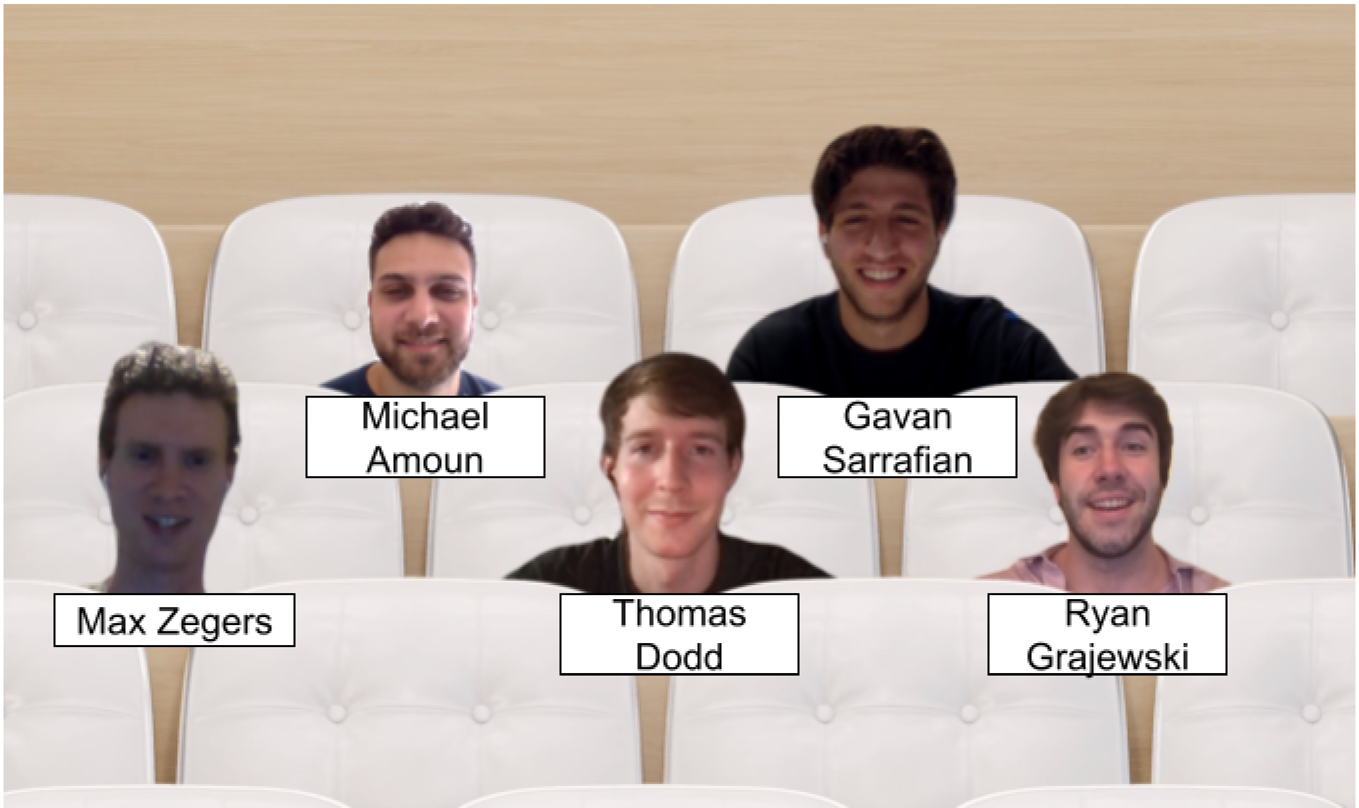
Team Final Report

Team: Space Cowboys
December 14, 2022



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1 | Executive Summary

NASA has launched project Artemis which has the goal of establishing a long-term presence on the Moon. Due to the high cost of transporting materials from Earth, one of the many challenges will be determining ways to use in-situ resources (ISRU) to create sustainable infrastructure. This problem is core to the 2022 NASA Big Idea Challenge, where proposals will be aimed at demonstrating promising technologies that enable any aspect of the metal production pipeline on the moon. After researching relevant lunar technologies, generating concepts and evaluating design conflicts through TRIZ, the team developed innovative solutions for manufacturing pressure vessels in the lunar environment as well as improved quenching and hardening techniques for aluminum on the moon.

The team initially planned to develop physical proof of concept models to evaluate how layered metal could function as a pressure vessel wall, and how potential polymers could function as molds for forming pressure vessels and smooth walls. A test was also planned to evaluate rapid cooling techniques for quenching aluminum. No proof of concept was planned for spectroscopy because the team determined that it was not feasible to model the concept or access and modify the needed equipment for a physical test.

During the process of creating the proof of concepts the team adjusted the models to be computer based analytical experiments because it became apparent that this would provide more useful data. Additionally, the transition was made because it was more feasible for a mostly remote team compared to physical models. The team created a model in SolidWorks to evaluate the rapid cooling and hardening of aluminum in a lunar environment with nitrogen. The team also performed a finite element analysis for an inflatable diaphragm to aid in constructing pressure vessels. The Von-Mises stresses and deformation were evaluated for different materials, to ensure this method could be used to form pressure vessels. Finally the team approximated the stresses a pressure vessel could withstand while still meeting factors of safety requirements.

Each model provided valuable insight to the concepts to help determine if they are worth pursuing in the future. The tests validated a few of our concepts, but also exposed new problems that indicated limited feasibility. Ultimately, each proof of concept can be improved with physical testing to validate the concepts and to account for unexpected events.

2 | Introduction

This project focuses on two main design concepts that were declared ripe for innovation by our team. One concept explores a new way to heat treat metals and the other explores a new possibility for how pressure vessels may be constructed in the lunar environment. These concepts were a result of various design methods throughout the semester. Some of the most influential methods were the House of Quality, numerous methods for exploring analogous domains, and using decision-matrices to narrow the focus onto our final concepts. In this report, we will present our innovative concept ideas, provide a discussion of the background research and engineering phenomena that helped formulate the proof of concept experiments, and evaluate the results from those experiments. We will conclude with an overview of the findings, including both the promising and unfavorable, and suggest areas for future improvement.

3 | Application of TRIZ/TIPS

As part of our design process, we used TIPS/TRIZ to overcome various design conflicts. For the pressure vessel concept, we began by selecting the elements harmed and improved with our pressure vessel design. Below are the results in **TRIZ Table 1.**

Table 1: TRIZ 1

Harmed	**Improved**	**Generalized Solutions**
11. Stress or Pressure	13. Stability of Object's Composition	[2, 35, 40]
14. Strength	32. Manufacturability	[1, 3, 10, 32]
36. Complexity of Design	38. Level of Automation	[10, 15, 24]
29. Manufacturing Precision	2. Weight of stationary object	[1, 10, 17, 35]

By using the best-fit combinations and generalized solutions, we were most inspired by the 3 following TRIZ solutions:

40.)
[Using Composite Materials] - The pressure vessel concept can be constructed using composite materials. Since there are high temperature requirements, composites may be an advantageous avenue to explore. This can be accomplished by using metal wires to withstand the tension forces of the vessel. Polymer or resin could be formed around the wire structure to ensure an airtight or watertight body. This would allow for a consistent and smooth surface finish on the inside of the vessel and provide a lighter weight solution.

24.)

[The go between principle] - During the manufacturing process, a temporary inflatable balloon could be used to support the wire wrapping manufacturing process. This could also support our liquid resin as it cures onto the metal wire body. Once the body of the vessel is formed, the balloon is deflated and removed from the mouth of the vessel.

17.)

[Principle of moving into a new dimension] - If the vessel is not able to withstand the operating pressures intended for the vessel and storage requirements, more layers of wrapping may be necessary to support greater tensile forces. More resin or polymer can be added to ensure an airtight or watertight seal if the vessel tends to fail in that manner. This would be considered an expanded dimension.

For our second concept, we also applied TRIZ to explore new avenues of design and analogous domains. For this second concept, we applied the TRIZ the same TRIZ method steps. Our second innovative concept was the metal quenching/hardening. Our first design consisted of taking advantage of the lunar environment, where we expose the annealed samples to the cold lunar atmosphere during the cyclical two-week cold phase of the moon. However, for steel or aluminum quenching, we discovered that the atmospheric temperatures would not be sufficient for rapidly cooling the metal to "freeze" the sample at the desired point in time. The quenching would also be limited to only a two-week lunar phase which would be undesirable for constant or frequent metal production. We opted to use Nitrogen gas due to the cooling properties inherent to nitrogen [1]. Our TRIZ results, shown in **TRIZ Table 2,** provided various general solutions for our design conflicts that were previously limiting our original concept. The TRIZ results for the quenching concept were as follows:

Table 2:TRIZ 2

Harmed	**Improved**	**Generalized Solutions**
32. Manufacturability	14. Strength	[3, 10, 11, 32]
11. Stress or Pressure	17. Temperature	[2, 19, 35, 39]
37. Difficult to control or measure	13. Stability of Objects Composition	[22, 23, 35, 39]
28. Accuracy of Measurement	38. Level of Automation	[10, 26, 28,34]

32.)

[Principle of Using Color]

A key aspect of tempering is detecting temperature. A color changing compound could be applied to the metal that shifts in color based on the surface temperature of the metal that's being cooled. This will add a visual queue to signify whether the nitrogen gas is correctly cooling the aluminum metal at an adequate pace or if controls need to be changed like shifting the velocity of the nitrogen gas.

39.)
[Using an inert atmosphere] - This principle of using a pure and inert atmosphere would likely be essential and advantageous to the metal quenching process; where the metal sample would be placed in a vacuum atmosphere with no gas or contaminants. When the nitrogen gas is released into the vessel, the gas would be more easily accepted into the chamber due to the vacuum and the increased control of the environment would allow for more precise quenching/cooling.
35.)
[Changing the Aggregate State of the Object]
The original concept utilizes nitrogen gas as a cooling agent during the quenching process. Rather than using a gaseous cooling agent, the design concept may benefit from the principle of changing aggregate states by employing a liquid form of nitrogen. Using a liquid coolant could reduce the need for a pressurized system that contains and releases the coolant over the heated metal, or at the very least reduce the pressure requirements.
28.)
[Replacement of a mechanical pattern]
The original solution uses a convection system to cool the part. With inspiration from this generalized solution, we could implement a different mechanical pattern through the use of conduction to aid in cooling. By using conduction in conjunction with the nitrogen gas, we can achieve much faster cooling times and greater cycle times to aid increased production. A simple cooled base plate could be used to support the metal and conduct heat from the base of the part while the nitrogen system accelerates cooling from the other exposed faces.
3).
[Principle of Locality]
The original concept specifies using homogenous nitrogen gas as the cooling agent. This concept could benefit from the Principle of Locality by introducing a non-homogeneous gas mixture as the cooling agent instead – a mixture of nitrogen gas along with other noble gasses could be used to allow “different parts of the object to carry different functions.” With each gas in the mixture having different convection coefficients, it may be possible to arrive at an optimized cooling process. The largest unknown, though, is still whether these new gasses would be available for production on the moon.

Results from this iteration of TRIZ yielded useful generalized solutions which we adapted to our design problem. The generalized solutions prompted useful and effective directions that improved our direction and gave us new insight and approaches that enabled us to further refine our metal quenching process. The 'Principle of Locality', and 'Replacement of a Mechanical Pattern' both had a major impact in developing our final concept. Ultimately, TRIZ bolstered our system design by relieving our design fixations and design conflicts. Section 6.1 of this report describes the results from our analytical calculations and results for the nitrogen gas quenching.

4 | Innovative Design Concepts

4.1 | A Method for Heat Treating Metal by Gas Quenching

4.1.1 | Concept Background and Motivation

High strength materials will be required for the construction of supporting structures that will enable a permanent presence on the Moon. The two abundant ores found on the moon that are available for this use are anorthite and ilmenite, which produce aluminum and iron respectively when certain forging methods are used. To be used in load-bearing infrastructure, metals produced from these ores will require heat treatment to attain desirable physical or mechanical material properties including higher strength and hardness ratings and lower internal stresses.

Metal hardening processes increase the hardness and strength of a material by raising the metal to a critical temperature and then rapidly quenching it to freeze the internal grain structure when the desired form is reached. Employing the hardening methods commonly used on Earth in the lunar environment is a major challenge because the quenching process requires resources that are scarce on the Moon like water, oxygen, or oil to achieve the rapid cooling effect. To enable the rest of the metal hardening process, the focus of this innovative design concept is developing a method for quenching that is adapted for the resources available on the Moon. For the proposed system, it is assumed that there are existing capabilities for heating the metal to the desired temperature as these would be required during the smelting process.

4.1.2 | Proposed Concept Description

The proposed concept for metal quenching is an inert gas quenching process that utilizes nitrogen gas extracted from lunar regolith as the cooling agent in a convection process. The process involves blasting a heated metal sample in a vacuum furnace with nitrogen gas at high pressure and velocity to quickly cool the metal at the desired cooling rate.

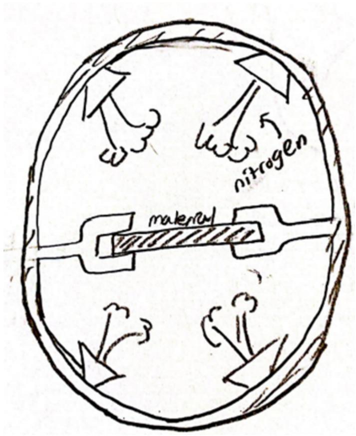


Figure 1: Conceptual sketch of the nitrogen gas quenching process

By varying the pressure and velocity of the nitrogen gas interacting with the heated metal sample, the heat transfer coefficient can be finely tuned so as to achieve the desired metal cooling rate. Increasing the pressure and velocity will produce a higher heat transfer coefficient, meaning more heat is convected away in a shorter period of time [2].

The required nitrogen gas is to be obtained from volatile deposits that have been embedded in lunar regolith by solar winds. These nitrogen deposits exist in the form of chemically bound nitrides which can be extracted from the regolith through a hydrolysis process[3]. While the total volume of nitrogen found on the Moon is an ongoing area of study, scientists have conducted experiments on samples of lunar soil which found that the average volume of nitrogen in mature samples is greater than 100 μgN/g. Lunar Breccias was found to have 68μgN/g, and lunar rocks were shown to have 37μgN/g [3].

The proposed concept for metal quenching is of high-value because it directly impacts the ability to construct more permanent infrastructure on the Moon by enabling the manufacture of high strength metals. The innovative aspect that is core to the concept is the usage of in-situ extracted nitrogen as the convection agent, and this is the aspect that will be explored in the proof of concept.

The grain structure can also be analyzed for a particular type of thermal quenching; however, we did not focus on the minuteness of the grain micro-structures in this research due to scope limitations. The focus of this concept was to test and verify whether or not the thermal effects of gas quenching were sufficient as a substitute for traditional quenching operations. Without the necessary thermal effects imparted on the material, there cannot be any meaningful effect to the grain structure; therefore, grain structure should be an area of focus for fine adjustments to the heat treatment process. Having access to the necessary instruments and tools for analyzing grain structure would enable this further research to be executed.

4.2 | A Method for Manufacturing Pressure Vessels

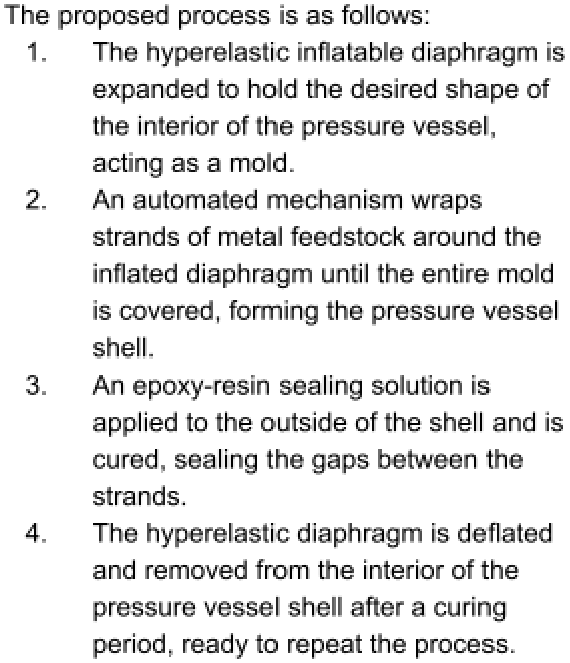
4.2.1 | Concept Background and Motivation

Another piece of equipment that is vital for sustaining a permanent presence on the Moon is the pressure vessel. In the context of a lunar settlement where there is a vacuum-like atmosphere, pressure vessels are critically important for the storage and transport of volatiles like air, other gasses, fuel, and water. Unlike other resources that are transported from Earth, the challenge inherent to pressure vessels is that their high mass and high volume makes their transportation expensive. The option of transporting numerous vessels to the Moon is simply not sustainable. Because they are high impact items, there is value in exploring ways to minimize the cost of transportation or develop new manufacturing methods that will enable their production on the Moon.

The focus of this innovative design concept is the development of a novel manufacturing method for use on the Moon using in-situ resources. Adapting standard methods for use on the Moon is challenging because engineers on Earth are able to take advantage of the well-established manufacturing infrastructure to construct pressure vessels in a series of steps. First, the raw material is pre-treated and cut into blanks. The blanks are then bent or rolled to form three distinct pieces of the vessel: two hemispherical heads and one cylindrical body. Finally, those components are assembled and the seams are fused shut by welding. Each of these steps requires large-scale machinery to accomplish and, considering the limited infrastructure and resources available on the Moon, is precisely why the method for manufacturing pressure vessels is ripe for innovation.

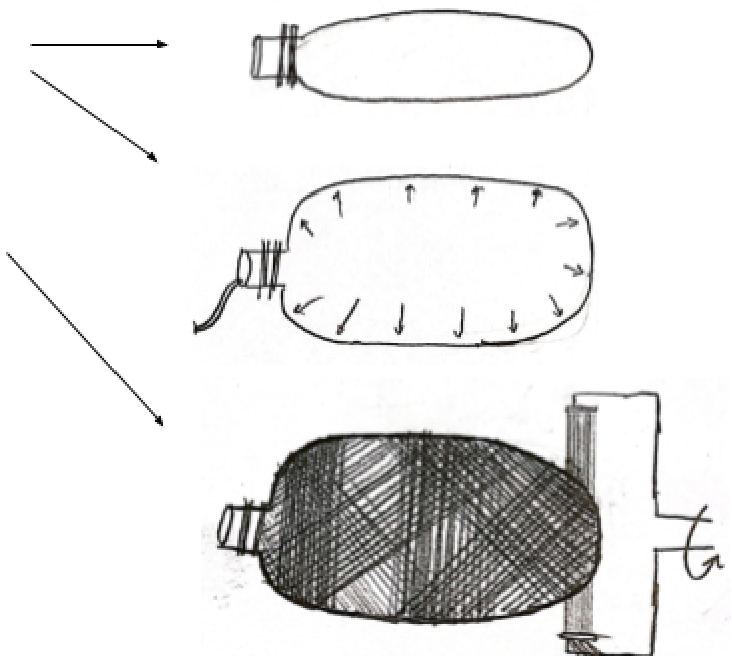
4.2.2 | Proposed Concept Description

The proposed concept is a manufacturing method that forms pressure vessels by tightly winding strands of in-situ metal feedstock around an inflatable diaphragm that acts as a mold for the desired shape. The micro-scale gaps in the hull formed by the overlapping pattern of feedstock strands will be sealed with an aerospace-grade epoxy resin. By using an inflatable mold composed of a hyperelastic composite, the process will be highly repeatable while also minimizing the resources expended during its production.



The proposed process is as follows:

1. The hyperelastic inflatable diaphragm is expanded to hold the desired shape of the interior of the pressure vessel, acting as a mold.
2. An automated mechanism wraps strands of metal feedstock around the inflated diaphragm until the entire mold is covered, forming the pressure vessel shell.
3. An epoxy-resin sealing solution is applied to the outside of the shell and is cured, sealing the gaps between the strands.
4. The hyperelastic diaphragm is deflated and removed from the interior of the pressure vessel shell after a curing period, ready to repeat the process.



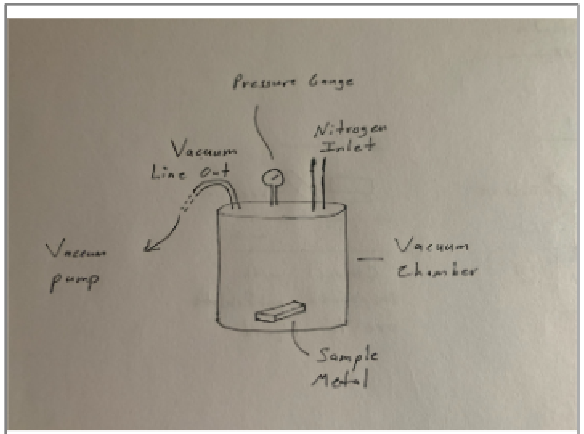
The proposed method has been designed around and validated against the ASME Boiler and Pressure Vessel Code designation of a division I pressure vessel, encompassing all pressure vessels intended to operate at internal or external pressure greater than 15*psi*[4]. This is an adequate benchmark to assume for the designed internal pressure of the vessel on the Moon considering that the primary use will be storage of volatile resources at pressures greater than that of the Moon's atmosphere.

The feedstock wrapping process is inspired by cutting-edge manufacturing methods used to form carbon fiber composite pressure vessels. While similar, the difference is that these methods require a permanent liner to wrap around. The ability to reuse the inflatable diaphragm is a highly innovative aspect that could drastically increase the efficiency of the manufacturing process. Further, the capability of forming the pressure vessel with entirely in-situ derived metal feedstock as the wrapping material is highly valuable because it minimizes the need for materials to be transported from Earth. These two innovative aspects are at the core of the concept and are explored further in the discussion of the proof of concepts.

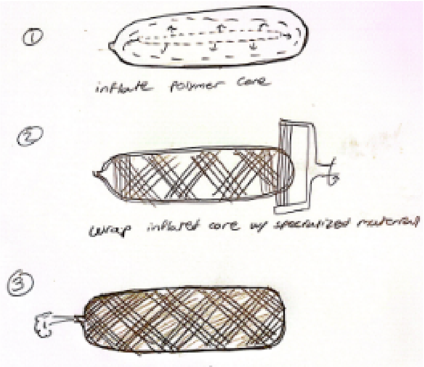
5 | Overview of Proof of Concept Plans

After narrowing down the final proof of concepts, the team continued to research and modify the plans for each concept. The team initially planned to have all proof of concepts be either physical tests or models, however that ended up not being feasible for the team. The plans were more complicated than expected and required a significant amount of time and resources that exceeded what was available for a mostly remote team. The team was able to modify each plan to be done with a computer model while still providing valuable data to guide future projects and research. The basic concepts for each model are shown below in the overview diagram. Table summaries of each plan are shown in Appendix A.

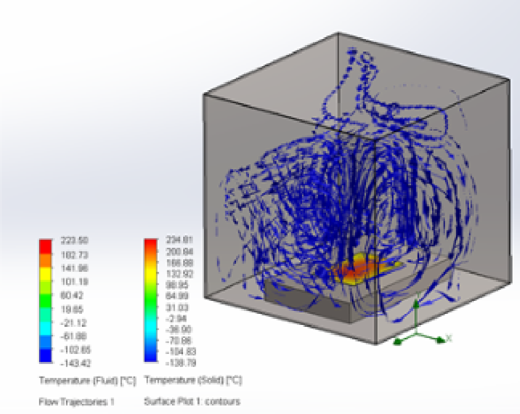
5.1 | Overview Diagram



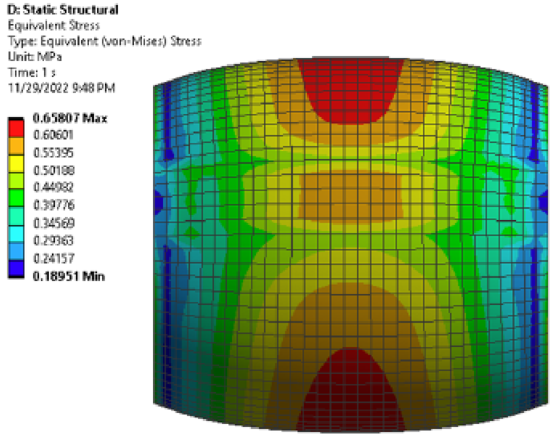
Name: Heat Treating



Name: Pressure Vessel Manufacturing



Name: Flow Simulation Cooling Test
Type: Computer Model



D: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1 s
11/29/2022 9:48 PM

Name: Pressure Vessel Inflatable Diaphragm
Type: Computer Model

Name: Pressure Vessel Material Construction
Type: Computer Model

5.2 | Concept 1 Heat Treatment Proof of Concept Plans

The concept of heat treating aluminum alloys with nitrogen on the moon is a new concept that would support major pieces of lunar infrastructure. The goal of this poof concept is to gauge the feasibility of nitrogen as a cooling agent in a lunar environment. We need to know if nitrogen can cool aluminum alloys fast enough to strengthen the metals.

Rapid cooling over specific temperatures can help preserve a desired grain structure in metals. There has already been research on the necessary cooling rates for various aluminum alloys. We plan to create an analytical model to determine if cooled nitrogen gas can cool at the necessary rates at various pressures. The results of this study will tell us if this concept is worth pursuing or researching for large scale implementation. The overall plan is depicted in Table A1 of Appendix A.

The study will use SolidWorks Flow Simulation to evaluate the cooling of an aluminum alloy sample with pressurized and cooled nitrogen gas inside a test container. This test will also be done under lunar gravity. The cooling times will be compared with known data to determine if this process can cool the alloy fast enough to harden it.

5.3 | Concept 2 Proof of Concept Plans

5.3a | Inflatable Diaphragm Proof of Concept Plan

The concept of using an inflatable diaphragm as the interior mold when wrapping a pressure vessel is highly innovative, but also presents significant risk in terms of feasibility. The goal of this proof of concept was to provide some confidence towards the inflatable diaphragm concept and to explore what types of materials would be available for the composition of such a diaphragm.

The proof of concept plan depicted in Table A2 of Appendix A was designed to explicitly answer the question: *under the expected loading conditions, does a material exist that can be used for the inflatable diaphragm without failure?*

Ansys FEA software was the intended simulation package that would be used for this analytical proof of concept. Because Ansys has a vast library of tabulated material property data, it was proposed that numerous different materials be simulated under the loading conditions in order to categorize the viable material solutions.

First, static loading analysis is performed and the Von Mises equivalent stress is analyzed. This provides insight as to whether the material may withstand the peak load conditions for one use. Second, fatigue failure analyses are attempted in order to explore the diaphragm’s material behavior over numerous cycles of loading. Results from this experiment would speak to the repeatability requirement of the diaphragm.

5.3b | Vessel Construction Proof of Concept Plan

The goal of this proof of concept is to evaluate the feasibility of our pressure vessel construction. More specifically, we want to determine if the pressure vessel is pressurized and if it can maintain that pressure. It is vital that the pressure vessel prevents fluids from moving between the pressure vessel and vacuum environment. To know if the material can be pressurized we must understand the material geometry as well as the material properties. Using these values, we will be able to analytically simulate the desired pressure we need to withstand.

Although we decided to conduct an analytical model to prove this concept, we had originally planned to conduct a physical experiment. The physical model was to be constructed with a stainless steel wire mesh and a generic epoxy resin/hardener solution. The wire mesh would serve as the structural base of the build while the epoxy would provide a leak proof seal around the surface area of the mesh. The difficulties with this setup related to physical constraints on the molding process of the epoxy to the wire mesh. In other words, simply pouring the epoxy over the wire mesh was not feasible without a mold to guide and retain the epoxy in place during the curing process. This plan is shown in Table A3 in Appendix AGiven the difficulties with this, we decided to pursue a computational analysis on this physical model. This analysis is explained in more detail in sections 6.2d-f.

6 | Proof of Concept Execution and Results

6.1 | Concept 1 - Heat Treating

6.1a | Heat Treatment Experiment Setup

Our most recent proof of concept plan of quenching/hardening has developed over the course of our project to reflect a progressively more innovative and effective concept for quenching aluminum. Our updated proof of concept plan is to use SolidWorks flow simulation to simulate cooling aluminum alloys with pressurized nitrogen gas in a lunar environment with resources only available on the moon. If the nitrogen can cool the alloy fast enough to harden the alloy based on known cooling times, then this concept should be further explored.

Prior studies identified a critical cooling range for aluminum alloys to be from 400 to 290°C as shown in Figure 2 [5]. Cooling at faster rates over these temperatures helps increase the strength of the alloys.

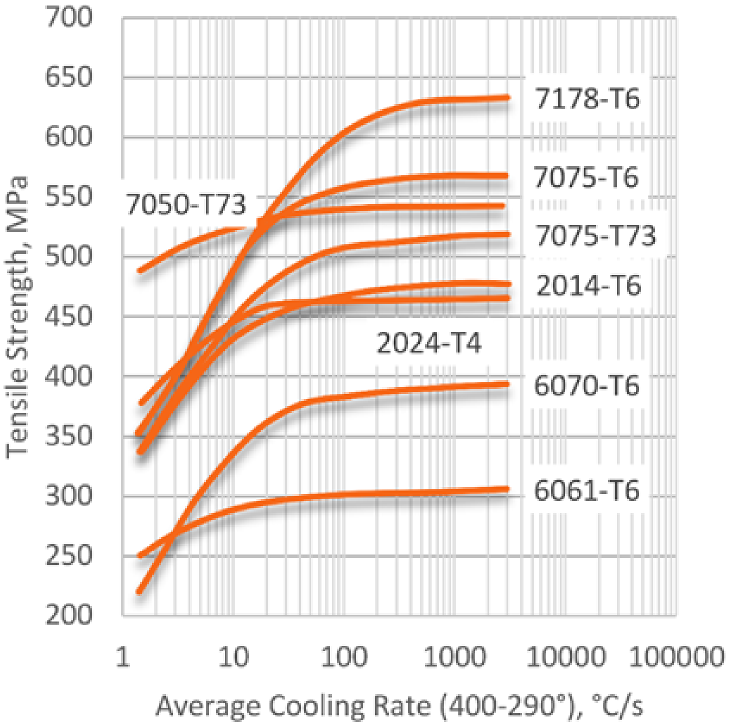


Figure 2, Cooling Rate to Harden Aluminum Alloys [5]

Using this information as a guide, our model will use a sample of aluminum 6061 and observe how quickly an exposed surface cools from 400 to 290°C using cooled nitrogen gas at different pressures.

A 0.5 m by 0.75 m by 0.1 m aluminum 6061 sample set into an iron mold encased in a sealed thin walled (0.01 m shell) 2 m by 2 m by 2 m iron box will be used in the test as shown in Figure 3. These resources can feasibly be obtained on the moon while a similar test can be performed in a lab [6]. Different tests will be done with cooled nitrogen at pressures of 20 bar, 200 bar and 1000 bar to gauge the viability of future tests and guide future designs. The nitrogen will be set to -146.96°C, this is the critical temperature and ensures that the nitrogen gas will remain fluid even at high pressures [7]. The test environment will use the lunar gravity of 1.62 m/s^2 [6]. After each simulation, the average cooling rate will be compared to the empirical data to ensure that the conditions can harden the aluminum [5]. If the aluminum can cool faster than 1°C/s, then that should justify further exploration with the ultimate goal of cooling as fast as possible over the critical temperature range.

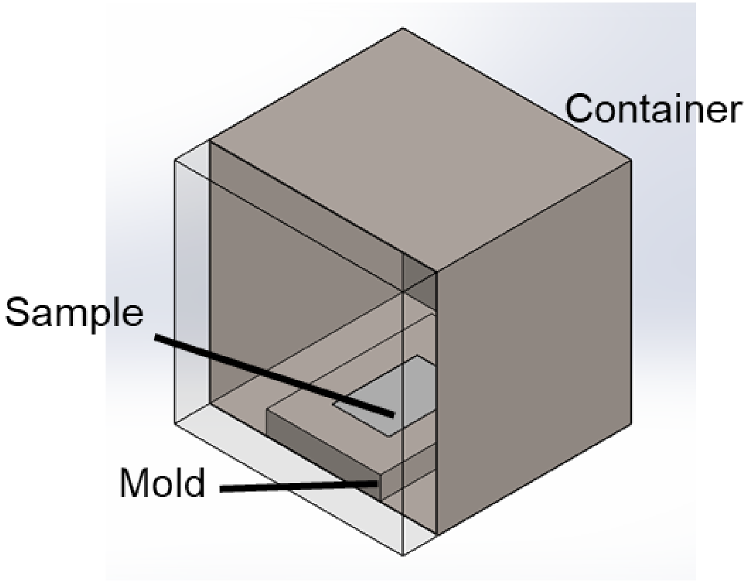


Figure 3, SolidWorks Model of Testing Setup

6.1b | Heat Treatment Experiment Results.

Heat treating was simulated with nitrogen gas pressurized to 20 bar, 200 bar and 1000 bar. These values were selected to gauge the effectiveness of cooling across pressures of varying orders of magnitude and help direct future experimentation.

The first test was run with the nitrogen set to 20 bar. The cooling rate is shown in Figure 4 below.

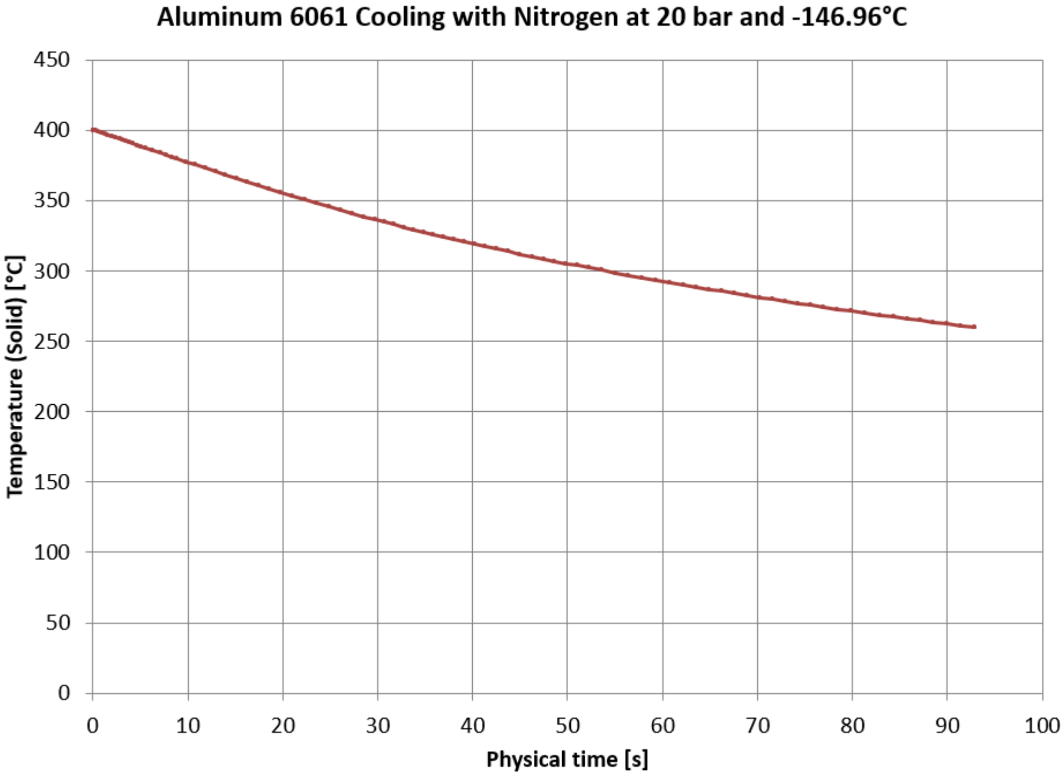


Figure 4, First Cooling Test Results

Based on these results, the average cooling rate for the surface of the aluminum alloy over the critical temperature range was -1.77°C/s. This should strengthen the aluminum 6061 tensile strength to around 260 MPa [5].

Tests were then done with the nitrogen pressurized to 200 bar and 1000 bar, as shown in the following two graphs in Figures 5 and 6. The cooling rates over the critical temperature range were -2.08°C/s and -2.48°C/s respectively.These results would marginally improve the tensile strength compared to the cooling rate under 20 bar.

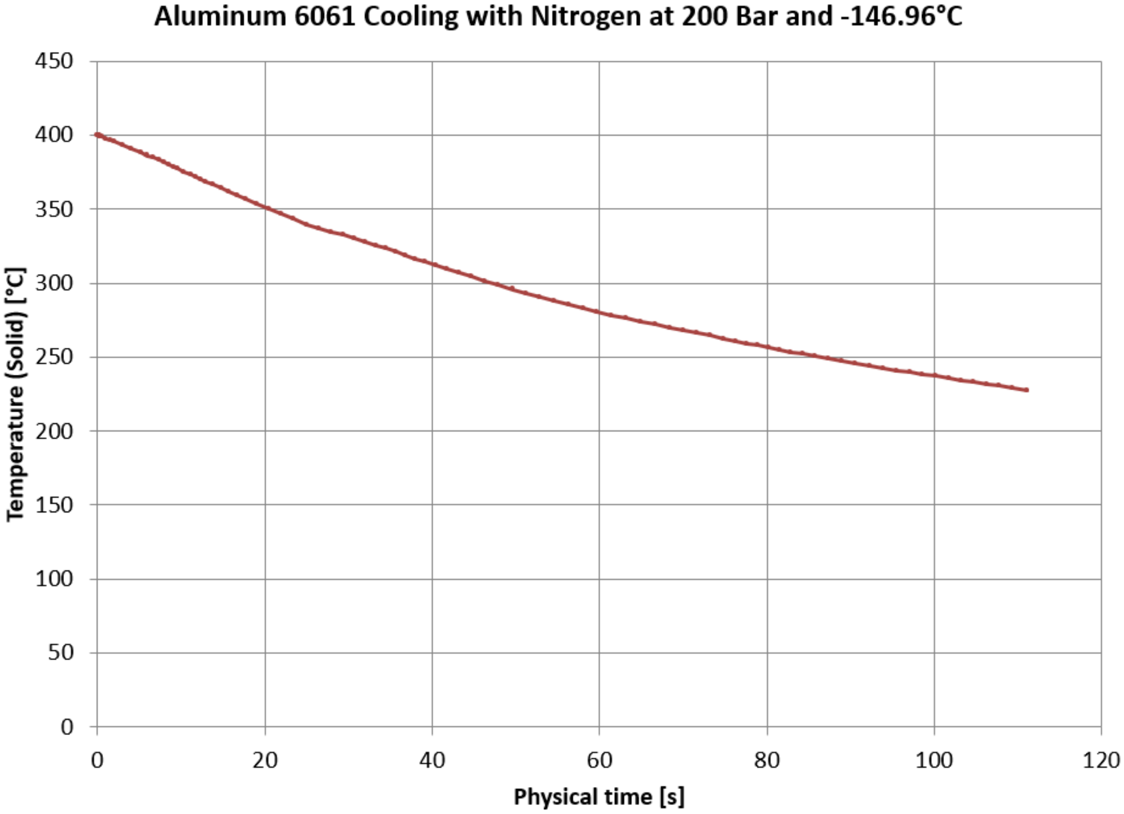


Figure 5, Second Cooling Test Results

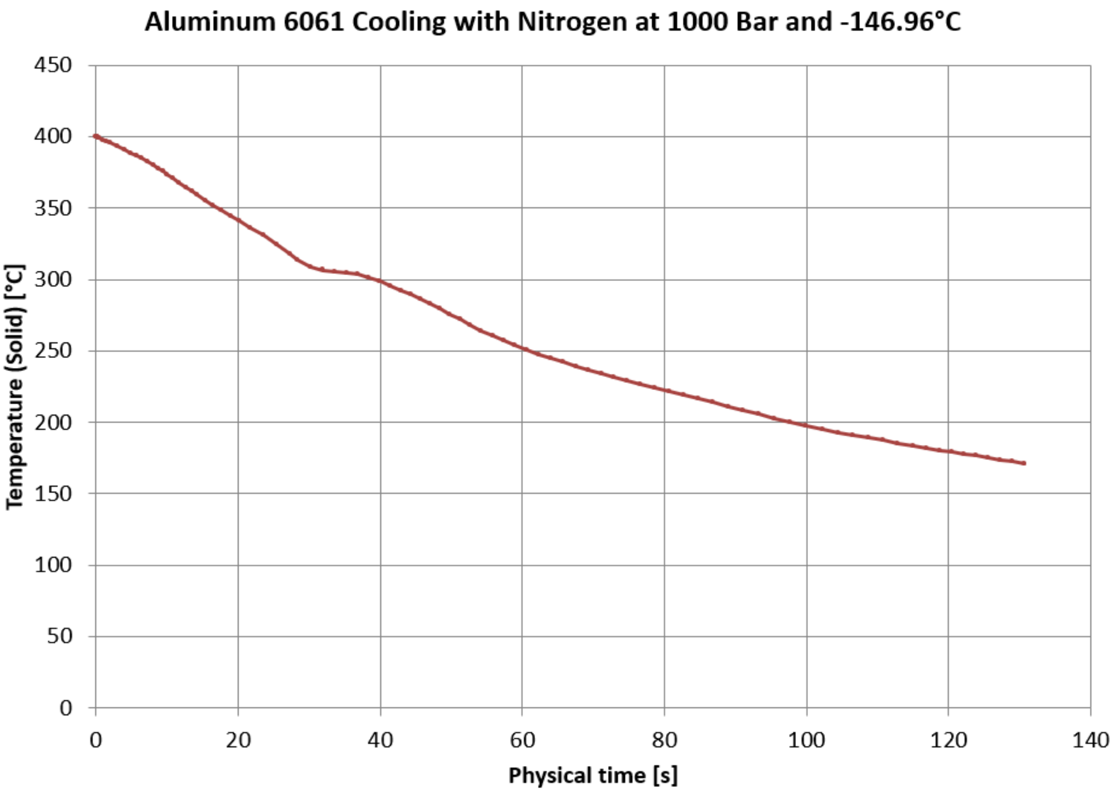


Figure 6, Third Cooling Test Results

6.1c | Analysis of Results

Based on these initial results, nitrogen should cool aluminum 6061 fast enough to effectively harden it at 20 bar, 200 bar and 1000 bar. One issue is that at 200 bar and 1000 bar at -146.96°C, nitrogen is in a supercritical state. In a real world lunar application it would be extremely challenging to store and use the nitrogen under these conditions. Additionally the cooling rate at high pressures is not significantly faster than at 20 bar. This is a promising concept to further explore however the test has significant room for improvements. There are also major limitations on the feasibility of this process that must be taken into account in future research.

The entire set up including the mold and box size and material impact the overall cooling, further research is needed to optimize these parameters. Additionally these results were all simulated and rely on empirical data. The simulation could be improved to better model lunar conditions besides gravity. This concept could be further improved through physical testing to evaluate both the cooling rates and metrics such as strength and hardness after cooling. Physical tests can be done focusing on lower pressures based on this data. Another improvement for this concept would be to focus on hardening specific parts. This study was meant to provide a starting point for further testing, so the testing sample was kept as a basic block. Parts of different shapes and sizes will cool and harden at different rates. Tests on specific parts could improve the efficiency and utility of this concept for the Artemis mission. As the mission progresses and lunar infrastructure becomes more defined tests can be done to meet the changing part needs.

Another area that must be explored and improved upon is the feasibility of obtaining and using the nitrogen on the moon for this process. Based on the set conditions and assuming the ideal gas law PV = mRT we can approximate the amount of nitrogen needed for each pressure test as shown below [8].

- Volume inside testing box, V = 7.46 m^3
- Temperature of nitrogen gas T = 126.19 K
- Nitrogen ideal gas constant R = 296.8 J/ (kg K) [9]
- Nitrogen pressure P = 20 * 10^5 N/m^2; 200 * 10^5 N/m^2; 1000 * 10^5 N/m^2
- Mass of nitrogen $m = \frac{PV}{RT} = \frac{P*7.46}{296.8*126.19}$
- m = 398 kg; 3983 kg; 19918 kg

Even under the smallest pressure this is still a significant amount of nitrogen needed to effectively cool the aluminum alloy. This concept also assumes that nitrogen is being harnessed from the lunar regolith. Assuming a lunar regolith nitrogen composition of 100 μgN/g we would need 3980 tons of lunar regolith to perform one cooling test at 20 bar (39830 tons at 200 bar and 199180 tons at 1000 bar) [2] . The cost needed to extract, pressurize and store the nitrogen gas likely exceeds the benefits of the relatively small amount of hardened aluminum alloy ,however further research should examine the viability of that process.Current studies of lunar regolith have found nitrogen in samples from the equatorial regions of the moon [14]. This nitrogen likely comes from space due to solar winds, so it is possible there is nitrogen in other regions [14]. Currently NASA is considering the lunar south pole for a permanent base, if there is no nitrogen there, this concept is even less feasible because of the resources needed to transport regolith across the moon [11]. Further exploration is needed to confirm if there is nitrogen near the south pole. The overall concept could likely be improved by finding ways to use less nitrogen. While the concept of using nitrogen to cool aluminum alloys can likely work to harden the alloy, the current process requires an extreme amount of nitrogen and resources that may not be feasible to perform on the moon. Identifying an ideal use for quenching or optimizing the overall process would greatly improve this concept. Other cooling techniques should also be considered.

6.2 | Concept 2 - Pressure Vessel Manufacturing

6.2a | Pressure Vessel Inflatable Diaphragm Setup

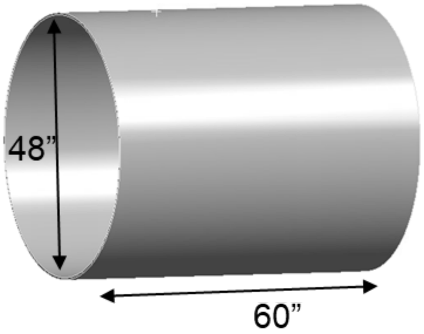
The goal for this proof of concept is to validate the repeatability aspect of the inflatable diaphragm component of the proposed pressure vessel manufacturing method. To achieve this, it was decided that an analytical model would provide the most confident data when compared with a physical model because stress and fatigue measurements would be strenuous.

The software package Ansys Mechanical was used to conduct finite element analyses for this analytical proof of concept. Numerous materials from Ansys' engineering data library were applied for each loading scenario with the aim of defining a general category of materials that would be most viable for the composition of the inflatable diaphragm.

The materials tested are:

1. SEBS (Shore A65) Rubber
2. EPDM Rubber
3. Styrene Butadiene (SBR)
4. Nitrile Hydrogenated Rubber (NHBR)
4. Neoprene Rubber
5. PVC-Plastic (flexible)
6. Polyethylene

While the ability to model complex 3D geometries is what makes FEA modeling attractive for this proof of concept, the geometry that was ultimately tested is a simplified cylindrical approximation of the pressure vessel body. This reduction in complexity was required in order to navigate around several critical computational errors that prevented the model from converging and highly distorted certain mesh elements near the locations of features. The model employed for all testing is shown in Figure 7. The dimensions of the cylinder were selected to be comparable to the size and volume of the pressure vessels studied by engineers on NASA's Apollo program [10].



Shell thickness = .375”

Figure 7: Cylindrical pressure vessel approximation model use for FEA simulation

The loading conditions employed for each material model were developed from a combination of research on the lunar environment, ASME pressure vessel standard codes, and properties specific to the tested material. These conditions are intended to capture the stress resulting from the uniform internal pressure that is required to inflate the material to size, the external compressive forces from the feedstock during the wrapping phase, and the thermal loading from the environment and heated feedstock throughout the process.

External compressive force was assumed to be a uniform 3 pounds per square inch, and the ambient temperature condition modeled that of the hottest temperature boundary on the Moon at 250℉.

Because each material that was tested demonstrated different mechanical material properties, the internal pressure required to inflate the diaphragm is inherently unique to each individual material. The pressure required to inflate and hold the shape of the desired mold was mathematically calculated for each material using a modified neo-Hookean strain energy function which assumes the material is incompressible and elastic [19]. This assumption is valid for the inflatable diaphragm concept as the reusability function requires the material to elastically deform. An example calculation is shown below for the material Styrene-ethylene-butylene-styrene block copolymer (SEBS Shore A65), a form of rubber. This same process was used for the other materials, and the resulting inflation pressures for the rest are tabulated in Table 3.

$$\mu_0 = Shear\ Modulus, \quad r = deformed\ radius, \quad r_0 = initial\ radius,$$
$$P = inflation\ pressure, \quad h_0 = vessel\ shell\ thickness,$$
$$\lambda = stretch, \ \ N = Instability\ Limit\ Point$$

$$\lambda = \frac{r}{r_0}\ and\ \mu = \ \mu_0\left(\frac{3-3N}{1-3N}\right)$$

$$P = 4\frac{h_0}{r_0}(\lambda^{-1}-\lambda^{-7})\frac{\partial W}{\partial I_1} \quad where \quad \frac{\partial W}{\partial I_1} = \mu\left[\frac{I_1-9N}{6(I_1-3N)}\right]\ and\ I_1 = 2\lambda^2+\lambda^{-4}$$

$$\therefore P = \frac{2h_0}{3r_0}\mu(\lambda^{-1}-\lambda^{-7})\left(\frac{2\lambda^2+\lambda^{-4}-9N}{2\lambda^2+\lambda^{-4}-3N}\right)$$

For SEBS (Shore A65):

$$\mu_0 = 168.21\,psi, \quad r = 24in, \quad r_0 = 6in, \ \ h_0 = 0.375in, \ \ N = 100$$

$$\lambda = \frac{24in}{6in} = 4\ and\ \mu = \ 168.21\left(\frac{3-3(100)}{1-3(100)}\right) = 167.08\,psi$$

$$P = \frac{2(0.375in)}{3(6in)}(167.08psi)((4)^{-1}-(4)^{-7})\left(\frac{2(4)^2+(4)^{-4}-9(100)}{2(4)^2+(4)^{-4}-3(100)}\right)$$

$$P = 1.4089\,psi$$

These equations were formulated in [19] for application to the inflation problem in rubber-like materials and soft tissues. The difficulty that arises with developing models for the pressure required to inflate elastic materials is that the expansion of the material does not linearly depend on the applied pressure. In fact, as shown below in Figure 8, there is a “limit-point instability” where the pressure required to stretch the material reaches a maximum, afterwhich the material continues to stretch further despite a subsequent pressure decrease.

These limit-point instabilities represent a threshold pressure value that must be reached for the material to expand and hold its shape. As a result, the pressure calculation above may not always be valuable for finding this threshold, and instead a plot of the inflation pressure versus stretch length should be used.

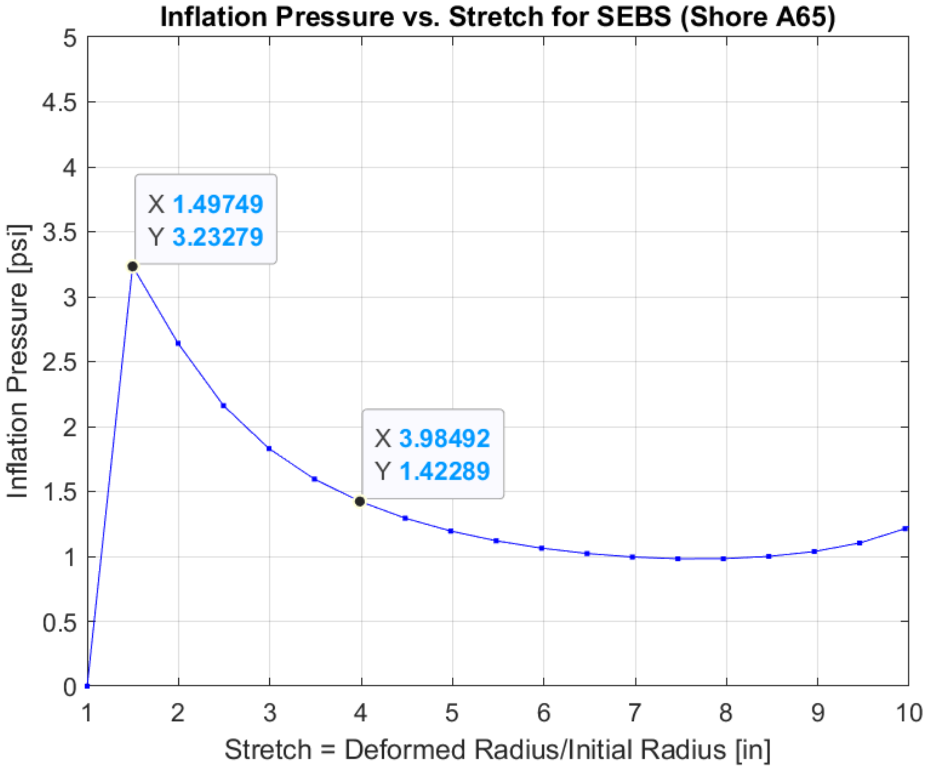


Figure 8: Inflation Pressure vs Stretch Length for SEBS (Shore A65). The peak represents the threshold inflation pressure, whereas the pressure output at stretch = 4 represents the pressure required to hold the desired expansion.

For the sake of this proof of concept, the larger threshold inflation pressure was used during simulation in order to test the material behavior at the maximum value. Tabulated below are the values obtained for the other materials that were tested. The Inflation Pressure versus Stretch plots for each material are documented in Appendix B.

Table 3: Material properties and associated inflation pressures

Material	**Shear Modulus [*psi*]**	**Calculated Inflation Pressure (at stretch = 4) [*psi*]**	**Inflation Pressure Threshold [*psi*]**
SEBS (Shore A65), Rubber	168.21	1.409	3.233
EPDM	787	6.741	15.311
SBR	217.96	1.8437	4.188
Nitrile Hydrogenated Rubber (HNBR)	94.78	0.802	1.823
Neoprene Rubber	297	2.512	5.707
PVC Plastic	158.22	1.338	3.04
Polyethylene	56177	475.202	1079

Results in the form of total deformation and Von Mises Equivalent Stress were computed for each simulation. These results were used to inform whether the material would fail under the described loading conditions, and to what extent the material could hold the shape of the desired pressure vessel.

It is important to also offer a discussion of the behavior of these materials under cyclic loading. While a discussion on the fatigue life behavior of each material was planned for this proof of concept model, accurate results for fatigue simulations could not be computed due to the modeling complexity required to capture the non-linear effects of the elastic materials tested. Further, it was discovered that even if a non-linear elastic simulation model was developed, fatigue life calculations still require an S-N diagram to inform the behavior under cyclic loading. These plots have not been developed or were not readily available for the tested materials due to the complexity of their material properties, making any efforts at understanding the fatigue behavior unfruitful.

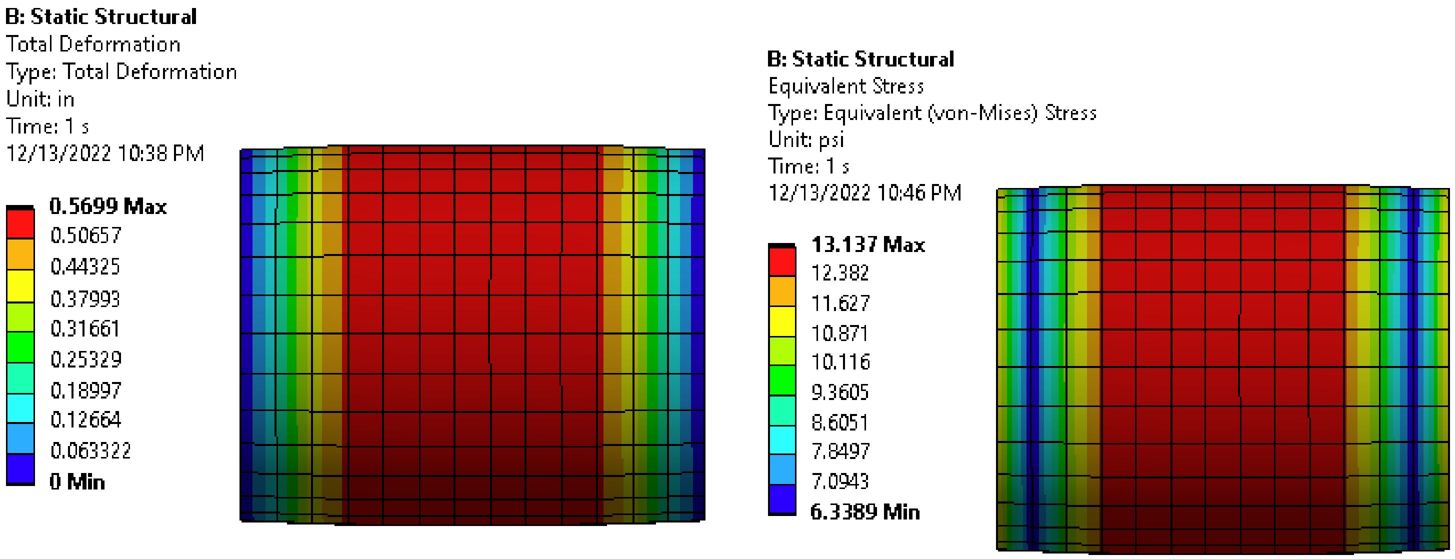
6.2b | Pressure Vessel Inflatable Diaphragm Results

The results plotted below are the output simulations from Ansys Mechanical. Both Total Deformation and Von Mises Equivalent Stress are evaluated. Key aspects to notice for these plots are the relative level of deformation and whether the max Von Mises Stress is greater than the yield strength of each material.

The Ansys automatic meshing function was adequate for modeling the materials SEBS Rubber, Styrene Butadiene, and PVC Plastic. In order to more accurately model the non-linear effects demonstrated by Nitrile, Hydrogenated Rubber a quadratic element Tetrahedral mesh was needed. Each model implemented a mesh-sizing method to minimize each element size to a maximum of 5 inches. For EPDM and Neoprene Rubber, the output plots are distorted because the simulation was unable to converge on a solution for the non-linear problem which can explain the unexpected output geometry.

SEBS Rubber (Shore A65)

$\sigma_{yield} = 823.38\, psi$



Figures 9a and 9b: Total Deformation and Equivalent Stresses in SEBS Rubber Diaphragm

EPDM

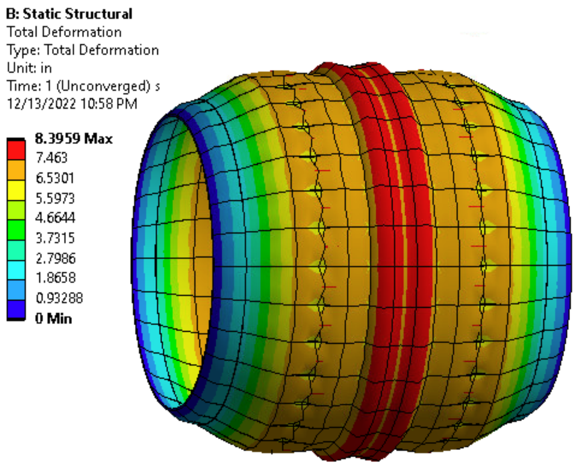
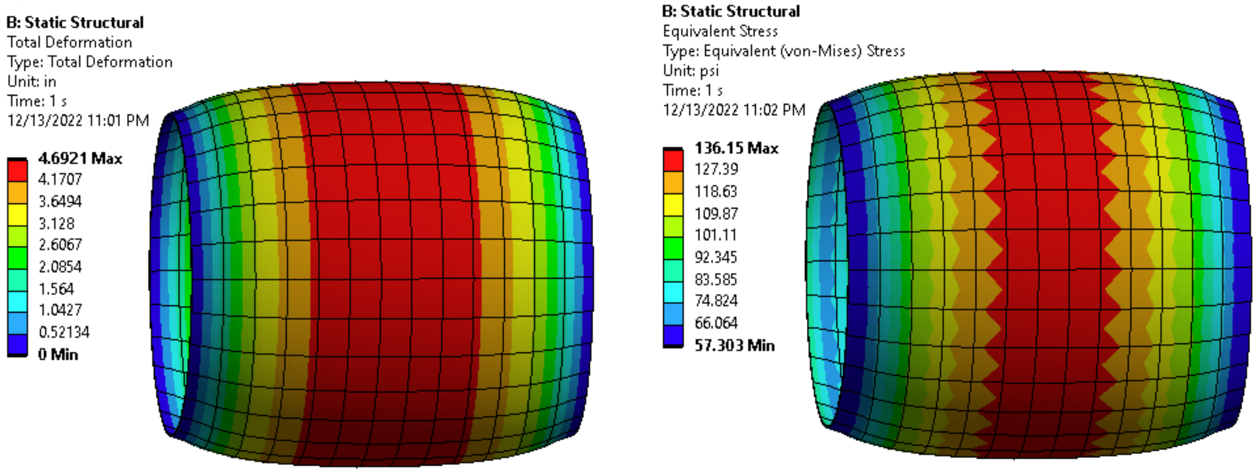


Figure 10:Total Deformation in EPDM Diaphragm

Styrene Butadiene (SBR) Rubber

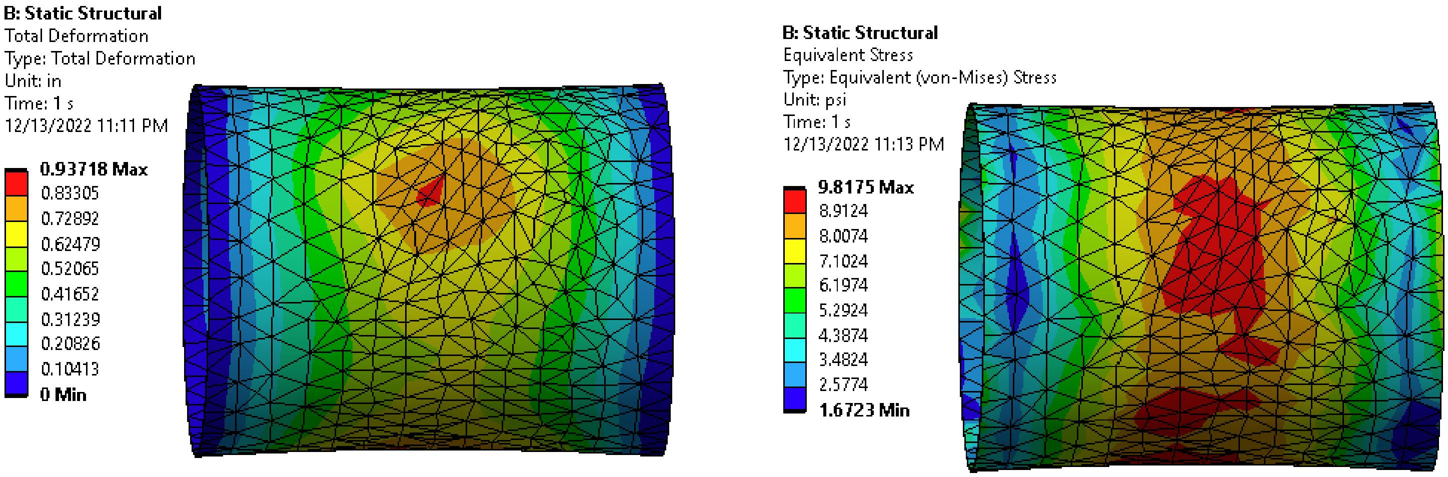
$$\sigma_{yield} = 648.61\, psi$$



Figures 11a and 11b:Total Deformation and Equivalent Stresses in SBR Rubber Diaphragm

Nitrile, Hydrogenated Rubber (HNBR)

$$\sigma_{yield} = 1123.5\ psi$$



Figures 12a and 12b:Total Deformation and Equivalent Stresses in Nitrile Hydrogenated Rubber Diaphragm

Neoprene Rubber

$$\sigma_{yield} = 145\ psi$$

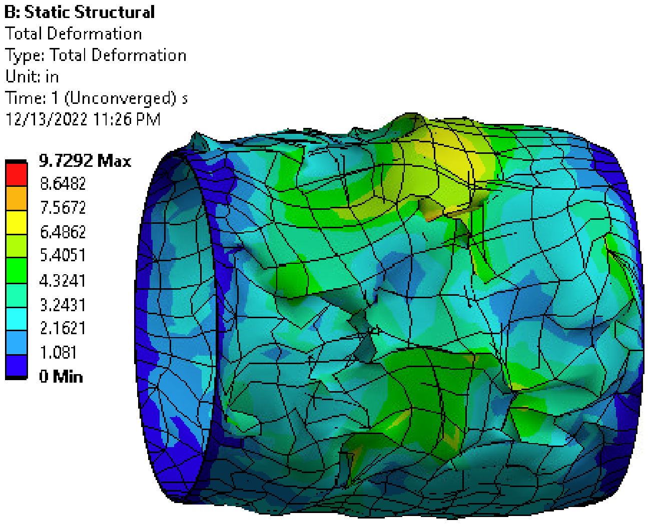
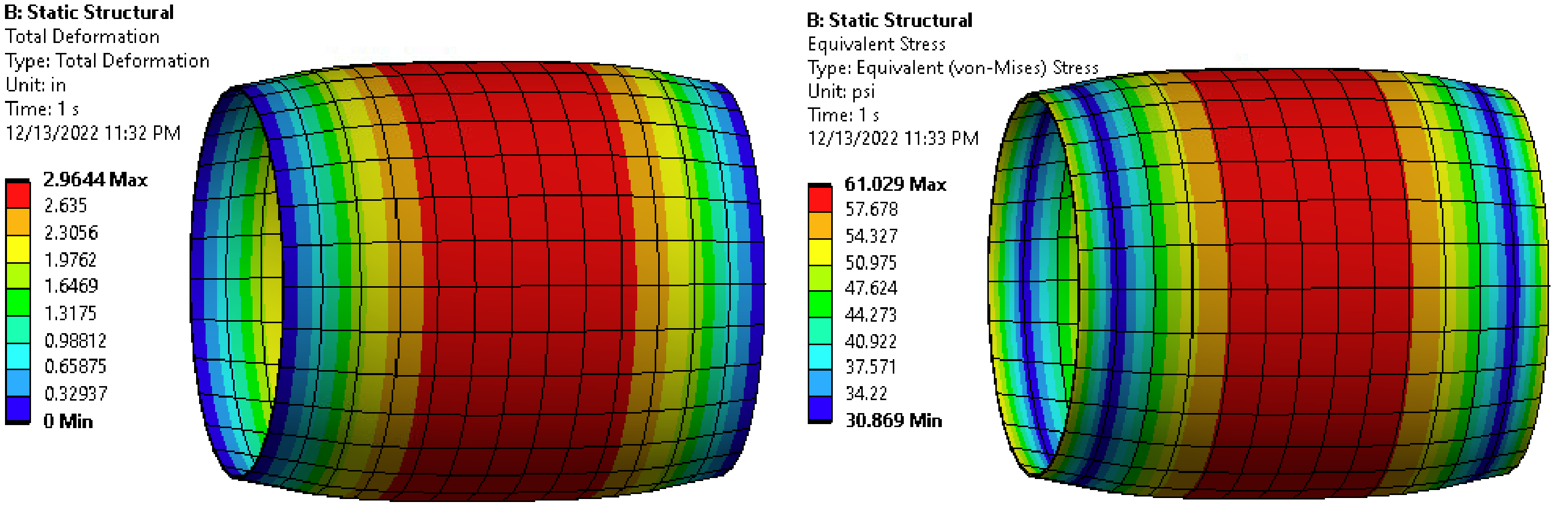


Figure 13: Total Deformation in Neoprene Rubber Diaphragm

PVC Plastic

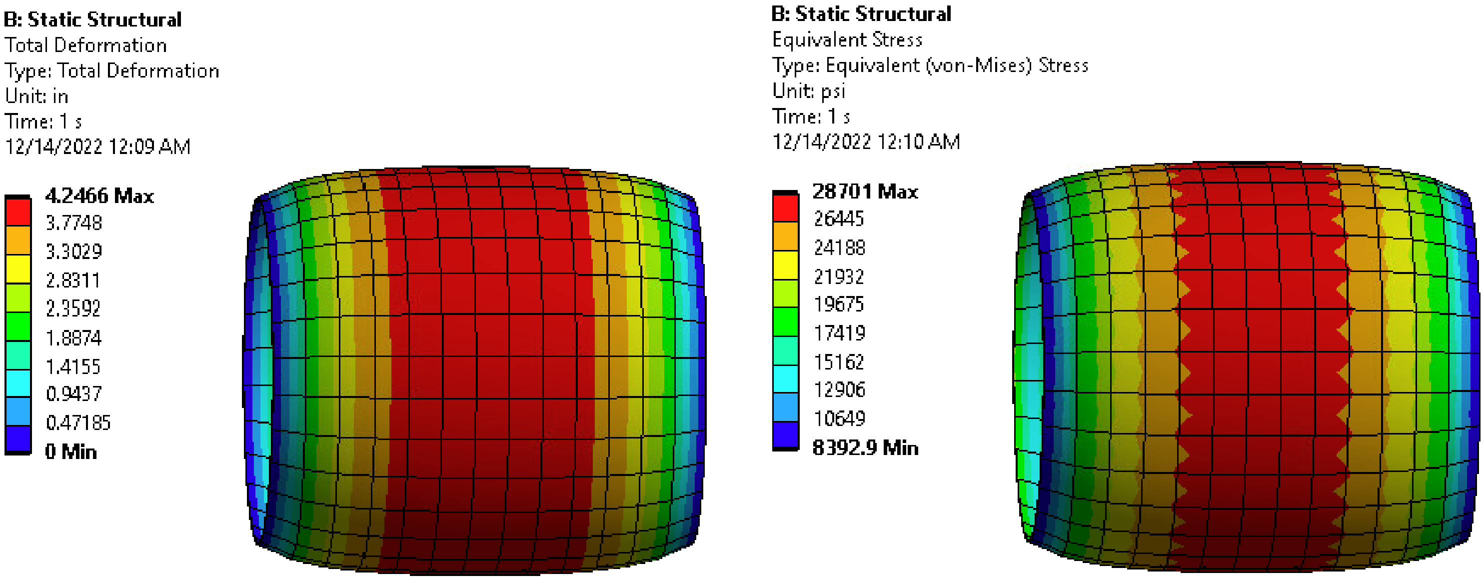
$\sigma_{yield} = 1521.4\ psi$



Figures 14a and 14b:Total Deformation and Equivalent Stresses in PVC Diaphragm

Polyethylene

$$\sigma_{yield} = 3625.9\ psi$$



Figures 15a and 15b:Total Deformation and Equivalent Stresses in Polyethylene Diaphragm

6.2c | Analysis of Results

The goal of simulating the described loading conditions for numerous materials was to first, provide confidence to the fact that there exist readily available materials that are capable of being inflated to the size of the desired pressure vessel and held rigid to provide a mold for the wrapping process. The results in the previous section demonstrate this first aspect to a certain extent. While four of the seven materials were able to withstand the loading conditions from a fracture mechanics standpoint, a glaring drawback of Styrene Butadiene, PVC Plastic was a large total deformation. Polyethylene was the only material to fail under the prescribed loading conditions.

In a perfect world, close to zero deflection would be expected because the internal pressure loading condition is designed to be the pressure required to inflate the initial model geometry to the desired form shown in section 6.2a. SEBS Rubber and Nitrile Hydrogenated Rubber demonstrated these effects. However, egregious deformation – in this case greater than 1 inch like that demonstrated by Styrene Butadiene, PVC Plastic, and Polyethylene – is a sign that the material is highly unstable at that designed pressure and is heavily impacted by the external pressure applied. Especially considering the reduced atmospheric pressure on the Moon, it is important for these materials to be capable of withstanding a high pressure difference between its internal contents and the environment outside.

A major takeaway after simulating these models was a profile for the type of material that may be used to accomplish the inflatable diaphragm concept: the material should be elastic or hyperelastic, have relatively high poisson's ratios, and comparatively low shear moduli. Of the seven materials that were tested, the four that produced valid and promising results – SEBS, Styrene Butadiene, Nitrile Hydrogenated Rubber, PVC Plastic, and Polyethylene – all demonstrated isotropic elasticity. The two models that became distorted during simulation – EPDM and Neoprene Rubber – do not demonstrate isotropic properties.

There is difficulty in confidently generalizing these properties as an exclusive definition of the materials that may be used for this purpose because the simulation algorithm and meshing technique inherently limited the range of accurate results to materials that demonstrated linear or close-to-linear properties.

Further, an analysis on the fatigue life behavior of each material would be needed to provide ultimate confidence in this concept. Due to the modeling complexity of this task for non-linear elastic materials as well as the fact that S-N plots are scarce for those materials, fatigue life and damage computations became too strenuous to compute using these models.

Although several obstacles were encountered that limited the viability of this analytical proof of concept, these experiments do provide sufficient evidence to support moving forward with more accurate and robust testing. The goal of determining whether there is a material that exists to satisfy the inflatable diaphragm concept for its intended use has been proven. It is promising that, given the uniqueness of the Moon's atmosphere, it has been shown that materials exist that can be inflated and used as a mold for pressure vessel manufacturing. Further development of this concept must require a cyclical loading analysis in order to prove the second aspect of this concept – whether the process is repeatable.

6.2d | Pressure Vessel Material Construction Setup

Here is an overview of the material construction related to the pressure vessel proof of concept. The vessel will be constructed using a stainless steel wire mesh and epoxy consisting of the general resin. The engineering justification for this is that the steel mesh should provide structural rigidity while the resin solution will flow over the gaps in the mesh creating a leak-proof seal. Epoxies are used in a handful of spacecraft applications such as potting for electronics and as adhesives for certain applications. The assumption here is that the voids in the steel wire mesh are small enough to allow negligible force to be action on the sections are the epoxy, while being large enough to allow the material to still be molded or bent to shape. The Epoxy manufacturing process would take place on the moon, so a space qualified epoxy can be selected in conjunction with a space grade steel mesh. A steel expanding machine is one option that can be used to expand standard sheets of steel and turn them into wire mesh sheets. The steel expanding machine that creates the metal mesh would be tested and optimized on earth in a similar environment, and then be shipped to the lunar surface. The steel mesh would have to have a custom geometry to ensure structural integrity. In addition, another machine will be needed to form the mesh into a cylindering vessel. This process was described and can be seen in section 4.2.2 above. For the following pressure vessel analysis and calculations we will take into account the assumptions and discussions that were presented in the vessel construction section.

In order to perform an analytical analysis to validate if the pressure vessel can be pressurized, we obtained information on the material properties of our model as well as the principle equation for the resultant stress acting on a thin walled pressure vessel. It is important to determine the maximum resultant stress that will act on the internal walls of the pressure vessel, as this can be used to determine if the vessel will withstand the forces or internal pressure that will be applied to it. This equation is described as follows

$$\frac{t}{ID} = \frac{1}{2}\sqrt{\frac{3(3m+1)P}{8m\sigma}} \tag{1}$$

This is the pressure vessel calculation equation, where t is the thickness of the material, ID is the pressure vessels inner diameter, m is a function of the poisson's ratio (ν), P is the pressure inside the pressure vessel, and σ is the resultant max stress acting on the material. This equation can be used in a number of ways. In this case, we used it to determine the maximum resultant stress being applied onto the constructed vessel.

Pressure vessels are designed to operate at a minimum pressure of 15 psig [16]. This was the benchmark pressure used to validate the feasibility of our concept. After this analysis was conducted, given our vessel's internal pressure of 15 psi, we will gather this resultant stress which can be compared to the material's yield strength.

To compare the material's yield strength to the maximum resultant stress that was calculated, we used the formula for factor of safety (FOS).

$$FOS = \frac{\sigma_{yield}}{\sigma} \tag{2}$$

Here, σ_{yield} represents the materials yield strength while σ represents the resultant maximum stress acting on the inside of the pressure vessel which was found from the pressure vessel calculation equation.

A factor of safety of less than 1 indicates that the material will fail if the given loading condition or test was conducted. A safety factor of 2 or greater indicates that a loading condition two times the calculated amount would have to happen for failure to occur, which is extremely unlikely if the simulation or calculations is accurate or verified. A factor of safety of 1.5 or greater is sufficient for space applications, as NASA has launched many vehicles with factors of safety at or near 1.5 [16]. Furthermore, in section 6.2e we will discuss the construction of the vessel, while section 6.2f will dive into this calculation for this constructed pressure vessel construction.

Epoxy’s resistance to UV rays and the lunar temperature range

During the presentation it was noted that if the chosen epoxy for this application was not UV and temperature resistance, then our vessel’s structural integrity could be compromised. Here we will set out to solve this problem. This problem could be solved using one of two different solutions.

The first option is to select and use a NASA space qualified epoxy that is suitable for spaceflight applications with prolonged solar exposure. As there might possibly be electronic components on the outside of the International Space Station (ISS), that are exposed to direct sunlight without the protection of the Earth’s Magnetic Field or the Van Allen Radiation belts. Unfortunately upon further research, multiple sources are pointing to the reality that such a UV-resistant epoxy does not exist [12][13]. Sources state that NASA uses epoxies but in all cases they are sandwiched between electronic boards, and well shielded for solar rays. From a radiation analysis perspective, epoxies are perfect for shielding electronic components because of their high density, but do not hold up to solar UV-rays. Since the first option is not feasible for the reason stated above, we will transition to the second possible option to solve this problem.

The second option is to shield the epoxy from the solar rays. A great option for this is using the lunar surface itself. Since such UV resistant epoxy does not exist, placing this manufacturing process deep in the Shackleton Crater, to minimize or completely prevent solar exposure. Shacklton is a crater that is located on the south pole of the moon. The inside of the crater is completely isolated from lunar rays, and is a perfect location to place this epoxy pressure vessel coating process. Here the only obstacle will be finding an epoxy that can withstand the colder temperatures that this shadowed crater poses. From sources, there are NASA space qualified epoxies that are qualified to temperatures of 4K or -452F [13]. Since the lunar surface's coldest temperatures are at -208F, this yields a considerable factor of safety when analyzing the thermal properties of such an epoxy. With all this research laid out, it is now certain that utilizing the Shacklton crater, and a space qualified epoxy will solve this UV and temperature range problem.

Parallel Pressure Vessel Solutions

NASA is using a wrapping process that is very different from our method. Rather than using an inflatable polymer interior to support a metal mesh, they use a metal interior pressure vessel layer and use a complex composite overwrapping. More specifically, this is known as a COPV or composite overwrapped pressure vessel. These are found on launch vehicles and spacecraft, and are critical containers required to support life [17]. It is promising that NASA uses a “wrapping” method, even if it is quite different from our solution. In addition to this, the American Society of Mechanical Engineers (ASME) and the International Organization for Standardization (ISO) laid out an easy to comprehend chart highlighting the five main types of pressure vessel assemblies as shown in Figure 16 below [18].

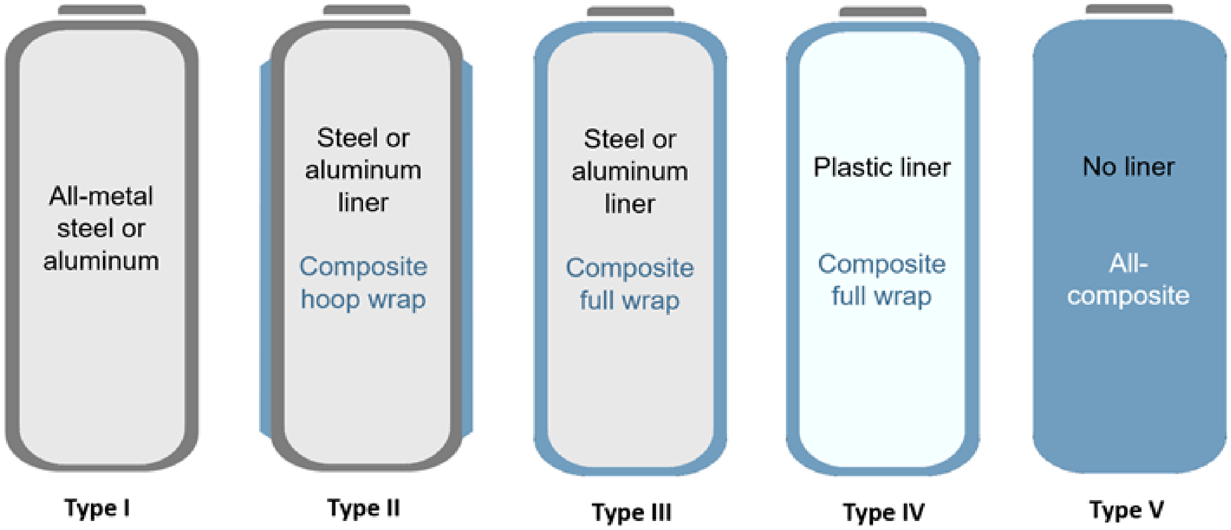


Figure 16: Pressure Vessel Types and Construction

6.2e | Pressure Vessel Material Construction Results

Now that the pressure vessel calculation equation has been introduced, we will further calculate the resultant stress acting on the interior wall of the pressure vessel as described in section 6.2d. For our particular lunar pressure vessel, we will use an internal pressure of 15 psi, for reasons stated above, thus $P = 15\,psi$. Furthermore, the inner diameter (ID) of the vessel must be at least one foot in diameter to provide sufficient storage space for both lunar findings and important equipment. For this reason, a pressure vessel has an internal diameter of 1 foot or 12 inches. So here $ID = 12in$. Additionally, the poisson's ratio of steel will be selected as the majority of the vessel will be constructed of steel. For steel poisson's ratio is 0.33, so $\nu = 0.33$. Calculating m, which is just 1/v, we get m = 1/0.33 = 3.03; or m = 3.03. Finally, the thickness t is largely dependent on the chosen thickness we intend to use for the metal wire. For our case, the team selected an approximately 0.5mm thick wire mesh sheet, though this could be further optimized as needed, and will be further studied with the plots below. In this case, the team selected seven wrapped layers of the 0.5mm thick wire mesh sheet for an approximate total thickness of 0.13 inches. So in this particular case, t = 0.13 in, but we will vary this parameter in Figures 17 and 18, below. Now that we have determined the values of our known parameters, we will continue by calculating the resultant maximum stress acting on the inside of the vessel walls. Solving the pressure vessel calculation equation above for the resultant maximum stress, yields the form below [19],

$$\frac{t}{ID} = \frac{1}{2}\sqrt{\frac{3(3m+1)P}{8m\sigma}} \quad \rightarrow \quad \sigma = \frac{9mP+3P}{8m(\frac{2t}{ID})^2} \tag{3}$$

Now, the equation above has been simplified to solve for σ, we can input our known values; $m,\ P,\ t,$ and ID, to solve for σ.

$$\sigma = \frac{9mP+3P}{8m(\frac{2t}{ID})^2} = \frac{9(3.03)(15)+3(15)}{8(3.03)(\frac{2(0.131)}{12})^2} = 39.3ksi \tag{4}$$

In the equation above, the maximum resultant stress on the inner walls of the pressure vessel is 39.3 ksi. Now we will compare this to the yield strength of steel based on the assumptions set out in the previous paragraphs.

$$FOS = \frac{\sigma_{yield}}{\sigma} = \frac{65.0\ ksi}{39.3\ ksi} = 1.7 \tag{5}$$

From the factor of safety calculation above we can see that when comparing the maximum resultant stress to the yield strength of steel, we achieve a factor of safety of 1.7.

Figure 17 is shown below. The max stress was plotted using the pressure vessel calculation equation above while varying the parameter t or the thickness. The X-axis shows the wall thickness of the pressure vessel in inches, while the Y-axis shows the stress applied to the inner wall of the pressure vessel in ksi. The thickness was varied simply because it's easy to adjust the number of wrapping layers. The dotted line shows the yield strength of the steel material.

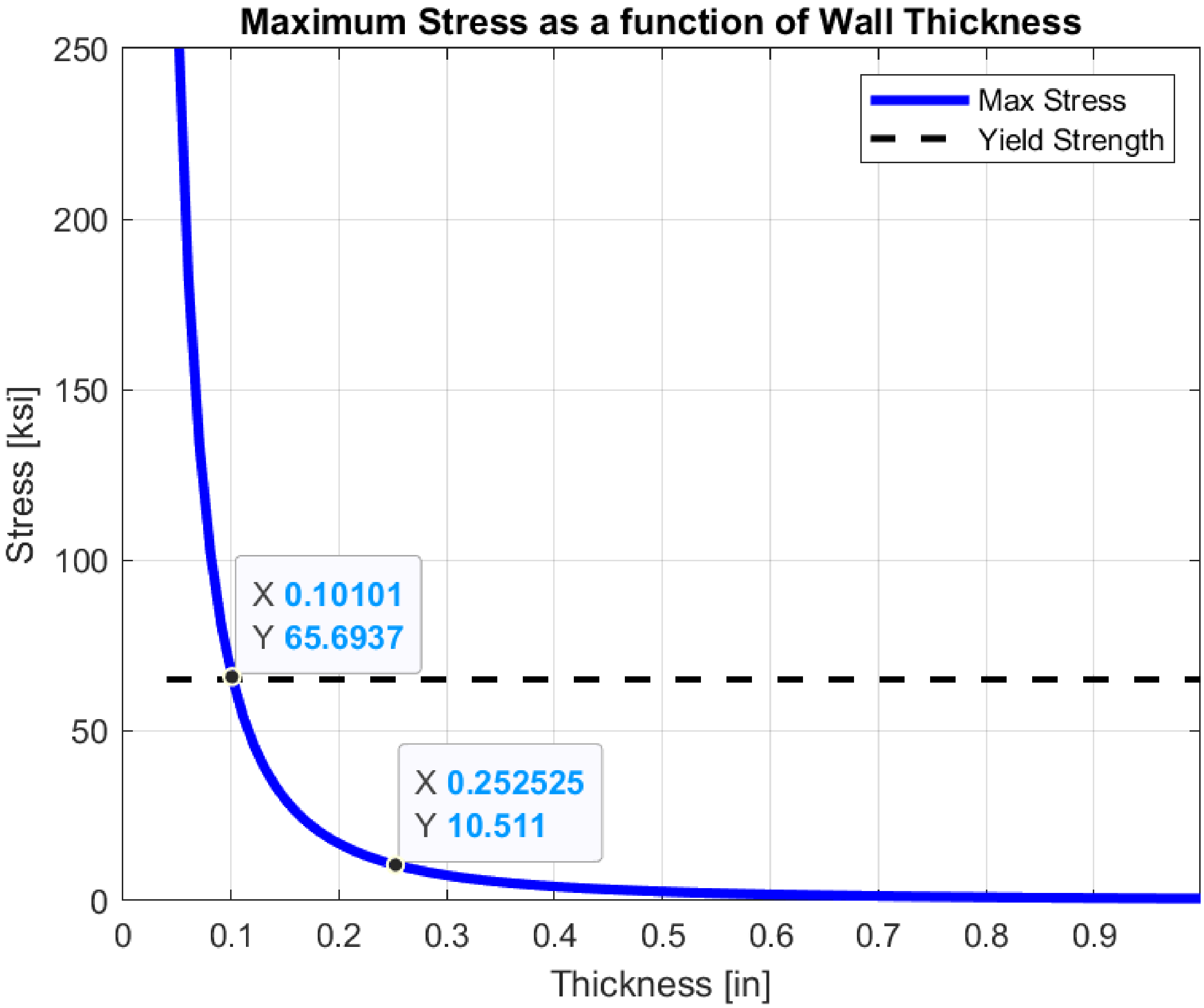


Figure 17: Stress as a Function of Wall Thickness

Figure 18 is shown below. This was plotted using the pressure vessel calculation and the factor of safety equations above while varying the parameter t or the thickness. The X-axis shows the wall thickness of the pressure vessel in inches, while the Y-axis shows the Factor of Safety.

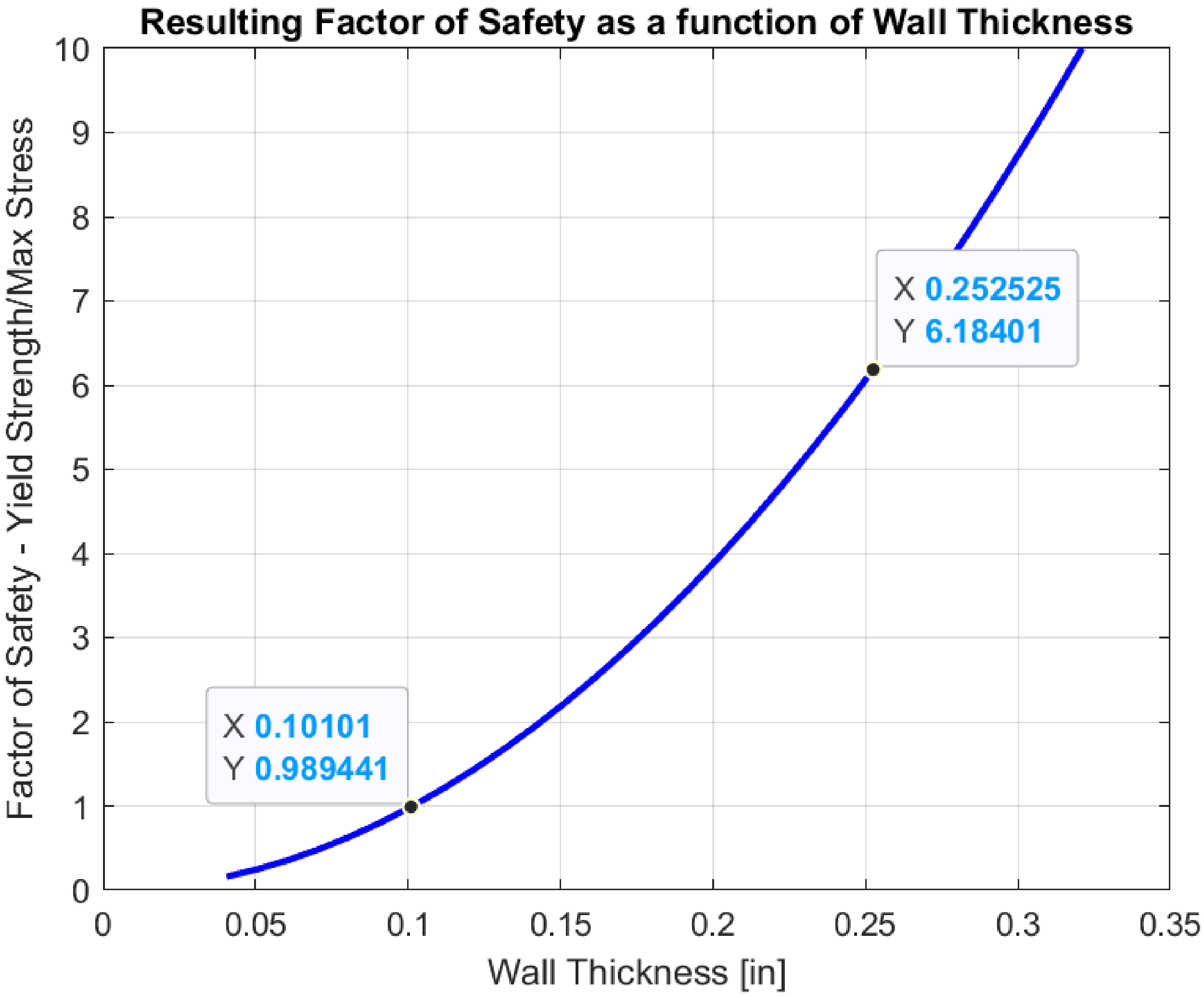


Figure 18: Factor of Safety as a Function of Wall Thickness

6.2f | Analysis of Results

Now, let's discuss the results of this analytical proof of concept to determine if constructing a pressure vessel by tightly winding in-situ metal feedstock and sealing with an aerospace-grade epoxy resin is feasible and pressurizable. The results above highlight the scenario of using a general steel and epoxy solution. Figure 17 describes the relationship between the stress acting on the inner wall of the pressure vessel and the thickness of the pressure vessel wall. This figure also illustrates a dotted line which is denoted as the yield strength of the material. This is the maximum allowable stress that the material can undergo before failure. As expected, the thicker the wall of the pressure vessel, the less likely it is to reach this yield strength. Given this, the absolute minimum pressure vessel wall thickness is equal to 0.10 inches.

Looking at Figure 18, we can also observe how the pressure vessel wall thickness relates to the factor of safety. It is important to reiterate that a factor of safety of 1.5 or greater is sufficient for most space applications. NASA has launched many vehicles with a factor of safety at or near 1.5 [16]. After finalizing the calculations in the previous section, it can be observed that the thickness of our material is set to 0.13 inches. This value correlates to a factor of safety of 1.7 which is above the desirable benchmark set by NASA. Furthermore, it is possible to determine an allowable range of thicknesses that fit within set safety bounds. Looking again at Figure 17, it can be concluded that once the blue line reaches its horizontal asymptote, there is no longer a need to increase the thickness. With that being said, this max limit is set at a factor of safety of roughly 6.18. Therefore, the range of thicknesses that meet our above constraints are $0.131" \leq t \leq 0.252"$.

Based on the above parameters, we've concluded that our physical model can operate at a pressure of 15 psi which is the minimum operating pressure for most general pressure vessels [16]. This validates that the pressure vessel model can be pressurized because the calculations are based on the material properties of a steel wire mesh paired with an epoxy sealing solution. Likewise, the chosen thickness matches similar household products that utilize a steel wire mesh component. Plotting the thickness helped us visualize the range of values that are associated with the material yield strength and the factor of safety which were two constraints we set on the problem. As mentioned in section 4.2.2, this model is ultimately aiming to simulate a pressure vessel constructed with tightly winding strands of in-situ metal feedstock around an inflatable diaphragm sealed with an aerospace-grade epoxy resin.

Although when looking at the pressure vessel construction through this one-point-perspective, the calculations seem to check out, it is important to note some of the other difficulties not discussed in this analytical model. For example, this model does not account for the varying temperatures in the lunar environment that will affect the curing process of the epoxy resin. Additionally, the temperatures can reach up to 250°F and since we are dealing with layers of extremely thin steel, these high temperatures may warp the metal during the assembly process. Accounting for these environmental effects begins highlighting additional concerns that would need to be addressed if this design concept were to be further developed.

7| Additional Research

Other Methods that Could be Applied to Perform Quenching

While the nitrogen gas quenching is a highly innovative and novel concept, there are other potential approaches that could be applied to quench metals to achieve desired material properties. One approach would be to adapt traditional quenching methods to the lunar environment. For this concept, the design must account for reduced gravity, extreme temperatures, abrasive conditions as well as many other engineering requirements. Liquids, rather than just gasses, must also be provided to enable rapid convection to occur. Execution of this concept would likely require a large enclosure, large volumes of liquids, temperature control systems, regular filtration and many other design adaptations that would create a cumbersome and complex design process. While traditional quenching could be adapted to the lunar environment, the implementation would require many external resources, frequent transportation of supplies and more maintenance. These are among the reasons we rejected this approach for our design concept. Therefore, this would likely be an inefficient and complex system that would not be well suited for the customer needs and the in-situ nature of the lunar forge.

Situational Considerations for Placement of Lunar Forge Infrastructure

Location of our feedstock processing systems is a key element to the success of the designs. A large majority of the lunar surface experiences extreme temperature variation. There's also the presence of abrasive dust and sands that often damages or completely destroys equipment on the moon. Our research findings indicate that the intended Artemis base camp will be located at the moon's south pole. This region contains naturally occurring craters, hills and valleys [11]. These effectively act as barriers to reduce abrasive damage to equipment. The south pole also contains water and exposure to small amounts of sunlight [11]. Studies have also found a higher abundance of materials such as iron and titanium oxide in these areas [15]. Researchers believe there could be more minerals below the moon's surface than initially expected and are currently searching the southern hemisphere for resources [15]. If researchers are able to confirm these resources, it would increase the viability of a forge. All of these are useful resources for the lunar forge operations. Our quenching system is required to be in the proximity of the production pipeline. Wherever the metal feedstock is leaving an annealing operation or hammer forging operation, the quenching operation must be located there as well. This is a basic requirement due to quenching/hardening being a time critical process performed while the material is at elevated temperatures.

8 | Conclusions

The team developed three different proof of concept models to help guide future improvements for lunar infrastructure. Aspects of each test validated the teams initial goals, however they also highlighted risks that limit the viability of these concepts. Limitations forced the concepts to be evaluated using computational models, but they all provided useful insights. The tests on heat treating highlighted the potential of nitrogen as a cooling agent, but it would require several thousand tons of regolith to get enough nitrogen to cool approximately 100 kg of aluminum, drastically limiting the feasibility of the concept. The pressure vessel design concept consisted of two proof of concepts. The first proof of concept model, aiming to provide confidence behind the inflatable diaphragm concept, proved to be too inaccurate to make any sweeping declarations of validity. However, the models produced satisfactorily concluded that certain materials may be capable of accomplishing the designed function. The second proof of concept concluded that a pressure vessel with a thin steel mesh and epoxy sealing solution of thickness 0.131” can withstand the minimum operating pressure of general pressure vessels. However, further discussion around constructing the pressure vessel in the lunar environment needs to be addressed for future developments.

9 | Resources

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Appendix A

Table A1: Heat Treatment Proof of Concept Plan

Aluminum Heat Treating Using Nitrogen Gas					
Customer needs	**Aspects to be tested**	**Associated physical principles and equations**	**Metrics to be measured (units)**	**Experiment/Method to be used to measure**	**Experiment Plan (Note 3)**
Functional Features					
Material must retain suficient ducitlity and hardness.	Ability to quickly cool metal sample to acheive a desirable grain structure and to have similar effectivness to liquid or oil quenching methods	$RHO \approx \frac{P_{(t)}}{RT_{(t)}} = \frac{m_{(t)}}{V}$ $q_x'' = h_x(T_{plate} - T_\infty)$ Cooling Rate	Temperaure Drop (C), Cooling Rate (C/s)	Flow Simulation Cooling Test	Heat metal sample to annealing temperature, place in vaccum chamber and quickly introduce nitrogen gas. Measure temperature drop. This will be done using SolidWorks Flow Simulation. Then compare with emperical data to evaluate strength. Run test at mutliple temperatures to evalate viability.
Test must use minimal nitrogen and lunar regolith	Ability to quickly cool metal sample to acheive a desirable grain structure and to have similar effectivness to liquid or oil quenching methods	$m = \frac{PV}{RT}$ Ideal Gas Law	Mass of nitrogen (kg) used	Analysis of cooling results	Calculate required mass of nitrogen based on pressure, temperature and volume used in Solidworks Simulation.

Table A2: Inflatable Diaphragm Reusability Proof of Concept Plan

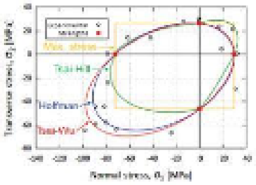
Pressure Vessel - Inflatable Diaphragm Reusability					
Customer needs	**Aspects to be tested**	**Associated physical principles and equations**	**Metrics to be measured (units)**	**Experiment/Method to be used to measure**	**Experiment Plan (Note 3)**
Functional Features					
The diaphragm must be capable of being used as a rigid mold around which feedstock is wrapped to form the pressure vessel shell	The structural integrity of the designed diaphragm under the expected loading conditions	$\sigma' = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2}$	Failure Stress and yield strength	Ansys modeling of static l	Measure material behavior under static loading conditions
The diaphragm must be reusable. This means numerous cycles of inflation and deflation, along with compressive stress from the wrapping process	Material strength, Fatigue life of the elastic material, repeatability of operation	Goodman's Equation: $\frac{\sigma_a}{S_e} + \frac{\sigma_m}{\sigma_{ut}} = 1$  Stress = F / A	Stress-Strain Curves	Diaphram reusability Feasibility Experiment (FEA)	Conduct FEA to model fatigue behavior of selected polymer. Validate with data from an experiment involving repeatedly stretching a sample polymer.
The diaphram will undergo thermal loading and exposure to the sun's radiation. The material should withstand these conditions	Thermal resistivity and stress and strain	$\sigma = -\epsilon E = -\alpha(\Delta T)E$ $\sigma = -\frac{\alpha(\Delta T)E}{1-\nu}$ Thermal stresses	root mean squared of the surface (i.e. surface finish)	Thermal loading tests	Measure the worst case temperature and radiation loadign conditions that lead to failure and compare with typical environment conditions on the Moon

Table A3: Pressure Vessel Construction Proof of Concept Plan

Pressure Vessel - Construction Feasibility

Customer needs	Aspects to be tested	Associated physical principles and equations	Metrics to be measured (units)	Experiment/Method to be used to measure	Experiment Plan (Note 3)
Functional Features					
Potential for using a pressure vessel constructed of a wrapped wire mesh and epoxy resin	Material strength, vessell geometery, maxmium stress	$\frac{t}{ID} = \frac{1}{2}\sqrt{\frac{3(3m+1)P}{8m\sigma}}$ $\sigma = \frac{9mP+3P}{8m(\frac{2t}{ID})^2}$	Resultant Maximum Stress acting on the inner walls of the pressure vessel (KSI)	Vessel Construction Feasibility, gather resultant maximum stress	We will solve the first equation for the resultant stress (second equation), for our given design. Then we will plot this stress vs. thickness, to further evaulate the design.
To ensure the pressure vessel can withstand the calculated maximum resultant stress from the internal pressure acting on the vessel	Structural integrity of the vessel, vessel design feasibility	$FOS = \frac{\sigma_{yield}}{\sigma}$	Factor of Safety (unitless)	Factor of safety comparing the maximum resultant stress acting on the vessel, to the materials yield stress	By varying the thickness parameter t, in the resultant stress equation, a range of suitable factors of safety can be determined. We will do this by plotting the Factor of Safety vs. Thickness (t), to determine a suitable vessel wall thickness design range.

Appendix B

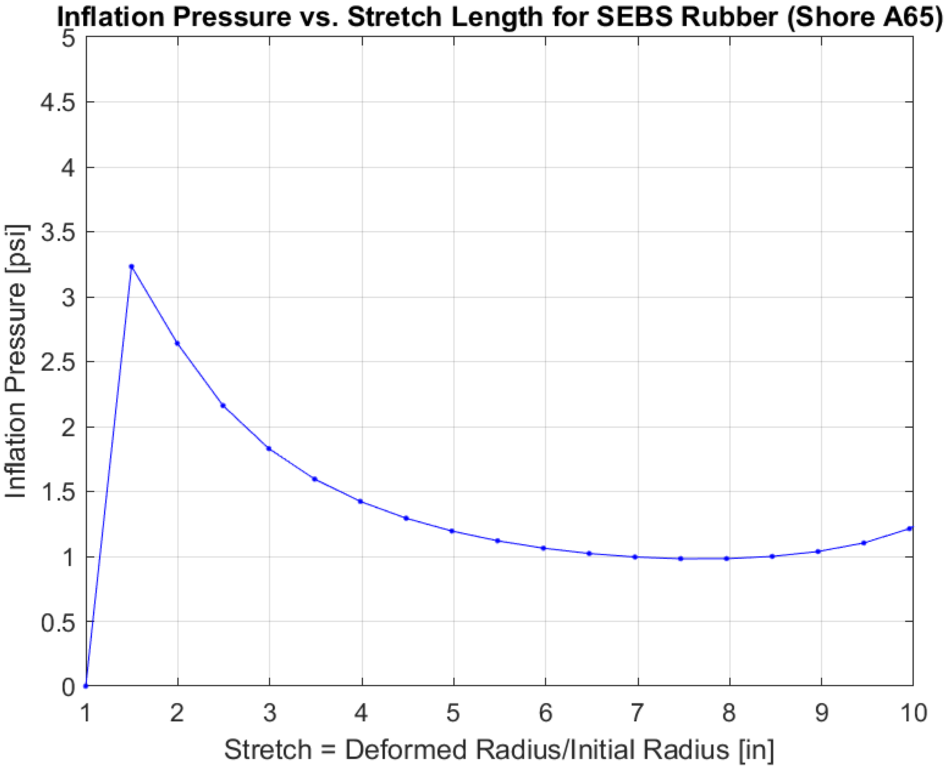


Figure B1: Inflation Pressure vs. Stretch Length for SEBS Rubber (Shore A65)

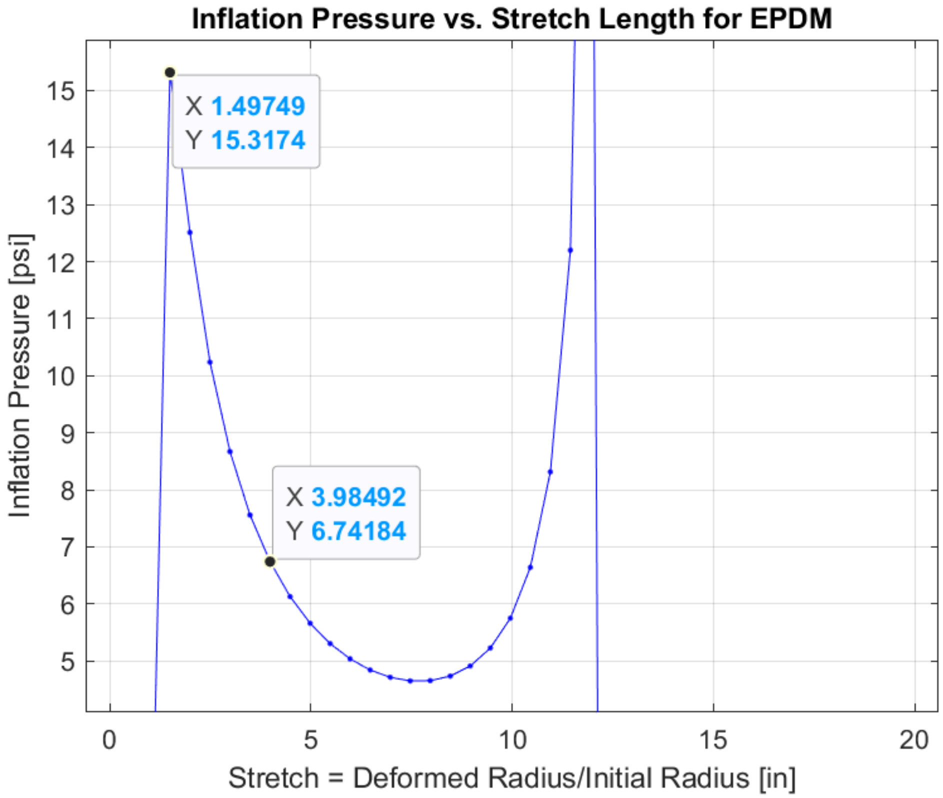


Figure B2: Inflation Pressure vs. Stretch Length for EPDM

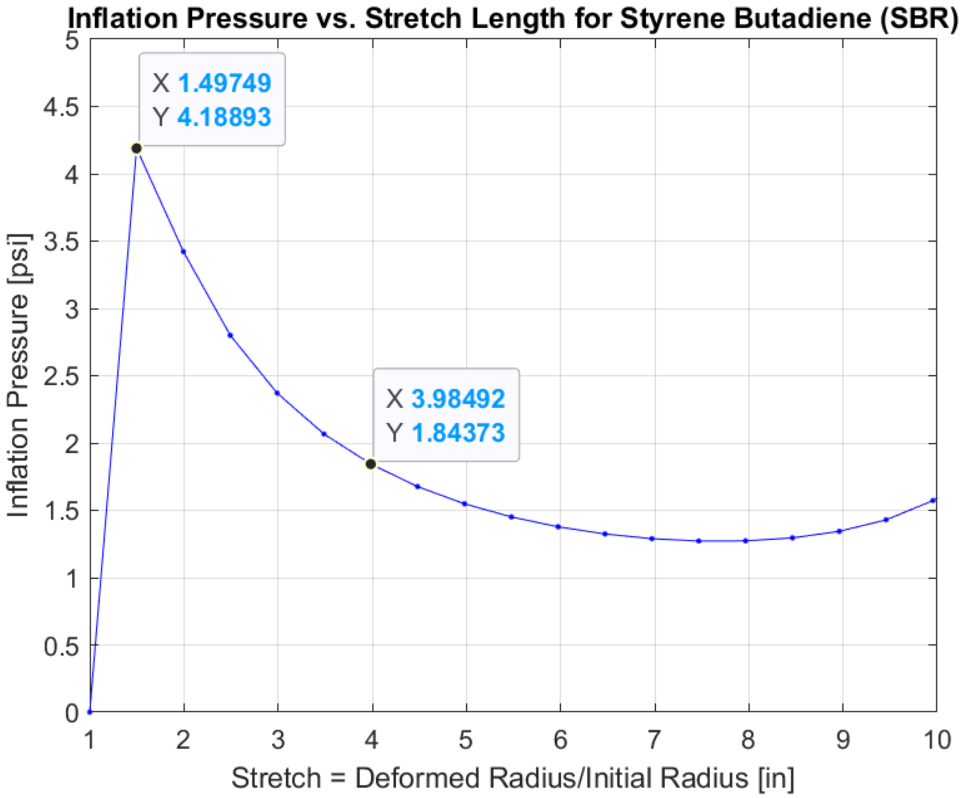


Figure B3: Inflation Pressure vs. Stretch Length for Styrene Butadiene (SBR)

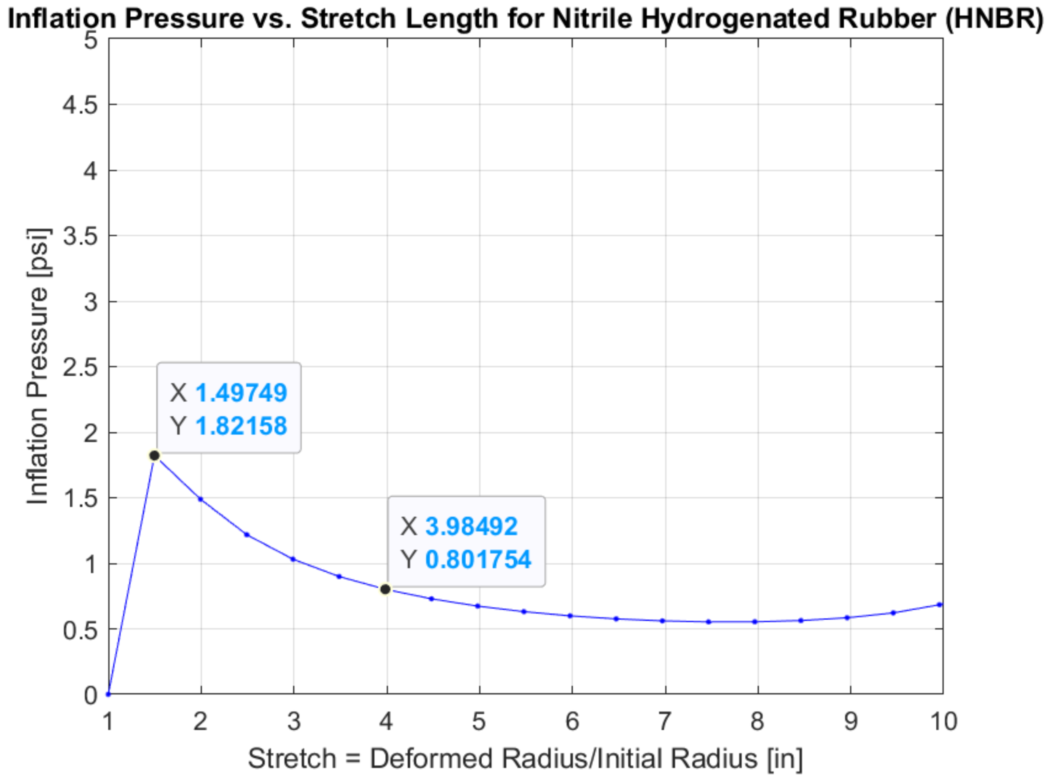


Figure B4: Inflation Pressure vs. Stretch Length for Nitrile Hydrogenated Rubber (HNBR)

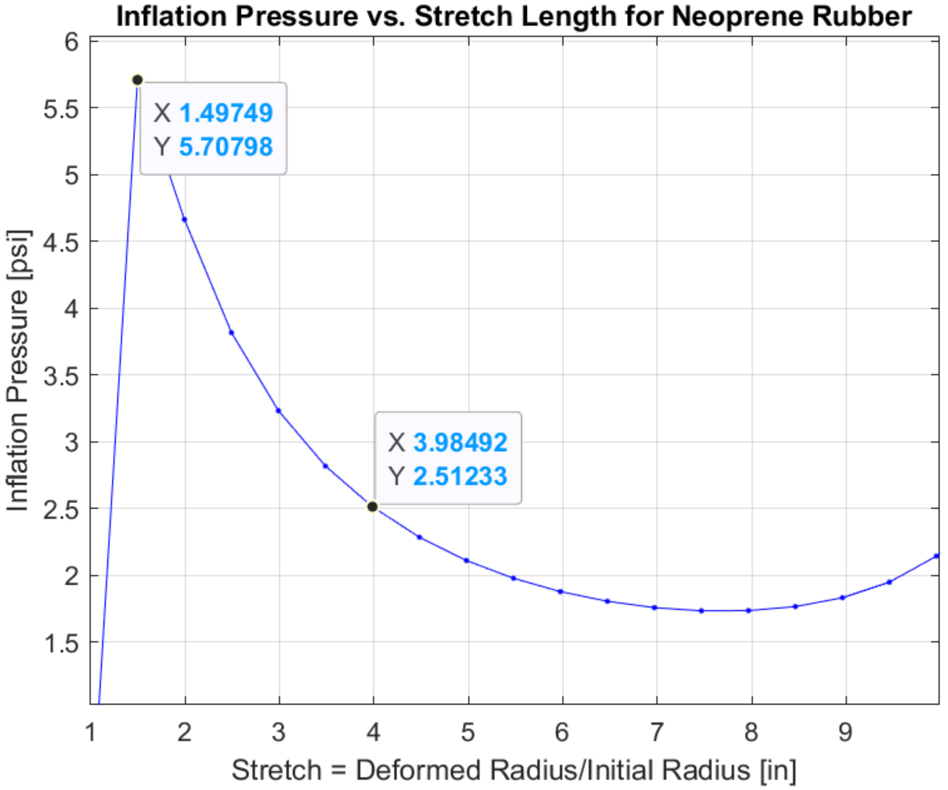


Figure B5: Inflation Pressure vs. Stretch Length for Neoprene Rubber

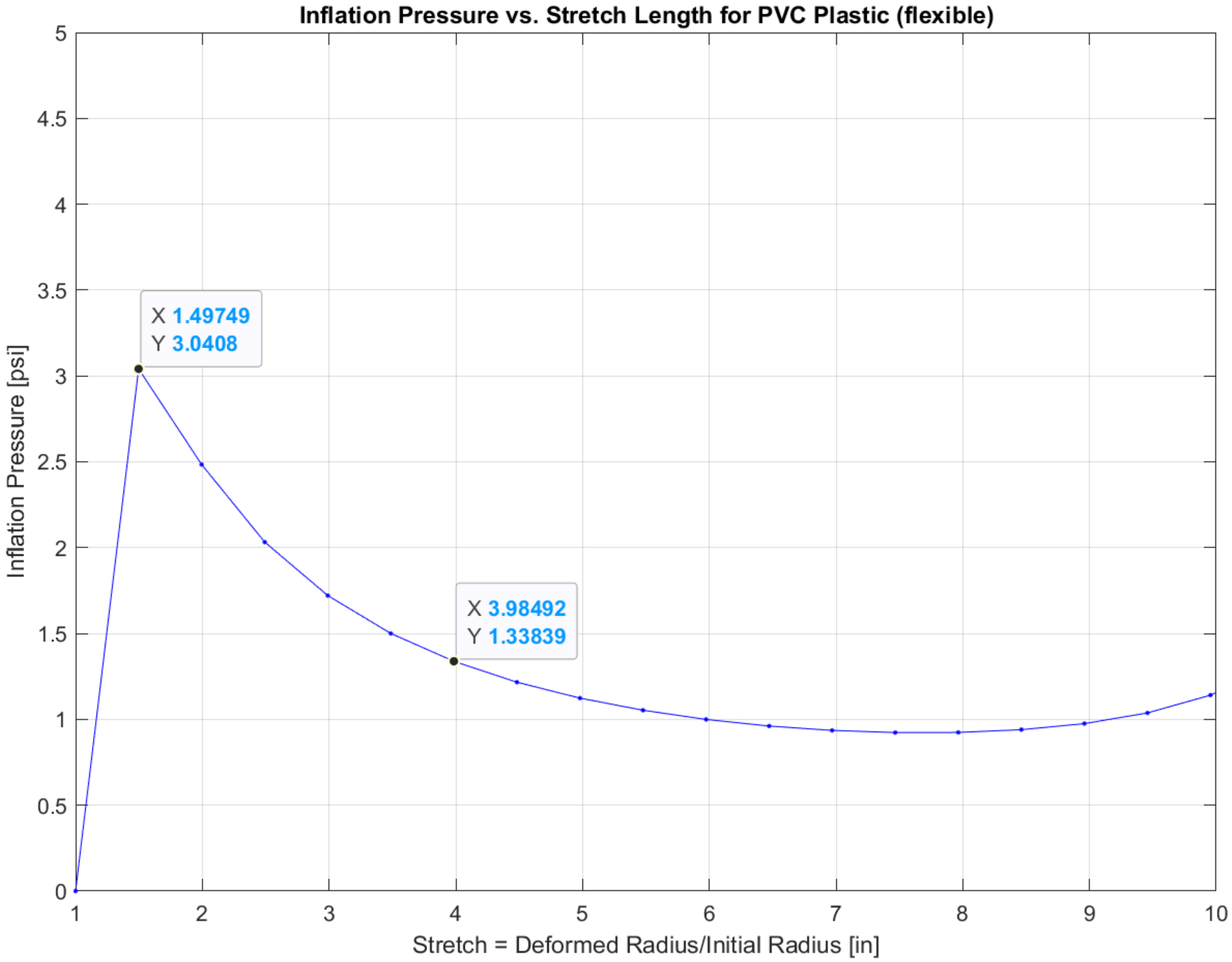


Figure B6: Inflation Pressure vs. Stretch Length for PVC Plastic (Flexible)

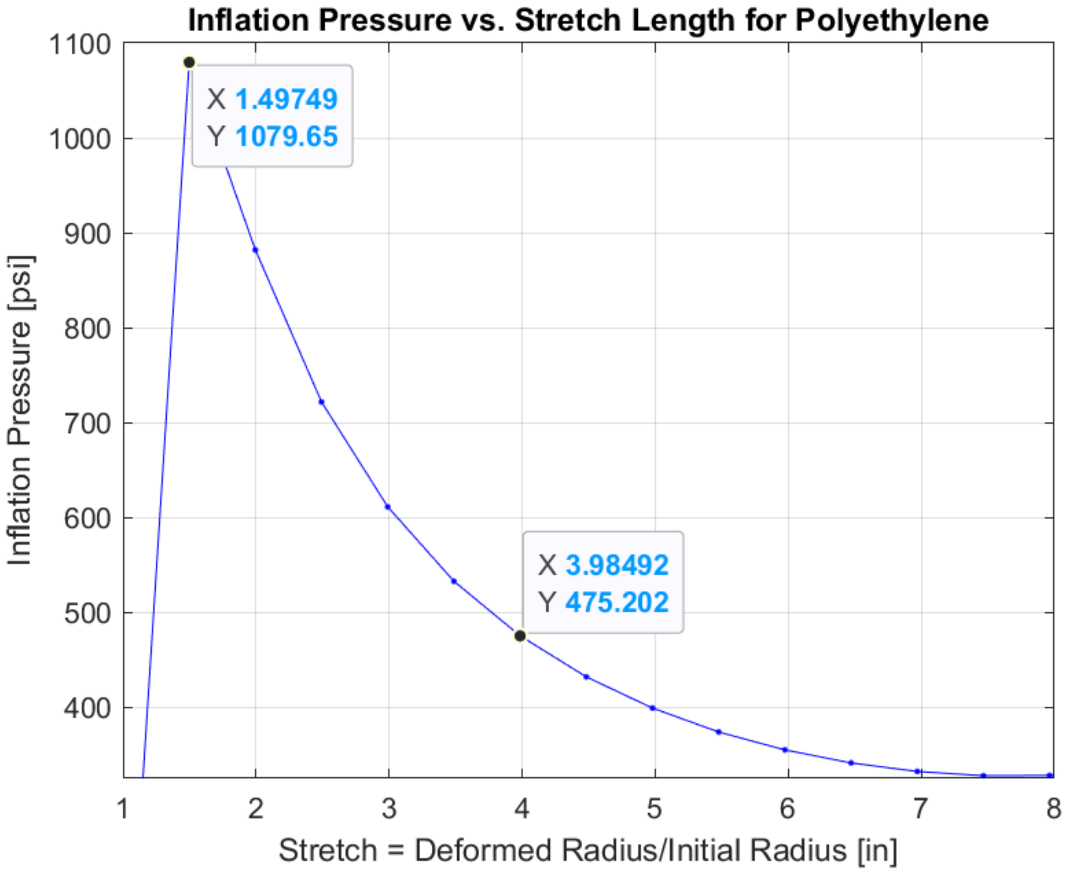


Figure B7: Inflation Pressure vs. Stretch Length for Polyethylene

Team Member Contributions

Work was done individually and during team meetings. All team members contributed to all sections and concepts; the descriptions included for each section were completed predominantly by the following members:

Executive Summary: Max Zegers
Introduction: Gavan Sarrafian
TRIZ: Thomas Dodd
Innovative Concepts (All Concepts): Thomas Dodd, Ryan Grajewski, Michael Amoun
Overview of Proof of Concept Plans: All team members
Proof of Concepts Heat Treating: Thomas Dodd, Max Zegers
Proof of Concept Inflatable Diaphragm: Ryan Grajewski
Proof of Concept Vessel Construction: Michael Amoun, Gavan Sarrafian
Additional Research: All team members
Conclusions: Michael Amoun, Gavan Sarrafian, Max Zegers
Resources/Appendix: All team members contributed different sources