Lunar PAD - On the Development of a Unique ISRU-Based Planetary Landing Pad for Cratering and Dust Mitigation

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Lunar PAD - On the Development of a Unique ISRU-Based Planetary Landing Pad for Cratering and Dust Mitigation

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As humanity seeks outposts on other planetary bodies such as the Moon and Mars, technology must enable safe, repeated landings and launches near habitation. The design of the Lunar Plume Alleviation Device (Lunar PAD) aims to mitigate plume impingement and abrasive regolith debris and protect the crew, lander, and surroundings. Key vent features have been designed to provide both structural support and a controlled exhaust flow, and their basic function has been analyzed via finite element analysis (FEA) and computational fluid dynamics (CFD) simulations. A subscale Lunar PAD model has been completed in October of 2020 that demonstrates its ability to be 3D printed. The Lunar PAD uses in-situ resource utilization (ISRU) methods and technologies to minimize launch mass and enable previously unimagined structures. The lessons from this work can be applied to the design, manufacturing, and testing of future full-scale landing pads. Together with future landing system developments, additive construction technologies, and plume and dust control efforts, the Lunar PAD may expand possibilities for human exploration of the solar system.

I. Introduction

Since the days of the Apollo landings, there has been an understanding of the need for planetary landing pads. Without intervention, the extreme heat and pressure from exhaust plumes pose impingement hazards to the crew, lander, and any equipment or facilities within the vicinity. In addition, plume-surface interactions (primarily viscous erosion [1]) have been shown to generate serious landing visibility impairments [2], abrasion risks from high-velocity debris (1-7 tons at 1-2 km/s, in the case of Apollo [3]), and cratering [1]. A lunar landing pad could mitigate all of these risks.

The Lunar Plume Alleviation Device (Lunar PAD) project aims to mitigate the problems of dust and plume impingement upon landing and launch of space-faring vehicles on the lunar surface. A reusable landing and launch pad that redirects the plume and mitigates the creation of dust ejecta has been designed to provide protection from these hazards. These development efforts align with NASA 2020 taxonomy numbers TX 7.2.5 “Particulate Contamination Prevention and Mitigation,” TX 9.3.1 “Touchdown Systems,” and TX 13.1.1 “Natural and Induced Environment Characterization and Mitigation,” [4] as well as the goal of achieving extended habitation on the lunar surface.

This paper will first provide background information regarding the work with lunar landing pads and the Lunar PAD project. Then, it will discuss the design itself, as well as the design process in order to demonstrate the motivation for choosing this complex design over a simpler one. It will then describe the printing process, including where it was successful and areas for potential improvements. Future considerations relating to ongoing plume analysis and dust mitigation research are then discussed. This report will then complement a future paper analyzing the success of the design itself, so that both may be used in combination as a guide towards printing and building more effective landing pads and 3D structures in the future.

II. Background

Although early concepts for lunar landing pads have been presented elsewhere [5], previous attempts to build and test subscale landing pads for the lunar surface have all focused on the sintering of lunar regolith to make tiles.

In 2010, Hintze explored the use of polymer coatings to stabilize furnace-sintered regolith simulant tiles [6]. They were tested with cold gas thrusters, resulting in some damage to the edges of tiles. Without applied heat, it is difficult to assess the response of this configuration to actual rocket exhaust.

Another subscale pad using interlocking furnace-sintered tiles made of crushed Hawaiian basalt was built and tested by the Pacific International Space Center for Exploration Systems (PISCES) under NASA’s Additive Construction with Mobile Emplacement (ACME) project. Built in late 2015 and tested in early 2016 [7], approximately 30 of the 100 interlocking tiles were destroyed or displaced by the force of a four second burn from an M-Class amateur rocketry motor.

This paper introduces a new paradigm for the construction of lunar launch/landing pads that utilizes the rapidly growing technology of additive construction, coupled with development of lunar construction materials being pursued under the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project at NASA’s Marshall Space Flight Center (MSFC) [8-10]. Using technologies and materials being developed at MSFC since 2004, a unique solution to the landing pad issue has been designed to be 3D printed on a planetary surface using in-situ materials.

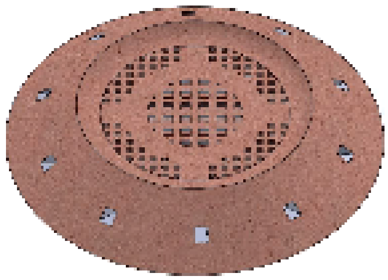
The Lunar PAD concept was first proposed at NASA's L'SPACE (Lucy Student Pipeline Accelerator and Competency Enabler) Virtual Academy Summer 2019 NPWEE (NASA Proposal Writing and Evaluation) Academy, under the name Dust DEVILS (Dust Deflector EDS Vehicle Intake Launchpad System). The students of the Lunar PAD team won funding from this proposal and were assigned NASA Subject Matter Expertise in order to move forward to a virtual Design Readiness Review presentation at NASA Marshall Space Flight Center in June 2020, where the funding was procured for the printing and testing process.

Before a full-scale prototype could be fabricated, it was necessary to test both the Lunar PAD design and the printing process itself by printing a subscale version of the pad. To do this, the Lunar PAD team worked extensively with ICON, an Austin-based 3D printing company to discuss strategies and possibilities for printing the complex design. Despite progress in the development of lunar print materials [10, 11], it was decided to use a Portland cement-based material (the ICON proprietary Lavacrete [12]) on the subscale pad to focus on the ability of the Lunar PAD design to be 3D printed and on the redirection of the exhaust plume via the unique pad design. This prototype print was then successfully completed in October 2020. Next, a hot fire test will be performed on the pad, with the assistance of Texas A&M University's Sounding Rocketry Team, to test the efficiency of the design by monitoring the temperature, strain, and exhaust flow and perform a comparison of the simulations to actual test data. Material samples will also be tested (compression on cubes, tension on cylinders, hyper-velocity impact on a plate, and 3-point bend tests on beams, all with varying types of reinforcement), courtesy of White Sands Test Facility, NASA Marshall Space Flight Center, and The University of Alabama in Huntsville. The Lunar PAD Team will then analyze the combined data of the printing process, hot fire testing, and materials testing in order to make needed modifications to the design and make plans for proposing a full-scale prototype.

While the process of analyzing the design is still underway, key information was gained regarding the 3D printing process itself during and in preparation for the print. 3D printing is a quickly developing field, and while many efforts have been made to investigate the possibilities of 3D printing various structures on Earth or in space, the Lunar PAD design posed unique challenges due to the overhangs and complex shapes of the print, and as such could likely not be fabricated with any method other than additive construction.

The pad design has gone through a total of ten revisions over the period of the project's nearly two-year time frame. The changes have sometimes been minor, while at other times major aspects of the project have changed. From its earliest creation it was intended to be used to mitigate dust ejecta on extraterrestrial bodies such as the Moon or Mars.

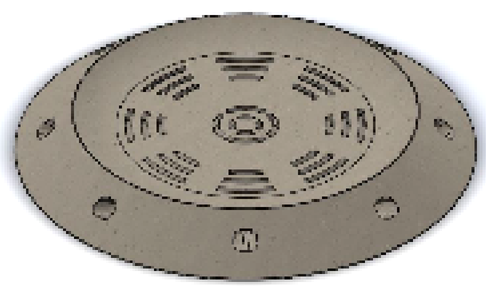
The primary focus throughout the development of the design was how the pad could mitigate plumes, and there were many ideas on how to achieve this goal. As shown in Fig. 1, the conception idea was a perimeter deflector that used the force of the exhaust created by a thruster to inflate a flexible and durable material such as tightly woven aramid fiber layers. This inflatable design was used to block ejecta and disperse heat flow. Due to complications involving optimal material selection, transportation challenges, and lack of viable autonomous installation processes, the flexible inflatable has since been replaced with the current Kinetic Energy Diffusers described later in this paper. This switch to a single piece of hardware simplifies the diffusion process while still achieving the same goals.

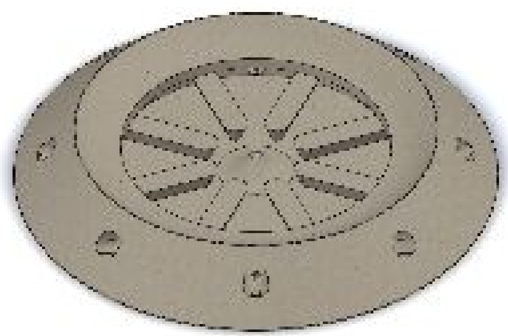


a) Full view b) Internal view

Fig. 1 Initial pad design

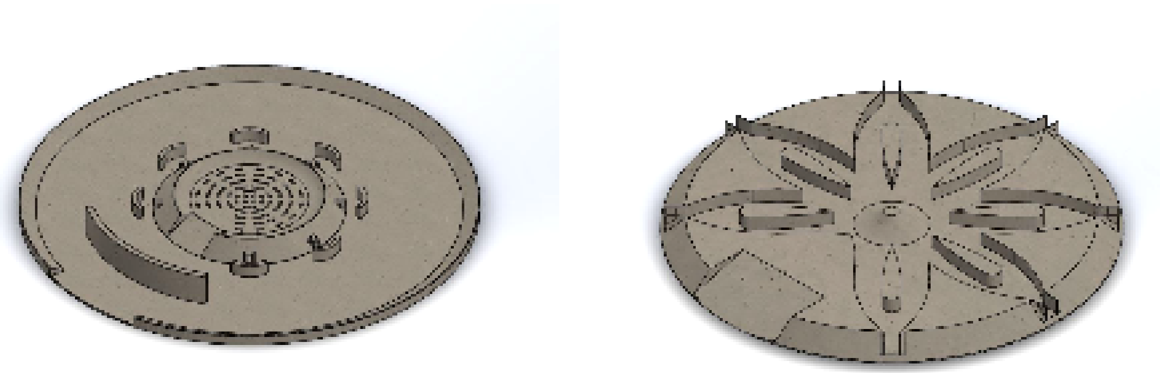
The other main focus was how to build a vented structure with large overhangs using 3D printed concrete. In order to reduce the size of the overhangs while maintaining the vented structure, it was necessary to create a support structure. As shown in Fig. 2, several variations were evaluated to determine which design would most efficiently balance having enough negative space to allow flow but not having overhangs too large to support. Once the current vent divider support design was chosen, the Lunar PAD team evaluated types of removable support material to further improve overhang support during manufacturing. Water-soluble foam was found to be the best solution. The experiments the Lunar PAD team has done with foam material in a 3D printed concrete structure is innovative and useful for Earth based construction, but not viable for space applications. The topic of removable support will be touched on more in the future considerations section.





a) Rev 1 b) Rev 1 internal view

c) Rev 2 d) Rev 2 internal view

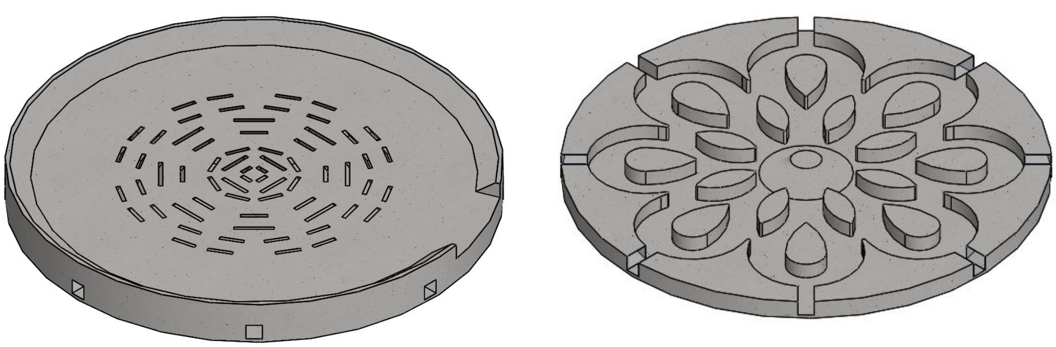


e) Rev 4 full-scale f) Rev 4 internal view

Fig. 2 Pad design at revisions one, two, and four. (Note that this figure shows only major design changes and not all revisions.)

III. Final Subscale Design

The final subscale pad design can be seen in Fig. 3 in comparison to the actual printed pad in Fig. 4.



a) Full view b) Internal view

Fig. 3 Final subscale pad design

Fig. 4 Printed internal view

The subscale Lunar PAD consists of two primary systems—the Landing/Launch Pad and the Kinetic Energy Diffusers (KEDs)—both of which contain several features that are unique in design and functionality (Fig. 5). The Landing/Launch Pad includes the grates, central cone, perimeter deflector, vents and vent dividers. The KEDs have two features: the Housing Frame and Housing Frame Anchor Rods. There are many other features being explored for full-scale implementation for both systems, which will be discussed later in this paper. The features that are present in the subscale design are described in the following sections of this paper as well.

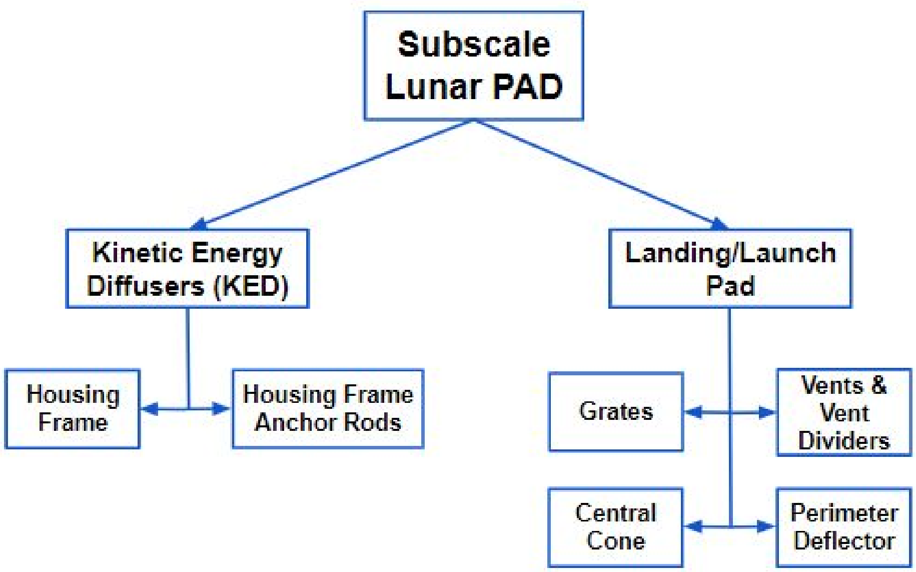


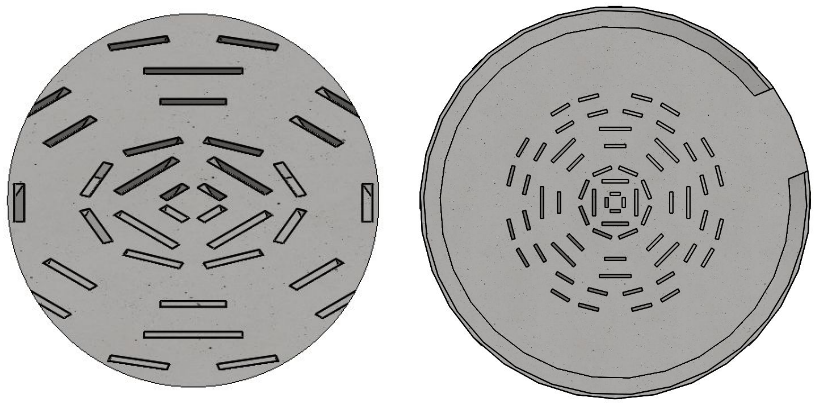
Fig. 5 Subscale engineering tree

A. Landing/Launch Pad

1. Grates

The primary objective of the grates is to capture exhaust in the vertical direction directly underneath a centered flow source, mitigating impingement effects such as overheating and stagnation. These issues may otherwise occur from the backflow of plume reflecting off of a surface. Additionally, the grates have been designed to maintain a small enough profile to still allow for a safe landing and egress surface without risk of a human foot, or lander leg falling through (See Fig. 7).

The grates are slanted at a 60 degree angle downwards from the horizontal, towards the outer diameter of the pad, and vary in length according to the vent dividers inside the pad (See Fig. 6). This allows exhaust to enter the inside of the pad, encouraging the flow to move outwards towards the KED openings.



a) Close-up b) Top view

Fig. 6 Grates

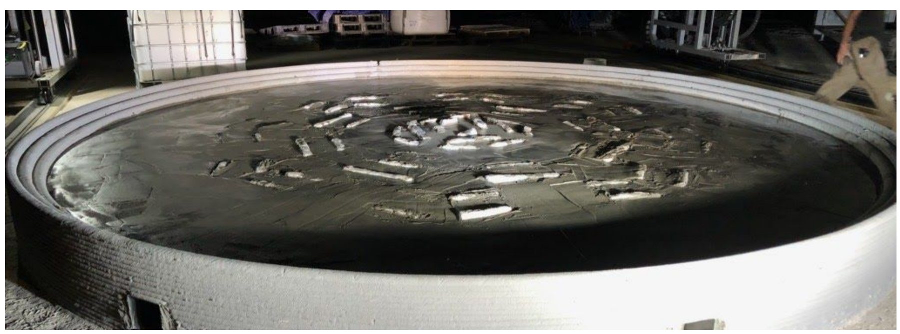


Fig. 7 Pad grates

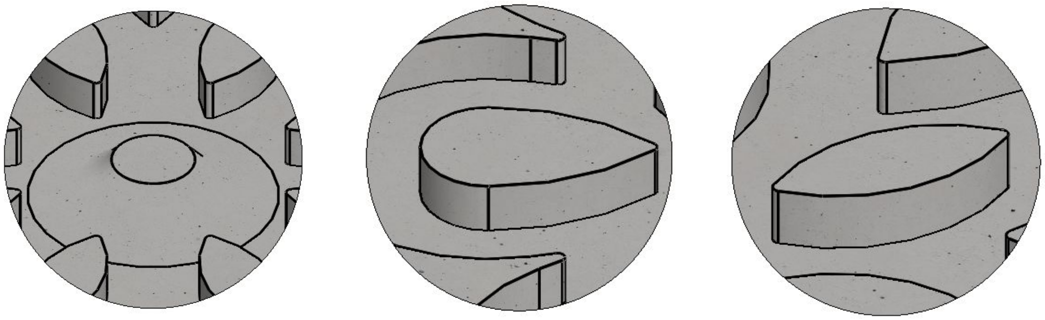
2. *Vent Dividers*

The vent dividers provide overhang support between negative spaces and assist in directing the exhaust from the center of the pad to the KEDs on the outer diameter. The amount of negative space in the vent layers is a trade-off between two desires; allowing as much exhaust as possible to flow to the KEDs to avoid high pressures that could backflow the exhaust, and minimizing the overhang area. Additionally, the vent dividers provide structural support to the pad's roof, as well as a path that decreases the pressure throughout the vent system by dissipating and distributing the flow as it reaches the KEDs.

The rounded side of the outer "teardrop" vent divider (See Fig. 8b) allows more negative space for exhaust to flow into the high-pressure converging point before flowing out of the KEDs. Each of the inner "leaflet" (See Fig. 8c) and outer "teardrop" (See Fig. 9b) shaped vent dividers prioritizes directing flow to the KEDs and avoiding high-pressure regions.

3. *Central Cone*

The central cone (See Fig. 8a) accompanies the inner grates by directing the exhaust flow away from the center of the pad and towards the KEDs on the outer diameter. While the inner grates are designed to maximize the exhaust capture, the central cone deflects the captured exhaust and further encourages it to flow outwards. The curved shape (See Fig. 9a) was chosen to increase acoustic efficiency and minimize the creation of motor stagnation and overpressurizing caused by impingement in the center of the pad [13]. The central cone also serves as a central support base to increase the structural integrity of the pad.



a) Central cone b) Teardrop vent divider c) Leaflet vent divider

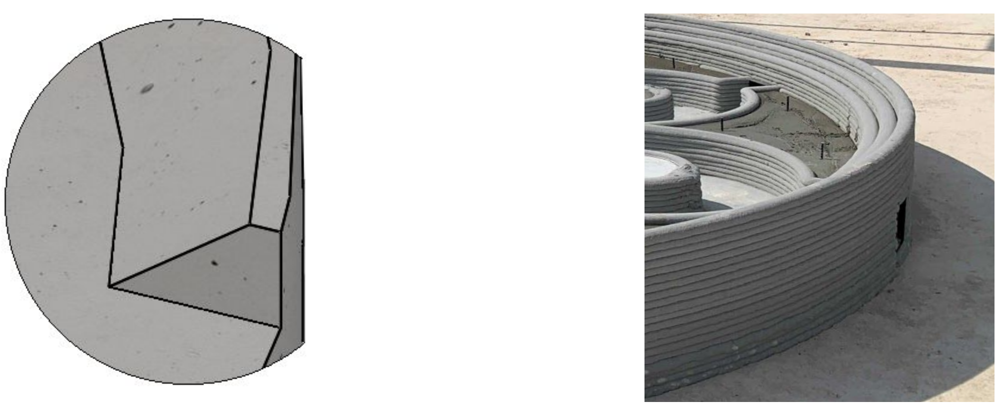
Fig. 8 Central cone and vent dividers

a) Printed and smoothed central cone b) Printed vent dividers

Fig. 9 Printed cone and vent dividers

4. Perimeter Deflector

Any exhaust, dust, and debris that do not go into the grates is directed up and away from the pad by the perimeter deflector to protect nearby structures, equipment, or personnel. It also directs the flow outwards to mitigate surface flow towards the motor. Although the pad perimeter deflector was originally intended to be a curved surface, the printed subscale design features a stepped deflector due to the nature of printing. The initial plan was to smooth the slope of the perimeter deflector (See Fig. 10a) in the same method as the central cone, but because the feature was not critical to the functionality of the subscale design, and due to time limitations, the decision was made to leave it stepped (See Fig. 10b).



a) Perimeter deflector b) Printed perimeter deflector

Fig. 10 Perimeter deflector

B. Kinetic Energy Diffusers

1. Housing Frame and Housing Frame Anchor Rods

The subscale KED housing frame is intended to demonstrate the ability to embed materials, and to test the durability of the pad during the extreme conditions it is expected to encounter. The housing frame is the primary point of contact between the subscale KEDs and the surrounding concrete. Similarly, the housing frame is the only part of the subscale KED that will be exposed to the high temperature and high pressure exhaust. There are two variations of subscale KED, with the only difference being the number and placement of housing frame anchor rods. One variation has two sets of one anchor rod while the other variation has two sets of two anchor rods (See Fig. 11). The reason for the two sets of designs is to test whether a single axis of rotation (one set of rods) will cause enough of a shift in the KED to cause damage to the pad when compared to two axes of rotation (two sets of rods).

Fig. 11 Manufactured KEDs

IV. Methods

A. Simulations

Computational fluid dynamics (CFD) and Finite Element Analysis (FEA) simulations are necessary tools for modeling plumes and their effects on landing pad designs. Prior to finalizing the prototype design, the Lunar PAD team performed several preliminary analyses. Simulations in SOLIDWORKS Flow Simulation were used to qualitatively evaluate exhaust flow through the pad during a static hot fire and ensure that the unique design features showed appropriate performance to reduce plume impingement effects when implemented into a full-scale launchpad. Static loading simulations in Siemens NX NASTRAN were used to confirm the structural integrity of the pad under expected stresses and to ensure that support was adequately distributed throughout the overhanging areas. Analysis of these sets of simulations led to the design evolution described in the background, and the process was repeated until there was enough confidence in the design to demonstrate satisfactory plume redistribution.

In the loading simulations, two main types of materials were used. The first material is lunar concrete. The exact material properties of the actual concrete to be used for the full-scale pad are unknown due to ongoing development of ISRU methods, but the properties of one example of "Mooncrete" researched in [14] [15] was used to approximate future lunar manufacturing materials. The second material is Lavacrete, which represents the material the pad was printed and cast with. Each material included fixed estimations in the initial conditions. Several simulations were run using qualitatively chosen test points, as well as the uniform force of gravity on the entire structure.

In the flow simulations, the subscale focus enables the Lunar PAD team to form hypotheses as to how the pad will react to the high temperatures and pressures induced by high velocity flow. Although full-scale Lunar conditions will be very different from the subscale simulation and testing conditions, the main focus of the flow simulations is the subscale test predictions. The placement of instrumentation for future testing was also based on modeled flow patterns combined with instrumentation installation and operation requirements such as temperature ratings.

B. Printing Process

Producing a subscale prototype is a key step in evaluating the design and printability of the Lunar PAD and preparing for future analysis. The landing pad prototype was manufactured using the gantry-style concrete 3D printing technology of ICON, which demonstrated the application of additive manufacturing to create unique geometries, and it contained several instrumentation placements to aid future testing efforts. The print was divided into 20 vertical layers of approximately 1-inch bead height. Layers 1-2 created the base of the pad, layers 3-10 the vent channels and dividers, layers 11-14 the top layer, and layers 15-20 the perimeter deflector. A thermocouple was embedded in the central cone during layer 2 to be used in future hot fire testing (See Fig. 13a). KEDs were placed at layer 7 and embedded into the concrete, and the printer continued to print over the anchoring rods (See Fig. 12).

Fig. 12 KED embedding

Once all printed layers were completed, the printer was used to create solid fills with a wetter concrete mix. The vent floor, interiors of the vent dividers, central cone, and outer edge shapes (referred to as “filled interior shapes”) were cast filled with concrete. During the initial print, the top two layers of the central cone did not quite join and, during the fill, drier waste concrete had to be applied to the gap as a patch to prevent overflowing. In the filled interior shapes, 6 inch pieces of basalt rebar were added to improve the bond between the cured concrete and the top layer.

There was an extended pause before printing the top layer during which additional instrumentation and the overhang support were installed. During this time, the central cone was also smoothed by using a wooden template of the curve as a reference and applying concrete around the stepped base. The patch was covered during the process of smoothing the central cone and is therefore not predicted to affect flow through the pad.

a) Thermocouple embedding b) Ceramic adhesive fiber attachment

Fig. 13 Instrumentation installation

A total of eight fiber optic sensors of three different types were installed (See Table 1). The process used ceramic adhesive (high temperature, corrosion-resistant adhesive cement known as Sauereisen) to attach the fibers to partially cured concrete surfaces (See Fig. 13b).

One five-meter Luna strain fiber was installed along the floor and part of the sides of the outer and inner vent dividers. The Luna fiber was extremely fragile, to the point where minor pressure applied to the fiber on the rough concrete ultimately cut the fiber. As a result, the procedure was modified to apply a layer of ceramic adhesive on the concrete, lay the Luna fiber on top, and apply a second layer to cover the fiber. One additional challenge encountered when installing the Luna fiber was the limited working time of the ceramic adhesive with the appropriate consistency to apply to a wall. Although these fibers were fragile, they were completely embedded in the ceramic adhesive, so there were no major concerns when stepping on them, but it was avoided regardless. After installation, the Luna fiber was checked with an FBG Interrogator and confirmed operational.

Six Loptek temperature fibers were installed along the floor near the walls. Each of the Loptek fibers were much more durable, relative to the Luna fibers, but still had a limited bend radius. During the installation process, a small object was placed under the fiber so that it was oriented upwards until the ceramic adhesive was sufficiently cured and the object was removed. This was done so that the temperature sensing section of the fiber was measuring the exhaust temperature in the vents instead of the surface temperature of the concrete. Due to the fact that the sensing section of fiber was exposed and protruding slightly upwards, there was special caution to avoid bending the fiber too much. Five of the six Loptek fibers were confirmed to be operational after installation, but the sixth was unfortunately broken.

One ten-foot Raman DTS temperature fiber was installed along the floor near the walls. This single fiber followed a similar procedure to the Luna fiber, but only on the floor, which resulted in fewer challenges with the ceramic adhesive and positioning. The Raman DTS fiber was also checked with an interrogator and confirmed operational.

Table 1. Fiber optic instrumentation placed in the pad during printing

Instrumentation	**Full name and description**
Brillouin SMF	Brillouin Single-Mode Fiber: Fiber optic sensing method where a reference signal is compared to a Doppler-shifted signal. Changes in strain / temperature will affect the extent of the Doppler shift and resulting signal.
FBG	Fiber Bragg Grating: Fiber optic sensing method where a periodic signal modulation takes a single measurement. Changes in strain / temperature of the fiber will affect the output signal at that point.
Loptek fiber	Temperature-sensing fiber optic with three discrete measurement points spaced 50mm apart.

Luna fiber	Strain-sensing fiber optic capable of continuous measurements.
Raman DTS	Raman Distributed Temperature Sensing: Fiber optic sensing method where physical vibrations reflect Stokes and anti-Stokes wavelengths that are subsequently detected. Changes in temperature will affect the ratio between the Stokes and anti-Stokes wavelengths detected.

Water-soluble Green Cell Foam was used to support overhanging vented areas (See Fig.14). The foam was pre-cut in pieces approximately 2 inches thick and of variable length according to the vent dimensions. The layout was designed based on whether the overhanging area contained grates or not. Since the foam came in 8-inch-high blocks in the extruded direction (the direction most resistant to the compressive forces of concrete), areas that did not contain grates were one piece high to match the vent height. For the grate areas, however, the pieces were cut such that the foam extended 4 inches into the top layer (i.e., to the surface of the pad), with another 4 inches in an attached underlying area. Most of the foam was low-density, but high-density foam was used for the grate pieces. Sets of an arbitrary number of pieces were assembled into blocks and wrapped in plastic (90-gauge LLDPE blown stretch wrap) to protect them from excess water in the poured concrete. Early tests showed that the foam degraded immediately upon water contact and that the plastic provided an imperfect seal on its own, so a high-strength, non-water-based spray adhesive was used to hold together the assemblies and seal the plastic wrappings. Once the assemblies were wrapped, they were placed in the pad vents and compressed into shape. From there, adjustments to the shape or filler pieces were added to better fit the complex shapes without gaps. A final layer of plastic was added over the crevices between blocks and/or filler pieces to add an additional layer of protection and ensure a smooth top surface. For the grate pieces that could not be as easily wrapped, tape was used to seal them together and prevent concrete from disrupting the continuous grate shape or running down the sides of the central cone.

Prior to the main casting of the top layer, a more viscous concrete mix was manually applied to areas of the pad that had a higher risk of concrete seeping beyond where it was intended. The thicker mix was applied in patches around the vent dividers to hold down the imperfect seal between the plastic and concrete (See Fig. 14). It was also applied to the top of each KED on the margin where the foam blocks met the box edge and on the external edge of the pad by the KEDs to fill any parts where the concrete outputted by the nozzle had not completely sealed in the boxes. Tape and viscous concrete were also placed along the seams of the central cone foam pieces to ensure that additional concrete was not poured on top of the central cone's already smoothed sides.

The top layer was then cast with concrete and smoothed with trowels. Upon completion of the top layer, the pad was covered with plastic tarps to slow the drying rate and prevent rapid evaporation of water that could lead to increased cracking.

Fig. 14 Foam and viscous concrete placement prior to the final cast fill

During the process, personnel monitored the pad for potential problems that might occur with the printing or casting due to the unique nature of the design requirements. They provided minor corrections such as spraying the concrete to prevent cracking from rapid drying, re-securing a KED that was knocked loose by the nozzle, patching and holding in place a small unstable area of layer 10, patching an area of the central cone inner cylinder that did not quite make a full circle (such that the casted interior did not drip down the sides), and manually adjusting the concrete material mix and printer path as needed. During the cast fill sections, personnel manually controlled the print nozzle, leveled the surface, and removed material deposited on the part of the foam that became the grate openings. While eventually these tasks may become automated, or future designs may eliminate similar risks, the on-site crew was an important component of the present effort and is important for risk mitigation in future efforts until such automation can be developed.

Throughout the printing process, imagery, notes, and in some cases distances measurements were made to record the progress of the pad as it was being printed as well as any minor defects. These evaluate the overall quality of the print and can also be compared to the state of the pad post-hot-fire to identify any damage.

V. Results and Discussion

A. Simulations

A key goal of the pad is to maximize flow through the vents, particularly near the central cone. However, the tradeoff is that the pad must still withstand loading to account for the maximum possible loading effects a lander could have, plus an additional margin of safety. As such, FEA loading simulations were conducted on the pad design to assess its support of the overhanging areas and overall structural stability. Furthermore, the flow simulations focus on replicating the subscale hot fire motor test that the Lunar Pad student team is performing on the pad.

The loading simulations results indicate that the pad will not break under the conditions tested in the simulations. Furthermore, for each material, displacement, stress, and strain measurements were taken to analyze the effects of the motor test stand load. Although the magnitudes of those measurements varied with material choice, the simulated stresses remained below the yield point of the concrete; the overall ability of the pad to support the hot fire loads was consistent.

The flow simulations results indicate that the pad will perform as intended with several notable behaviors and reactions. The exhaust velocity measurements throughout the pad show that exhaust is in fact coming into the grates, passing through the vents, and exiting through the outer diameter KEDs. Additionally, the exhaust is being directed radially outward by the central cone and diverted to the outer diameter by the vent dividers. Although high pressures and temperatures have been measured directly underneath the motor, these were expected and mitigated to the best ability of the current design. Modeled steady-state surface exhaust temperatures exceed the typical Portland cement temperature before structural integrity loss (2200 K - measured, 1088 K - Portland cement), but considering the short burn time and high thermal mass of the pad, it is unlikely that the pad itself will actually reach or exceed these temperatures. Similarly, for each of the KEDs, the exhaust surface temperature exceeds the typical A36 steel temperature before structural integrity loss (up to 1000 K - measured, 616 K - A36 steel), but for the same reasons described above, it is also unlikely that the KEDs themselves will actually reach these temperatures. It is also worth noting that some measurements, including heat transfer, thermoelectric effects (Seebeck effect), and degradation were not part of the simulations. Temperature measurements and visual indicators observed during the hot fire test will allow better interpretation of future model results.

B. Printing Process

All concrete features were successfully printed or cast, and overall, smooth print surfaces were achieved across the central cone and top surface. The pad was inspected during various curing periods and processes, and although several minor imperfections in the print were noted and evaluated, these flaws were generally superficial, and none signify a major flaw in the process or design. A feature-by-feature comparison of the completed print to the CAD model can be found in the design section in Figures 6-10 and demonstrates good adherence to the planned structures. In addition, the prototype successfully implemented hollowed channels by use of a sacrificial filler material that maintains structural integrity (in this case, foam), and embedded materials that stand in place of full-scale landing pad features.

The print layers were of good quality and had apparent structural integrity. No collapsing of the overhanging surfaces or delamination between layers was observed, and the rebar reinforcements were successfully bonded into the bottom layers. There are some variations in layer thickness (“pulsing” seen in layer 4 and varying height), but several pad dimensions were measured during the inspections, and they are all within 1 inch of the CAD model dimensions, with the largest discrepancy attributable to an area of the vent floor where the fill did not reach full height of the second print bead. The patched areas mentioned in the methods section were either on the exterior of the pad or under the smoothed central cone, where they are not expected to influence the hot fire test. There is one section where the top two layers do not quite meet in the perimeter deflector that was not patched since it did not have a structural effect on the pad.

The cast surfaces showed some minor marks and unevenness. For example, there were several small, non-structural cracks observed after the partial cure. They were particularly located around a KED, around an outer vent divider rebar, and on the outer diameter of the pad near the thermocouple. There were also some rough surfaces on the perimeter deflector and top surface from the cast fills (e.g., small drips of concrete or trowel marks) and where the fibers were installed using the ceramic adhesive. None of these flaws is believed to threaten the structural integrity of the pad or its durability in future hot-fire testing.

The single, concrete-embedded thermocouple required special precautions as it laid out into the pad center and pressed between printed beads. The printer operator is capable of starting and stopping the print at any point, but this ability was limited to emergencies as it would result in lost time and defects in the print. As a result, the thermocouple needed to be manually positioned from the outer diameter to the center of the pad while the printer was operating. The special precautions for the thermocouple ultimately did not have a significant impact on the printing timeline and the placement of the thermocouple.

The eight fibers had fewer limitations as they were installed during the vent layer support filling. Unlike during the thermocouple installation, the printer was not moving and printing, so Lunar PAD team members were free to step inside the vent layer and spend more time carefully embedding the fibers in ceramic adhesive without worrying about large equipment hazards. The process of installing the fibers was time-consuming and required extra attention being given to the fragility of the fibers, so the ability to focus on installation instead of hazards likely resulted in a higher installation quality and safer installation process.

The first two filled interior shapes had slight disbonding with the printed edges at the top, but those cracks were later filled during the casting of the top layer. The remaining interior filled shapes were cast with a thicker mix. The rebar placement was also adjusted to ensure ~6 cm extending above the surface of the filled shape rather than 5-5.5 cm for the first three fills. Although the two vent divider fills had rebar extending into the top layer, the rebar in the central cone was covered prior to the final top layer fill step.

During the final cast fill, some plastic from the wrapped foam was seen to catch in the concrete, and some small pieces of drier concrete were caught in the wet concrete during the troweling process. However, the foam remained intact, and overall, a solid and smooth top layer was achieved.

The most notable issue with the pad shape was a radial incline on the top layer, which can be seen in Fig. 7. Because the foam assembly plan relied on compression and the central cone shapes could only be cut with limited precision, the blocks sitting on the central cone sat higher than the rest of the pad. During the cast fill, concrete was filled to near the top of the grate shapes without realizing the error, resulting in a bowed top surface shape in which the pad rises higher in the center by up to about two inches relative to the outer diameter of the top surface. However, the concrete maintains constant thickness throughout the layer. Upon return to the site to inspect the completed pad, the team will make the determination of whether an attempt should be made to smooth the top surface of the pad (and if so, to what extent). If there is no smoothing, detailed measurements can allow the hot fire analysis to account for the new top layer shape when comparing the results to the model output.

C. Discussion

These subscale modeling and printing efforts address several elements necessary to manufacturing future lunar launchpads. First, the key flow and support features of the Lunar PAD design have been supported through simulations and translated to a subscale prototype concrete model. At a high-level, the printing process demonstrated the ability to manufacture the design using additive manufacturing and tasks such as filling or object placement that are largely realistic to perform on the lunar surface using the predicted technological capabilities. The process also incorporated the use of basalt rebar to support joints between separately-printed or cast layers, which could be applied to future efforts to experiment with different manufacturing methods or create stronger materials. Finally, the process included the installation of several temperature and strain measurement devices, which will allow the refinement of future designs after hot fire testing data is analyzed.

The Lunar PAD prototype took a total of four full days to complete, counting from the start of material deposition. Day 1 covered the printing of layers 1-20, day 2 covered cast fills of the floor and two vent divider interiors and the beginning of foam preparations, day 3 covered the remaining interior shape fills, central cone smoothing, fiber placements, and most of the foam assembly, and day 4 covered the remaining foam assembly and top layer cast fill. Although all of the foam was pre-cut into shapes outside of the timeline, the process of gluing the pieces together, wrapping and sealing them with plastic, and fitting them into the pad was lengthy. Low-density foam pieces were prone to cutting errors, and the difficulty in accurately predicting the foam's compression in the non-extruded directions led to the need to reshape pieces and produce last-minute fillers and covers for areas with imperfect fits. Thus, while the foam proved very effective from a structural standpoint, it carried a notable process cost, and another support method would be used for lunar or martian applications anyway due to the need to operate in a near-vacuum environment.

Due to the high temperatures expected in the hot fire, the instrumentation had to be protected, in this case by embedding them in either concrete (for the thermocouple) or ceramic adhesive (for all others). Embedding in the concrete required the thermocouple to be manually adjusted to avoid interfering with the printer nozzle and bead. Embedding the fibers later with adhesive required stopping the print timeline, though it had no impact in this case as it could be done simultaneously alongside the foam preparations. The physical effects of installing instrumentation on the pad include slightly increased roughness on surfaces from the ceramic adhesive (see Fig. 12) and imperfect shapes from the embedding. In terms of risk to the instruments themselves, it was also noted that the rough texture of concrete posed a hazard to the sensitive fibers. The surfaces on which the fibers were installed also had an impact on the ease of installation; the ceramic adhesive more readily adhered to concrete than the metal KEDs, although it formed a strong bond with both, and was easier to apply to the flat floor of the pad rather than the walls depending on the consistency of the ceramic adhesive. As future landing pad designs are built and tested, the instrumentation installation will likely remain an important consideration as there is a need for efficient processes and methods of gathering data.

At the time of writing, the subscale pad has completed the 28-day concrete curing period, and recent observations have shown that it maintained structural integrity throughout the cure. Upon return to the site, the foam will be removed, leaving the vent channels open, and a hot-fire test stand and motor will be set up, along with additional instruments and observing equqipment. The pad will be tested using an M-class amateur rocket motor, comparable to that used in the PISCES hot fire test, to validate or improve upon the design simulations. Due to the extensive planning, analyses, and placement of instrumentation throughout the pad, it is believed that the observations gathered in the planned hot fire test will represent the most detailed analysis of a landing pad prototype yet undertaken, independent of the overall success or failure of the design, and provide valuable insights for future technology.

VI. Future Considerations

A. Full-Scale Design Considerations

The design described so far reflects the subscale prototype. While a full-scale lunar or planetary design would follow the same concepts, several additional requirements and challenges become relevant. A lunar design requires additional features for improved ejecta control and human safety, and the processes for its manufacturing (and potentially damage repair) would be tailored to the system specifications of the future lunar additive construction technology. Furthermore, to justify the investment, the pad should be reusable, and it should accommodate the full range of expected landing profiles (including off-center landings), nozzle types, and fuel types for future missions. Because of the uncertainties surrounding many of these requirements, the full-scale Lunar PAD concept remains qualitative. However, the Lunar PAD team has identified some basic changes that could be made to the subscale design that may begin an initial path towards a full-scale (lunar) design, drawn conceptually in Fig. 15.

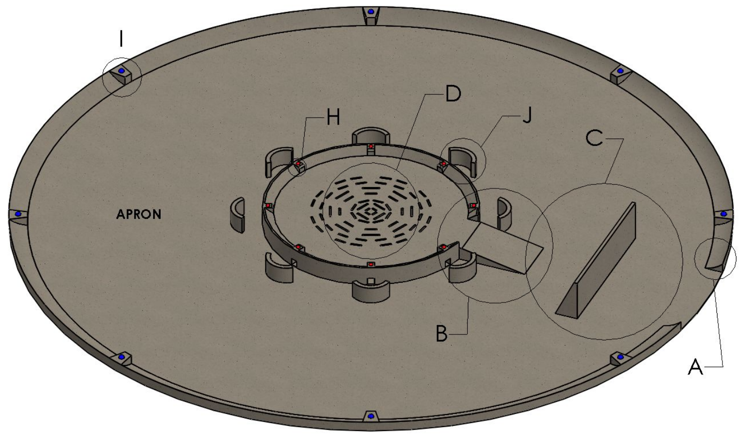


Fig. 15 Full-scale concept, featuring an apron (labeled APRON), apron deflector (A), ramp (B), ramp deflector (C), KED deflectors (J), and safety light places (H and I), as well as likely modifications to the internal features and KEDs (not shown). The design of each feature will likely evolve due to remaining dependencies and unresolved details.

First, the size of the landing surface should be scaled to accommodate the size and landing accuracy of the expected missions. This project explored versions of the pad between 20 to 40 m in diameter (estimated from the previous Apollo landings) as an initial reference. It has been suggested that it might be necessary to have a landing pad as large as 100 meters in diameter [5, 16], especially when accounting for off-center landings with an uncertainty of up to 10 m, but an exact estimate cannot be made without further information on future landers. In general, dimensions can be optimized based on landing accuracy and other landing aids (radio beacons, lights, etc.). None of the Lunar PAD full-scale design features are exclusive to a specific scaling, and specific considerations are discussed below.

In addition to a larger pad diameter, a dust-protective apron extending to approximately twice the pad diameter is recommended, as well as an additional deflector to contain the plume at the perimeter. The apron would help prevent the creation of additional debris. The flat surface could be created in a number of ways, including 3D printing or any method of securing the existing regolith. Although the apron is shown as a surface layer in Fig. 15, a redesign may be considered that would raise its height to essentially that of the central pad. This modification would provide ramped exits for the KED exhaust in the apron and provide a larger flat surface for landing. In addition, any high-speed plume/particles not captured by the pad could be mitigated by a larger blast shield at the apron outer perimeter as shown in Fig. 16 [17], replacing the deflectors that were part of the apron and landing surface perimeters. Work by Morris [18] indicates that the highest velocity particles tend to leave the landing site at very shallow angles (~3-17 degrees above horizontal). This, coupled with the need to protect nearby habitats/structures, suggests the need for a blast shield at the perimeter of the apron to mitigate the effects of these high-speed particles. This blast shield would have a height of approximately the tangent of three degrees (supersonic ejecta) to seventeen degrees (subsonic ejecta) times the pad diameter to mitigate the effects of the high-speed plume/particles. A smaller diameter pad/apron could reduce the required height for this blast wall.

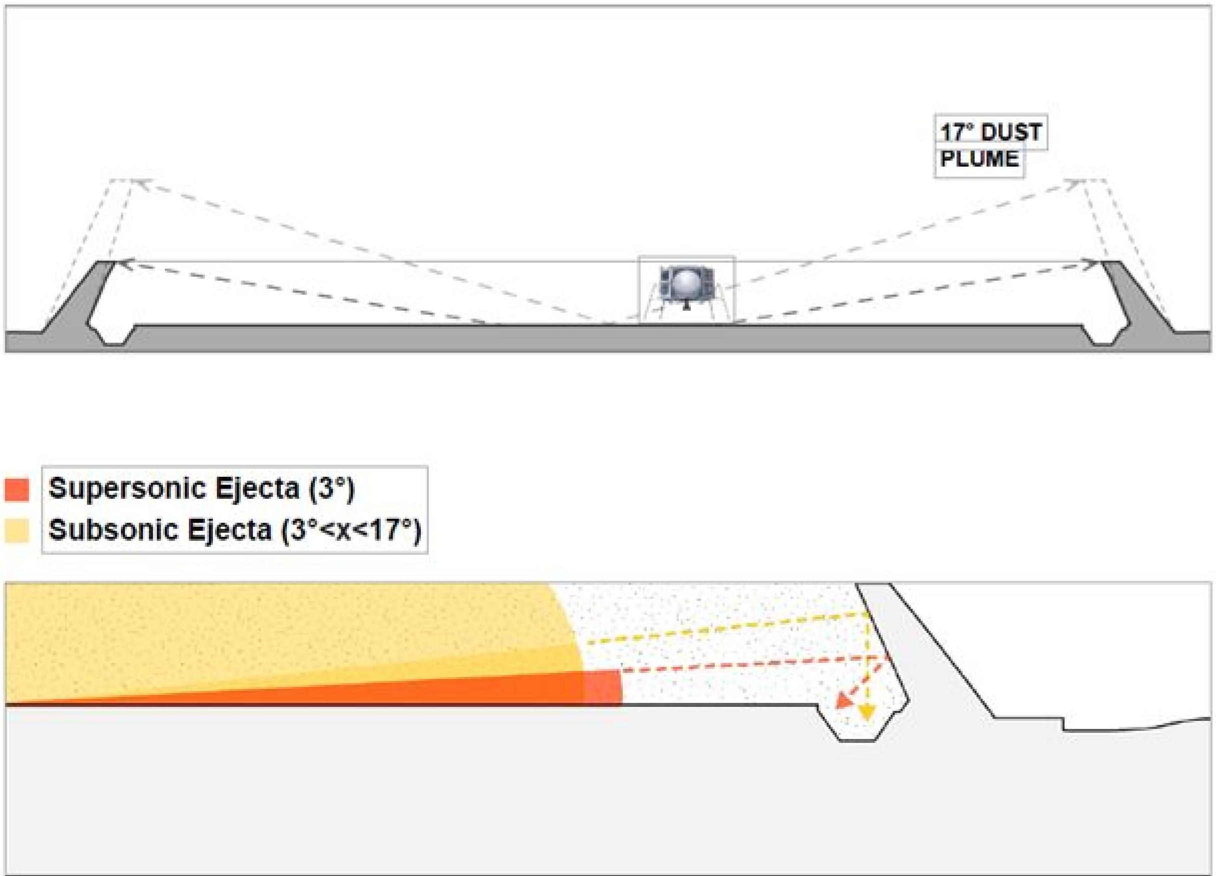


Fig. 16 Blast wall considerations to mitigate high-speed particle damage

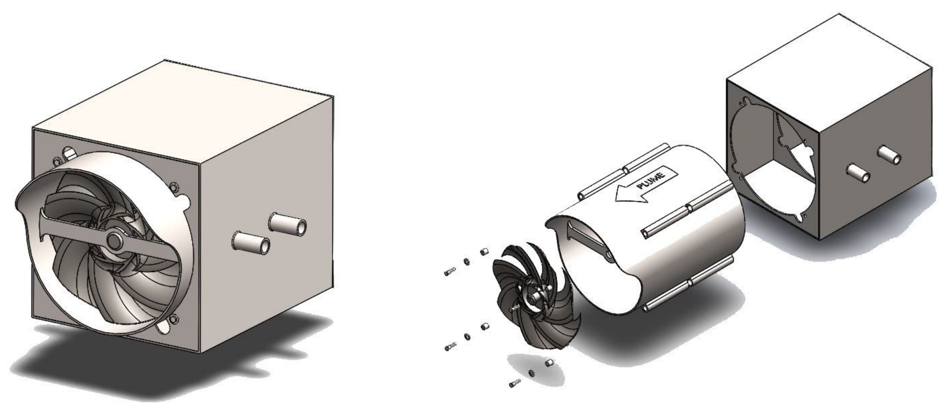
For scaling the landing pad features described in the subscale design section, the two main options are to directly scale the feature dimensions in proportion to the pad diameter or to create additional flow features. Using a constant scaling factor would preserve the numbers, relative proportions, and angles of all features and retain the most similarity to the testing and modeling already taking place through the present Lunar PAD activities. Scaling may also allow for faster construction compared to creating additional vents, depending on the preferred overhang support method. Any deviations should therefore be justified by cost or functional improvements in the revised design.

One example is grate sizing, which is a tradeoff among exhaust capture, human/lander safety, and manufacturing precision. It is desirable to have the total grate area maximized for the exhaust capture but to keep the size of individual grates smaller than the width of a human foot (<7.9 cm [19]) in at least one dimension. The grates should therefore be close to the lower limit on sizing but increased in number compared to the subscale landing pad prototype proportions. (The grates on the subscale pad are larger relative to the top layer of the pad because if they were scaled exactly, their width would not be feasible for testing or capturing exhaust.) The placement of grates may also change if the vent design is adjusted.

The radially staggered vent divider design balances support and flow in the subscale, but proportionally scaling the pattern for a full-scale pad would result in larger gaps between structural supports and perhaps unnecessary support size. An alternative to increasing the size is to add more staggered layers with increasing numbers of vent dividers. Having several proportionally smaller vents could increase the cross-sectional area through which exhaust can flow, decreasing the related stresses, and the more even distribution of the internal support could decrease the thickness requirement to support the overhanging top layer. Whether these efficiency advantages outweigh the simplicity of proportional vent scaling has yet to be determined. The optimum vent design will likely depend on the final diameter scale.

If the vent outputs are scaled proportionally, the size of the KEDs may become problematic for transporting to the Moon. The KED frames can pack closely into one another, so reducing size and increasing number may be more efficient, but transportation costs will remain a key consideration. The KEDs would likely only be needed on the vents that point towards the habitat or other areas requiring abrasion protection, particularly if there is an apron and/or other dust mitigative technology already applied to sensitive areas regardless of rocket hazards. It is also possible that the increase in pad diameter decreases the flow rate through the KEDs such that they need not cover the same proportional area as in the subscale pad. If additional vent divides are implemented, one option is to have them converge near the outputs on the habitat-facing side of the pad to reduce the needed number of KEDs. Further research into the scaling specifications should seek to address a) how much KED area will be required given the human landing system plume specifications and landing pad dimensions, b) how the transportation costs scale with KED size and number, and c) how KED function is affected by additional divides or convergences.

While the subscale version of the KED is effectively a stand-in to demonstrate embedding the housing, when the plume enters a full-scale KED (Fig. 17), it hits a curved blade that will include space to flow through but require any particles to first hit the curved blades and lose some of their kinetic energy. If there is a lot of force, this will also cause the blades to spin, increasing the collision rate while converting some of the excess energy into the circular fan motion. Additional resistance can be added to the KED blades if the rocket exhaust flows turn out to be particularly high-energy after dissipating through the vents. Until the design has been tested, the KEDs are assumed to only partially dissipate the energy rather than completely stopping any high-velocity exhaust and/or particles. Due to the fine nature of the regolith, a filtering mechanism would likely be ineffective without clogging exhaust flow, so the current concept assumes 3D printed walls to redirect the KED output flows away from the habitat. In the concept shown in Fig. 17, these KED deflectors would extend from the surface up to at least 2-3 times above the KED height and have a shape that contains any debris at the output from continuing forward or spreading horizontally. Preliminary simulations indicate that a vertical, curved shape may be most effective. (Alternatively, the blast walls shown in the redesigned apron concept in Fig. 16 could serve the same purpose.)



a) Front view b) Expanded view

Fig. 17 Full-scale Kinetic Energy Diffuser concept

In addition to the scaling considerations and additional KED features, the full-scale design should also include a ramp to allow easy ingress and egress of astronauts and cargo. Access to the ramp requires a gap in the pad perimeter deflector or blast wall, so the design includes a wall behind the ramp with a margin on either side to provide the same redirection function. As an additional safety feature, the pad design should include visual markers for the landing sequence in case sight to the pad is obscured by the landing plume during descent. These visual markers shall be placed at the edge of the flat elevated surface to help the pilot avoid landing on uneven territory, such as the rim between the elevated and non-elevated pad sections. Existing FAA Advisories could be used as guidelines for determining the placement of safety lights [20]. Solar powered lights should also be considered to reduce power draw, depending on the development status of that technology, or as an alternative, resistance from the full-scale KEDs to may eventually be used to power a circuit when the lander approaches.

Finally, it should be noted that the problems of dust and debris mobilized by a launch or landing are two-fold: first, it poses a hazard to the vehicle, and second, it can increase the dust exposure to surrounding equipment. Lunar PAD is primarily a "source-reduction" method of dust mitigation; that is, it prevents dust hazes from being generated in the first place. A key advantage of this approach is that it can be combined with "equipment-level" methods of dust protection that may already be in place to protect sensitive equipment from dust risen from ordinary surface activities. Peripheral dust protection measures are not included in the subscale design but are recommended for the full-scale to create a multi-faceted system of protection and to complement ongoing surface activities. There is a 2020 SBIR solicitation for the advancement of both active and passive dust protection technology that could be applied to equipment on the lunar surface [21]. If a resulting technology can be scaled and adapted to protect all necessary equipment, it could complement the function of a launchpad and add an additional layer of protection. Additionally, clearing dust off the pad before use will be important, particularly on the top surface where the flow does not go through the KEDs. A cover and/or any active clearing technology used on surrounding equipment may be suitable for this purpose.

The full-scale design has been deliberately left qualitative due to being largely unconstrained at this stage in the lunar lander and landing pad design process. However, demonstrating the key features through this subscale pad represents the first step, and the Lunar PAD team hopes to inspire future development to meet the challenges that would arise in a complete lunar mission.

B. Future Overhang Support Methods

The lunar overhang support must either avoid filling the vents or be cleared prior to a landing to avoid interfering with exhaust travel, and it should not rely on excessive material weight brought from Earth. Although dissolvable materials would not work on an extraterrestrial surface, the concept of removable support is valid. On terrestrial plastic printers, thin strands of plastic infill commonly support an overhanging surface and then are broken away once the print is complete, and the same process could theoretically be attempted using sparse concrete in the vents. However, removing hardened concrete would be much more difficult. If the vents were instead solidly filled, then a softer material such as tightly-packed regolith could be used, but the removal would face similar challenges such as accessing the vents, generating sufficient removal force, ensuring safety of the pad and surrounding structures, and designing a rover to complete the task autonomously. The most ideal option would be a material that could sublimate on its own over time in the low atmospheric environment, leaving the vented pad structure behind without further support removal processes, but finding an extractable material of that nature may not be possible. Although the sublimation of extracted sulfur has been investigated in the context of lunar concretes [22], Grugel and Toutanji [23] estimate the rate to be 2.50808×10^{-8} g cm^{-2} s^{-1}, or ~955 days, to sublimate 1 cm of material under approximate lunar surface conditions, which would translate to requiring potentially hundreds of years if it were used in the Lunar PAD.

As an alternate idea to filling the entire vent area, support could be placed in bridges across interior features such as the vent dividers to provide a reinforcement layer on which the overhangs of the top layer could be printed. Such "overhang bridges" could be printed separately from the pad in a nearby area and then transported and placed on top of the completed vent layer, either all at once or in sections. Ridges could be printed into the pad design to aid placement flush to the previous surface top, or latches or embedded parts in the solid-filled features could be used to hold the structure(s) in place. Any material used would have to support the concrete placed on top of it, and transporting the separate pieces may be a challenge, but less material would be needed than filling the entire vent, and it would likely not need to be removed. One option is to bring a strong material from Earth (e.g., carbon fiber) to 3D print a roof layer that matches the pad dimensions of the and grate locations, or to bring the material in pre-shaped sheets if it does not complicate transportation to the lunar surface. However, existing ISRU technology should be investigated first due to the potential to greatly reduce the support needed from Earth. The same regolith-based 3D printing material as the pad is one option, and if needed, additional support could be added to it in the form of reinforcement mesh or basalt rebar like that demonstrated in the subscale pad.

C. Future Tests

As mentioned in the background section, there are still several tests planned in order to help evaluate the success of the current Lunar PAD subscale design. In addition to a continued evaluation of the overall design, the Lunar PAD team recommends investigating several questions relating to materials selection and component design in the short-term future, as first steps towards addressing these future considerations. The KED design will be re-evaluated upon completing the hotfire test and additional simulations to identify areas of possible impingement and to provide more accurate information about the impact the KED has on the particle velocity. Additionally, while the present work has focused on the flow redirection functionality of the pad, the materials must also withstand extreme surface environments including vacuum, temperature extremes, radiation, regolith abrasion, and micrometeorite bombardment. Testing should most pressingly include radiation testing during the binder material selection process, testing the chemical degradation of all components when exposed to the chemical and fuels used in a full-scale lunar lander landing, and extensive testing on options for reinforcement material to determine the best combination of strength, durability, ease of transport, and cost.

As the landing pad concept is developed, some longer-term tests will likely become necessary as well. In addition to 3D-printing advancements, future work should include designing and testing a remote assembly process for the components. The Lunar PAD team also recommends evaluating the effect of the lander approach angle on the efficiency of the design, and the effect of the fuel type on the KED and overall Lunar PAD efficiency. Testing should ensure that all components of the pad are verified to be safe for humans to interact with.

This is not meant as a comprehensive list of questions to answer before a full-scale version of the pad is ready for use, but these are vital pieces of information needed in order to make key design decisions, and so are key areas to expand the scope of this project. The full-scale pad will likely require many iterations, future innovations, and repeated testing. However, the work so far has been promising.

VII. Conclusion

This paper has presented the first published 3D printed lunar landing and launch pad prototype. The Lunar PAD reimagines the design of landing and launch pads on extraterrestrial surfaces, and the project has resulted in a successful construction of a 3D printed pad capable of use in upcoming hot fire testing. The insights from the design evolution and printing process have already contributed valuable information regarding embedded materials, instrumentation placement, overhang support, and the printing and casting methods. This information is vital for future subscale and space-based work with this pad, but can also inform other 3D printing projects as well. The results from this hot fire test, performed under the instruction of the Texas A&M University Sounding Rocketry Team, will be used to improve the design of the pad and guide future work.

There are many exciting opportunities for the Lunar PAD design, including projects that may provide an opportunity for demonstrating and potentially deploying the Lunar PAD in the future. One such opportunity is Artemis Phase 2, which is aimed at building capabilities for Mars missions and will involve sustained lunar surface exploration and lunar orbit staging capability. This could allow an early-on test of a full-scale or subscale landing pad printed on the moon. The Lunar PAD design has the capability of enabling repeated landings of the reusable human landers as part of longer lunar surface explorations such as Artemis Phase 2.

Humankind's future of habitable outposts on extraterrestrial surfaces is reliant upon the access to a reusable landing and launch pad that utilizes in-situ resources. A design such as the Lunar PAD could be among the first manmade structures on the lunar and martian surfaces. The Lunar PAD could also be used as a demonstration of in-situ construction technologies that could be used to create future habitats, shelters, roads, walls, and other surface infrastructure. The Lunar PAD project aligns with upcoming NASA missions and could revolutionize landing and launch pad technology for humankind's upcoming journey to the Moon, Mars, and beyond.

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