AEGIS

Arizona State University

Aegis - Inflatable Lunar Landing Pad System

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QUAD CHART

Concept Synopsis

Aegis is an inflatable landing platform which is capable of autonomously deploying to increase safety and reliability of lunar landers. The system is designed to deflect the exhaust gasses of lunar landers thereby reducing regolith ejecta generated during landing. Aegis is deployed on the lunar surface where it using 6 auger anchors in its base to secure itself to the ground. It deploys the 14 m diameter landing tarp using inflatable beams. Once deployed, Aegis provides a reusable precision landing zone for incoming landers.

Image depicting concept

Innovations

- Aegis high temperature - insulative multi-layer tarp is a innovative technology and has widespread applications for utilization of inflatable lunar infrastructure.
- The deployable perimeter deflector shield is innovative approach to significantly reduce regolith ejecta by diverting exhaust gasses away from the ground.
- The approach of using inflatable beams as actuators to deploy a system or structure advances the State of the Art (SOA) for inflatable deployed infrastructure.
- Novel helical pile anchor system design for operation on the lunar surface for maximum vertical and lateral pull strength

Verification Testing Results & Conclusions

Relevant environment and Earth Analog testing was conducted to advance the TRL from 2-5 over the course of the project. A Comprehensive Testing Plan (CTP) was developed to manage the testing for TRL advancement for each subsystem. In Phase I, simulation was used to validate designs prior to testing. In Phase II, testing campaigns were conducted on critical components. This included relevant environment testing such as: structural testing of inflatable components, tarp, and heat shield, thermal ablative testing, dust abrasion testing, and drapability testing, high velocity exhaust testing. Earth Analog testing was conducted on the system at SP Crater, AZ to conduct final verification of deployment in a relevant environment resulting in a successful completion of the verification testing and achievement of TRL 5.

EXECUTIVE SUMMARY

Aegis, the inflatable lunar landing pad is a novel system entirely designed, built, and tested by a multidisciplinary team of students from Arizona State University in response to the 2024 NASA BIG Idea Challenge to provide a low Size Weight and Power (SWaP) solution for reducing regolith ejecta generated by lunar landers.

Aegis's operational scenario starts with it being carried onboard early Commercial Lunar Payload Service (CLPS) landers such as Astrobotic's Griffin. After touchdown, Aegis will be deployed ~50m away from its parent lander using a small rover. Aegis will then anchor itself into the ground using screw anchors mounted on the base of the landing pad. After its anchor sequence is complete, it will use compressed nitrogen stored onboard to automatically inflate and deploy the landing pad tarp surface to prepare for the next lander. Aegis was designed to accommodate both visual fiduciaries and communications equipment to enable precision landing. Upon vertical descent of a lander, the main heat shield will protect components from the hot exhaust plume while the deflector shields redirect exhaust gasses upward at a 32.5° angle to prevent regolith ejecta from blowing horizontally along the ground. Once the lander has touched down, the deflector shields are deflated allowing rovers and other equipment to be offloaded. After unloading, the deflector shields can be reinflated for subsequent landings.

The design of verification testing of Aegis focused on rigorous systems engineering and testing critical components to advance the Technology Readiness Level (TRL) to TRL 5. This included testing components under relevant environmental conditions including thermal degradation, inflatable deployment in Earth Analog (EA) environment, and high velocity exhaust testing. The Aegis Comprehensive Testing Plan (CTP) was developed in Phase I and used to establish design requirements for the landing pad system. To maximize successful testing outcomes, extensive simulations were conducted prior to each physical test. During environmental testing, component level stress testing was conducted on the tarp apron, heat shield, and inflatable beam structures. Anchor pull testing was performed to calculate the vertical and horizontal anchor strength. Dust abrasion mean-time-to-failure (MTTF) testing was conducted on the tarp to determine the resistance to lunar regolith simulate abrasion. Compliance testing of the novel tarp construction was tested to determine the foldability of the material. Earth analog testing was conducted on a 1/5th scale system at SP Crater near Flagstaff AZ to assess deployability and hot exhaust testing was conducted at Friends of Amatuer Rocketry near Mojave CA to test exhaust deflector performance.

Through simulation driven design, comprehensive testing, and rigorous systems engineering Aegis has developed four unique and novel innovations including an inflatable deployment mechanism that can be reconfigured for other solutions to achieve low SWaP constraints, high temperature resistant flexible multi-layered composite material capable of withstanding temperatures over 2726.85°C for 15s, a deployable exhaust gas deflector design, and a novel helical pile anchor system designed for lunar operation. Each of these unique innovations add to the body of research which will further enable current and future lunar missions which will rely on advancements in low SWaP solutions for deploying large structures and flexible and rigid materials capable of surviving high temperatures.

PROBLEM STATEMENT & BACKGROUND

Problem Description

The challenge being addressed in this proposal is to “design, develop, and demonstrate novel uses of low Size, Weight and Power (SWaP) inflatable technologies, structures, and systems for lunar operations.” The terrain on the lunar surface is composed of regolith which is made up of fine-grained basaltic and anorthositic rocks and ranges in typical grain size from 40 μm to 800 μm [1]. It has been shown that these fine-grained particles are prone to create debris clouds caused by landers and can travel at typical speeds of 2 km/s, potentially resulting in damage to nearby landers or equipment. Some debris could even be ejected into lunar orbit, resulting in damage to orbiting spacecraft and further damage upon re-entry to the lunar surface [2][3]. This not only poses a threat to equipment and instruments due to abrasion and contamination but also to the ability of landers to land near each other or near existing structures [1][4]. The current solution to this problem is to create safety offset zones around landers to prevent other vehicles from landing in the vicinity [5]. For building a sustained presence on the Moon, landers will likely need to land near each other such that they can be used for collaborative purposes, for example to carry larger payloads that can be assembled on-site. It is for this reason that we are proposing Aegis as an inflatable landing system to reduce dust and debris generated by landers thereby allowing for closer proximity of landings, and potentially simplifying the construction of outposts and the establishment of a sustained human and robotic presence on the Moon.

Proposed Solution

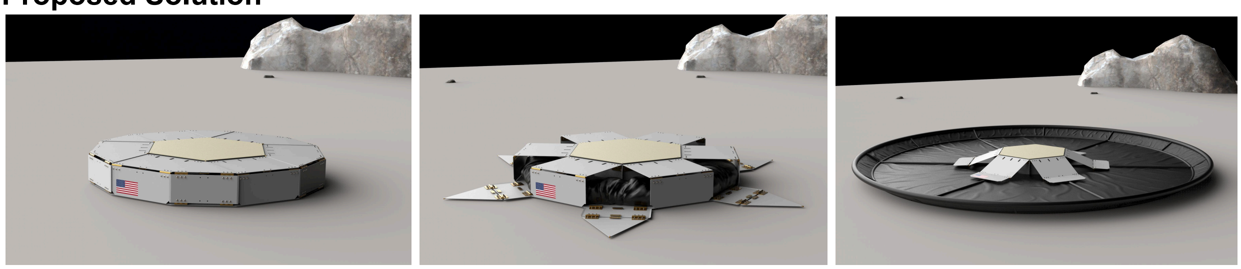


Figure 1. Aegis Inflatable Lunar Landing Pad System

Named after the shield of the Greek goddess Athena, Aegis was designed to protect landers and their surroundings from harmful lunar regolith. Aegis is a complete landing system designed to autonomously deploy a 14m diameter reusable inflatable landing pad on the lunar surface. In its stowed configuration for transport to the lunar surface, it fits into a hexagonal container measuring 5 x 0.75m that includes all required systems for deployment of the landing pad, including compressed gas, power, and communications equipment. The Aegis system includes five major subsystems: the inflatable structures, high temperature multi-layered tarp, the rigid enclosure and heat shield, anchors, and the electrical/communications and control system. The design of each subsystem was driven by the requirements to survive the extreme temperatures caused by typical lander descent engines [6][7]. The rigid enclosure designed for Aegis was intentionally designed to serve as the center of the landing pad and include a high temperature zirconia coating on a carbon-carbon composite in the center to deflect the heat. The landing pad floor consists of a unique multi-layer composite tarp which is made up of alumina felt and Kapton film sandwiched between knit carbon fiber blankets and stitched with ceramic thread. The inflatable structures including the spokes and outer perimeter deflector are made up of vectran inflatable beams with an elastomeric bladder (polyurethane) and an outer cover of zirconia and knit carbon fiber.

Mission Scenarios and Use Cases

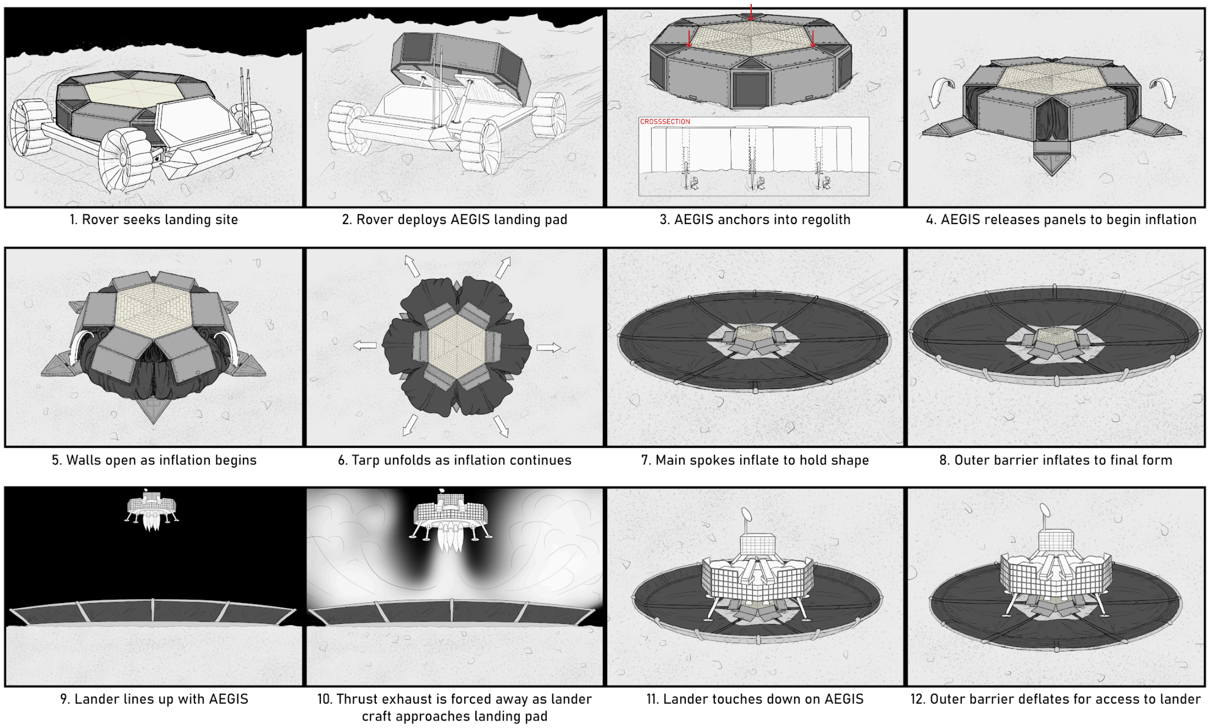


Figure 2. Aegis Concept of Operations

Aegis was designed to be deployed to the lunar surface onboard a CLPS lander such as the Astrobotic Griffin lander, which could carry a small rover, separate from Aegis, to deliver the system to the lunar surface (Fig 2.2). Once delivered to the lunar surface, Aegis uses screw anchors to securely anchor itself to the ground (Fig 2.3). After it has anchored to the ground, it uses mechanical spring deployment mechanisms to open its inflatable enclosure and commence with inflating the landing pad (Fig 2.4). Using compressed N2 stored in its base, it inflates to create a hub, spoke, and wheel design (Fig 2.7).

Aegis was designed, built, and tested as a complete landing pad system which can be deployed to the lunar surface to reduce lunar regolith ejecta. Through this project, this concept was advanced from TRL 2 to 5 by a team of students from Arizona State University. This technical paper serves as a demonstration of the innovative technology and testing strategies developed through rigorous systems engineering to develop a solution which contributes to the State-of-Art and further advances NASA’s mission to return to the Moon.

PROJECT DESCRIPTION

Description of the Concept

Aegis is an inflatable landing pad system designed to minimize Size, Weight, and Power (SWaP) metrics and reduce the interaction between exhaust gasses and lunar regolith. To do so, Aegis utilizes a lightweight multi-layered composite tarp stitched around an inflated skeleton, which when inflated reaches 14 m in diameter. At its rim, the inflated skeleton is angled 32.5° to redirect exhaust gasses away from the lunar surface. During transit, the inflatable skeleton and tarp are rolled into the central enclosure where they are encased by the system's enclosure assembly.

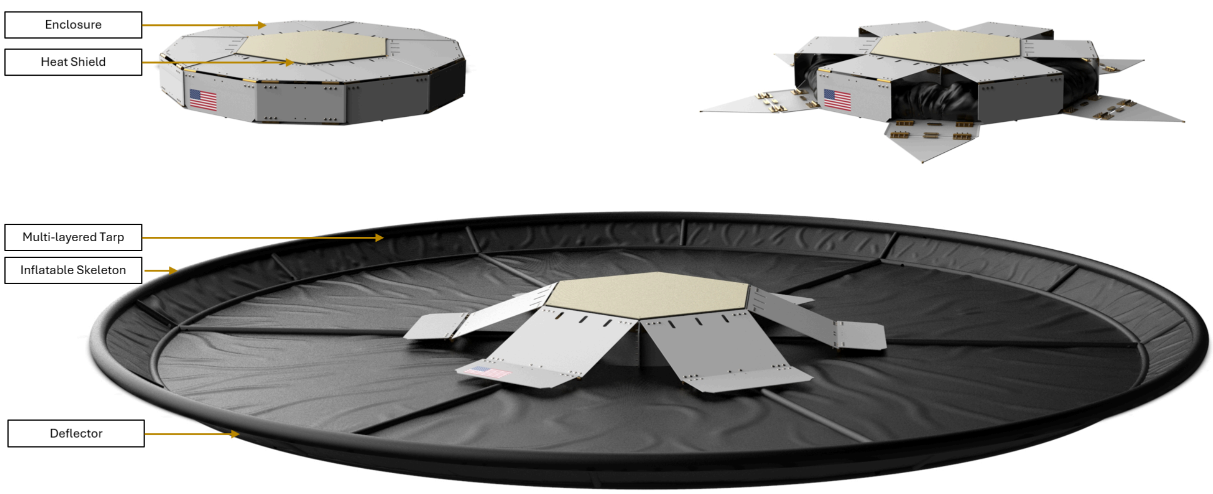


Figure 3. Aegis System Overview

At the center of Aegis lies the enclosure, where electronic and pneumatic components are housed, as well as auger style anchors used to resist any lateral and pull-out forces during landing procedures. Given the centralized placement of Aegis's critical components, the heat shield is required to protect them from the most thermally intensive spot during landing procedures. The heat shield was designed using inspiration from the Parker Solar Probe and the Space Shuttle heat shield tiles. To accommodate multiple landing cycles Aegis is constructed to deflate and inflate its deflector spokes to lower the deflector down for supply extraction.

Aegis consists of five key subsystems: the enclosure and heat shield, inflatable structures, high temperature multi-layered tarp, base anchors, and the electrical/communications and control system. The complete system was fabricated at 1/5th scale for Earth analog testing. Individual test articles were manufactured at full scale to conduct relevant environmental testing. For the purposes of this project, all subsystems were designed with flight ready hardware in mind but non-flight ready components off the shelf (COTS) were used for testing.

Enclosure

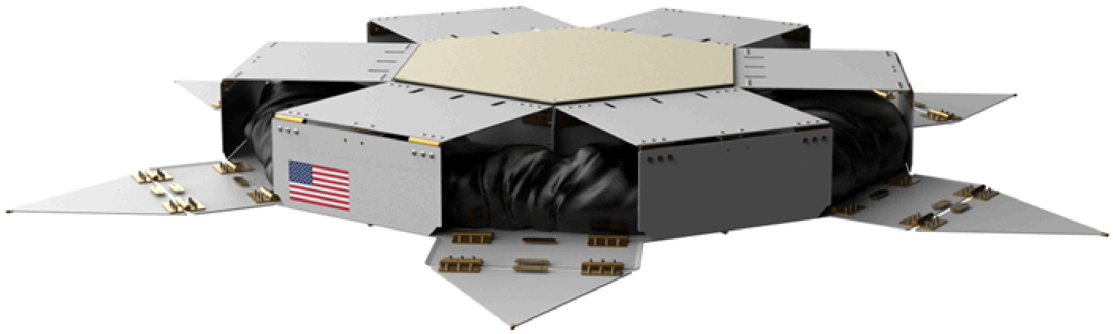


Figure 4: Enclosure Design

The enclosure is constructed out of 6061 aluminum sheet metal and encompasses the stow space for the tarp and skeleton, as well as the housing where both the control system and anchors reside. Its exterior panels are spring loaded at each pivot point, and overlap with each other at their corners. This allows the system to transform from stowed to deployed state without the use of actuators, only the release of frangible nuts located at the corner of each triangular panel. For cost and repeatability, the Earth analog model substituted frangible nuts for servos motors.

At the enclosure center lies the housing where the electronics, compressed gas, pressure transducers, solenoid valves, anchors, and battery reside. Compressed nitrogen gas is stored at 2300 psi, as seen in propellant tanks designed for the Adelis-SAMSON Nano-Satellites cold gas thruster system [10]. Once in place to inflate, solenoids will transfer the stored nitrogen to the inflated skeleton.

Heat Shield

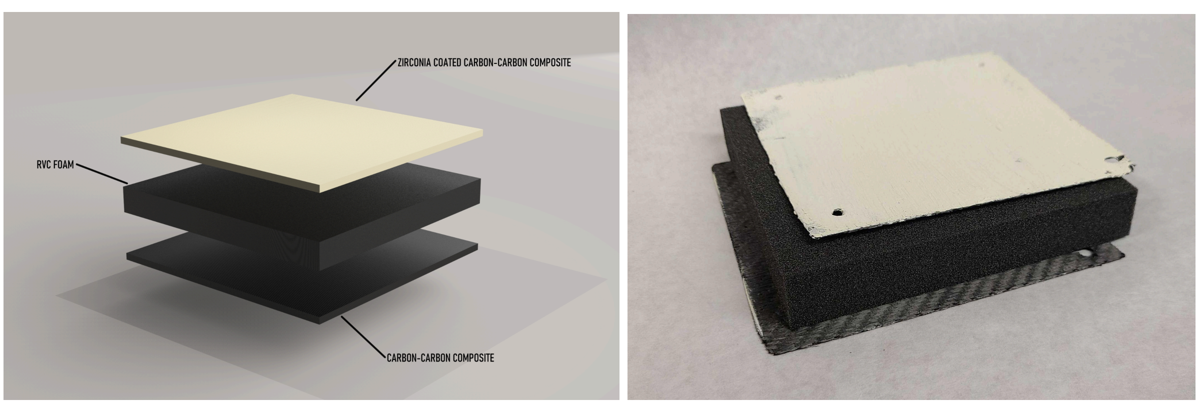


Figure 5. Heat Shield Design (left) and Test article (right)

The heat shield, a 3m wide hexagon, lies directly above the housing and serves to protect internal components from the intensive thermal loading from exhaust gasses of 2726.85°C. The heat shield is modeled after the Parker Solar Probe through its use of two carbon fiber-reinforced carbon composite sheets (CFRC) which sandwich a layer of reticulated vitreous carbon (RVC) foam. The top-most CFRC sheet is treated with a layer of plasma-sprayed zirconia powder, by A&A Spraying Services, to both increase its durability and make the carbon carbon safe and inert in an otherwise oxidizing atmosphere. Beneath the lower sheet of CFRC, a vacuous pocket is used in conjunction with mylar spacers to standoff the heat shield and limit heat transfer into the interior of the enclosure.

Tarp

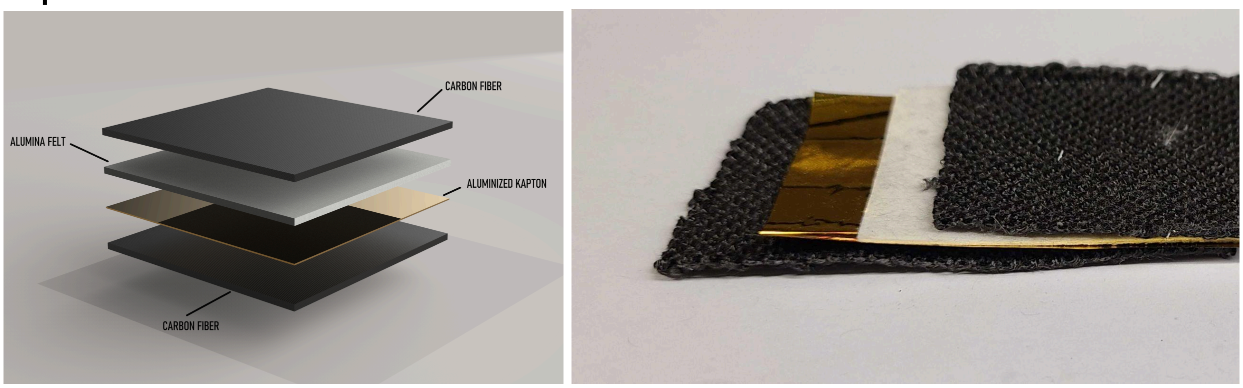


Figure 6. Multi-layer Tarp Material Stackup design (left), Test article (right)

Aegis's tarp utilizes an innovative multi-layer stack-up of materials to create a thermally insulative, structurally sound, and impermeable assembly. Both the top and bottom layer are knit carbon fiber, and sandwiched between is a layer of alumina felt, to provide insulation, and aluminized kapton, to decrease permeability (Fig 6). To affix each layer, a ceramic thread was used to stitch together test articles for thermal ablative testing, uniaxial tension testing, dust abrasion testing, and foldability testing. In addition to the multi-layer test articles, two 1/5 scale tarps were sewn: one for high velocity exhaust testing using only the carbon fiber knit and one for Earth analog deployment testing using rip-stop nylon. The tarp constructed for high velocity exhaust testing was constructed using knit carbon fiber for heat resistance during the test. The tarp constructed using ripstop nylon was constructed for repeated packing and deployment to be used in Earth analog deployment tests.

Inflated Skeleton

The crux of Aegis's functionality and adherence to low SWaP requirements is its inflated skeleton. The full scale system consists of custom 12.7cm diameter elastomeric bladders encased in a kevlar sheath and pressurized with nitrogen to 206.843kPa (30 psi). Initial analyses based on critical wrinkling conditions, shown below in Figure 7, were used to minimize beam diameter without compromising structural rigidity [12].

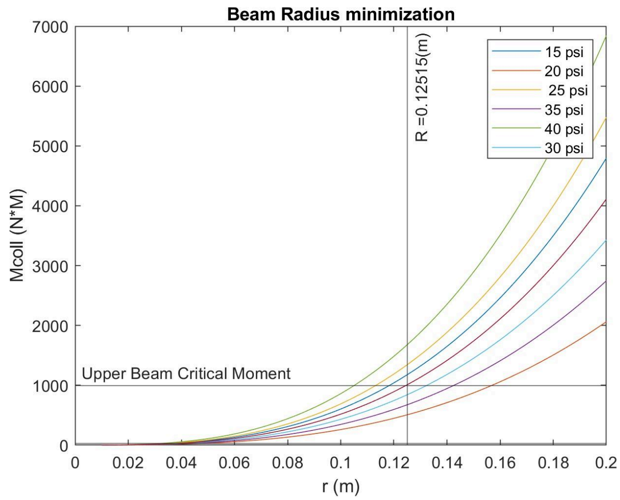
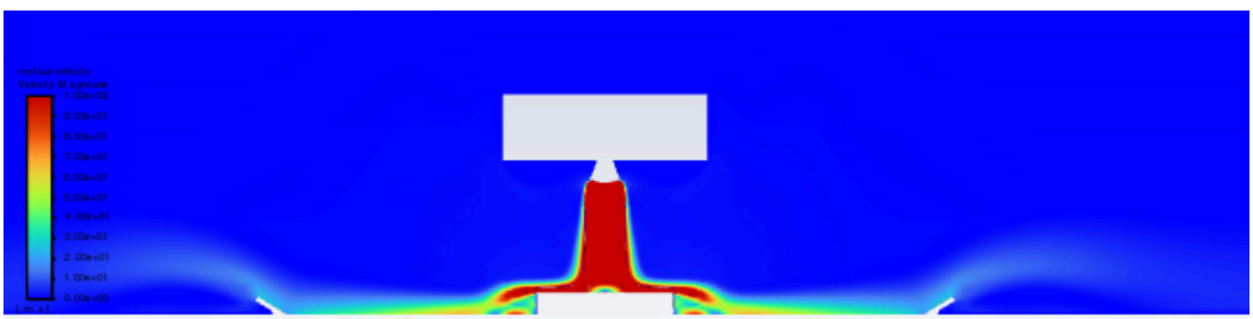


Figure 7. Beam Radius Optimization

Using Computational Fluid Dynamics (CFD), the team conducted 2D Axisymmetric fluid flow simulations to evaluate the optimal landing pad dimensions, ranges of which can be seen in Figure 8. Dimensions were optimized to decrease fluid shear stress on the ground whilst minimizing the pressure applied on the deflector walls. Additionally, important properties such as gas temperature and velocity were used to inform detailed analysis. Alternate system specifications can be easily found for different lander sizes via the same process.



Landing Pad Dimension	Testing Range	Final Dimensions
Total Pad Diameter	10-15 meters	14 meters
Deflector Angle	30 - 45 degrees	32.5 degrees
Deflector Length	0.5 - 1 meters	0.7 meters

Figure 8. Gas Deflection Study

Aegis's team entered this project with no experience in manufacturing inflated components. As such, inflated prototype construction was assessed to be one of the most dominant challenges for this project. For component level testing of the inflatable team, a test article made from ballistic nylon and encased in a knit kevlar measuring 12.7cm in diameter and 15.24cm long was acquired from Petersen inflatables. The knit kevlar was hand sewn for the device under test. This device allowed for pressurization up to 206.843kPa.

Figure 9. Bestway Inflatable (Left), In-house prototype Inflatable (Right)

For the 1/5 scale prototype, the team worked with Bestway USA, a local inflatables manufacturer to construct the deployment model inflated skeleton. In addition to the outsourced manufactured inflatable system, the team built in-house a laboratory prototype of the inflatable system to prevent critical-path delays in the timeline. The in-house prototype was sent for high velocity exhaust testing, while the final version arrived in time to be used for Earth analog deployment testing (Fig 9).

Anchors

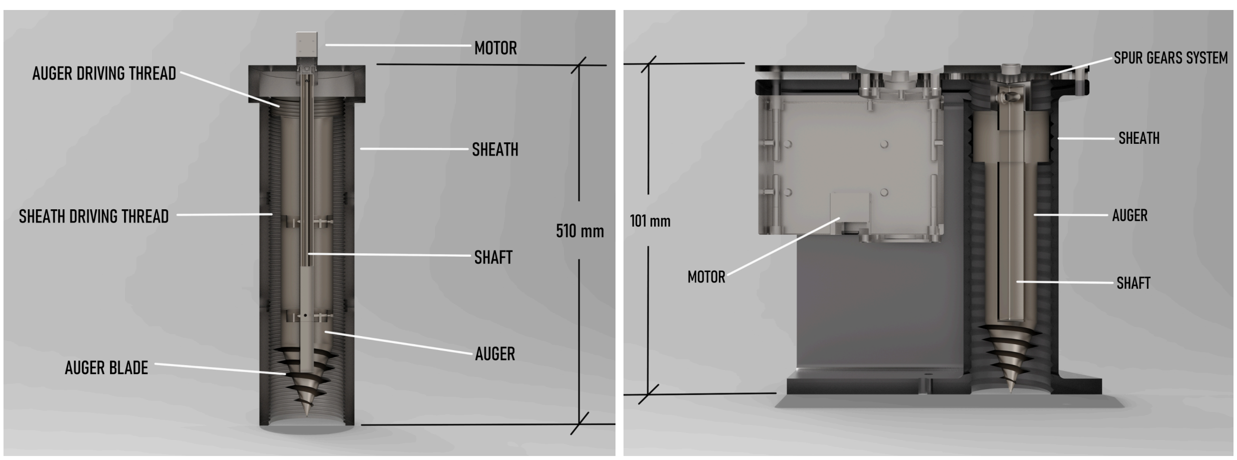


Figure 10. Anchor Cross Section: Full scale design (left), 1/5 Scale Earth analog prototype (right)

Aegis was designed to secure itself to the ground through six anchors mounted in the enclosure. The resulting anchor design is a novel autonomous helical pile foundation deployment system. The system includes four main components: Motor, Sheath, Shaft, and Auger. The Auger has one driving thread that mates with the sheath. At the end of the Auger is the Auger Blade acting as a plate to resist vertical pull-out, and the shaft's thickness resists the lateral pull-out. Initial predictive models based on a fine-grain soil [8] and required vertical and lateral pull-out forces of 6.1 N0.622kg) and 103.8 N(10.58kg) respectively, drove the critical dimensions of the auger to 42 cm in length, and 8.32 cm in diameter. Test articles of the full scale anchor subsystem were constructed for conducting vertical and lateral pull tests while a 1/5 scale version of the augers were constructed for Earth analog deployment testing.

Electrical and Control System

The control system was designed to actuate the inflatable subsystem, anchor subsystem, and enclosure subsystem while also providing a human-machine interface for deploying each subsystem for Earth analog testing. The control system uses an ESP32C6 as the primary controller for actuating six servo motors (releasing enclosure), six continuous servo motors (driving anchors), and two solenoid valves (inflatable system control), while a single pressure transducer measures pressure in the inflatable system. The electrical schematic for the implemented prototype is shown in Fig 11. For lunar purposes, the chosen components for the design would need to be replaced with their heat resistant and radiation hardened versions followed by testing under harsher conditions.

The embedded software program on the controller implements a state machine in which each state corresponds to a stage of the deployment process: Anchor Deployment, Tarp Deployment, and Inflation. The inflation state makes use of a bang-bang controller to maintain pressure in the tarp volume by actuating the solenoids and using data from the pressure transducer as feedback. Moreover, the software also incorporates states that support the packaging of the Aegis system such as deflation, tarp locking, and anchor retraction, along with safety states designed to mitigate risk to Aegis or the lander during operation. Additionally, the software also implements a web-server as a user interface (UI) enabling wireless control of the system's states. The simplicity of this design increases our confidence that it will function properly on the moon.

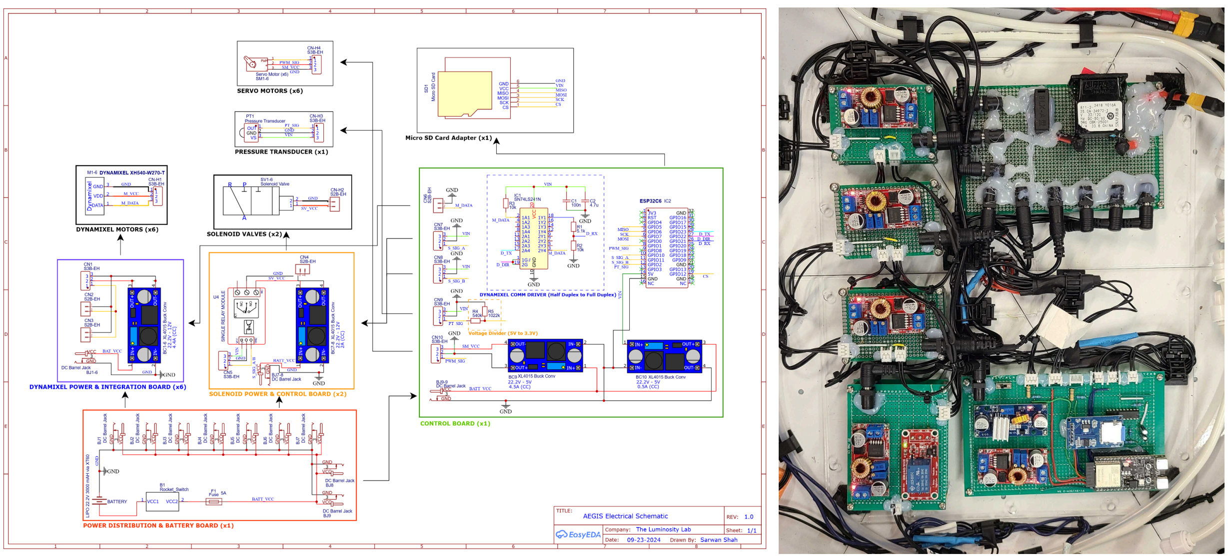


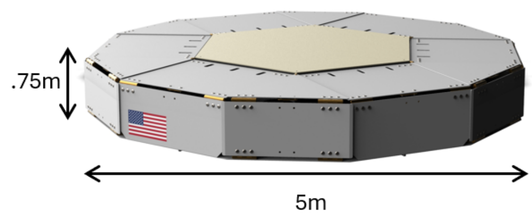
Figure 11: Earth Analog Electrical schematic (left) and breadboard prototype (right)

The table below summarizes the power requirements of the designed electrical system for Aegis's earth analog prototype. For Earth analog testing, a 3000 mAH 22.2 V LiPo battery was used to power the system.

Table 1: Electrical System Power Requirements

Total Nominal Current Draw	11.06A
Total Max Current Draw	39.82A
Total Nominal Power Consumption	114.82W
Total Max Power Consumption	411.9W

Technical Specs of Earth Analog Prototype
Earth Analog Mass: 22.67 kg
Stowed Volume: 4.48 m^2
Deployed Volume: 32.3 m^2
Nominal Power Consumption: 114.82 W, 11.06A
Max Power Consumption: 411.9W, 39.82A
Processing Requirements: 512KB RAM, 1 CPU
Deployment Time: 76 seconds



Integration with Existing Lunar Landers

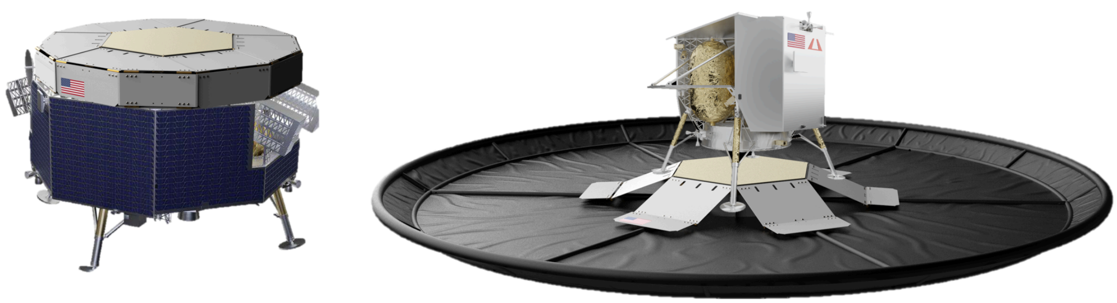


Figure 12. Aegis delivered to the lunar surface on Astrobotic Griffin (left), Aegis serving as a landing pad for Astrobotic Peregrine (right)

Aegis is designed to be delivered to the lunar surface by commercial landers such as the Astrobotics Griffin lander. The Griffin Lander is capable of carrying 500 kg payload and can provide 1 W/kg of payload and 10 kbps/kg of payload [11]. This would allow the Griffin to easily carry Aegis and the rover (that will be delivering Aegis) and provide the necessary bandwidth to communicate with Aegis during its mission. Once it is deployed on the moon, it can repeatedly receive landers such as the Astrobotic Peregrine lander.

Potential Stakeholders
Due to the increase in lunar surface activities and the push to build a sustained presence on the Moon, landing frequency will continue to increase. This capability of a deployable landing pad is of great interest to any stakeholder trying to land in close proximity to both existing landers and future outposts on the Moon. This includes Commercial Lunar Payload Service (CLPS) providers, NASA, and foreign space agencies. In addition, For science missions to the lunar

surface, requirements for lander providers could be defined to require a landing pad solution or a safety zone requirement.

Risk Management

Remaining project risks are extremely low and are primarily focused on the final forum and presentation. The primary risk is loss of data from testing to be included in the final presentation. To mitigate this, data has been backed up and stored in secure cloud storage. The secondary risk is travel to the forum being disrupted due to unforeseen events. The top ten risks are shown in Table 1 below and the likelihood and consequences are plotted in the Risk Matrix shown in Fig 13.

Table 2: Top Ten Risks

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Loss of data	2	5	→	M	All data will be securely stored in a cloud environment to reduce loss of	Active
2	Health and safety delays in travel to forum	1	1	↓	A	data due to equipment failure. Data is backed up in at least 1 location.	Active
3	Damage to prototype prior to final presentation submission	1	1	→	M	Each component of the design has multiple team members who have contributed which mitigates the risk of a single person missing the forum and leaving a gap in knowledge of the project.	Active
4	Leak Developed During Transit	1	1	→	M	All photos and video necessary for the final presentation have been collected but extra care will be taken to maintain the integrity of the prototype prior to the final presentation.	Unactive
5	Rocket Fire Ablation Failure	1	1	→	M	Extensive care will be placed on the safe and secure transport of the system with design considerations made to minimize the risk of internal punctures. Additionally, sealants will accompany the system at all times to hotfix any small damages that may occur.	Unactive
6	Damaged Test Specimens	1	1	→	M	Rocket fire testing will be the final system test and is scheduled at least a month in advance to the final forum to give adequate time for system repairs or necessary modifications.	Unactive
7	Unanticipated Burst Failure	1	1	→	M	Test specimens will be cordoned off in a safe environment and only removed when necessary to be worked with.	Unactive
8	Manufacturing Partner Delays	1	1	→	M	Specialty safety precautions will be put into place whenever systems are pressurized and even more stringent precautions will be implemented when at high pressure. Additionally, environments during inflation will be curated to minimize the risk of premature burst failure.	Unactive
9	Project Exceeds Allocated Budget	1	1	→	M	Components that must be manufactured out-of-house will take special priority in design finalization and procurement. Testing timelines will allocate ample buffers for delays.	Unactive
10	Leak Developed During Transit	1	1	→	M	The project budget will be constantly evaluated throughout the project lifespan and early care will be placed on minimizing costs where possible.	Unactive

L = Likelihood (1-5)
1 = not likely
5 = extremly likely
C = Consequence (1-5)
1 = low consequence
5 = high consequence

LxC Trend
↓ - Decreasing (improving)
↑ - increasing (worsening)
→ - unchanged
NEW - added this month

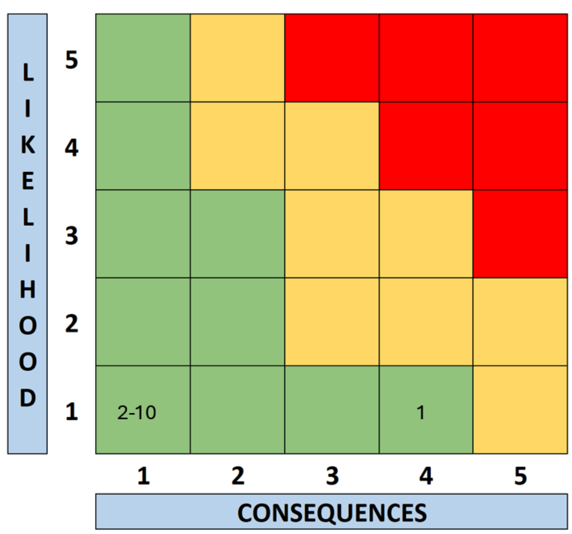


Figure 13. Risk Matrix for remaining project risks

VERIFICATION TESTING ON EARTH

Summary
The Aegis team designed and executed a wide variety of tests to progress Aegis to TRL 5 over the course of this project. Early on, the team did extensive research into the loading conditions, and critical requirements necessary to validate in order for Aegis to succeed. These critical requirements were then used to develop a Comprehensive Testing Plan (CTP), which documents and defines all tests needed to advance Aegis to TRL 5.

Tests are broken into Phase I, II-A, and II-B. Phase I contains simulations used to validate testing procedures and loading conditions prior to physical testing. This ensures that tests are both productive and relevant to the subject of interest before resources are invested into their execution. Phase II-A consists of controlled laboratory testing on individual test articles to validate key metrics in an isolated manner. Phase II-B testing involves relevant environment testing where the system components and integration are evaluated in earth analog environments. By utilizing these three testing phases the Aegis team ensured all system requirements would be addressed.

Inflated Beam Structural Tests
Compression testing was performed on the inflated beam to evaluate its deformation while supporting a lander's leg. The Kevlar jacket was custom made by the team to test the structural performance of the beam. A 102.05 kg compressive force was applied over a 105.68 cm^2 area at a strain rate of 4 mm/min. The test was performed at 137.895 kPa to ensure the test was safe well below the beam's rated pressure and then again at 172.37 kPa. The test was completed successfully without beam failure.

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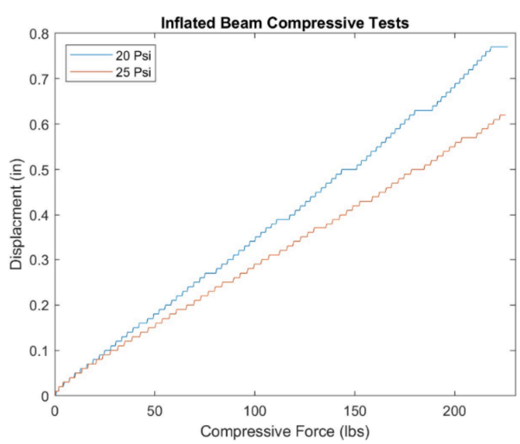

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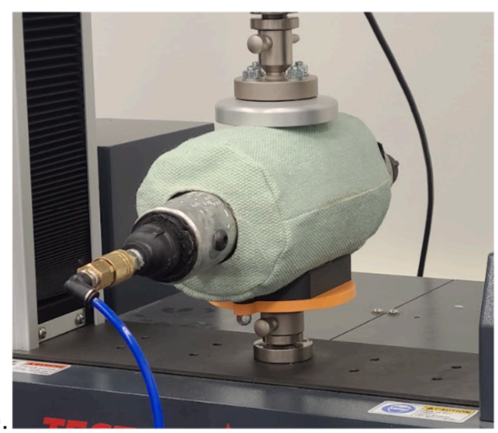


Figure 14. Compression testing of Inflated Beam

To characterize the structural rigidity of inflated members at the deflector perimeter during loading conditions, a three point bend test was performed to analyze the reactive forces while kinking occurred in the upper ring when supported by the deflector spokes. Using a three point bend fixture, the same sample was displaced at a strain rate of 2 mm / min until a linear displacement of 25.4mm was reached. This test was again performed at both 137.895 kPa and 172.37 kPa.

a. b.

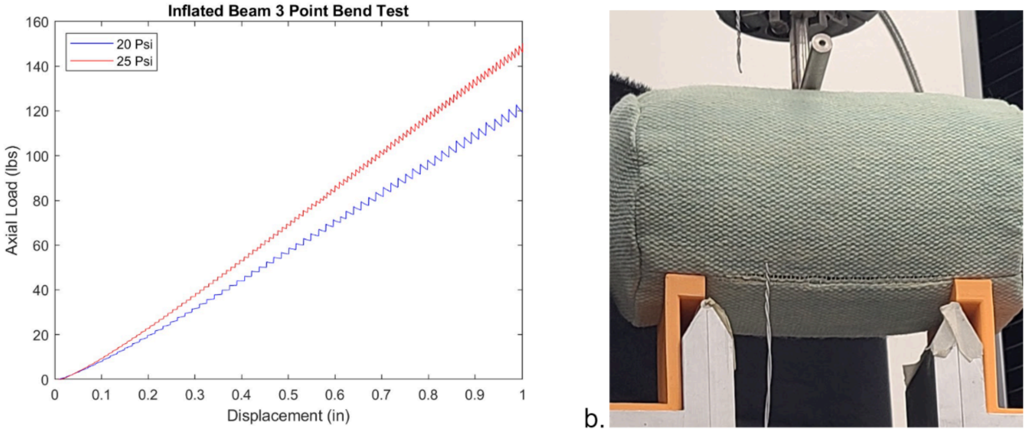


Figure 15. Three Point Bend Test of Inflated Beam

Inspection of test articles after loading revealed slight degradation in the kevlar sleeves stitching, seen in Figure 15.b . In future models this can be mitigated by utilizing a wider stitch pattern to better distribute tensile forces.

Tarp Structural Tests

Uniaxial tension testing was conducted on the tarp to test the strength and failure modes to simulate the condition of a lander's foot causing the tarp to stretch under tension. To test this, a test article was constructed which included a 50mmx50mm sample of the multilayered tarp clamped on one end by two pieces of aluminum which simulated the mounting interface of the tarp to the enclosure (Fig 16.b). The specimen was tested at a quasi-static strain rate of 0.001/s.

a. b. c.

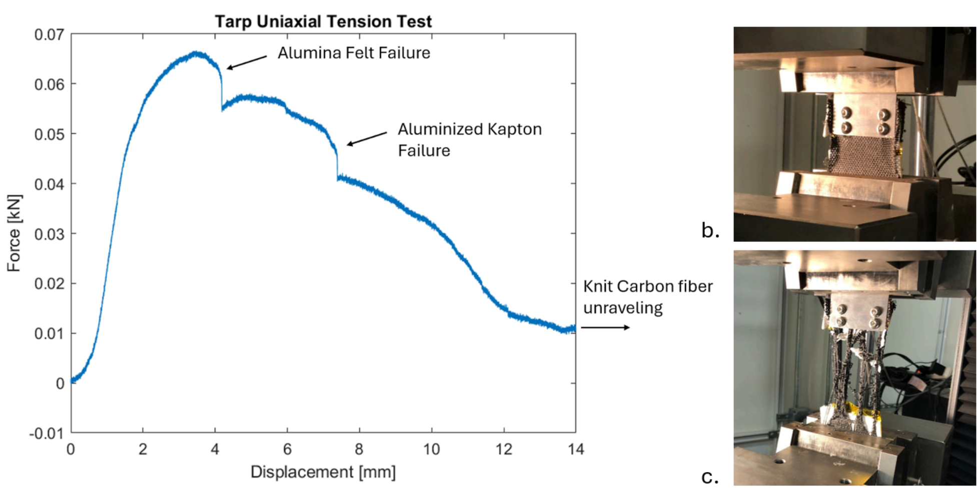


Figure 16. Uniaxial tension test of tarp

From Fig 16.a, it was observed that the three different materials (carbon knit, alumina felt, and aluminized kapton) failed at different displacements resulting in a composite force vs. displacement curve. This information is valuable for better understanding of the tarp's ability to survive a lander's foot applying a tensile force to the tarp. The information collected in this test can be used to approximate the tarp as a single material for further design and simulation of similar structures.

Thermal Ablative Testing
To determine the operational effectiveness of the heat shield and tarp during landing/takeoff operations, thermal ablative testing was performed. The ASTM Standard Test Method for Oxyacetylene Ablation *(ASTM E285-08(2020))* was used to design the testing procedure and test articles for both the tarp and the heat shield.

Thermal ablative testing was conducted using oxyacetylene torch with an argon flood to reduce oxidation of the material to more closely simulate an oxygen free environment. The specimens were tested under two scenarios: the first was thirty-second direct heat during which the temperature was monitored using a thermocouple on the backside of the specimen. The second test conducted applied direct heat while measuring the amount of time until burn through.

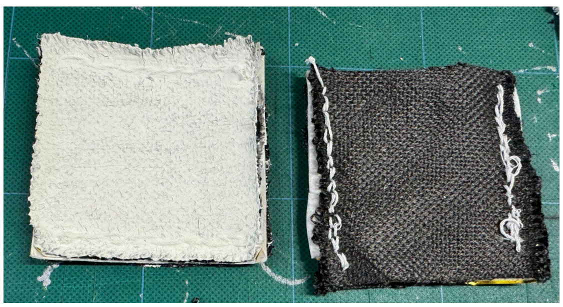
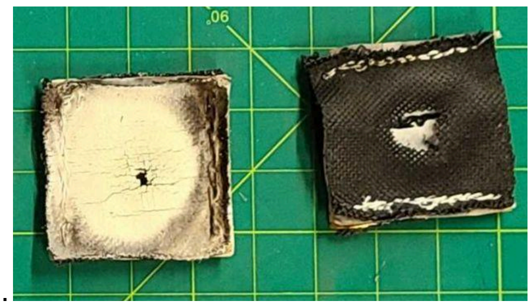
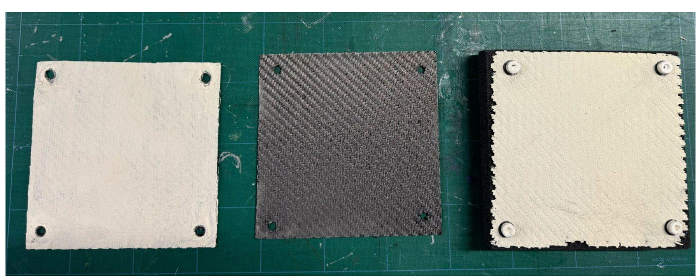
a.  b. 

Figure 17. Tarp thermal ablation test articles: Zirconia coated (left), uncoated (right), pre-test (a), post-test (b)

Tarp - Two test articles were constructed to test the Zirconia coated tarp and the uncoated tarp (Fig 17). From the test, the uncoated tarp survived for 14s until burn through of the top layer of the carbon fiber while the backside temperature reached a maximum 539.44°C. The Zirconia coated tarp survived 50s until burn-through while the backside temperature reached maximum of 993.89°C. From this test it was found that the zirconia coated carbon fiber survived over 3X longer than the uncoated tarp. This is a significant finding and can be further studied to optimize the coating to maximize burn through time for time temperature environments.

a. 

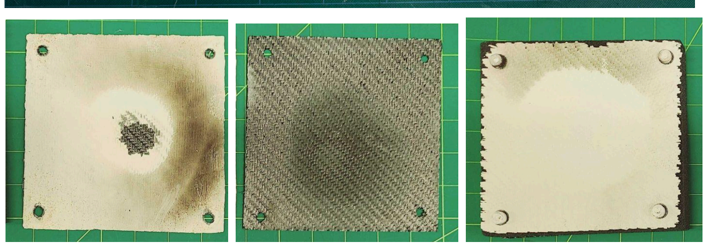
b. 

Figure 18. Heat shield thermal ablation test articles: Zirconia coated carbon-carbon plate (left), uncoated carbon-carbon plate (middle), 3-layer heat shield with zirconia coating (right), pre-test (a), post-test (b)

Heat Shield - three test articles for the heat shield were constructed: zirconia painted single layer sheet of carbon-carbon composite, uncoated single layer sheet of carbon-carbon composite, and the full multi-layered heat shield plasma spray coated with zirconia (Fig 18a). From this test, it was observed that the uncoated carbon-carbon composite sustains more damage than the zirconia coated carbon-carbon composite. From the zirconia painted carbon-carbon specimen it was found that the degradation of the coating was due to the thermal deformation of the specimen causing it to flake away exposing the bare carbon fiber resulting in its failure. The test article for 3-layer heat shield was tested and showed excellent performance. After 30 seconds of direct heat, the bottom side temperature was measured at 52.22°C on the backside while the coating on the top survived direct heat for more than 2.5 minutes after which the test was stopped due to it showing no signs of thermal degradation. Under the conditions tested, the heat shield performed exceptionally well with regards to heat dissipation. These results are very exciting and valuable for advancing the state of the art of low mass - high temperature materials.

Tarp Characterization
Air permeability - Initial analysis and CFD Simulations assume the tarp stackup is not permeable to exhaust gasses, however all fabric elements will have some permeability. Aegis employs an aluminized kapton film layer to create a major reduction in air permeability, however this layer is the most prone to thermal degradation so another stackup without aluminized kapton has been tested as well. The test fixture was assembled in house to align with designs from ASTM D737 (Figure 19.b). Results seen below in Figure 19.a show a meaningful restriction in air flow in both permutations with even better results in those with aluminized kapton.

Drapability - The drapability, or fabric stiffness, test observes the natural behavior of the material under its own wait. By slowly pushing the test strip off the platform in accordance with ASTM D1388, we can see at what length the material bends to the desired angle (Fig 19c). The tarp was unable to reach the desired angle, meaning that the material is considered stiff. However, this is likely attributed to the close stitching for the test article, as the tarp was easy to fold and roll by hand when prepared for transport.

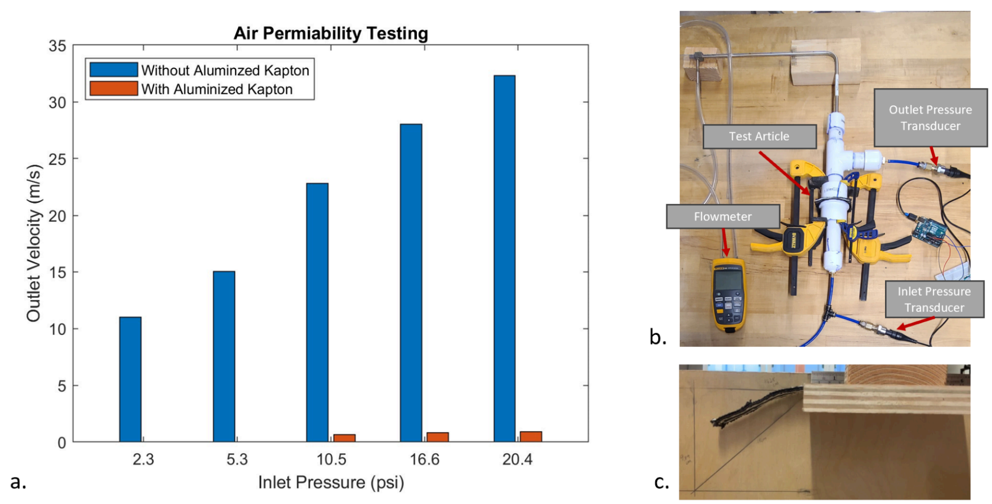


Figure 19. Air Permeability Testing data (a.), Air Permeability Test Setup (b.), Drapability Test Setup (c.)

Abrasion - Given lunar regolith's highly abrasive nature, the carbon fiber tarp was evaluated for mean-time-to-failure (MTTF) of its ability to resist fraying while being drawn across lunar regular simulant. On average, a 2.54cm by 15.24cm swatch of carbon fiber when pulled across a jagged rock coated in regolith simulant remained intact for 0.91 linear feet meters before degrading completely. While these conditions are not common to Aegis's concept of operations, further exploration into coatings and additional materials increasing the abrasion resistance is recommended to ensure safe continued use.

Anchors

The anchor subsystem was evaluated under three tests: vertical pull-out, horizontal pull-out, and deployment in an earth analog environment of coarse grain sand, as in Figure X. Prior to running tests, an analytical model based on the Independent Bearing Method [8] was constructed to validate laboratory testing results.

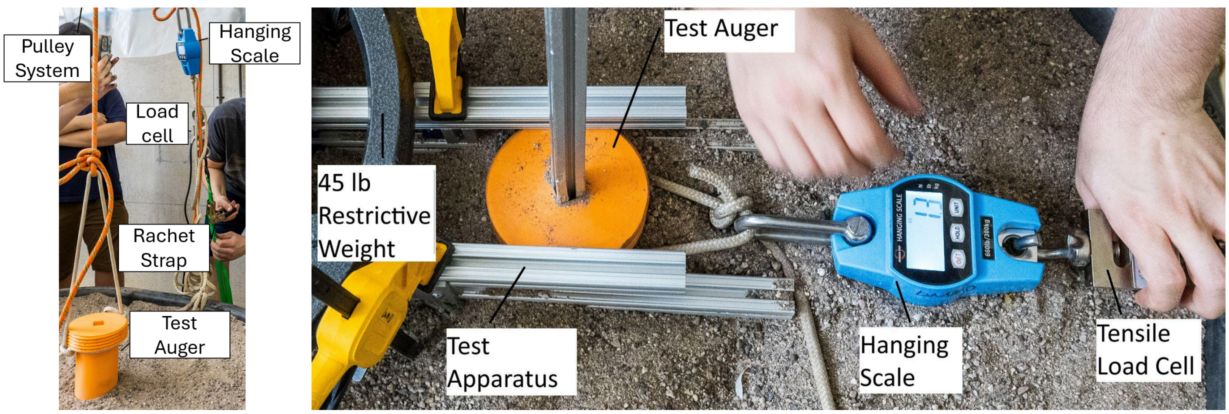


Figure 20: Vertical Pull-out (left), Horizontal Pull-out (right)

Both vertical and horizontal pull-out tests were performed by burying the anchor until it protruded one centimeter above the sand. A design trade study was first performed by testing a Helical Pile design, then subsequently testing a Wood-Screw inspired design. For the horizontal pull test, a custom test fixture was designed to constrain the anchor to only lateral motion for testing with the Wood-Screw design.

Table 3. Anchor Pull-out Testing Results

Anchor Style	Lateral	Vertical
Helical Pile	51.50 N	969.228 N
Wood Screw	673.46 N	558.52 N

Rocket Exhaust Testing

To evaluate the ability for Aegis to redirect exhaust gasses, rocket fire testing was performed at the Friends of Amatuer Rocketry (FAR) test site in the Mojave desert. For this test, an Aerotech M1419W-P motor capable of generating an average thrust of 1419N over a burn time of 7.1 seconds was used. Based on the specifications of the motor, it reached a peak temperature of 1173.79°C. A custom steel text fixture was designed to hold the motor at a height of 1 meter above the heat shield. The entire test was documented using multiple cameras; including four GoPro cameras, a DSLR, and a DJI drone, which also captured thermal imaging. This comprehensive videographic and thermal dataset is crucial in further refining the design and performance of the AEGIS system for future iterations.

During the initial 4 seconds of motor ignition, exhaust gasses were successfully deflected 40° from horizontal with minimal gas permeation through the deflector walls. The test article then underwent a rapid unplanned disassembly for the rest of ignition. It was determined that the motor used for this test was significantly oversized and unnecessary for the test goals. From these results, the Aegis team can be confident that the inflated structure is capable of decreasing regolith kickup during lunar landings, while also identifying future design requirements for the full scale system.

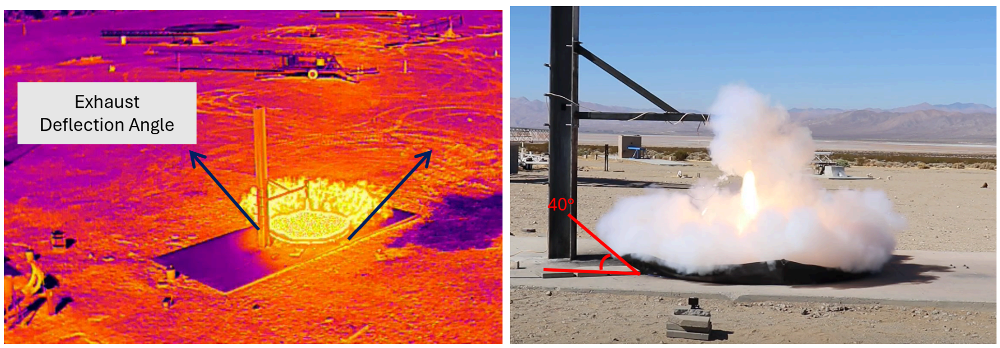


Figure 21. Infrared (IR) image of rocket exhaust (left), Exhaust deflection angle (right)

System Deployment

Aegis's final verification test was conducted to demonstrate its ability to perform each step in its concept of operations successfully in an Earth analog environment. This test was performed at SP Crater Lava Flow near Flagstaff AZ which serves as an Earth analog for the lunar terrain. For this test, Aegis was placed in its stowed position in an area with minor debris (<1.27cm diameter), with a 4° inclination angle. Using the control system, each sub-system was remotely deployed following the order defined by the con-ops. First, all six anchors were driven into the volcanic dust. Next, the exterior panels were released allowing for the spring actuation to open the inflatable enclosure doors. Finally, the system's inflated skeleton was automatically pressurized to 13.79 kPa (2 psi) with air using the onboard control system controlling the pressure from its internal tanks resupplied by an external source. Upon pressurization, the inflated skeleton expanded the tarp into its deployment configuration. While transforming the skeleton complied to minor debris and disturbances and was able to successfully deploy. Finally, the system was depressurized and repressurized multiple times to deflate to modify the system's rigidity for the payload instruction and subsequent landings. During repackaging for repeated deployments. It was found that, folding the tarp and skeleton in an accordion manner towards the enclosure yielded the smoothest inflation process.

The successful testing of Aegis for deployment in an Earth analog concluded the final verification and testing for advancement of the system to TRL 5.

Figure 22. System Deployment: Anchor Actuation t = 0s (a.), Spring Release t = 34s (b.), Inflation begins t = 37s (c.), Partial inflation t = 55s (d.), Inflation Complete t = 76s (e.)

Safety Plan

Safety was of the utmost importance for the Aegis team throughout the project. All laboratory work and testing was conducted under ASU lab safety guidelines by the student team using required PPE. This included the utilization of respirators, coveralls, safety glasses, and ear protection when required for the work being conducted. Earth analog field work testing was conducted by the student team in accordance with ASU Environmental Health and Safety (EHS) department Standard Operating Procedures for field testing and in accordance with local and state regulations. This included required safety training for personnel driving to and from testing, and following required field testing procedures, and following leave no trace principles when testing in the field. Field testing conducted at Friends of Amatuer Rocketry (FAR) in Mojave CA was planned and executed by the student team in accordance with facility safety plans and procedures and overseen by a FAR representative with HPR certification. For this test, the ignition system was set up by an HPR representative and ignition and observation was done remotely from a safe distance in the facilities observation bunker. Cameras were set up prior to testing to capture data and were controlled remotely for safety purposes.

Results and Conclusions

The technical objective set in the proposal was to design, build, and test an inflatable system to reduce dust and debris generated by lander exhaust plumes and provide a safe landing zone for lunar landers. In pursuit of this goal, the team developed an innovative low SWaP inflatable system with a reliable con-ops which utilizes inflatable beams as actuators to deploy the high temperature tarp system. In addition, the team developed a unique design for a multi-layered high temperature tarp designed to withstand indirect exposure to hot exhaust gasses further advancing the state-of-the-art for high temperature flexible materials. The team also developed and tested a novel anchor subsystem for securing Aegis to the lunar surface. Finally the team demonstrated that the deployable perimeter deflector shield is an innovative and effective solution for diverting exhaust gasses away from the ground surface to reduce regolith ejecta.

Over the course of this project, the team has successfully completed the objective by advancing the system from TRL 2 to TRL 5 as demonstrated through relevant environment and Earth analog verification and testing. Over the course of seven months, the Aegis student team has fully designed, prototyped, manufactured, and tested each subsystem and system in accordance with the comprehensive testing plan developed to advance Aegis to TRL 5.

PATH-to-FLIGHT

Through the BIG Idea Challenge, Aegis has been advanced to TRL 5 after testing critical subsystems and components in relevant environments. To prepare for future lunar missions, Aegis will be advanced from TRL 5 to TRL 8. This will include major subsystems and components such as the inflatable structure, tarp, heat shield, anchors, inflatable control system and pressure vessel, power electronics, thermal management system, main compute and communications hardware, and software.

TRL 6 Advancement
To advance Aegis from TRL 5 to 6, the existing design would be scaled up to full size based on the con-ops requirement to demonstrate full system operation in a relevant environment. This would include the addition of a communications system to communicate with incoming landers, improving structural integrity to survive launch loads and support the weight of a lander, anchor improvements for operation in a lunar dust, thermal management system to dissipate heat from the electronics, and proper enclosure design to prevent dust ingress. Final demonstration of TRL 6 would include full TVAC of the system, vibration testing for launch, deployment testing in an Earth analog, and lander vertical descent and take off.

TRL 7-8 Advancement
For advancement to TRL 7, every component in the design would be replaced with heritage or flight ready components. This includes all motors, actuators, electronics, pressure vessels. The system prototype would be qualified by sending it onboard a CLPS mission to the moon as a tech demonstration of deployment and lander testing for a small lander such as the Intuitive Machines Micro Nova. Upon successful testing and deployment in a space environment on the lunar surface Aegis would reach TRL 7 shortly followed by TRL 8.

TRL 9 Advancement
Upon successful advancement to TRL 8, the tech demonstration unit deployed on the lunar surface could be used for a CLPS lander such as the Astrobotics Peregrine. This would allow for a very cost effective advancement to TRL 9. Following the tech demonstration, the Aegis system would be a flight proven system to be utilized by future missions to protect landers from lunar regolith ejecta.

Plans and Opportunities to Continue Development
To continue advancing Aegis to TRL 6, any remaining funds from the BIG Idea Challenge will be used to further the TRL. Following this, grant opportunities, such as NASA Tech-Flights will be targeted as potential opportunities. The team has had conversations with Tech Flight providers to discuss opportunities for a tech demonstration for advancement to TRL 6. Following TRL 6, grant opportunities for tech demonstrations for lunar surface operations will be targeted to support further TRL advancement.

PROJECT MANAGEMENT

Team leadership and management approach

The Aegis team was co-led by students Grant Lesley (Mechanical Engineer Undergraduate) and Elizabeth Arnold (Electrical Engineering Masters) and broken down into subsystem groups made up of (1-3 students) including: material science group, anchor group, research group, inflatables group, electronics and software group with most students contributing on multiple subsystems. All-team meetings were conducted twice a week while subsystem group working sessions were scheduled weekly. Team communication was facilitated through frequent team meetings, small efficient subsystem groups, and modern communication tools such as Slack and Zoom.

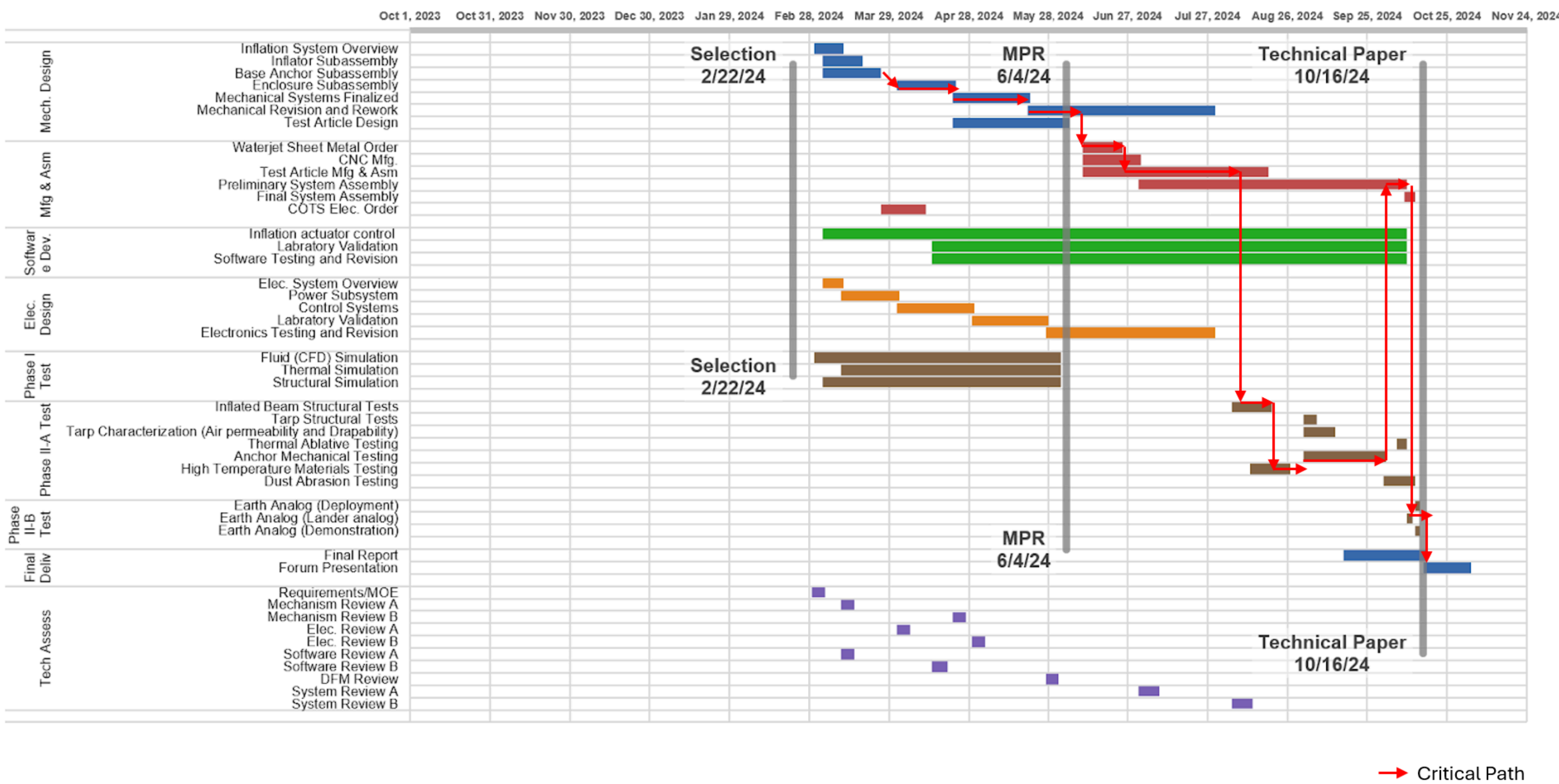
Throughout the project, decisions were made through team consensus following a rigorous systems engineering approach for the design, engineering, and testing of the system. The team heavily used design reviews based on analytical models and simulation driven design to make informed design decisions which would impact final test and demonstration performance. This was accomplished through the development of a comprehensive testing plan (CTP) which was developed in Phase I of the project to rigorously evaluate design decisions based on the testing requirements for TRL advancement.

A core component of the Aegis team was the integration of interdisciplinary teams and workflows. With 11 different degree programs represented, the Aegis team was composed of students from: Mechanical Engineering, Electrical Engineering, Material Science, Computer Science, Computer Engineering, Chemical Engineering, Sustainability, Mathematics, Industrial Design, Graphic Design, and Fashion Design. This wide range of skill sets enable the team to develop the most innovative solutions to many complex challenges through the project. In addition, it resulted in engaging a diverse group of students across various academic backgrounds creating a new model for developing solutions to complex problems.

Detailed timeline

The project timeline for Aegis was broken down into design, manufacturing & assembly, and testing for each system and subsystem. The project was designed such that each subsystem had defined requirements outlined in the CRP which could be tested independently from the remaining system. This enabled the team to complete tasks in parallel as much as possible maximizing the team's efficiency in the schedule. The critical path for the project tracked closely with the development of the mechanical systems and from the timeline below it can be seen to be most heavily driven by the inflatable system. By comparing the final timeline to the proposal timeline, the Earth Analog testing schedule slipped 3-4 weeks which was a result of manufacturing delays with the inflatable structure which required rework. To manage this delay, the team created a stand-in prototype of the inflatable system which allowed the team to conduct laboratory testing of the complete system to test integration. Upon arrival of the final manufactured inflatable prototype, the team was able to seamlessly integrate it into the system within 2 days.

PROJECT TIMELINE



Detailed budget

The proposed budget and actual expenditures for Aegis are well aligned. The main deviation from the proposed budget was the estimated expense of travel to the final forum. Due to the forum being moved to Las Vegas the cost for travel greatly reduced. The additional travel budget was used to support sending more students to the final forum and to travel for additional testing. Remaining budget for student hours has been encumbered through the end of the project and will be spent by the conclusion of the final forum. Remaining budget for travel is dedicated to costs for travel to the final forum. The remaining materials budget has been allocated to cover final manufacturing costs of the inflatable prototype used in final deployment testing. Lastly, the remaining budget in Testing Costs and Facilities has been allocated to cover facilities costs for laboratory testing of the anchors and dust abrasion testing.

Gift-in-Kind:

Zoltek: Carbon fiber was gifted to the team by Zoltek for the multi-layer tarp.

Budget Period of Performance: February 1 - December 31, 2024

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Description	Rate / #	Phase 1 3/1/24 - 6/30/24	Phase 1 Budget Remaining	Rate	Phase 2 7/1/24 - 11/15/24	Phase 2 Budget Spent	Phase 2 Budget Remaining	Total	Total Phase 1&2
A. Direct Labor - Key Personnel									
Tyler Smith	2.5%	$ 1,250.00	$ -		$ 1,563.00	$ 1,563.00	$ -	$ 2,813.00	
								$ -	
Subtotal Salary		***$ 1,250.00***	***$ -***		***$ 1,563.00***	$ 1,563.00	$ -	***$ 2,813.00***	
Direct Labor - Other Personnel									
Management Intern		$ 5,893.00	$ 325.00		$ 7,367.00	$ -	$ 7,367.00	$ 13,260.00	
Undergraduate Hourly Students		$ 20,808.00	$ -		$ 23,868.00	$ 23,061.00	$ 807.00	$ 44,676.00	
Suri Interns		$ 2,500.00	$ 2,500.00		$ 2,500.00	$ -	$ 2,500.00	$ 5,000.00	
Subtotal Other Personnel		***$ 29,201.00***			***$ 33,735.00***	***$ 20,825.00***	***$ 12,910.00***	***$ 62,936.00***	
B. Fringe Benefits									
Faculty	35.23%	$ 440	$ -	35.23%	$ 551	$ 1,560	$ (1,009)	$ 991.02	
Students	1.65%	$ 482	$ -	1.65%	$ 557	$ 174	$ 383	$ 1,038.44	
Subtotal Fringe		**$ 922.19**			**$ 1,107.27**	**$ 861.21**	**$ 246.06**	$ 2,029.46	
Total Labor Costs (A+B)		**$ 31,373.19**	**$ -**		**$ 36,405.27**			**$ 67,778.46**	
C. Direct Costs - Equipment (any individual item over $5,000)		**$ -**			**$ -**			**$ -**	
D. Direct Costs - Domestic Travel		**$ -**			**$ 24,060.00**		**$ 24,060.00**	**$ 24,060.00**	
E. Other Direct Costs									
Materials and Supplies		$ 28,050.00	$ 12,753.00		$ 3,950.00	$ 4,605.00	$ (655.00)	$ 32,000.00	
Testing Costs or Facilities Rental		$ 9,820.00	$ 6,170.00		$ 4,820.00	$ 3,488.68	$ 1,331.32	$ 14,640.00	
Consultants		$ -			$ -			$ -	
Services		$ -			$ -			$ -	
Subcontracts/Subawards		$ -			$ -			$ -	
Miscellaneous		$ -			$ -			$ -	
Total Other Direct Costs (E)		***$ 37,870.00***	***$ -***		***$ 8,770.00***			$ 46,640.00	
F. Total Direct Costs (A+B+C+D+E)		**$ 69,243.19**	**$ -**		**$ 69,235.27**			**$ 138,478.46**	
Modified Total Direct Costs, if applicable								$ -	
G.i. University Indirect Costs (Phase I & Phase II)	0%	$ -		0%	$ -			$ -	
G.ii. Space Grant Indirect Costs (Phase II only, if applicable)				0%	$ -			$ -	
G. Total Indirect Costs		**$ -**			**$ -**			**$ -**	
H. Total Direct and Indirect Costs (F+G)		**$ 69,243.19**			**$ 69,235.27**			**$ 138,478.46**	
% of Total Budget (Phase I should be 50%; Phase II should be 50%)		*50.00%*			*50.00%*				

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