris, impairing sensing and navigation during precision landings on the Moon or Mars. These effects could also cause damage to the lander vehicle or even loss of the vehicle and mission.

## **BACKGROUND**

Spaceflight experience with landings on both Moon and Mars have indicated significant issues that arise with rocket plume lofted regolith (planetary dust) when ascent/descent module chemical propulsion rocket engines interact with the loose, fine regolith of the surface.

Analysis of both Apollo lunar landing imagery and computational models indicate that sub-micron to 100 micron-size particles can reach ballistic trajectories with velocities of up to 2000 meters per second (m/sec) in the vacuum environment of the Moon. Analysis also indicated that the Apollo mission descent engines on the Lunar Module (LM) excavated approximately 2000 metric tons from the landing site. (Metzger, 2014). In addition, erosion of the surface was seen in the recent Mars Science Laboratory (MSL) which successfully landed on Mars using a “sky-crane” vehicle. (Sengupta, 2014). Landing large spacecraft (> 1,000 kg) on unstable and self-eroded regolith surfaces creates a serious risk to a successful vertical landing, which could cause loss of mission and crew. Takeoff is also dependent on suitable inclinations of the vehicle (the

NASA Apollo missions limit was 12 degrees from the horizontal) and a stable launch structure foundation.

Such regolith erosion volumes and high ejecta velocities could also represent significant threats in damage from sand blasting of co-located infrastructure of a landing site in the build-up of a base/outpost. For example a Mars Ascent Vehicle (MAV) could be damaged from another space craft landing which would jeopardize the crew's journey back to Earth.



**Figure 1. Photographic Evidence of the Mars Skycrane / Curiosity Lander Descent Engine Rocket Plume Excavating and Lofting Dust at the Gale Crater Landing Site. Photo: NASA/JPL**

A mitigation approach is required for planetary surfaces where repeated launch/landings are required in order to build up and operate a surface base site. One of those mitigation strategies is to stabilize the regolith of the VTVL landing area to significantly reduce the risk of high velocity ejecta particles created by the entry descent engines of launch/landers where high velocity gas interacts with the regolith surface and entrains regolith particles in its flow path. Various regolith stabilization strategies were investigated to determine a viable mitigation for these rocket plume effects at a VTVL site.

## **DESCRIPTION**

The Additive Construction with Mobile Emplacement (ACME) project, In-Situ Vertical Takeoff / Vertical Landing (VTVL) Pad task is a joint venture between NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program, NASA Kennedy Space Center and the Pacific International Space Center for Exploration Systems (PISCES). The VTVL pad task is one part of a larger ACME additive manufacturing effort using indigenous

materials. The technologies used in this task are also directly applicable to robotic horizontal construction methods for building foundations for large in-situ concrete structures that will be 3D printed using Automated Additive construction (AAC).

The ACME project aims to increase the technology readiness level (TRL) of 2D horizontal construction using robotic methods with VTVL pad in-situ materials and in-situ construction from TRL 3 to 5. The goal of NASA/GCD, is to develop ACME for use on planetary surfaces, to create both horizontal structures such as foundations, pads and roads as well as three dimensional, vertical construction structures such as blast protection berms, un-pressurized shelters and pressurized habitats. In addition to the TRL advancement of VTVL pad robotic technology, the constraints placed on this task by the planetary surface environment and the effects of rocket plume impingement and debris ejecta were the focus of the NASA work under this task.

The TRL increase in VTVL pad technology is possible by combining the expertise, technologies, indigenous Hawaiian volcanic basalt materials and goals of NASA Kennedy Space Center (KSC), and the Pacific International Space Center for Exploration Systems (PISCES).

The end goals of the project were to:

- Be the first analogous terrestrial demonstration of tele-operated robotic VTVL pad construction using planetary analogous basalt materials
- Investigate construction materials made from regolith, to identify optimal planetary VTVL pad construction materials
- Advance the TRL of robotic VTVL pad hardware and processes to provide risk reduction and capabilities to future missions
- Provide the gateway to fabricating VTVL pads, on demand, in precursor space missions (prior to humans arriving) with in-situ resources, reducing the need for sizeable structure launch up-mass
- Provide a significant return on investment by enabling future NASA missions (such as large Mars landers (18-40 tonnes) not feasible without the capability to mitigate plume effects such as via the construction of VTVL pads in situ (using planetary surface regolith based materials), and doing so with significant (external to NASA) leveraging of funding from the state of Hawaii, to realize a joint venture, in-situ demonstration in Hilo, Hawaii.
- Provide a first step towards evolving VTVL pad construction for use on space missions to Earth's Moon, Mars and beyond.

The current state-of-the-art in VTVL landing pads is TRL 3 (Analytical and experimental critical function and/or characteristic proof-of-concept) with regolith materials being developed that are as strong as, or stronger than regular terrestrial Portland cement based concrete. The goal was to develop the technologies required to achieve TRL 5 (System/subsystem/component validation in relevant environment).

This task, which was completed by KSC, and PISCES, defines the state-of-the-art for the development of construction materials using in-situ Hawaiian materials (which are similar to planetary materials). For the purposes of ACME, fabrication of 2D horizontal structures were demonstrated by NASA KSC and PISCES, made from Hawaiian volcanic basalt materials; KSC showed the feasibility of using regolith-derived materials in the construction of sintered basalt pavers for a “bulls-eye” central landing pad area (3m x 3m) and concepts were generated for the surrounding VTVL gravel pad apron (20 m diameter) stabilization methods.

The ACME project is relevant to the NASA Agency’s vision and mission as defined by NPD 1001.0, NASA Strategic Plan. The ACME project and its partnerships fulfill all three strategic goals:

1. Strategic Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space. ACME will provide the background knowledge and capability necessary to build structures in space using in-situ resources.
2. Strategic Goal 2: Advance understanding of Earth and develop technologies to improve the quality of life on our home planet. Technologies to improve the quality of life on our home planet is another goal of the ACME project. The synergistic work with the PISCES and NASA will provide a VTVL robotic construction system with which pads and foundations will be constructed; this technology has a vast amount of applications on Earth ranging from helicopter landing pads to foundations, parking lots, roads, sidewalks, patios, plazas, driveways and other 2D structures. Additionally, PISCES has an agreement with the State of Hawaii to investigate the construction of housing using local Hawaiian basalt, therefore avoiding importing cement from the mainland.
3. Strategic Goal 3: Serve the American public and accomplish our Mission by effectively managing our people, technical capabilities, and infrastructure. The ACME project leverages significant matching funds from the State of Hawaii for PISCES. The ACME project leverages NASA Field Center capabilities in contour crafting, simulants, and materials production and characterization at NASA Marshall Space flight Center (MSFC); as well as regolith handling, regolith construction material research, and autonomous systems at KSC.

The ACME project also fulfills specific NASA strategic objectives:

- Objective 1.1: Expand human presence in the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration. The ACME VTVL pad robotic system was designed with planetary surface environments considerations, analogous environments in Hawaii and relevant regolith simulant materials were used in the experiments.
- Objective 1.7: Transform NASA missions and advance the Nation’s capabilities by maturing crosscutting and innovative space technologies. The ACME VTVL task matured terrestrial robotic construction technologies and basalt based materials to provide the capability of producing 2D pad structures on other planets while utilizing in-situ resources for the structures.

- Objective 2.3: Optimize Agency technology investments, foster open innovation, and facilitate technology infusion, ensuring the greatest national benefit. PISCES will use knowledge gained to facilitate infusion of the technology into the Hawaiian economy using local indigenous volcanic materials.
- Objective 3.2: Ensure the availability and continued advancement of strategic, technical, and programmatic capabilities to sustain NASA's mission. The goal of the ACME VTVL task project is to mature NASA's robotic construction capabilities and thus significantly reduce the amount of mass to be launched from Earth for the construction of planetary infrastructure.

The project success criteria were defined by the NASA In-Situ VTVL Pad requirements, as well as the ACME team goals for the advancement of TRL for 2D horizontal structures.

- Reduction in launch mass by utilizing 100% in-situ resources (regolith as feedstock).
- Mature the TRL of:
  - o Basalt pavers for VTVL pads from TRL 3 to 5.
  - o Robotic basalt paver emplacement technologies from TRL 3 to 5.
  - o Gravel stabilization using in-situ materials from TRL 2 to 3.
- Ability to build an entire 20 m diameter VTVL paver pad/foundation structure in less than 120 hours.

## **TECHNICAL APPROACH**

### **System Description:**

The purpose of the VTVL landing pad demonstration is to demonstrate the technologies and in-situ materials required to tele-robotically emplace a VTVL landing pad on a planetary surface so that subsequent missions can land with increased safety, reliability and repeatability. Without a VTVL system the rocket plume may cause large craters to form underneath the lander vehicle and eject regolith debris at velocities up to 2000 m/s.

The VTVL In-Situ Landing Pad element task consists of a "bulls-eye" central landing pad area (3m x 3m) that will demonstrate the technology required for repeatable VTVL operations with impinging rocket plumes. The apron area surrounding the robust bulls-eye pad area (20 m diameter) will be capable of supporting an off-nominal, contingency landing (where the vehicle has drifted), but is not designed to have the extended lifetime of the bulls-eye material since it is for contingency landings only.

Additionally, the PISCES sees a potential to expand basalt rebar technology into terrestrial applications within the State of Hawaii as an emerging economic development project for civil engineering. Currently, Hawaii imports iron rebar from China, but has experienced the high expense of transportation and quality issues with the imports (rust, manufacturing quality, etc). Given the fact that the Hawaiian isles are made of basalt material, it follows that there may be industrial potential for eventually fabricating basalt rebar in Hawaii for a substitute to iron rebar

for civil engineering projects within the State. This will provide the technology, the unique partnership, and testing activities leading to a new and viable economic activity in the state of Hawaii, which could result in a reduction of imports and an improved balance of trade.

## **ROLES AND RESPONSIBILITIES**

The following outlines the roles and responsibilities of PISCES in this project:

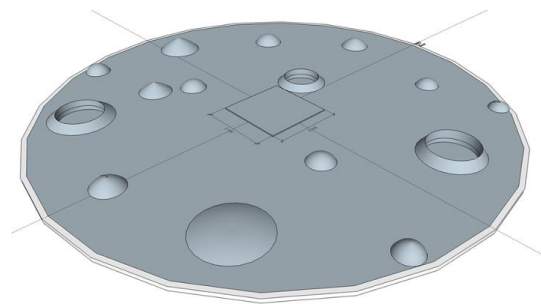
- Provides high quality lunar analogue test site (selection and site preparation)
- Provides large tele-robotic operating systems for construction
- Provides overall engineering integration & Interface Control Document (ICD) between the robotic rover and the construction implements hardware
- Responsible for procurement of a kiln and paver production
- Provides operations control for robotic construction leveling, grading, paver deployment
- Performs loads tests / verification after completion

The following outlines the roles and responsibilities of NASA KSC:

- Provides system requirements and Concept of Operations (ConOps)
- Develops the design and manufacturing protocol for basalt paver
- Mold design, interlocking, thermal heating/cooling profile
- Provides an adjustable bulldozer leveling blade
- Design and development of the rover Paver Deployment Mechanism (PDM)
- Provides technical support personnel to PISCES for landing pad construction phase
- Possible tele-operation of the rover from KSC Swamp Works via NASA communications router, using the Space Network Research Federation (SNRF) system.

## **LUNAR LANDSCAPE CONSTRUCTION: “MOONSCAPE”**

PISCES developed and completed the construction of a KSC-designed lunar landscape. The lunar landscape was the designated location for the tele-robotic construction of the VTVL pad. PISCES located the test site at the Puna Rock Quarry in Kea-au, Hawaii (near Hilo). Basalt fines (sub 150 micron) were brought into the site as working material for the center bulls-eye. The outer apron areas of the moonscape were filled with a mix of basalt sand, gravel and larger particles.



**Figure 2. Oblique Computer Aided Design (CAD) view of PISCES VTVL Basalt Moon-Scape with simulated Hills and Craters**



**Figure 3. Aerial View of actual PISCES in-situ VTVL Basalt Moon-Scape**

### **BASALT VTVL PAD CONSTRUCTION OPERATIONS**

The Strategic partners shown in Table 1 all contributed to the VTVL project, with the indicated responsibilities. The combined effort and commitment of these organizations enabled a successful joint venture to prove the feasibility of tele-robotic construction of a VTVL pad.

**Table 1: VTVL Pad Joint Venture Team Members and Contributions**

<b>Partner</b>	<b>Project Responsibility</b>
PISCES	Provided planetary rover, basalt test site, paver fabrication and test operations
NASA-KSC	Developed overall test requirements, paver design, fabrication method and molds, developed gripper for paver deployment, PDM, integration of the robotic arm, design of lunar landscape, hot fire test requirements and solid propellant rocket test stand
Honeybee Robotics, Inc.	Provided robotic manipulation arm for deployment of pavers
Argo, Inc. – Canada	Manufacturer/provider of basic robotic rover system to PISCES
County of Hawaii R&D	Co-funding to PISCES for research and development in basalt material as a construction substitute versus concrete

### **VTVL Pad System Construction Concept of Operations:**

The construction operations were completed in Hawaii by PISCES at a basalt rock quarry site. The following phases were used to achieve the final configuration of the pad.

**PHASE 1 – Prepare the “lunar” analog site for construction by leveling and grading with PISCES rover/KSC blade – Full VTVL pad perimeter**

1. Develop VTVL System Concept. *20m x 20m pad with 3mx 3m bulls eye area.*
2. Select VTVL Site. *Puna Rock Quarry, 16-669 Milo St, Keaau, HI 96749*
3. Evaluate Geotechnical Foundation. *Basalt rock at 200 feet height above sea level, with good drainage.*
4. Secure perimeter: *Ensure that VTVL operations can proceed without hazards to work force or the public. Clear Rocks and deposit dry basalt regolith fines*
5. Site preparation. *Tele-robotic leveling with robotic rover mounted bulldozer blade*
6. Site preparation. *Tele-robotic grading with robotic rover mounted bulldozer blade*



**Figure 4. PISCES rover with KSC leveling back-blade**

**PHASE 2 – Compaction and fine finish - PISCES' blade on rover with compaction roller attached – Bulls Eye Pad Area**

7. Site preparation- *Tele-robotic compaction and fine blading for final foundation configuration*



**Figure 5. Robotic Compaction Operations**



**Figure 6. Robotic leveling and grading**

### Soil Compaction:

Soil compaction analyses were performed of the bullseye area prior to and post compaction. The results are shown in Table *a*. A sample of the bullseye fines were sent to a lab to be used as the reference standard. The results exceeded the requirement of 1.8 g/cm<sup>3</sup> for soil compaction.

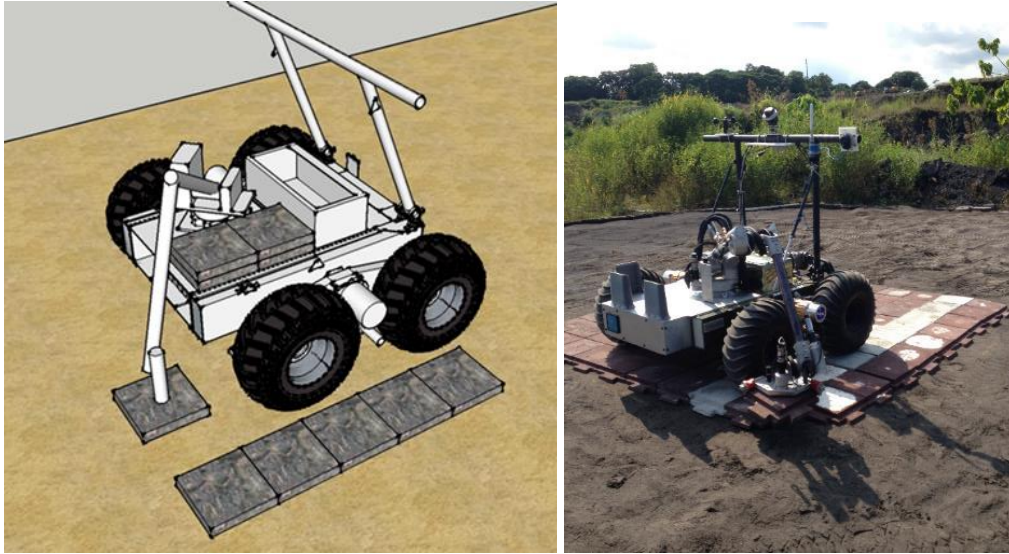
	Lab	Pre-Compaction Field Analysis			Post Compaction Field Analysis			
	Standard	smpl1	smpl2	avg	smpl1	smpl2	smpl3	avg
Moisture	<b>0.10%</b>	6.60%	7.40%	7.00%	7.0%	7.0%	6.40%	6.8%
Wet Density (gr/cm <sup>3</sup> )	<b>2.124038</b>	1.811679	1.8917711	1.85172512	2.4396	2.490859	2.417174	2.449211
Dry Density (gr/cm <sup>3</sup> )	<b>NA</b>	1.69955	1.7620222	1.73078633	2.279416	2.327471	2.271407	2.3
Densisty relative to Std		80%	83%	81%	107%	110%	107%	108%

### Bullseye Grading & Leveling:

*The grade of the bullseye area of the VTVL was measured after operations and was found to be within the requirements for the project.*

### PHASE 3 – PISCES rover emplaces pavers using KSC PDM

8. VTVL pad surface: *Tele-robotic emplacement of basalt interlocking pavers in “Bulls Eye” (3m x 3m) central landing location.*



**Figure 7. Paver Deployment Mechanism (PDM) on PISCES Planetary Rover**

#### **PHASE 4 – PISCES rover/roller compact outer apron**

9. VTVL pad apron: *Tele-robotic grading, leveling and compaction of VTVL pad outer apron*

VTVL pad apron: Tele-robotic grading, leveling and compaction of VTVL pad outer apron. During this stage the PDM payload was removed from the rover and replaced with the heavy leveling blade. The rover was used again to complete the grading and leveling of the Apron area surrounding the bullseye.



**Figure 8. Outer apron area after being graded & leveled.**

## **PHASE 5 - Rover places/levels additional gravel on apron**

10. VTVL pad apron: *Tele-robotic emplacement of gravel*



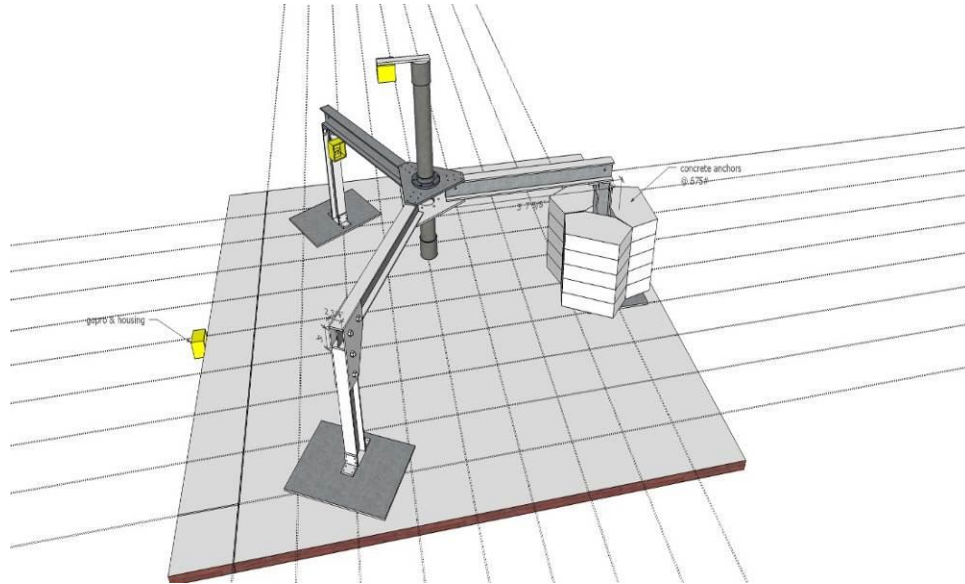
**Figure 9. Final VTVL pad bullseye and gravel covered Apron.**

## **PHASE 6: VTVL Pad Rocket Engine Verification Testing**

11. VTVL Vehicle Rocket Thrust Testing: *Test stand emplacement*

The rocket selected for the hot fire test is a Class M solid propellant engine model RMS-98/15360 (N3300) manufactured by Aerotech. The engine has 940 lbs of thrust and a total impulse of  $13,410 \text{ N}\cdot\text{s}^{-1}$  with a 4s burn time. This thrust level matches some of the commercially available VTVL landers that are flying today at terrestrial locations.

The test will be a stationary test with the engine mounted on a fixed test stand (figure 10) and the nozzle placed 0.45 to 0.5m above the center paver. The objective of the test is to verify that the basalt pavers maintain structural integrity throughout the engine firing. In addition high speed and infra-red video data and other instrumentation will confirm that the gas flow path at the paver joints does not create any adverse effects to the VTVL bullseye pad system.



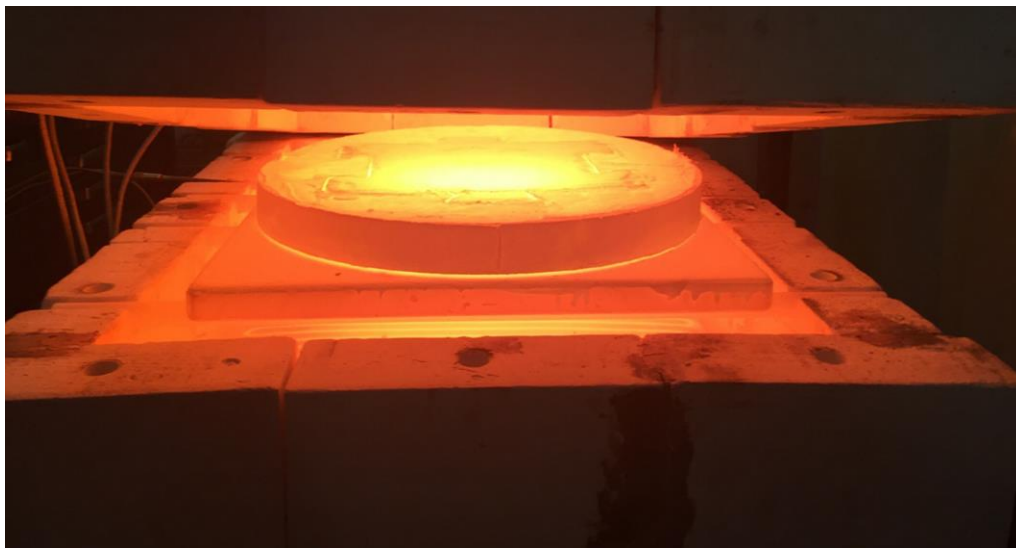
**Figure 10. Hot Fire Test Stand Design Concept**

12. Simulated Rocket Engine “Hot Fire” Validation Test:

A static rocket engine firing of a Class-M, 1000 lb solid-propellant motor is planned for March 2016 in Hawaii to validate and test the performance of the ACME basalt VTVL pad. Results of this performance test will be published at a later date.

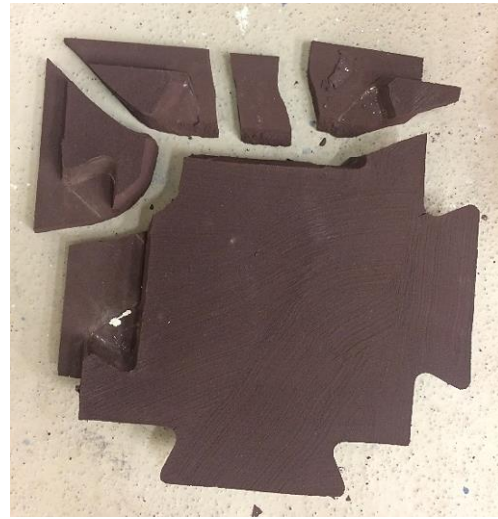
**BASALT PAVER PRODUCTION**

Pavers were designed for the 3 meter-by-3 meter VTVL bulls-eye stabilized surface such that they would interlock and be thick enough to provide adequate compression strength. The pavers were constructed from sub-150 $\mu$ m basalt fines, with no additives. For the final paver design, one hundred (100) pavers would need to be fabricated to accommodate the VTVL bulls-eye.

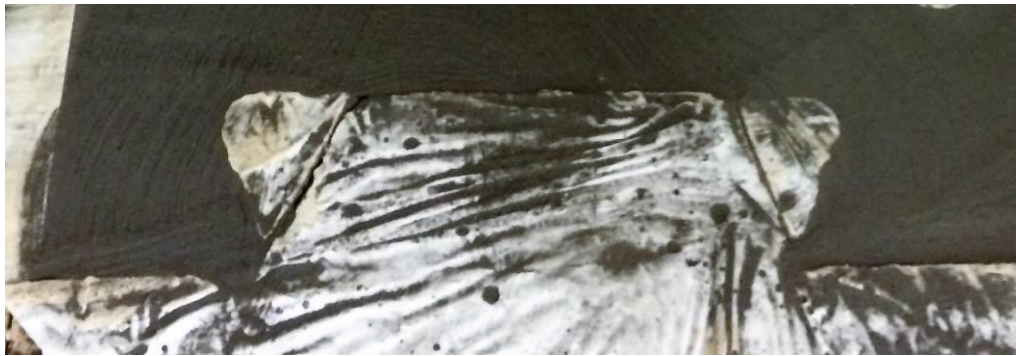


**Figure 11. High Temperature Basalt Paver Fabrication in Kiln**

Paver production was a complicated task, turning out to be more of an “Art” in defining the proper thermal profile, particle sizes, and mold design for thoroughly sintering the basalt without creating cracks/breakage in the pavers. The spring/summer 2015 timeframe saw a steep learning curve in designing a thermal profile that would create a suitable basalt paver. The resultant thermal profile was an approximately 30-hour run time in a high temperature kiln, with a maximum sintering temperature of 2,100°F. Early paver prototypes consistently failed in the same manner and revealed lateral stress areas where the pavers were pulling against the molds upon thermal contraction of the paver. These failures were resolved by making part of the molds “float” such that the molds would slip upon paver contraction. Prior to making the molds float, only about 10% of the pavers were intact by the end of the run-time.



**Figure 12. Failed Paver**

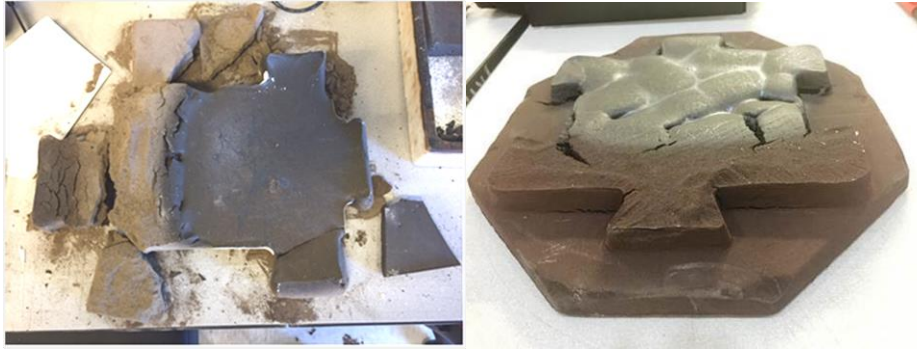


**Figure 13. Floating mold**

The post-modification intact rates improved to 50%, but revealed secondary stresses that accounted for the remaining failures. These secondary failures were due to vertical stress from the pavers contracting and pulling against the ledges of the mold. Due to the geometric constraints of the molds, and additional floating modifications were not feasible. To reduce vertical contraction, the sub-150 $\mu$ m basalt fines were mixed with #4 basalt sand. Various mix-ratios were tried and a 50% sand/fine ratio was found to offer the best performance with minimal shrinkage and overall failure rates dropped to less than 10%. The overall profile was finalized in September 2015 at which time paver production started in October 2015 and completed in December 2015.



**Figure 14. Vertical stress fractures**



**Figure 15. Basalt paver production issue with hot spots and cracking during April/May 2015 – Problems resolved later in August 2015**

## **CONCLUSION**

This collaboration was between a team led by PISCES and NASA Kennedy Space Center Swamp Works and also included contributions from Honeybee Robotics, inc, Argo, inc (Canada), and the County of Hawaii.

A prototype VTVL pad using only in-situ basalt materials found at the analogous test site on the Big Island of Hawaii was successfully constructed using a tele-operated robot with various implements. Tele-operations were proven to be feasible via internet communications from NASA Kennedy Space Center Swamp Works in Florida to Hilo, Hawaii. One hundred sintered basalt interlocking pavers were fabricated and assembled with a robot arm and a custom gripper system to form a bullseye central landing pad area (3m x 3m) for repeatable VTVL operations without significant rocket plume impingement surface erosion or ejecta. The outer apron up to a diameter of 20 m was covered with gravel using a tele-operated bull dozer blade implement. The gravel will suffice for off-nominal landings but will not have the life cycle of the bullseye pad area. With surface navigation beacons on the pad and thrust vectoring on the vehicle, repeatable landings should be possible on the bullseye.

PISCES began integration and test operations in the field in late October 2015 and successfully completed robotic construction operations in late December 2015. A static hot fire test to simulate an approximately 4,448 N thrust VTVL lander will proceed in the spring of 2016 to validate the construction methods by testing VTVL pad performance under solid rocket propellant hot gas plume impingement conditions.

## **ACKNOWLEDGEMENTS**

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