Analysis on an Inflatable, Multi-Shelled Membrane Structure for Lunar Additive Manufacturing

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With NASA's Artemis campaign goals of establishing a human presence on the moon, the need for supporting infrastructure grows. Amentum Space Exploration Group, alongside many industry and educational partners, has developed a Moon-to-Mars Planetary Autonomous Construction Technology Toolbox that highlights various lunar construction technologies and material candidates. A lunar regolith-based concrete is one of the more versatile material candidates for creating lunar habitats, landing pads, and other critical lunar infrastructure as it can be manufactured using in-situ resources; however, a pressurized environment is required to achieve proper curing. Previous designs for a pressurized additive manufacturing structure have been criticized due to massive obstacles such as material transport costs, workspace limitations, and extreme structural stresses. The University of Tennessee Space Institute senior design team proposes an inflatable, multi-shelled membrane structure for a mobile or permanent additive manufacturing facility with the capability to fabricate critical lunar infrastructure elements. The senior design team details the structural analysis, thermal analysis, environmental study, material selection, potential manufacturing and testing methods, and further steps into the creation, development, and applications of such a structure. This proposed structure meets the need for supporting lunar infrastructure to assist in the Artemis campaign and Amentum Space Exploration Group's goals while also addressing the shortcomings of previously proposed designs.

I. Introduction

During the presidency of George H. W. Bush, the Space Exploration Initiative was enacted during which the First Lunar Outpost (FLO) program was proposed in 1991 [1]. In 1992, a paper published by the University of Puerto Rico detailed the designs of a FLO habitation module including extravehicular activity support, medical facilities, waste management, and other concepts such as reduced gravity furniture and lifestyle analysis [2]. While the FLO is just one concept, several designs of lunar habitats have been proposed by the European Space Agency, the National Aeronautics and Space Administration (NASA), and other space agencies. Such proposed ideas include inflatables, cable structures, and modular based lunar habitats [3], but, even with commercial space flight bringing renewed interest and reducing launch costs, transporting prefabricated structures or raw materials from the Earth is not practical.

Amentum Space Exploration Group (ASEG), an American based contractor, alongside several academic and industry partners, has developed a Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) toolbox. MMPACT details various lunar construction capabilities, material candidates, and manufacturing methods that can be applied on the lunar surface. One such capability is the manufacturing of concrete on the lunar surface

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with lunar regolith. This is a promising method of creating lunar habitats in addition to other critical lunar infrastructures such as landing pads and roads. However, manufacturing of this lunar concrete requires the presence of an atmosphere to avoid the vaporization of water used in manufacturing processes.

II. Environmental Considerations and Mitigation Strategies

The lunar surface is a harsh environment that poses many risks to the operation of long-term lunar structure. Such risks have been identified and detailed below alongside potential mitigation strategies:

A. Thermal Management

The surface temperature of the lunar surface is between -274 Fahrenheit (°F) to 134.6 °F with an average temperature of 8 °F [4]. Due to this temperature range, stress due to thermal expansion and contraction can be significant and must be considered in addition to the change in pressure experiences between the layers of the lunar structure.

To mitigate the effects of solar irradiance, an outside layer can be applied to the dome. Kapton is a good choice given its operating temperatures of -452 °F and 752 °F [5]. In addition to this, a system for managing and maintaining pressure changes due to temperature changes is also suggested. This is further discussed in Section IV including detailed results from a heat transfer simulation.

B. Micrometeorite Impact

Micrometeorites pose a risk of damaging the environmental enclosure and even causing catastrophic failure if the damage is substantial.

A study done by DuPont shows that Kevlar is used in Micrometeorite and Orbital Debris (MMOD) protection [6]. While the specific study shows the differences between DuPont's Kevlar EXO and traditional Kevlar used in MMOD, such as Kevlar 29 and Kevlar KM2 or KM2+, more readably available Kevlar have strong material properties to provide micrometeorite protection. Material selection is discussed in detail in Section III.

C. Moonquakes

A moonquake is the lunar equivalent of an earthquake; however, moonquakes are notably different than earthquakes in cause. While earthquakes are mostly caused by the shifting of tectonic plates, lunar seismic activity can originate from a variety of sources including deep moonquakes, thermal moonquakes, shallow moonquakes, and meteoroid impact [7,8]. Shallow moonquakes, the strongest variety, are thought to be caused by the Moon shrinking over time due to its interior cooling. Unlike earthquakes, which last minutes due to dampening by the Earth’s crust, shallow moonquakes can last hours since the Moon’s crust is much more rigid. This makes them a critical consideration for structural analysis. All seismic data on the Moon was collected through a network of four stations during the Apollo landing missions from 1969 to 1972; however, none of that data was collected directly from the lunar south pole [9]. This poses a problem because the lunar south pole is a prime candidate for the location of a lunar base.

While moonquakes could pose an issue, mitigation may not be needed. In addition, depending on the structural load, this risk could fall within a reasonable factor of safety.

D. Regolith

During the Apollo missions, lunar regolith was shown to cause damage to space suits, and other critical mission equipment [10]. Lunar regolith is abrasive and carries a high electric charge that causes it to adhere to surfaces. This can pose issues from damaging fabric material to clogging clamping devices.

The clamping design proposed in Section III is designed around this issue and should not be affected. Likewise, it is not expected that any abrasion from lunar regolith is to occur that would pose a significant issue to the outer shell of the enclosure with the proposed materials.

E. Radiation Material Degradation

According to a report published by NASA, solar radiation has a negative effect on various materials such as thermoplastics, adhesives, and metals [11]. While there is not sufficient data to determine the exact material degradation of the materials chosen by the design team, it is expected that, if no protection is provided, tensile strength, fatigue stress, impact strength, and other important material properties will be affected.

According to a study conducted by Narci Livio et al. [12], Kevlar is comparable in radiation protection to Polyethylene already used in the International Space Station. In addition, Kapton, while used for thermal protection, also offers radiation protection [5]. However, not much information is available for the effects of radiation Kevlar. Given this, and the lack of facilities and instruments to conduct testing towards material degradation due to radiation at the University of Tennessee Space Institute, further protection may be needed.

III. Design Criteria – The Bubble

Concrete manufacturing with materials extracted from the lunar surface solves one of the most difficult problems with supporting long-term human habitation on the Moon – and provides a foundation for the habitation of other distant planets – the cost of transporting materials from Earth. Through the MMPACT toolbox, ASEG provides avenues to acquiring raw resources, manufacturing lunar concrete, and even 3D printing entire lunar structures, but a major difficulty is that the manufacturing of concrete depends on liquid water. Water cannot exist as a liquid in a near-vacuum, such as the environment on the Moon and other planets. Instead, the water boils off, and when used in concrete manufacturing, leaves behind pockets of gas in the concrete mix as it hardens. This effectively diminishes concretes incredible property of withstanding compression, rendering it useless for construction on the lunar surface. This project's purpose is to devise and demonstrate a structure that can be used to provide a pressurized environment for concrete construction.

A. Requirements and Considerations

For this project to be successful, the structure would need to maintain a minimum pressure of 0.5 atmosphere (atm) or 7.348 pounds per square inch absolute (psia) with a target pressure of 1 atm or 14.696 psia. It would need to be deployable on the lunar surface with minimal support, as well as being relocatable with minimal support and non-reusable components. This structure would need to withstand the harsh environment on the lunar surface, such as impacts from micrometeorites, the abrasive properties of the lunar regolith, exposure to moonquakes, exposure to solar radiation, and the thermal cycling from exposure to the Sun. To provide ample space for the construction of lunar structures, the desired dimensions is of a dome with an 80-foot diameter and a 20-foot center ceiling height.

B. Design Overview

To provide a pressurized environment that can be deployed and relocated with minimal support, the structure design is based on using a flexible, membrane shell that can be inflated to atmospheric pressure. This shell will be supported by the pressure force acting on the inside face of the shell, and it will be mounted to a ring that will serve as a foundation for the shell. The difficulty posed by a self-supported, inflatable structure is managing internal pressure exerted over a large area. At 1 atm, the shell would experience tremendous stress, promoting the use of a more advanced material for the shells. To overcome this challenge of managing this pressure over the large area, our design employs the use of multiple shells, stacked and spaced over one another, as shown in the cross-sectional view in Fig. 1. By using multiple shells, the pressure force can be stepped by a delta pressure (Δp) across each shell, allowing each shell and clamp structure to only support the Δp instead of the target pressure.

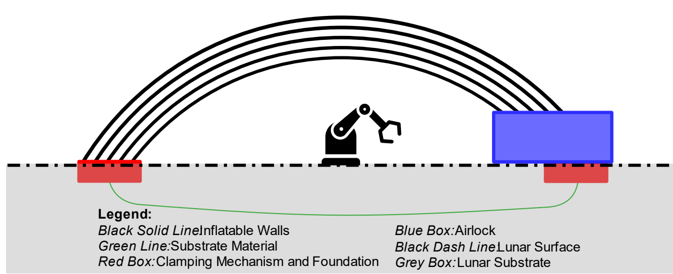

Figure 1. Bubble Design Overview.

This inflatable structure design – The Bubble – enables a robotic arm to be placed in the structure to 3D print the desired lunar structure. Once the structure is completed, it can then be relocated to another location.

The Bubble's three main components are the shells, clamps, and foundation. The shells are a flexible material, such as fabric, that can be used to contain the atmospheric pressure needed to facilitate the existence of liquid water. The clamps are modular components that are designed to clamp onto the shells and fix the shells in place. The foundation serves as a base to mount the clamps, as well as counteracting the uplifting force from the interior pressure.

Fig. 1 also shows two additional components: substrate material and an air lock. The substrate material is essentially a shell that is buried below the lunar surface to act as a lower seal of The Bubble, and it falls under the shell design area. The airlock is a mission parameter requirement that is likely to change between missions, but the design is outside of the scope of this report.

By separating the three main components instead of a unified integration, it allows the design to be modified between missions without the need for a major redesign. The shells and clamps can be resized based on the target dimensions, and the foundation can be modified or changed following the size of the structure or utilizing existing structures or technologies.

C. Shell

A material will need to be used that is strong enough to withstand the pressure differential while also protecting from micrometeorites, solar radiation, and other hazards on the lunar surface as discussed in Section II. Several viable candidates for the shell material are Vectran NT, Nextel, and Kevlar 49. These materials would serve to provide enough strength to keep the structure intact while pressurized while also protecting against the environmental hazards. An airtight liner would be needed to ensure that there would be no issues with pressurization and such a liner would not need to have the same mechanical properties as the shell materials and could likely be a plastic film. The best option for the shell material is Kevlar 49 due to its high tensile strength and wide range of applications. More investigation into the shell material would be beneficial to see if there are better options that are more suitable for the lunar environment or if Kevlar 49 is the best choice.

A multi-leaf dome design will be used for the shell with a diameter of 80 feet and a height of 20 feet. To create a dome with these dimensions, each dome leaf will have to be made from a section of a leaf for a complete hemispherical dome with a diameter of 100 feet. The number of leaves can be adjusted to accommodate the number of clamps used for the base. An example of a scaled leaf for an 8-foot diameter, 2-foot-high dome is shown in Fig 2. The top of the dome will have a circular cap to prevent all of the dome leaves from coming to a point and aid in ease of manufacturing.

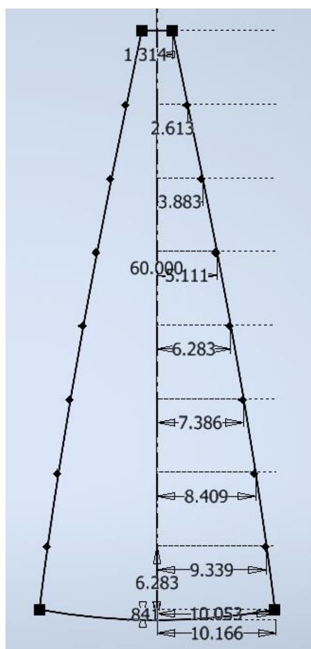

Figure 2. Dome Leaf for Scaled Model.

D. Clamp

For the clamp, it is necessary to be designed such that there are minimal unique parts to allow interchangeability through multiple redeployments. The design needed to account for the angle of the shell to prevent any unnecessary bending stresses in the shell material, and most importantly, it needs to be airtight. The chosen design is a three-component design, with each set of components making up a clamp that will be repeated around the base of the shell. to form the clamping ring. Fig. 3 and Fig. 4 show the induvial pieces and how they are assembled to form the complete ring.

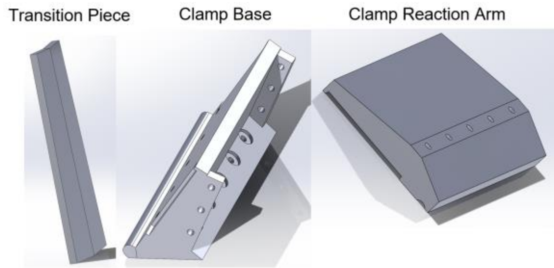

Figure 3. Three Main Components of the Clamp.

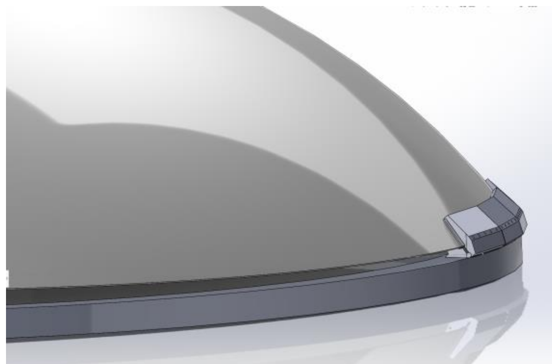

Figure 4. Clamps Integrated with a Shell.

This design was chosen as a single overall clamp design that could be used between different shells with only minor adjustments for the dome's diameter and height. The clamp is designed to be a simple lever mechanism to compress and hold the fabric. This was chosen so that there will be no penetration though a shell, allowing it to be redeployed without the need to align multiple holes between multiple clamps. This design is also simple enough to prevent failure due to the lunar regolith buildup, as there are no moving parts, and there are no joints or other complex features for the lunar regolith to congregate.

To seal between clamps, the sides of the clamp are designed to be flat and parallel to other clamps so that a simple gasket material can be used. To assist with sealing between clamping surfaces, a transition piece, as shown in Fig. 3, is used. This piece fits into a recess between two clamps to provide a continuous surface for the shell to be compressed against. This piece is designed to transition between clamp bases and clamp reaction arms, so that there are no gaps or pinch points exposed to the shell.

To attach to the foundation, a series of bolts will be used to attach the clamp base to the foundation. The base of the clamp is flat to allow another gasket material to exist between the clamp and the foundation, maintaining the airtight seal. This attachment method allows the foundation to be heavily modified between deployment, with the only requirement being that the foundation has a flat surface for the ring of clamps and a method to bolt the clamps to the foundation.

Additionally, a smaller scale, continuous ring clamp is designed with a similar physical concept to provide easy pressurized access of a small region of lunar regolith. Whether this region is used for the same 3D printing technique or simply a protected human traversable volume is open to mission requirements. The size of this ring is currently determined by the largest diameters of transport vessels to the Moon but could be expanded upon with on-site lunar welding, however, until this process is reliable, all manufacturing considerations are done before leaving for the Moon. Currently, the largest expected lunar transport is the SpaceX Starship, consisting of a nine-meter internal cargo bay. This diameter is used for the outer ring of the structure and so shells for this ring can only be smaller. Differently from the modular clamp design, this shell intends to maximize usable area by employing a vertical clamp with the intent of creating a hemispherical dome. The materials for the shells would be the same as the larger dome structure, only smaller. The current iteration of the design is a nearly solid ring of nine-meter diameter with an average thickness of about five inches to resist the warping and stresses of the lunar environment as well as the pressures of the dome.

The thickness does assist with the planting of the structure as it is intended to be partially buried but the weight is helpful once in place. The clamp and bubble concept can be seen below.

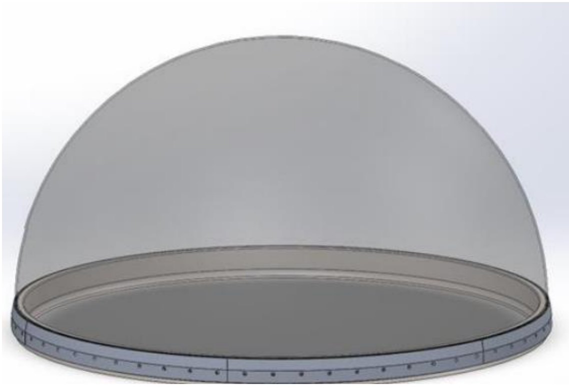

Figure 5. Miniaturized Dome Structure Concept.

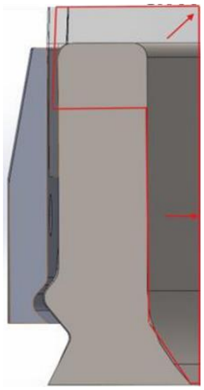

Figure 6. Side Profile of Miniature Dome Clamp Design, with the Clamping Plate (blue) and Base Ring (gray).

The clamp design follows many of the same principles as the larger structure although with right angle mitigation in the base ring. The red outlined area of Fig. 6 is the pressurized zone and inside the dome structure. The clamping design does not punch through any fabric and is bolted below the pressurization line to act as a lever on the fabric. The bolt recesses are the only current lunar regolith build up zones but should be large enough to easily clean out by hand if needed.

Primary drawbacks of this method are currently thermal cycle stresses of the lunar environment and the weight of all pieces being too heavy for human manipulation of the lunar surface. However, strides in a lunar crane system by multiple private and government projects are proving this hurdle to be smaller than expected. This dome structure is also similarly mobile compared to the larger shell structure but as the interior is not large enough to effectively 3D print whole structures but rather large blocks or pieces of them. Therefore, the usefulness of moving the structure is reduced when deflating and removing completed materials works for much less effort. A permanent hub structure with multiple miniature domes could provide the most utility as that would allow a centralized pressure regulator and air locks connected to more permanent human habitation.

For both structure designs, a foundation is required to attach the clamp to the lunar surface. For this foundation, the requirements are that there is a flat surface for the clamp attach to that can be sealed, and the foundation will need to be able to withstand the forces generated by a pressured dome. This design did not choose a foundation design, as mission parameters and technology currently in development will dictate how the foundation is constructed. Lunar concrete is a useful material to manufacture the foundation, but most lunar concrete formulations that would be effective for the mass needed to withstand the forces of the dome require liquid water, the issues of which were previously discussed. The existence of liquid water for large lunar concrete structures is what this dome design aims to solve, so it was recognized that another technology from different groups would be needed to make this clamp design successful, so the focus on the foundation was applied elsewhere.

IV. Analysis

A. Loads

Before any analysis can be done, all possible loads the structure might experience during its operation must be identified. All structures have a dead load (DL) which is the weight of the structure. The dead load on the Moon will be 83.4% lower than on Earth as the Moon has an average gravitational acceleration of 0.166 g or 5.34 ft/s^2. The Bubble will also experience an internal pressure load (PL) defined by the target internal gauge pressure divided by the number of shells. Due to the boundary condition that clamping imposes on the structure, classic spherical pressure vessel equations are not valid as the stress-state will be more complex than uniform biaxial tension. Instead, FEA is the best way to calculate stress distribution in the Bubble. As previously discussed, shallow moonquakes are a major concern for any long-term structure on the Moon. Despite the lack of seismic data for the lunar south pole, work like that done by Ruiz et al. [7] provides an excellent framework for the preliminary seismic hazard analysis that is critical for the development of a seismic load (SL) case for any long-term lunar structure. Thermal loading (TL) is another critical consideration for lunar structures as the Moon's surface temperature cycles from extremely hot to extremely cold. Using Diviner temperature data from the lunar south pole, the effective temperature range for the structure would be -274 °F to 134.6 °F. For materials such as that for gaskets and the shells, this extreme temperature could lead to catastrophic failure. For this reason, more advanced materials should be considered for the structure. With this information, a possible static load combination table for a lunar structure is shown below.

Table I. Possible static load combination table for a lunar structure.

Load Combinations		
Combination	Load Components	Description
1	DL + PL + SL + TL^-	Dead load, pressure load, seismic load, and low-temperature load.
2	DL + PL + SL + TL^+	Dead load, pressure load, seismic load, and high-temperature load.

B. Failure Criteria

The materials being considered for the shells of the structure are fiber-reinforced elastomer composites; these are orthotropic materials. The linear elastic properties needed to define the compliance matrix for an orthotropic material are E_{11}, E_{22}, E_{33}, ν_{12}, ν_{23}, ν_{13}, G_{12}, G_{23}, and G_{13} where E_{ii} is the directional modulus of elasticity, ν_{ij} is the directional Poisson's ratio, and G_{ij} is the directional shear modulus. The out-of-plane properties of woven fabric are difficult to define through testing. As an alternative, the aggregate properties of woven composite can be simulated in Ansys Material Designer. This is done by defining the constituent material properties, such as yarn and matrix, and composite geometry, such as weave type, fiber volume fraction, yarn fiber volume fraction, shear angle, yarn spacing, and fabric thickness. From the inputs, Ansys Material Designer will create a representative volume element as shown in Fig. 7 that can be meshed and then analyzed to output the aggregate elastic and thermal properties.

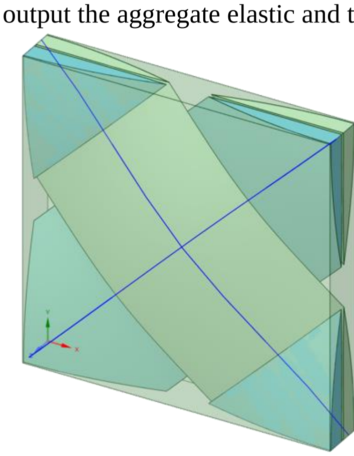

Figure 7. Representative Volume Element of a Woven Composite created in Ansys Material Designer.

To assess failure from stress results, failure criteria is needed. For isotropic material (like the metal used for the clamp), the von Mises stress criterion is most suitable as yielding will be considered failure. For the orthotropic shells, failure criteria become more complex. One of the better suited failure criteria for orthotropic materials is Tsai-Wu [13], but it requires an additional empirical constant making it much harder to implement. A good alternative is the Tsai-Hill criteria [14] since only three empirical constants are needed: the tensile strength in the longitudinal direction (X_{11}), the tensile strength in the transverse direction (X_{22}), and the shear strength (S_{12}). The failure index (FI) for the Tsai-Hill failure criteria is shown in Eq. 1.

$$\left(\frac{\sigma_{11}}{X_{11}}\right)^2 - \left(\frac{\sigma_{11}\sigma_{22}}{{X_{11}}^2}\right) + \left(\frac{\sigma_{22}}{X_{22}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = FI \quad (1)$$

Although this criterion is simpler, it has the downsides of not being able to differentiate between tensile and compressive failure or whether failure occurs in the fiber or the matrix; however, since the structure is being pressurized in tension, compressive failure can be neglected. Additionally, distinguishing between fiber and matrix failure is unnecessary; only overall failure of the fabric needs to be considered. Other than the clamp and shell, other modes of failure that require consideration are bolt failure, gasket failure, and slippage of the shell in the clamping mechanism.

C. Suggested Structural Analyses

The suggested analyses to adequately analyze the structure are a static structural analysis using the sample load combinations, a linear dynamic analysis to analyze the structures response to seismic loading, and a thermal fatigue analysis to analyze the effects of the extreme lunar thermal cycle.

D. Heat Transfer

Due to computational limitations, a one-dimensional (1D) simulation was chosen. A 1D simulation is quick and computationally inexpensive to run. In addition, it also allows for easy management of boundary conditions, and, while the results are not as accurate as a higher dimension simulation, provides reasonable results that can be used for the expected thermal behavior of The Bubble.

For a 1D simulation, a rectangular segment of The Bubble will be analyzed using Ansys Fluent [15]. The boundary conditions applied are a solar irradiance of 1361 W/m^2 [16], and a constant temperature of 8 °F, or the average surface temperature of the lunar surface, is applied at the bottom layer. It will be assumed that a layer of coated Silver-Aluminum Oxide Kapton will surround the outer shell with a solar absorptance of .08 corresponding to the available data by NASA [17]. Lastly, it will be assumed that the shells of The Bubble are Kevlar 49 and are inflated with air. The total time simulated will be a full lunar day cycle of 2 weeks. A time step of 240 seconds or 4 minutes will be used for a total of 5000 iterations with 20 iterations per time-step. The result of the simulation is shown below:

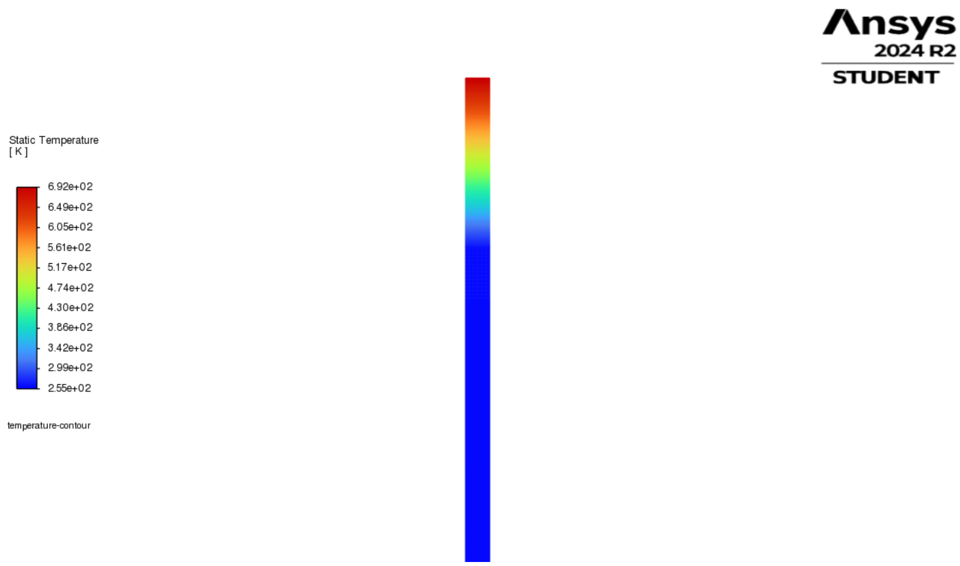

Figure 8. Resulting Temperature Gradient 2 Weeks.

As seen in the figure above, after 2 weeks the max temperature reached at the outer shell is 692 Kelven or 785 °F. These results show that, despite applying a layer of coated Kapton, temperatures still exceed operating temperatures by 33 °F. Due to this, more testing is still being conducted for the thermal analysis of The Bubble. Possible options include running simulations with other coatings, using different gases to pressurize the shells, or looking into ways to actively cool The Bubble.

V. Conclusion

Several designs of a lunar habitat have been proposed by space agencies with designs ranging from inflatables to modular based habitats. However, even with commercial space flights bringing renewed interest and lowering launch costs, transportation of materials limit opportunities. A lunar regolith-based concrete allows for the manufacturing of lunar habitats, and other critical lunar infrastructure. By utilizing resources found on the lunar surface, the need for transporting raw materials from Earth is limited. However, a constant pressure of around one atmosphere must be maintained during the manufacturing process. In support of this, the University of Tennessee senior design team proposes an inflatable, multi-shelled membrane dome to serve as a permanent or semi-permanent manufacturing facility. This structure, named The Bubble, is designed to withstand the harsh environment of the lunar surface in addition to meeting the design criteria set by the senior design team and Amentum Space Exploration Group. Further analysis and testing are needed to prove reliability and capability. As a continuation of this project, a 1:10 scale prototype of The Bubble is currently in development by the senior design team to show proof of concept.

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References

[1] NASA. (2024, October 17). Space Exploration Initiative (SEI). https://www.nasa.gov/history/sei/

[2] Andino, A. F., Silva, D., Ortiz, N., Alvarez, O., Colon, J. A., Colon, M., Gonzalez, I. C. (1992). First Lunar Outpost. USRA Advanced Design Program, Proceedings of the 8th Annual Summer Conference: (pp. 237-249). NASA.

[3] Ruess, F., Schaenzlin, J,. & Benaroya, H. (n.d.). Structural Design of a Lunar Habitat. https://doi.org/10.1061/ASCE0893-1321200619:3133

[4] NASA. (2025, February 10). Weather on the Moon. https://science.nasa.gov/moon/weather-on-the-moon/

[5] DuPont, DuPont Kapton Summary of Properties. https://www.dupont.com/content/dam/electronics/amer/us/en/electronics/public/documents/en/EI-10142_Kapton-Summary-of-Properties.pdf

[6] NASA, DuPont, The Next Generation of Kevlar Fiber for Improved Micrometeoroid and Orbital Debris Protection, https://ntrs.nasa.gov/citations/20230014548
[7] Ruiz, S., Cruz, A., Gomez, D., Dyke, S. J., & Ramirez, J. (2022). Preliminary approach to assess the seismic hazard on a lunar site. Icarus, 383. https://doi.org/10.1016/j.icarus.2022.115056
[8] NASA., Moonquakes, https://science.nasa.gov/moon/moonquakes/
[9] Nakamura, Y., Latham, G. v., & Dorman, H. J. (1982). Apollo lunar seismic experiment - final summary. Journal of Geophysical Research, 87(Supplement). https://doi.org/10.1029/jb087is01p0a117\
[10] McSweeny, Kelly, Lunar Soil Is a Dangerous Nuisance for Astronauts https://now.northropgrumman.com/lunar-soil-is-a-dangerous-nuisance-for-astronauts, Northrop Grumman
[11] NASA, Nuclear and Space Radiation Effects on Materials, https://www.nrc.gov/docs/ML1533/ML15334A202.pdf
[12] Narici, Livio., Casolino, Marco., Di Fino, Luca., Picozza, Piergiorgio., Rizzo, Alessandro., Zaconte, Veronica., Performances of Kevlar and Polyethylene as radiation shielding on-board the International Space Station in high latitude radiation environment, https://www.nature.com/articles/s41598-017-01707-2
[13] Tsai, S. W., Afb, W.-P., Wu, E. M., & Louis, S. (n.d.). A General Theory of Strength for Anisotropic Materials.
[14] Tsai, S. W., Strength Characteristics of Composite Materials, NASA CR-224, 1965.
[15] Ansys® Fluent, 2024 R1, ANSYS, Inc.
[16] NASA. (2024, January 11). Moon Fact Sheet. https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html
[17] AZ Technology. AZ-93 White Thermal Control, Inorganic Paint/Coating. https://www.aztechnology.com/product/1/az-93