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PORTLAND STATE UNIVERSITY

PSAS Composite LOX Fuel Tank Final Design Report

by

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An undergraduate capstone report submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering.

Sponsor: Portland State Aerospace Society

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Team Members and Contributions

Primary Contributions:

- **Neil Benkelman** - Project Manager, FEA, Documentation, Part Fabrication, Conceptual Design.
- **Russell Berger** - Analytical Lead, CAD Lead, Part Fabrication, Conceptual Design.
- **Alex Farias** - Team Lead, Budget Management, MME Dept Liaison (Ordering/Budget Communication), Part Fabrication, Conceptual Design, Experimental Design.
- **Francesca Frattaroli** - Experimental Design Lead, Research, Conceptual Design, Documentation.
- **Weldon Peterson** - Documentation, Layups, Dimension & Tolerancing.
- **Chris Wilson** - Layups, Part Fabrication, Experimental Design, Conceptual Design, Dimension & Tolerancing.
- **Dr Jun Jiao** - Project Advisor.

Table 1: Team Members and Contributions Summary

Name	Conceptual Design	Analytic Design	Research	Layups (Physical Prototyping)	Experimental Testing	Documentation	Part Fabrication	Modeling	OSGC Proposal
Neil Benkelman	X	X		X	X	X	X		X
Russell Berger	X	X	X		X		X		
Alex Farias	X	X	X	X	X		X		X
Francesca Frattaroli	X	X	X		X	X	X		X
Weldon Peterson	X			X	X	X		X	
Chris Wilson	X			X	X	X	X	X	

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1 Executive Summary

1.1 Project Objective Statement

Design, fabricate, and test a proof-of-concept liquid oxygen composite fuel tank prototype that can be scaled up by Portland State Aerospace Society (PSAS) for use on their first liquid-fueled rocket.

1.2 Final Status of Design Project

The manufacture of custom, light-weight, single-piece, metal tanks is beyond the budget and scope of an amateur rocket team. Off-the-shelf pressure vessels are heavy and cannot be optimized to fit rocket geometry. Therefore, the goal of this project is to develop a structurally and chemically safe propellant tank that utilizes a pre-existing rocket airframe structure [1] and light-weight composite materials that will achieve a large propellant mass ratio. The following is a list of the key client requirements for the project:

- Tank must be compatible with liquid oxygen (LOX) for duration of fill and launch cycle.
- Tank maintains integrity and seal when pressurized to 3 ATM (45 psi).
- Tank is able to withstand compressive load of at least 4000N (900 lb).
- Design has a factor of safety of at least 2.

The final tank design must be compatible with the existing modular airframe design [1] and utilize existing structural materials donated to PSAS. The primary challenge is the carbon fiber provided contains an epoxy resin that is not compatible with LOX. Therefore, this design is focused on incorporating an inert, functionally impermeable liner that maintains a seal across the range of operating pressures and temperatures.

The current version of the design incorporates four main subsystems: a structural composite shell, rings to support the shell, a liner to isolate the LOX, and end caps with fittings for plumbing. The design employs a Polytetrafluoroethylene (PTFE) tube that is sealed at the ends via radial compression between the support rings and end caps using a shrink fit. External layers of carbon fiber and honeycomb material provide structural strength.

1.3 Key Performance Metrics:

A liquid-nitrogen (LN_2) filled, 3:10 scale tank was crush tested, and failed under a load of 9500 lbs yielding a factor of safety greater than 10. The shrink-fit end caps were designed to provide the seating pressure for PTFE given in the American Society of Mechanical Engineering (ASME) pressure vessel code, section VIII. Analysis suggests the seal improves at cryogenic temperatures. A hydrostatic pressure test was performed in which the tank maintained a pressure of 100 psi before leaking through the seal, providing a factor of safety of greater than 2.

The thickness of the liner was chosen based on the ability to machine a liner in-house while maintaining a uniform wall thickness. The current thickness exceeds the theoretical thickness necessary for the liner to function as a LOX barrier. Provided the liner maintains the seal as expected at cryogenic temperatures, the LOX is fully isolated from the carbon fiber epoxy resin.

All tank parts and manufacturing processes can scale to a flight ready tank. PSAS will be provided with an open source, python-based stress calculation tool to assist in future design iterations. Other documentation provided to PSAS will include a detailed bill of materials (BOM) and manufacturing procedure tutorials for all developed components.

2 Client Requirements

2.1 Background

Portland State Aerospace Society is building a rocket with the intention of reaching an altitude of 100 kilometers (the Von Karman line). For this to be possible, the rocket's propellant mass ratio (how much propellant you need compared to the total rocket mass) must be optimized. The total mass of a rocket is typically 85% propellant and 15% vehicle and pay-load [2]. This ratio makes dry mass reduction a major point in any rocket design. PSAS set the goal of the development of a composite tank to hold their LOX propellant. The main assumption in setting this goal is that a tank fabricated using composite materials will significantly reduce the propellant to mass ratio when compared to a conventional aluminum tank. Recognizing that there are significant challenges associated with designing a composite tank, the team was asked to provide a proof-of-concept design without being constrained by mass.

2.2 Project Requirements

2.2.1 Complete List of client requirements:

- Tank must be compatible with liquid oxygen (LOX) for duration of fill and launch cycle.
- Tank maintains integrity and seal when pressurized to 3 ATM (45 psi).
- Tank is able to withstand compressive load of at least 4000N (900 lb).
- Design has a factor of safety of at least 2.
- Tank design and manufacturing process can scale to final launch vehicle dimensions (tentatively approximated as 10″ diameter).
- Tank must be compatible with previously developed modular airframe design.
- Target tank manufacturing cost is $1000 with an acceptable upper limit of $4000.
- Complete documentation of research, analysis, manufacturing processes, and testing to be made publicly available on the PSAS Github repository.

2.2.2 Description of Key Client requirements:

PSAS designated four main requirements for the successful completion of this project. The first of these requirements, and arguably the most important, was for the tank to be LOX compatible. LOX is an aggressive oxidizer and the epoxy resin contained in the carbon fiber used in the fabrication of the tank is highly flammable. Therefore, should the two materials come into contact, there is a high probability of combustion occurring. Such an event would mean catastrophic failure at or before launch, and a loss of the rocket. Consequently, the tank design must isolate the LOX from the carbon fiber layers. No direct LOX compatibility testing was performed at this design stage due to the associated difficulties and risks, instead materials with documented LOX compatibility were selected and the ability of the tank to retain a liquid seal at operational pressure was selected as the key LOX-compatibility performance measure, as it establishes the isolation of the LOX from the flammable structural materials.

It also needs to be shown that when scaled up to flight ready sizes, all tank components are able to withstand predicted flight loadings. PSAS provided the results of optimization calculations for their liquid propellant rocket; these calculations predicted the peak flight loads to be 3ATM internal pressure with an axial compression loading of 4000N. The ability of the prototype tank to withstand these pressure and compressive forces constitute the second and third main client requirements, respectively. The pressure performance is measured by a hydro-test in which the tank is subjected to internal pressurization, and failure is defined as visible leakage of water from the tank seals, or structural failure, whichever occurs first. The compressive strength of the tank is evaluated via an axial compression test to failure.

In designing a rocket that utilizes a fire accelerant such as LOX, safety is a major concern. The standard minimum factor of safety in aerospace applications is 1.5 [3], balancing the need for safety and weight optimization. To this end, PSAS established a minimum factor of safety of 2 on all components. This minimum factor of safety constitutes the fourth main project requirement. The pressure and compression performance tests must show tank failure at above twice the anticipated operational loadings.

The tank developed here is a proof-of-concept prototype, however, the tank must be scalable to the expected full-size dimensions of the rocket at launch. The current, tentative, diameter of the full-scale tank is set at 10 inches. Therefore, any manufacturing process used in the fabrication of sub-scale tank components must also be achievable for the full-scale counterparts. This includes all in-house manufacturing, layup procedures, component assembly, testing, and validation analysis performed. The performance measure of this fifth requirement is less quantitative than the four main requirements, but the minimum success criterion is the identification of resources and tools accessible to PSAS that could be utilized to produce a full-sized tank.

The current rocket airframe design is composed of several carbon fiber modules, held together by aluminum mating rings with radially oriented fasteners. PSAS stipulated that the LOX tank must also be modular in design. This was interpreted in two ways. First, our design must allow the addition of future features that will interface with airframe modules. This means that required modifications cannot not interfere with the functionality of the tank. Second, the tank does not fit inside the rocket, but rather the outer walls of the tank are also in line with the walls of the rocket.

As a part of the amateur rocket community, PSAS also requires that the cost to produce the rocket not prohibit other self-funded, university rocket clubs from replicating the work. PSAS set an arbitrary target manufacturing cost of $1000 with a maximum cost of $4000.

Finally, All work performed by PSAS is available to the public, leading to the fourth main requirement that all fabrication procedures, materials, engineering analysis, and design processes associated with the tank be well documented and available through the PSAS Github repository. The open source nature of the project allows any future persons adopting this tank design to replicate the work done or modify the functional tank design to suit their needs.

3 Conceptual Design Summary

3.1 Background

The composite tank designs explored and pursued in this project all share common manufacturing methods and design characteristics informed by the 2014 PSAS LV3 Airframe Capstone [1], which produced a composite airframe structure proven capable of withstanding the expected compressive flight loadings at ambient temperatures. The composite tank is also required to possess the same external geometry as the airframe models to allow for modular integration. For these reasons, the primary tank design concepts center around preserving the established airframe structure (See Figure 1).

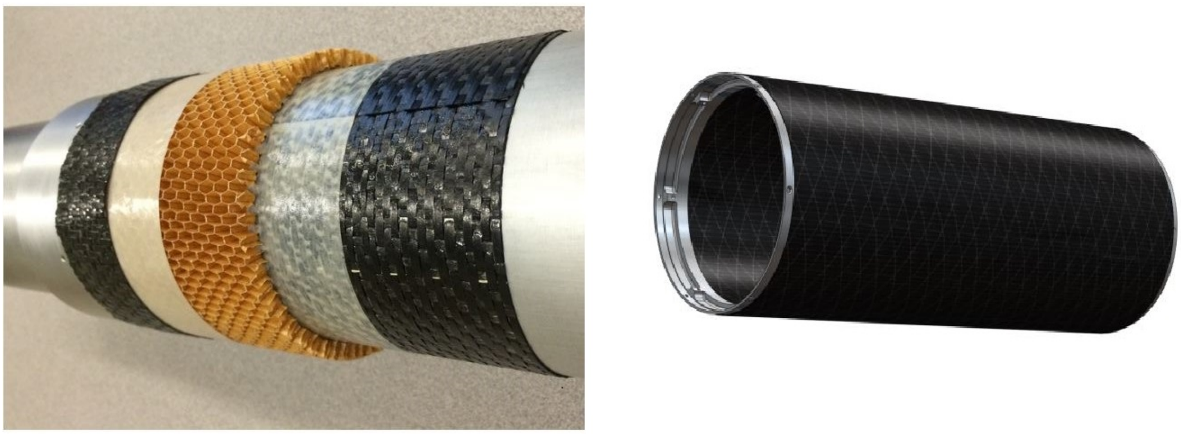

Figure 1: ***LV3 Composite Airframe Internal Layering Configuration (left) and Final Airframe Structure (right), Source: PSAS Composite Rocket Airframe Capstone Report, 2014***

The LV3 Airframe structure consists of a unique layering of sheets of epoxy-embedded carbon fiber, Nomex honeycomb, and Metlbond adhesive, formed around a mandrel (removable aluminum cylinder) and onto aluminum rings that allow for modular mating of multiple airframe structures. This airframe design serves as the launching point for the composite tank designs.

3.2 Analysis of Concept Selection

The primary challenge of designing a composite fuel tank was making the tank compatible with LOX while preserving the existing PSAS airframe module structure. Chemical incompatibility between LOX and the carbon fiber epoxy resin could lead to spontaneous combustion if they interacted. Therefore, the isolation of LOX from the airframe became the driving design challenge. In order to mitigate this issue, it was concluded that a chemically inert barrier was needed to line the inside of the tank and segregate the propellant from the carbon fiber epoxy. The material chosen for this purpose was polytetrafluoroethylene (PTFE). A detailed discussion of this design choice can be found in Section 4.4.

PTFE is only readily available in a few basic geometries from vendors. The most convenient geometries for use in a cylindrical tank are *sheet* and *tube*. Anticipating material and manufacturing lead times, the team chose to pursue two primary designs in parallel, one for each bulk material shape. Both were accomplished using a 3″ inner diameter to save time and materials.

Keeping in mind the client requirements that the tank be scalable and reproducible, the manufacturing process for this tank also greatly influenced the design selections and development.

Material selections and sealing mechanisms employed in the following designs are available and machinable at larger scales, and the airframe structural layering process was preserved as much as possible. More detailed descriptions of scalable assembly and manufacturing methods can be found in section 5.1.

3.3 First Design: Gasket and Sheet Liner Tank (Rejected)

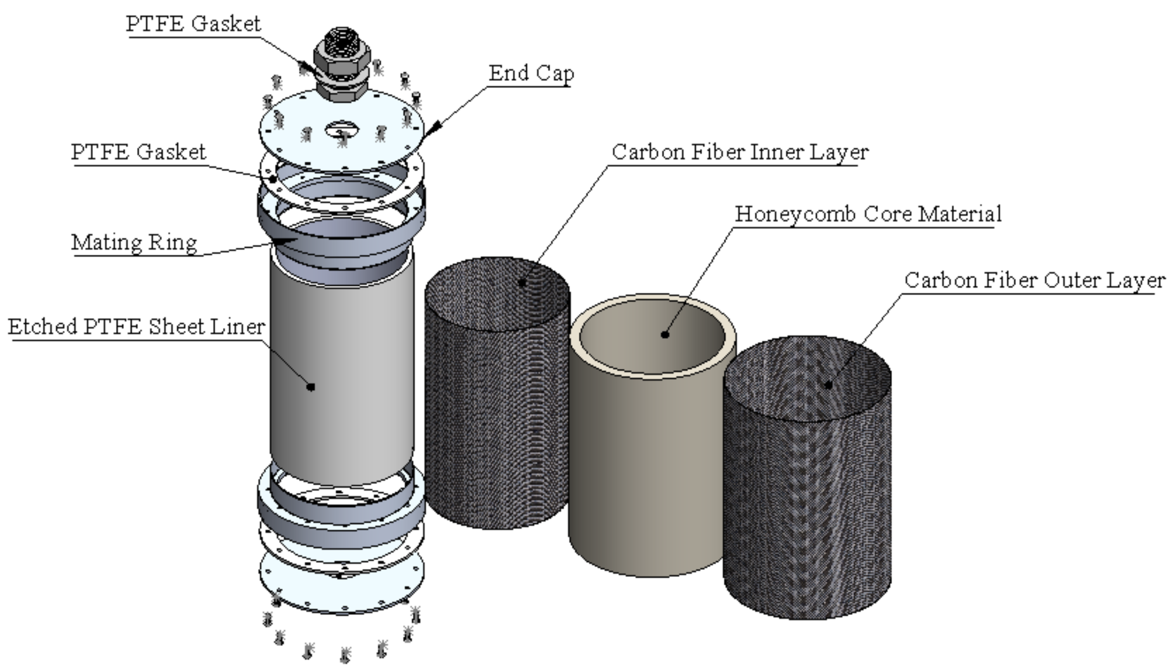

Figure 2: ***Exploded View of Initial Sheet-Liner CAD Design***

The first tank design utilized an 1/32″ PTFE sheet liner, which was easily integrated into the pre-existing airframe layup process as an additional layer material. PTFE is known for having a very low coefficient of friction with nearly all other materials, making it very difficult to adhere to the other tank components. To overcome this, the liner material was chemically etched on the outside and then wrapped around an aluminum mandrel, with a thin strip of aluminum sheeting sealing the seam in the PTFE sheet. This sheet chemically isolated the LOX from the carbon-fiber layer, but did not serve to seal the tank. Aluminum mating rings and end caps were developed to seat a PTFE gasket and allow for an additional through-wall plumbing, which serves to seal the tank (see Figure 2).

3.4 Second Design: Shrink-Fit and Tube Liner Tank (Final Design)

The second tank design employed a virgin (un-etched) PTFE tube with a 1/8″ wall thickness for the liner. Similar to the sheet liner design, the liner slid over a mandrel and subsequent materials were laid up onto it. The mating ring and especially the end cap designs deviate from the sheet liner design. Rather than being glued into place, the liner was held in place by radial compression between the mating rings and the inner lip of the end caps (see Figure 3). After thermally contracting the end caps, they slide into the ends of the tank and expand outward to press the liner against the mating ring extensions. This shrink-fit procedure isolates the LOX from the carbon fiber layers and seals the tank, without the use of additional gaskets.

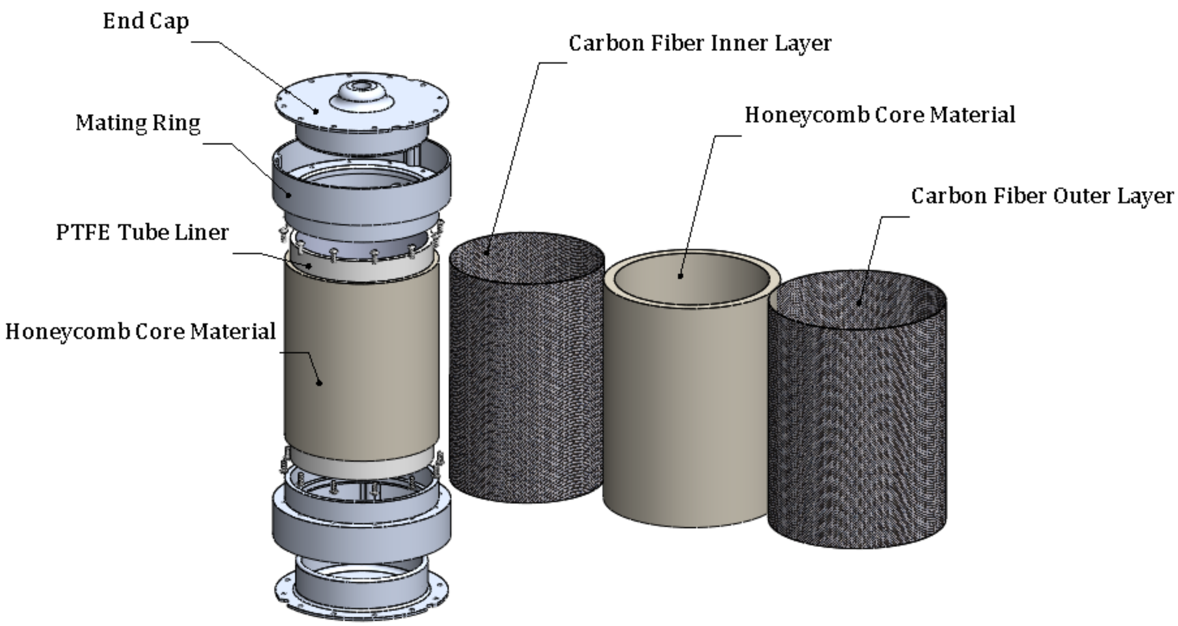

Figure 3: ***Exploded View of Shrink-Fit CAD Design***

3.5 Comparison of Designs

Pre-etched PTFE was readily available in 1/32″ sheets, while the thinnest tube vendors were able to provide had 1/8″ walls. Upon receipt, the tube walls were actually thicker than 1/4″, requiring them to be manually turned down on a lathe before use, making the sheet liner design immediately easier to fabricate. Other advantages of the sheet design concept were the ease of its manufacture, scale-ability, and reduced weight relative to the tube design. A PTFE oxygen permeability calculation found in the supplemental design artifacts led us to the conclusion that the liner would easily perform its function at a thickness as low as 0.02″. Disadvantages of the sheet-liner design included multiple seams and gaskets subject to potential failure, and the risk of adhesive-LOX contact.

An advantage of the tube design is that the shrink-fit employed to hold the liner in place prevents the need for etching. Since the shrink fit also compresses the liner enough to form a seal, the associated design had fewer total parts than the alternative, and eliminated potential contact between LOX and adhesive materials with unknown reactive properties. Disadvantages of the tube design include a demand for higher-precision geometric tolerancing to achieve a successful shrink-fit, which translates to higher component costs for outsourcing or higher skill and resource requirements for in-house manufacture.

Since it was unknown whether either design would be effective, it was decided to develop both designs into the physical prototyping stage. Ultimately, through analysis and testing, the shrink-fit tube tank proved to be the superior design (see Figure 7). As detailed in section 5.4, testing yielded a positive result in all aspects of the shrink-fit tube tank design. The sealing mechanism of the shrink fit was successful and provided minimal leakage when subjected to a hydrostatic burst test, with leakage occurring at 100 psi (above the required factor of safety of 2). Under compression loading at cryogenic temperatures, the tube design withstood a load of 9500 lbs (ten times the expected operating force of 900lbs). In contrast, the sheet design showed minimal success when subjected to hydrostatic pressure (did not achieve expected operational pressure), and hence was abandoned at that stage.

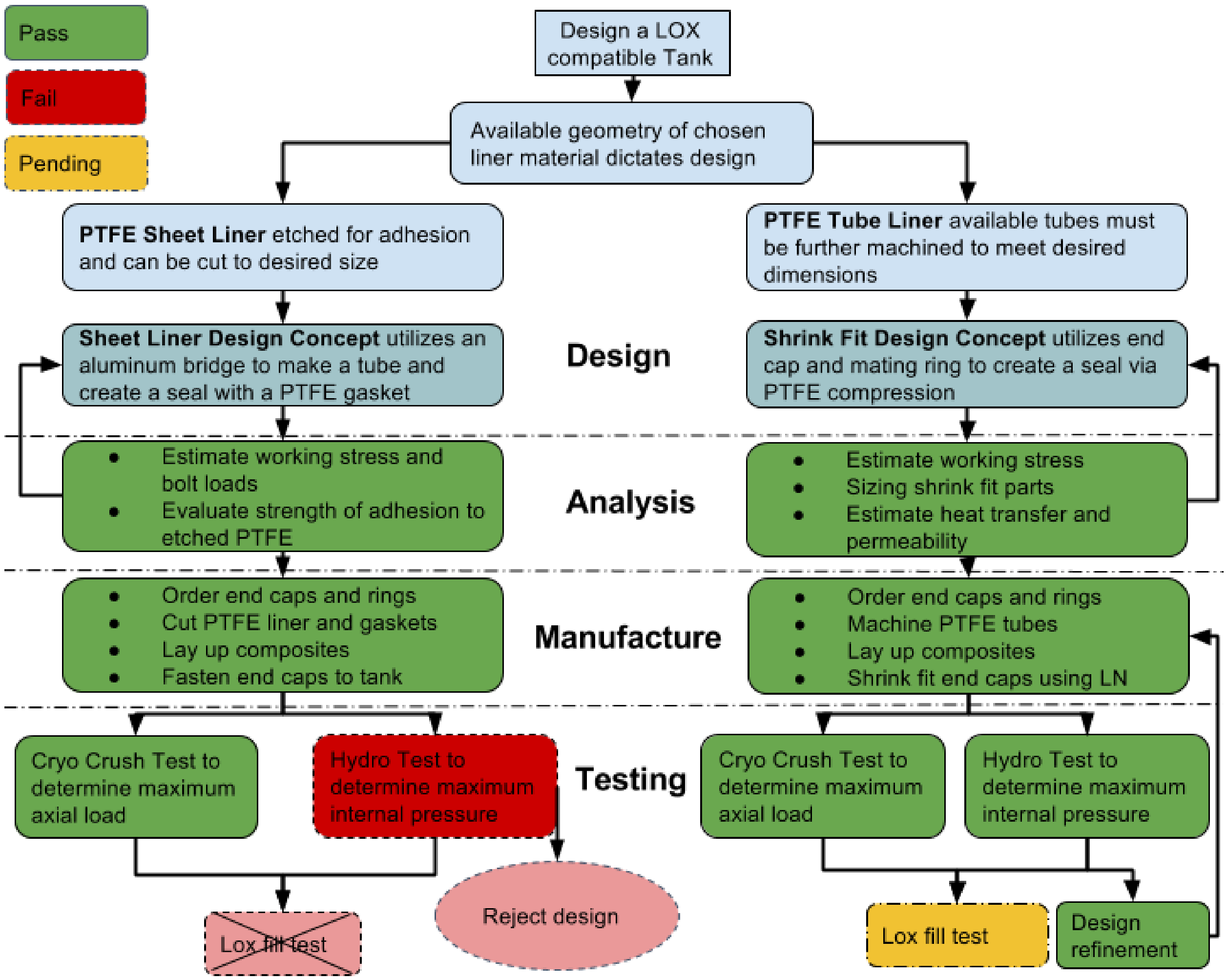

*Figure 4: **Flow Chart Outlining Tank Design Process and Outcomes***

4 Subsystem Highlights

4.1 Mating Rings

Figure 5: ***Shrink-Fit Mating Ring V1.0 CAD Design***

6061-T6 aluminum was chosen as the material for the mating rings. It is a common aircraft material due to its high strength-to-weight ratio. Aluminum also has no ductile to brittle transition temperature, giving it superior impact resistance at cryogenic temperature. The mating rings on the other airframe modules are also made of this material. This eliminates any concerns about mismatched thermal expansion properties and corrosion as a result of galvanic coupling at the interface between the tank and other modules.

The mating rings were designed to be the backbone that holds the whole design together. All other subsystem components connect to these parts. The carbon fiber and Nomex layers have no strength before curing, and therefore necessitated the use of a mandrel to wrap these materials into shape during compression molding, a process described in Appendix **??**. The mandrel must be removed after curing, which means the tank at this stage must have open ends. The rings have 12 threaded holes in a circular pattern that match a hole pattern on the end cap so that the two components can be fastened together with 3-48 screws. With the knowledge that hole alignment during the shrink fitting process would be important, a triangular keyway was added to the mating rings as a method of straightening the end cap during the shrink fit application so that all fastener holes are aligned once completed. An 1/8″ cylinder extends from the ring into the layers, providing a surface for the composite sandwich structure to adhere to, and an offset on the interior to seat the PTFE liner. A lip extending away from the tank was designed as a placeholder on the ring which will gain mating features to integrate the tank to the rocket's airframe.

4.2 End Caps

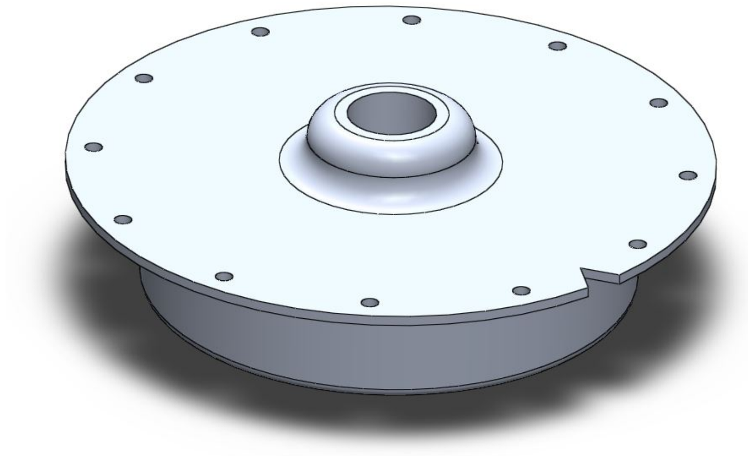

Figure 6: ***Shrink-Fit End Cap V1.0 CAD Design***

The material chosen for the end caps was 6061-T6 aluminum, which incorporated a 1/16" thickness plate with a rounded central portion to account for the addition of fitting valves. Twelve through holes were placed along the outer rim of each end cap, allowing fasteners to pass through and secure into the associated mating rings. In between these locations, a triangular cut was added in order to align with the keyway mentioned above, to aid in the shrink fitting process during tank fabrication. On the bottom portion of each cap, a longitudinal surface was recessed down into the tank, in order to provide a seal by compressing the PTFE liner in between this portion of the end cap against the mating ring.

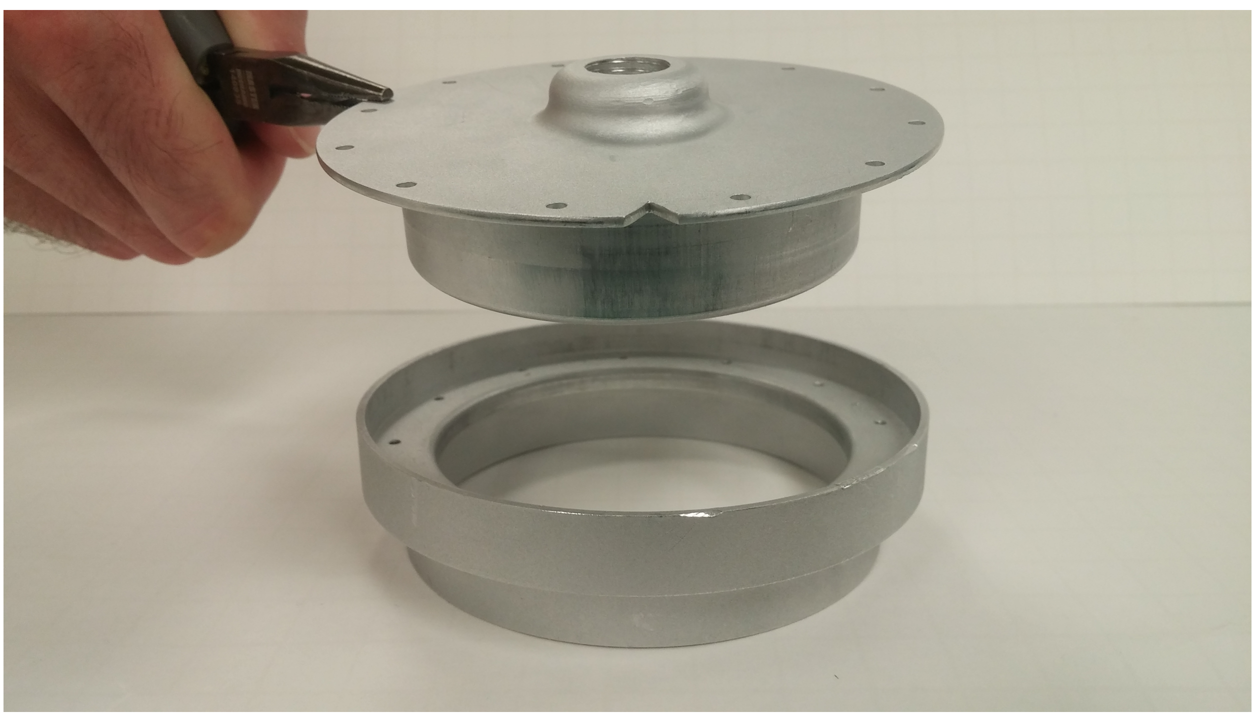

Figure 7: ***Shrink-Fit End Cap and Mating Ring V1.0***

4.3 Layering Configuration (Adhesive, Nomex, Carbon Fiber)

Carbon fiber material is advantageous in aerospace design due to its outstanding strength-to-weight ratio, which is far superior to that of metals [4]. The layering scheme used in our design was adapted from the airframe design developed for PSAS by the LV3.0 Capstone Team [1]. Three materials were donated to the team by PSAS. These were woven carbon fiber sheets, a 1/4"-thick honeycomb core material called Nomex, and a structural adhesive film designated Metlbond. Additional Nomex sheet in 1/8" thickness was purchased to accomodate the geometry of our mating ring design. Carbon fiber layers provide the tank with strength in the axial and tangential directions, and the Nomex layers provide strength in the radial direction. with structural support from external loads including the rocket's weight and thrust, and internal loads from the pressure of the oxidizer.

A 1/8" Nomex layer is placed just outside the PTFE liner, followed carbon fiber, then 1/4" Nomex, and another layer of carbon fiber. Structural adhesive is placed between each of the layers, and is the outermost layer to provide a smoother skin than carbon fiber (see Figure 8 and A).

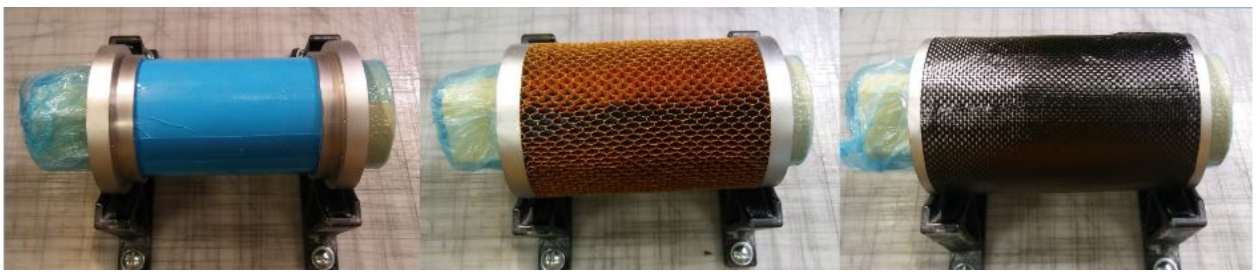

Figure 8: ***Material Layers (left to right): Metlbond Adhesive, Nomex Honeycomb, Carbon Fiber***

4.4 Liner Materials

Fluorocarbon polymers are particularly well suited to low temperature applications because they are the only known materials that retain a measurable ductility at temperatures very close to absolute zero (-269°C). This makes them ideal for use as insulators and as static seals at these temperatures [5].

The liner would have to survive the carbon fiber curing process or be integrated after laying up the structural shell of the tank. It would also need to be held in place by either an adhesive or some mechanical joining method. The team was provided with a structural adhesive that could be cured in tandem with the carbon fiber, so it made sense to place the liner and cure simultaneously. This decision to co-cure required that the liner material maintain integrity over the full range of temperatures between the boiling point of liquid oxygen (-183°C) and the curing temperature of the composite materials (176°C). Only two materials were found with these capabilities. They were ethylene tetrafluoroethylene (ETFE) and polytetrafluoroethylene (PTFE). Ultimately, PTFE was chosen on the basis of availability and cost.

4.5 Shrink Fit Seal

The sealing of the tank was accomplished with a shrink fit, which led to the overall success of the design. This was performed by submerging the aforementioned end caps into a LN_2 bath to sufficiently cool, and therefore shrink the radial dimensions of the cap. Simultaneously the layered module was heated in an oven to provide expansion to the mating rings. The end caps were then gently inserted, one end at a time, into the mating rings, and pressed into place with a dead blow hammer. The achievement of this process was that the PTFE liner was compressed between the two aluminum surfaces, effectively seating it so that it functioned as a gasket and formed a complete interior seal to the tank. This method was superior to previous design concepts that needed additional gaskets and had more potential leak paths. This sealing method also does not require any additional sealant or caulking, as it purely mechanical with no seams. It also eliminated the need to adhere the PTFE liner into place.

Axially oriented stainless steel fasteners help hold the end cap onto the mating rings. This was done as a redundant safety precaution, in case the friction force between the PTFE and aluminum proved insufficient.

5 Performance Summary

5.1 Manufacturability

Manufacturability was a major concern with this design. We were successful in developing a manufacturing procedure, but not without challenges.

The carbon fiber and honeycomb core layers that make up the structural shells of the tank came in woven fabric and sheet, respectively. Because of that, there needed to be something in place to hold their shape during an oven curing process. This aspect was adopted from the procedure developed by the LV3.0 Capstone Team, as previously mentioned. They made use of a cylindrical aluminum mandrel. Our innermost layer was the PTFE tube that served as the liner. We found no vendor that could provide us with tubes at the desired wall thickness, and had to develop our own method to produce a liner with proper dimensions. This solution involved the machining of a foam mandrel for use on a lathe (see Figure 9), which later served as the structural support during the curing process.

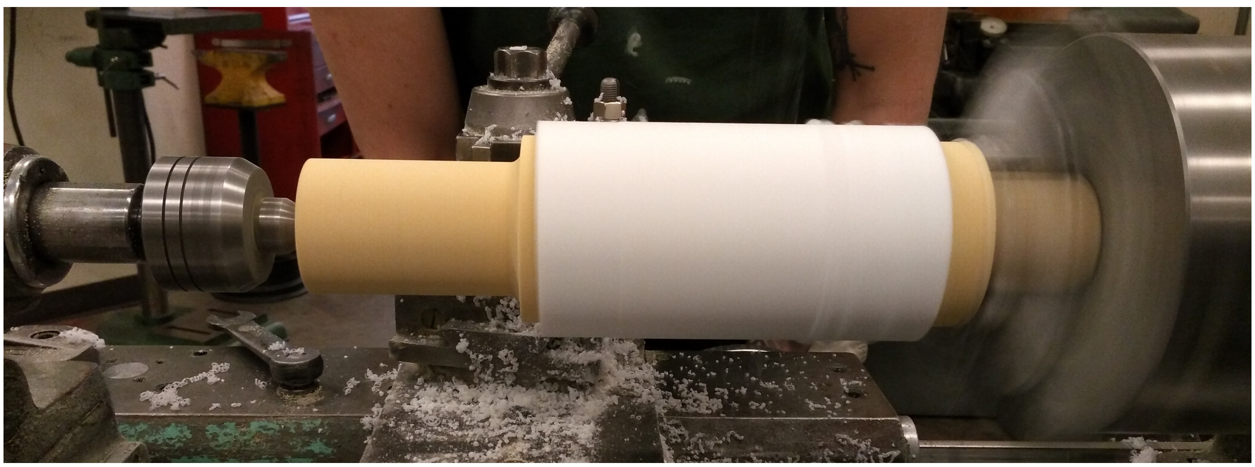

Figure 9: ***Turning down of PTFE tube on foam mandrel***

We chose to have our aluminum mating ring and end cap manufacturing outsourced due to the tolerances that needed to be met in order for the shrink fit to be successful. These parts worked well immediately, allowing us to prove the concept before spending time and resources learning how to machine high-quality parts at PSU.

Performing the shrink fit often required multiple attempts to align the bolt holes properly. In one case, parts were sacrificed as we were not able to abort the process quickly enough to separate them and make another attempt. To mitigate this issue, the design has been updated to allow easier alignment during shrink-fitting (see Figures 10 & 11) and new parts have been ordered.

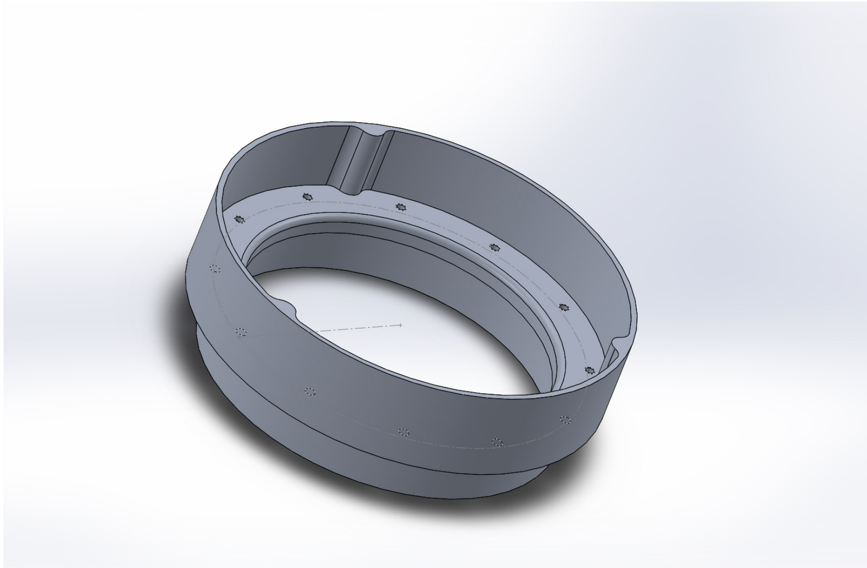

Figure 10: ***Updated Main Ring Design V1.1***

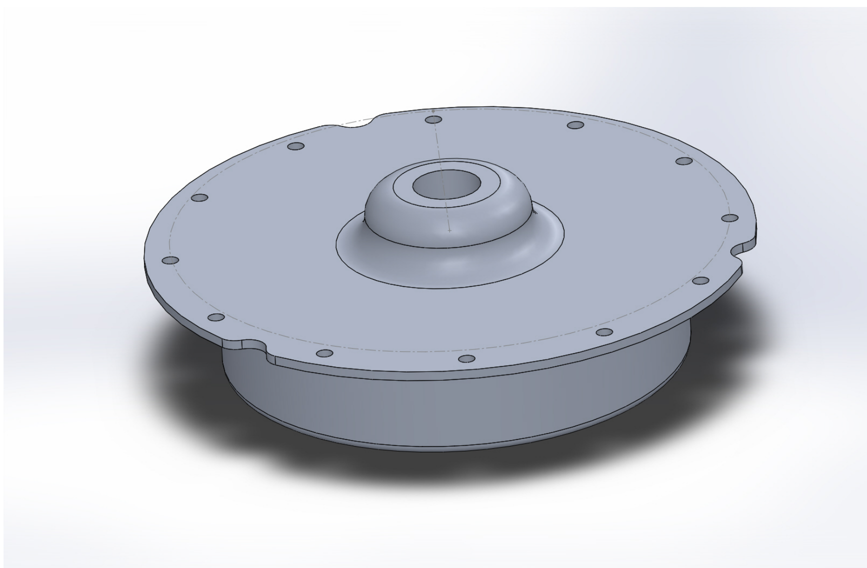

Figure 11: ***Updated End Cap Design V1.1***

This updated design includes extended keys and ring lip to better guide and seat the end cap, along with a smaller end cap through-hole for improved in-house threading.

A document which fully details the manufacturing process we developed can be found in appendix E.2.

5.2 Scalability

Scalability of the design components is not a difficult manufacturing issue, with the exception of the PTFE liner. We are confident that it will be possible to manufacture a 10″ machinable foam mandrel and turn a PTFE tube on it to the desired thickness with a large lathe. Our PTFE vendor does not provide tubes of this size, so further research is necessary to find them.

Analysis shows that when scaled up, the tank will perform as well, or better, than the proof-of-concept tank. Each analysis explored both a 3″ inner diameter and a 10″ inner diameter. These analyses are found in the supplemental design artifacts.

5.3 Cost

We were given an upper limit of $4000 for the total cost of the tank, excluding the donated materials. The final tank cost came out to just under $1800, with the outsourcing of mating ring and end cap manufacture. The total project cost and bill of materials for the final tank design can be found in Appendix G.

5.4 Testing Results

A hydrostatic burst test procedure (see Appendix F.2) was used to confirm the tank module would be able to withstand the design pressure of 3 atm. This initial test was run using water as the test fluid for safety reasons. We will continue to test successful designs using a cryogenic fluid such as liquid nitrogen (LN_2) and LOX at future stages of the development process.

Initial testing of the shrink-fit module returned promising results. There was no observable leakage until the internal pressure exceeded 100 psi. At that point fluid was observed leaking from the holes placed in the end-caps to attach plumbing fixtures. Therefore this test yielded a factor of safety of 2.2 satisfying the client requirement. The expectation is that with a few small alterations the design will be even more robust. Details of the subsequent alterations to the design, and the expected results, can be found in Section 6.

Figure 12: ***Hydrostatic Pressure Test Setup***

Many of the structural elements of the tank module were adapted from a previous capstone team. Due to their work there was adequate data concerning expected performance of the module under compressive loads at ambient temperature. Therefore greater emphasis was placed on discovering how the module would perform under cryogenic loading conditions. To investigate this, modules were filled with and submerged in LN_2, then crushed using a compression testing apparatus (test procedure in Appendix F.3). This test greatly exceeded expectations, resulting in the tanks surviving a compressive load of 9500 lbs before visual and audible failure. This well exceeded the expected operational loading of 900lbs, reaching a FS of over 10.

Figure 13: ***Shrink-Fit Tank Design V1.0 after Cryo-Compression Failure***

6 Final Status

The Final Tank design is shown below in Figure 14.

Figure 14: ***Final Tank Design, Shrink Fit Tube Liner V1.1***

The success of this project was due in large part to the fact that we pursued multiple designs in parallel. This allowed for some redundancy in the case that one design failed design criteria. This in fact occurred, and we were able to move seamlessly into focusing on the shrink fit design.

Achieving a successful shrink fit mitigated many of the concerns associated with the project requirements. This design lengthened leak paths and removed the necessity of gaskets or other sealing mechanisms. It also reduced the required bolt load subjected to the fasteners.

A key step in producing this design required obtaining the PTFE tube liner with the desired wall thickness mentioned above. Much time was spent looking for a supplier of PTFE that could produce such a tube, to no avail. This led to the development of our own process to manually machine a proper liner. This involved creating a machinable foam insert to maintain material integrity during the machining process. Not only did this insert provide structural support, but also reduced the heat transfer to the working material due to the porosity of machinable foam.

We were fortunate to identify a vendor which provided very quick lead times to produce rings and end caps. This enabled us to fabricate and test multiple design iterations.

We have shown that we exceed the design factor of safety for pressure at ambient temperature, and compressive load at cryogenic temperature. We believe our current design has the capability to meet the client requirements for all combined flight loadings. Because LOX compatibility has not been verified, additional testing must be performed. Due to the dangers concerning testing with liquid oxygen, we are working with PSAS and the Air National Guard to design and perform tests under proper safety procedures. For these tests to be meaningful they will need to be performed at working pressurized conditions.

Before any pressurized LOX testing is done a shrink fit tank should be pressurized with LN_2. There are various methods that have been discussed. One would be to use the hand pump we used to hydro test the tank. Questions arise about whether the hand pump will work and the accuracy of the pressure gauge at cryogenic temperatures. Another avenue is to fill the tank with LN_2 and seal it at both ends. As the LN_2 boils the pressure will increase inside the tank, and pressure as a function of time can be estimated and a burst pressure can be calculated.

It may be possible to achieve a stronger tank if the outside wall of the PTFE tube was chemically etched similar to the sheet liner, especially when a thinner tube is used. Stress calculations were done under the assumption of perfectly bonded surfaces within the layering. Due to the mismatched coefficients of thermal expansion between the various materials, being able to adhere the PTFE to the layering scheme would mitigate any potential deformation or shifting of the liner.

When working with PTFE at cryogenic temperatures we observed that when thermally cycled the PTFE does not recover to its original dimensions when brought back to ambient temperatures. This leads to the recommendation that the PTFE be thermal cycled before any machining is performed. This will allow for a better fit and less variability in manufacturing of the tank.

There are a few things that could have been accomplished which would have resulted in further progress regarding this project. As stated earlier, much time was wasted attempting to locate PTFE tubes of a desirable wall thickness. If we tried machining the tubes ourselves earlier we could have begun the manufacturing process sooner. This would have resulted in more testing and further refinement. Much of the wasted time was due to unresponsiveness of some suppliers.

Additionally, organizing liquid oxygen testing at an early date would have been immensely helpful. Due to the dangerous nature of LOX, it takes a substantive amount of time to prepare, develop, and organize proper tests which can be conducted safely. Doing this early on in the project would have allowed LOX compatibility testing to be within the scope of the project work.

Though the scope of work on this project temporarily comes to a close, development will continue. Design iterations and further testing have already been scheduled, and further progress will be made in the coming months leading up to integration and launch of this fuel tank by PSAS. Following the recommendations above will allow for a much smoother replication of the work detailed in this report.

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[1] PSAS, "PSAS LV3 Airframe Github." [Online]. Available: https://github.com/psas/lv3.0-airframe 1, 4, 10, 33

[2] D. Pettit, "NASA - The Tyranny of the Rocket Equation," 2012. [Online]. Available: https://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.htmlhttps://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html 2

[3] G. N. Mangurian, "The Aircraft Structural Factor of Safety," Tech. Rep., 1957. 3

[4] W. D. Callister, *Materials science and engineering : an introduction*. John Wiley & Sons, 2007. 10

[5] Zesus, "Low Temperature Properties of Polymers," *Key Engineering Materials*, vol. 59-60, pp. 35–46, 1991. 10

Appendices

A Supplemental Images

A.1 Layer Assembly Sequence

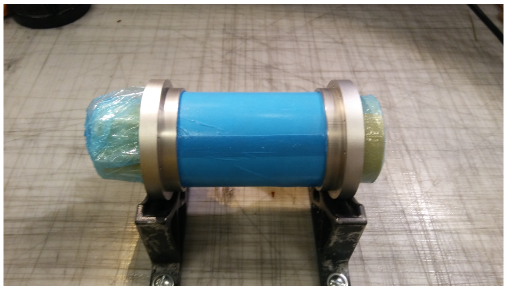

Figure 15: ***First Layer: PTFE Tube with Metlbond Layer***

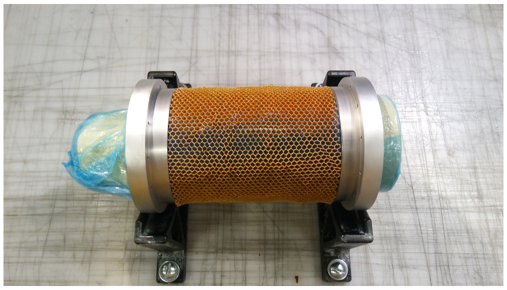

Figure 16: ***Second Layer: Nomex Honeycomb***

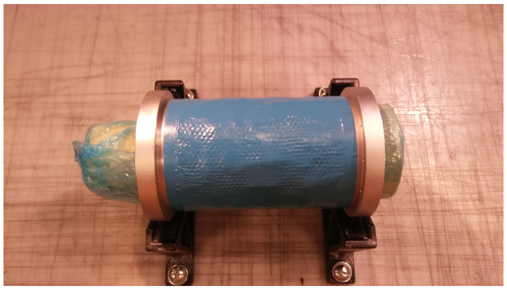

Figure 17: ***Third Layer: Metlbond Layer***

Figure 18: ***Fourth Layer: Inner Carbon Fiber Layer with Metlbond Layer***

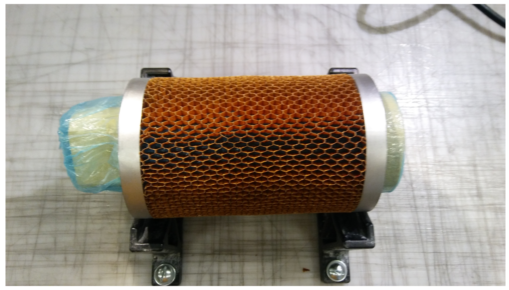

Figure 19: ***Fifth Layer: Outer Honeycomb Layer***

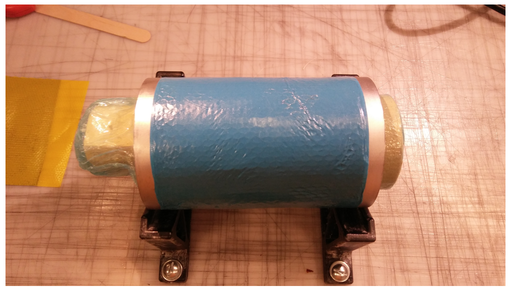

Figure 20: ***Sixth Layer: Metlbond Layer***

Figure 21: ***Seventh Layer: Outer Carbon Fiber Layer***

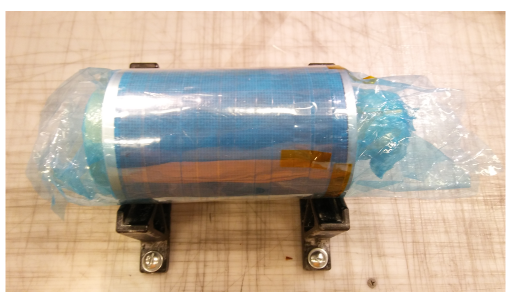

Figure 22: ***Eighth Layer: Shrink Tape over Release Film Layer***

Figure 23: ***Vacuum Sealed Tank Layers in Autoclave***

B Catalog of Design Artifacts

The following is available at `https://github.com/psas/composite-propellant-tank`:

- Readme (Summary of Project and Design Artifacts)
- Analysis
  - Calculations (Hand Calculations and Python Scripts)
  - Finite Element Analysis (Code, Results, and Documentation)
- CAD
  - Archived Designs
  - Current Designs
- Design Ideas (Notes and Concept Drawings)
- Materials (Material Data Sheets and Property Information)
- Manufacturing (Procedural Documents Outlining Manufacturing Methods)
- General Documents (Project Meta Documents, Capstone Class Documents)
- Research Documents (Literature Review Documents)
- Resource Documents (How Tos and Readme documents for Git, Jupyter, etc.)
- Safety (Documents Outlining Safety Procedures)
- Tests (All Test Documentation)
- Presentations (Documentation from Team Presentations)
- Finances
  - Budget
  - Bill of Materials
  - Quotes
  - List of Suppliers and Industry Contacts

  - Grants and Awards
- Misc. and Photos (Miscellaneous Content and Un-catagorized images)
- Team Roles
- Standards of Documentation
- Master Meeting Notes
- Contacts (Contact Info of Individuals Related to Project)

C Concept Analysis

C.1 Concept Selection Process:

The requirement constraints of this project, along with available manufacturing, material, and financial resources, restricted the concept design to a cylindrical tank assembly with a carbon-fiber composite body. This occurred fairly early on in the concept selection process and was not heavily debated due to its lack of viable alternatives. However, the identification and design of tank subsystems was very much up for debate and the following sections describe designs that were considered, as well as justifications for our final design decisions.

C.1.1 Liner

A chemically-insulative liner was quickly identified as a necessary subsystem to prevent LOX from making contact with the carbon-fiber epoxy resin in the tank walls (a known reactant). Although the project contract stated our intention to use a polymer to line the tank, we did briefly consider the use of a very thin aluminum or titanium liner. We made decisions using a discussion and voting format as opposed to scoring matrices. The thin metal liner concept was abandoned because it would require a forming process that would likely require the manufacture of a die, which would be expensive and lock us into one size of liner. PSAS recommended we use PTFE, but we also considered ETFE and PCTFE. All three are known for their chemical inertness, which is necessary to avoid weathering in the highly oxidizing environment to which they will be subjected. ETFE has the lowest oxygen permeation rate, but was not selected because its recommended working temperature is only 1 °Cbelow that boiling point of oxygen, where PTFE has a permeation rate similar to most thermoplastics, and remains ductile at working temperature (-183 °C), and according to Dupont, as low as -268 °C. PCTFE has the highest strength, but also has the highest glass transition temperature at 45 °C, so we abandoned it due to concerns of cracking due to the low temperature and high stress application. For these reasons, we chose to line the tank with PTFE.

It was then necessary to decide on a method of applying PTFE to the inner surface of the tank. We first considered spray-on coatings and rotomolding. Both require that the tank be made and sent somewhere to have the liner added, or that we build or purchase equipment to deposit it ourselves. The curing process for these applications exceeds the working temperatures of the METLBOND, used to adhere the structural layers to one another as well as to the end caps of the tank. Those methods also use a granulated resin, which increases the porosity of the liner and has a negative impact on oxygen permeability and strength. We decided that the best solution was to purchase tubing with a specified inner diameter to be incorporated into the layup process. This decision has the added benefit of providing more control over, and better uniformity of, the liner thickness.

After contacting several PTFE providers, we were informed that the minimum thickness of an affordable 3″ ID x 5.25″ tube is 1.5 mm (the manufacturer that promised to produce this thickness has since failed to do so, leading us to develop our own manufacturing methods E.2. Since 1.5 mm was our lower thickness limit for a PTFE liner, a brief analysis of permeation was performed to get an idea of how much oxygen could make contact with the carbon fiber epoxy resin over a 3 minute flight duration. The approximate volume of oxygen at 3atm that will have permeated through the PTFE liner after 3 minutes at room temperature is 0.035 cm^3 . Since permeability increases exponentially with temperature, and our tank will be operating at cryo-temperatures, it is expect oxygen permeation to be negligible, and therefore risk of fire to also be negligible. Our research has produced no data quantifying the concentration of oxygen necessary to cause epoxy resin combustion, and the flammability of the material is debated within the aerospace community, however, the carbon-fiber layer is not impermeable, and a slow diffusion of oxygen through the PTFE liner is expected to diffuse into the atmosphere eventually.

C.1.2 Tank layers

To build upon the work of previous capstone teams, the outer layers of the tank have a design similar to the skin of the rocket. We had some flexibility in terms of how many layers we use, and how thick the Nomex core can be, but to avoid "reinventing the wheel," we did not overhaul the general lay up design.

The first tank design included the 0.06-inch PTFE liner as the innermost layer, followed by a 0.01-inch inner layer carbon fiber fabric, a 0.1875-inch layer of Nomex, and a 0.01-inch outer layer of carbon fiber fabric. Metlbond structural adhesive film is used at each material interface. The rings are attached by 0.015-inch thick extensions lapped between the liner and inner carbon fiber layer.

A simplified steady heat transfer analysis was performed on a multi-layered cylinder to simulate conduction through the composite layers and determine the time it would take for a full tank of liquid oxygen to boil off and empty the tank. Convection and radiation heat transfer effects were neglected and the material properties were assumed to be constant. The Nomex honeycomb layer is considered to be made of mostly air and its conductivity was assigned accordingly. Since PSAS launches their rockets in Brothers, Oregon in the middle of the summer, the temperature of the carbon fiber at the outer edge of the tank is assumed to be at equilibrium with the ambient air temperature at 38 °C. The temperature of the tank's PTFE inner layer is assumed to be at equilibrium with the liquid oxygen at -183 °C. The total thermal resistivity of the composite layers was determined to be 5.42 K/W and the heat transfer rate was 40.77 W. Assuming steady operating conditions, the heat transfer rate into the tank was equated with the latent heat of vaporization and the rate of evaporation is determined to be 0.1905 g/s. For a 596 cm3 tank with 680 g of fuel, the approximate time to boil off all of the liquid oxygen was determined to be 1 hour. See Table 2 for material properties, complete calculations can be found in the provided design artifacts under Analysis/Calculations.

To gain insight into the tank's ability to withstand the stresses due to internal pressure and thermal expansion, a general analysis of strain in multi-layered cylindrical pressure vessels was performed. The basic concept is that the total strain in each layer is the sum of the pressure strain and the thermal strain, and that the layers are bonded together so that the strain in layers are equal at the interfaces. An initial calculation was done for the materials and layer thicknesses of the 1/32″

Table 2: Important Material Properties

Material	O_2 Permeability at 25 ℃ ($cm^3cm/(cm^2Pa{\cdot}s)$)	CTE (10^{-6} in/in/°F)	Yield Stress (psi)	Young's Modulus (psi)	Heat Conductivity (W/m-K)
PTFE	3	48	16000 (at -320 °F)	80100 (at -320 °F)	0.25
6061-T6	-	13	40000	10150000	167
Carbon Fiber	-	-1	500000(UTS)	25375000	0.5 - 0.8
NOMEX	-	19.4	No Data	493000	0.07
Air	-	-	-	-	0.026

liner design, and it was shown that the layer with the lowest factor of safety, 1.67 based on yield strength, is the inner carbon-fiber layer. This analysis does not account for the end conditions of the cylinder or the stress concentration at the end of the aluminum extension that is lapped between the liner and the inner carbon fiber layer.

C.1.3 Rings

The final tank must mate with the rest of the rocket. A mating ring that connects airframe modules was designed for PSAS by a previous capstone team. Our design features rings that can later be given these mating details, but our main goal is to prove the tank can hold liquid oxygen at the specified pressure, so these details are being left out in the interest of saving time.

Each member of the group was asked to make several concept drawings of ring and end cap geometry (example shown in Figure 26), with a focus on securing end caps and other module rings, and positioning the aluminum lapping area between material layers. We met and voted on which designs we would move forward with, and narrowed the options down to two. The first used fasteners oriented in the axial direction and sandwiches a gasket between the end cap and mating ring. The second used threaded surfaces and teflon tape. Ultimately, we decided to move forward with a design incorporating fasteners. This decision was made based on manufacturability of a scaled up tank. While it is possible to cut threads on a 3-inch prototype, threading 11-inch diameter cylinders is not practical. To achieve a small pitch, the lead angle would need to be extremely small. If it is possible, it is unlikely that student groups like us would have the skill to machine such threads, and outsourcing this machining operation would likely be prohibitively expensive.

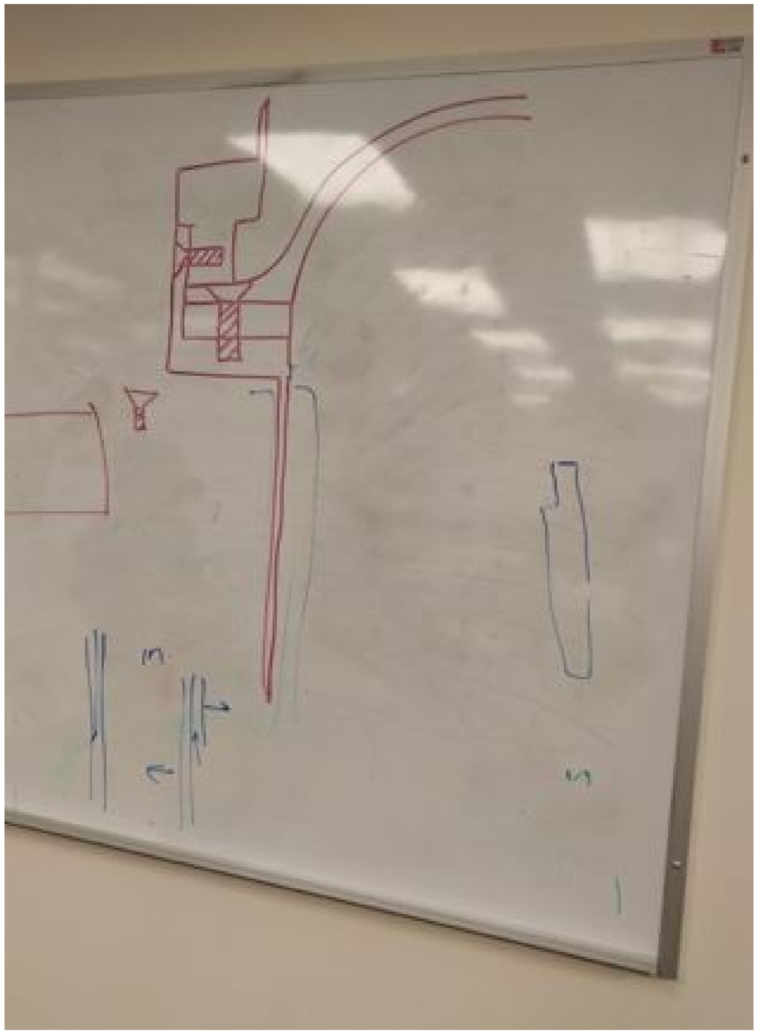

Figure 24: ***Example Rejected Concept Design Drawing***

Another design consideration was the location of the lapping portion of the aluminum rings. We elected to position this feature so that it directly interfaces with the liner to create as much of a barrier between the carbon fiber and fuel as possible. Our reasoning for placing the liner inside this feature is that the aluminum has the greatest coefficient of thermal expansion, and will contract to pinch the liner. If we were to place the liner outside the aluminum lap, the difference in thermal contraction coefficients would act to separate the aluminum from the PTFE.

It would have been ideal to have the end caps and rings be combined into one part, but during the layup process that we have been taught by members of the PSAS airframe team, the carbon fiber has to be cured in an oven under compression to prevent air pockets in the structural adhesive layers. A mandrel is used for support during this process, and could not be removed if the end caps were not separate. The lapping feature is offset from the inner edge of the ring by the thickness of the liner, allowing the liner to fit inside the ring on the mandrel. The rings also feature threaded holes to fasten end caps onto the cylinder.

C.1.4 End Caps

We originally considered a curved end cap design, shown in Figure 25, was created under the assumption that "rounder is better," and that a dome shape would minimize stress concentrations. We understand now that the area where the dome portion meets the flange portion is a stress concentrator, and that the interface between the end cap and ring is far more likely to fail than the end cap itself, especially at an internal pressure as low as 3 atm. We eventually abandoned, since this geometry is going to be very challenging to machine. A brief discussion of what we are going to consider is located later in this document. The current design features countersunk holes for the fasteners, a design element that is likely to change, since it is not necessary to have them flush with the top surface of the tank. We have not yet begun to incorporate fittings for plumbing into the design. Gasket

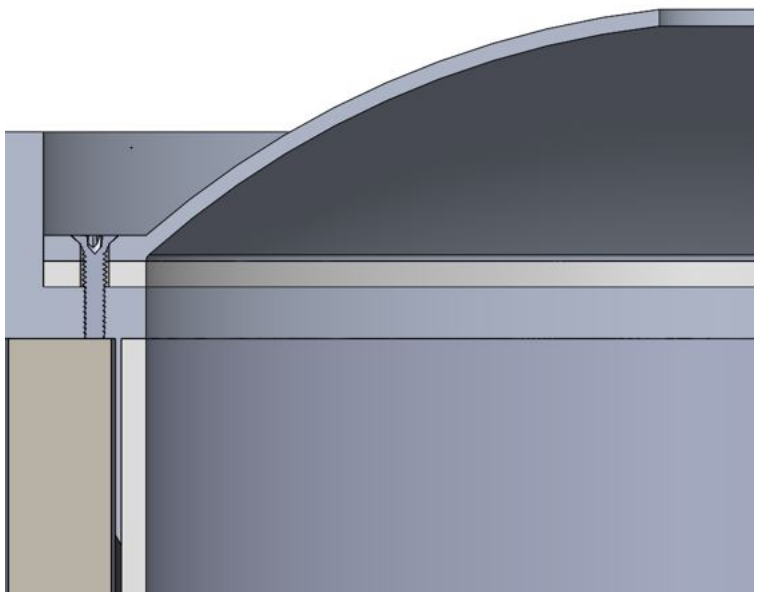

Figure 25: ***Rejected Curved End Cap Design***

The current design uses 24 0-80 x 0.25″ flat head machine screws, 12 for each end cap. They were chosen simply because they were the smallest fasteners available, and need to fit in the flange area of the end cap. As mentioned in the discussion of the end cap design, the final fastener type is likely to change to a bolt to eliminate the need to countersink holes, and increase the volume of the frusta in the clamped material so that the bolts carry less of the load. For now, we have done a bolt stress analysis, and found that 12 0-80 x 0.25″ bolts on each end cap are sufficient to carry our expected load, with a factor of safety of 1.7. A detailed analysis can be found in design artifacts.

One of our greatest concerns has been whether or not the Metlbond adhesive would be able to hold up under the various stresses it will be subjected to, as previous PSAS capstone teams only subjected the material to compressive testing. There is a lapping portion of our ring design that will be covered in this adhesive to hold all subsequent layers together, as noted in the ring design section above. It was necessary to test the strength of this adhesive between etched PTFE and aluminum, as well as carbon fiber and aluminum. This required the fabrication of material coupons for both tests. Coupons were created by cutting pieces of each material to a specified area, securing the materials in place using the Metlbond adhesive, and subjecting them to the curing process. The bonding zones of each coupon were kept consistent by 0.25″ x 0.25″ squares of

Metlbond adhesive for the coupons being tested by our manual apparatus, and 1″ x 0.25″ pieces for testing with the apparatus in the lab. The size of the PTFE interface was controlled by cutting strips 0.25″ wide. Following assembly of each coupon, the batches were wrapped in a release film and breather material, then subjected to curing temperatures inside a vacuum bag. This is the same curing process that we plan to use when building the tank. The completed test coupons can be seen in Figure**??** below.

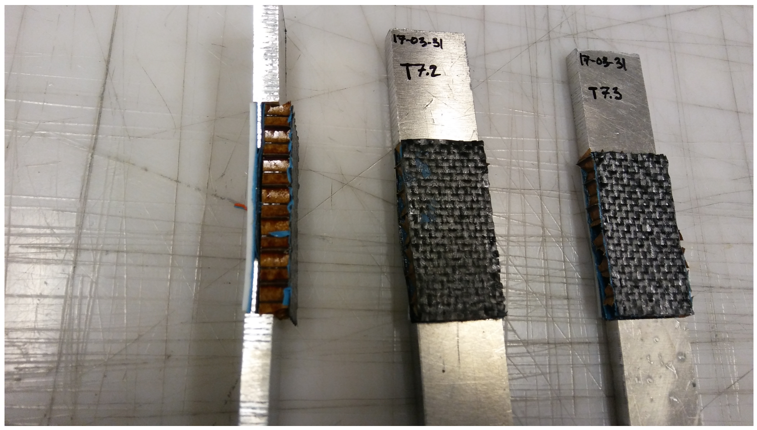

Figure 26: ***Metlbond Shear Stress Coupons***

To perform the manual tensile testing experiment, an apparatus was assembled using a support frame, steel rod, an assortment of hooks and chains, a 6 gallon bucket, 30 gallon bin, scale, and a water source to provide weight. The testing coupons were hung from the steel rod, and connected to a hanging 30 gallon bin which was then filled with water until the coupon failed. After failure, the testing apparatus was then weighed on a scale to determine the force at failure. This was then translated to an engineering stress to be compared with given strength values of each material. This data will be compared to the Laboratory data once that portion of the experiment has been completed.

C.2 Identification of Potential Design Problems:

We believe the most likely sources of problems will be thermal expansion mismatches at cryogenic operating temperatures and the possibility of the fuel oxidizing the structural adhesive. The large difference between curing temperature and operating temperature and the mismatch of thermal expansion properties will cause our materials to push and pull on each other, resulting in additional stresses occurring at material interfaces.

Oxidation causes many materials to deteriorate, and the effect of LOX on Metlbond remains unknown. We will test the integrity of the adhesive and other exposed materials after thermal cycling, and eventually after exposure to LOX.

C.3 Sheet Design

The sheet design has a 1/32″ thick PTFE liner. PTFE is known for having a very low coefficient of friction with nearly all other materials, making it very difficult to adhere to the other tank components. To overcome this, the liner material was chemically etched on the outside and then wrapped around a mandrel and secured into a cylindrical shape using a structural adhesive film known as Cytec Metlbond. A 1″-wide bridge made of 1/32″ aluminum sheet was employed along the outside of the seam to seal it. An inner layer of woven carbon fiber fabric, followed by a 1/4″ layer of honeycomb patterned core material known as Nomex, and an outer layer of the same material as the inner layer were then wrapped over the liner, with adhesive film between each layer. Support structures were needed at the ends of the carbon fiber body to hold the layers in place during curing of the carbon fiber resin and adhesive, and during removal of the mandrel. This was accomplished via a thin cylinder that extended out of the rings by 1/2″. This cylinder was sandwiched between the liner and structural layers. These structures also provided a way to fasten end caps onto the tank and space for future module mating features. Henceforth, these structures will be referred to as mating rings. End caps were necessary to close the tank and are enclosed within the rocket airframe. They feature holes for plumbing fixtures, and are each fastened to the mating rings with 12 axially aligned 3-48 stainless steel screws. 6061-T6 aircraft aluminum was chosen as the mating ring and end cap material. This design decision is detailed in section 4.1. The interface between the mating rings and end caps provided an escape path for the LOX, necessitating the use of a gasket. Again, PTFE was the chosen material here. The layup procedure for this design can be referenced in Appendix E.2.

C.4 Tube Design

The second design employed a virgin PTFE tube with a 1/8″ wall thickness for the liner. Similar to the sheet liner design, the liner slid over a mandrel and subsequent materials were laid up onto it. Rather than being glued into place, the liner was held in place by radial compression between a support ring and an end cap. The support rings, henceforth referred to as mating rings, include a 1/2″-long cylindrical extension that fits between layers of carbon fiber and a honeycomb patterned core known as Nomex. This extension is 1/8″-wide to have adequate strength to compress the liner from one side. Therefore, a 1/8″-thick layer of Nomex rests on the outside of the liner so that its outer diameter is flush with the outside of the ring extension. The next layer is woven carbon fiber, followed by a 1/4″-thick layer of Nomex, and a final outer layer of carbon fiber. Thus, the mating rings serve three functions. They provide space for features to be added later that will mate with other airframe modules, they are a solid material to fasten the end caps to, and they are a backing for the compression of the liner. The end caps are round, flat plates with threaded holes in the center for plumbing. They are held in place via 12, axially oriented 3-48 stainless steel screws each, which thread into the mating rings. The end caps also feature an 1/8″-thick cylindrical extension similar to those described in the mating rings that serve the same purpose. After thermally contracting the end caps, they slide into the ends of the tank and expand outward to press the liner against the mating ring extensions. The gap allowed between the end caps and rings is sized so that it is slightly thinner than the liner. A keyway was employed to ensure alignment of the screw-holes.

Using an altered ring/cap design to provide a shrink fit in order to seal the tank. Tubes were purchased at a 0.25″ wall thickness, wall thickness to be incorporated into a layup. (something along the lines of the difficulties or something regarding this issue, then referencing more detailed description below in subsystem highlights of manufacturing process developed to solve this issue) Coupled with this ring and endcap design, the tube was inserted between the mating rings, with the end caps secured using a shrink fit to compress the cap onto the PTFE tube liner to provide a seal on the tank. The material layers used in the sandwich layering were 2 layers of carbon fiber, one layer of 0.25″ overexpanded nomex honeycomb, and one layer of 0.125″ nonexpanded nomex honeycomb on the interior layer of the tank to account for the thicker 'lapping portion' of this mating ring design. The layup procedure for this design can be referenced in Appendix E.

There are two major advantages to this design. The first eliminates the extra seam caused by wrapping the PTFE sheet, which provides a more uniform interior liner. The second is that it does not require PTFE etching, or the addition of sealant along any interior edges or seams of the tank.

D System-Level R-M Matrix

System requirement-measurements for Cryogenic Tank

		Units	atm	lb	$	% (hours of manufacturing)	$	y/n
		Performance measures	Burst Pressure	Buckling Load	Cost of tank after development	Percentage of tank manufactured at PSU	Cost of machined parts	Documentation of manufacturing and Testing procedures provided to PSAS
	Target design requirements for Cryo-Tank		1	2	3	4	5	6
1	The Tank can hold liquid oxygen without bursting into flames	9	x	x				
2	The Tank is affordable	3			x	x	x	
3	The Tank is reproducable	9			x	x	x	x
4	The Tank doesn't leak	9	x	x				
5	The Tank is made of donated composite material	9			x	x		
7	The Tank shall withstand stress resulting from temperature, pressure, and vehicle body loads	9	x	x				
8	The Tank is scalable for larger rocket design	9			x	x	x	x
			27	27	30	30	21	18
		Lower Acceptable	6	1800	-	50	-	yes
		Ideal	10	-	1000	100	0	-
		Upper Acceptable	-	-	4000	-	2000	-

E Subsystem Manufacturing

The functionality of the tank design is dependent upon all the subsystems working in tandem. Meaningful testing could only be performed at the system-level, therefore no requirement matrices and performance evaluations were made at the subsystem-level. Further subsystem performance evaluation would be anticipated at later full-scale tank design stages, when weight and strength optimization is expected to occur. Performance improvement at the subsystem level occurred primarily through the development of improved manufacturing procedures, outlined below.

E.1 Liner

We were unable to find a vendor for PTFE tubes that could provide them with wall thicknesses less than 1/8″. All vendors told us that part deflection would be too much of an issue, and our tubes would not be uniform. Those that claimed to be able to provide 1/8″ walled tubes delivered products that did not meet the dimensional specifications outlined in the order. For these reasons, we needed to develop a process to reduce the wall thickness of the tubes we were provided.

The concept of pressing the PTFE tube tightly onto a support mandrel and turning the outer diameter of the tubes down on a lathe was introduced. Metal mandrels did not dissipate heat generated by the cutting quickly enough, and the tube would expand and lose grip on the mandrel, resulting in slipping and tearing of the material. This was overcome by changing the mandrel material to machinable foam. The foam is porous, and has a rough surface so that it maintains grip of the tube.

Early attempts had the mandrel supported at one end by the chuck on the spindle of the lathe, which resulted in a lack of concentricity and a nonumiform wall thickness in the tubes. Supporting the other end with a live center resolved this issue.

The following is the procedure for making the mandrel and turning 3″ tubes, in its current form. It can serve as a guide for anyone attempting to do this at a larger scale, and the numbers can be adjusted to suit those scenarios.

Obtain a piece of machinable foam that is about 4″ x 4″ x 12″. The extra material allows for some error when you begin cutting away material. Locate and mark the centers of each of the ends. Turning will be easier of you can trim down the corners as shown in Figure 27. We did this with a band saw. At one end, remove some material, leaving a 2″ knob that is narrow enough to fit into the chuck of your lathe. It should look similar to Figure 27. The next step will be turning the foam until you obtain a cylindrical shape.

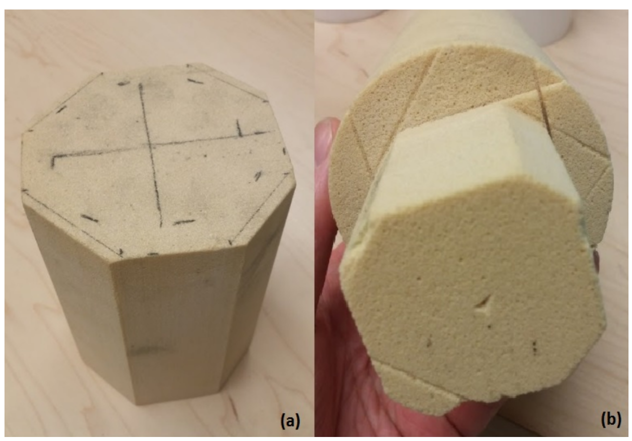

Figure 27: ***(a) machinable foam prior to turning into cylinder; (b) Knob to secure into chuck***

Secure the knob end into the chuck, attempting to orient the foam such that its central longitudinal axis is shared with the axis of rotation of the spindle. Place a live center into the tail stock of the lathe and slide the tail stock toward the part until the live center sinks about a centimeter into the foam. Secure the tail stock into its position on the ways.

We recommend running the spindle at about 300 rpm. Machinable foam cuts very easily, so any cutting tool material will work. A rounded cutting tool will make the job go faster than a pointed one. The foam does not produce chips like other materials, but rather produces powder, so it advisable to wear a mask and run a shop vac to catch the majority of this material as you cut. You should be able to cut about 0.05″ off the diameter per pass. Periodically measure the outer diameter until you get it down to about 3.05″. At this point, begin taking 0.005″ per pass and attempting to force the tube about a centimeter of the way onto it. This will require you to move the tail stock out of your way each time. It is important for the tube to be very tight now because the tube will get easier to stretch and remove as material is cut away. Once you have reached the desired outer diameter, begin turning down the diameter a little bit further on a few inches of the tail stock end so that later you can face the tube without cutting into the mandrel. Make sure that at least 6″ of the mandrel remains at the outer diameter cut for the tight tube fit. Afterward, you should have a foam mandrel that looks like the one pictured in Figure 28.

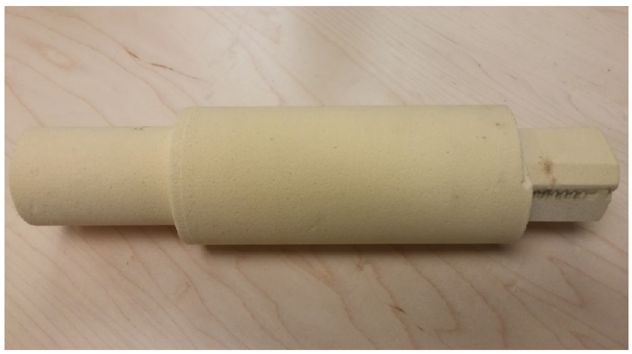

Figure 28: ***Finished machinable foam mandrel***

The tubes we ordered came in 12″ lengths. The tank uses a 5.25″ liner, so each tube needed to be cut into two 6″ lengths. We did this on the band saw.

Leaving the mandrel in the chuck, press the tube onto it so that about a centimeter hangs over the reduced diameter portion of the mandrel and face the tube using a pointed tool. PTFE can also be cut with the spindle running at 300 rpm. After facing, push the tube the rest of the way onto the larger diameter portion of the mandrel as shown in Figure 9. The closer it is to the spindle, the better the finished part quality will be. Using a rounded cutting tool, begin cutting away material at a rate of 0.015″ - 0.02″ per pass. If you are getting tiny chips, increase your feed rate. If you are getting long strings that wrap around the part, reduce your feed rate. Periodically check the wall thickness until you reach the desired dimension. Then, remove the tube from the mandrel and turn it around so that you can face the other end.

E.2 Module Manufacturing Procedure

Purpose and Scope: The intent of this procedure is to provide direction for the fabrication of a proof-of-concept shrink-fit fuel tank prototype module. The tank assembly process can be found in a separate document.

Tools and Equipment: The following materials and equipment should be collected and on hand at the beginning of the lay up procedure:

- Machinable foam mandrel (3″ OD)
- Aluminum Mating Rings (qty 2)
- Aluminum End Caps (qty 2)

- Templates for inner carbon fiber, Nomex, and Metlbond adhesive layers (qty 3)
- Templates for outer carbon fiber, Nomex, and Metlbond adhesive layers (qty 3)
- Template for inner lapping portion of the mating rings adhesive layers
- Nomex honeycomb material (1/4″ and 1/8″ thick)
- Carbon fiber
- Goop tape
- Shrink tape
- Kapton tape
- Release film
- Acetone compound for cleaning
- Sandpaper (3 different grits 320, 800, and 1500)
- Vacuum bag material and breather cloth
- PTFE tube machined to 1/8″

Facility Equipment:

- Exhaust fans or hoods
- Freezer (for storage of materials)
- Oven (for curing process)
- Vacuum pump
- Heat gun (preferably with variable temperature control)
- Small plastic tubs or paper cups for water (for sanding)
- Circular razor blade
- Workstation equipped with risers on which you can perform the layup procedure

Safety:

- Gloves (nitrile or latex) should be worn at all times to avoid contaminating working materials. Some materials are hazardous upon contact.
- When using possibly hazardous materials (cleaning agents, etc) have exhaust fans in place and operating or work under an exhaust hood.

Initial Tips/Suggestions:

- Staying clean and organized is very important.
- A heat gun is critical for dealing with the adhesive film (METLBOND). However, be careful to keep it on the lowest setting as the adhesive becomes difficult to handle as it warms up.
- Adhesive film (METLBOND) can be difficult to from the backing (orange side), especially while wearing gloves. You can use a tongue depressor or razor blade against the edge after adhering it in place. Remove the orange side first, leaving the removal of the white side until you have positioned and adhered the layer.
- Take care when placing the carbon fiber as the adhesion with the METLBOND is strong and nearly instant.
- When cutting the carbon fiber sheets, take care to stay in line with the fiber as this will provide a stronger final structure.
- When creating the templates, cut them long enough to allow for some overlapping (¼”) of the adhesive and carbon fiber layers.

General Requirements: This preparation procedure only reflects the steps taken in the creation of modules for testing. It does not address the steps that should be taken to prepare the aluminum parts for long term exposure to the carbon fiber and adhesive layers. For information regarding flight-ready fabrication of these parts refer to the aluminum mating rings procedure followed by the 2014 PSAS LV3.0 airframe team[1].

Materials:

1. Use the templates to cut all of the required carbon fiber, Nomex, and adhesive layers before beginning any work (place in freezer until needed to preserve adhesive properties).
2. It is critical to ensure that all work surfaces are clean. This includes all workbench surfaces and the surrounding floor space.
3. Arrange multiple workstations, each for a specific task to help expedite workflow.
4. Clean all the metal tools and part surfaces using acetone. All cleaned surfaces should leave no visible residue on a towel when wiped clean.
5. Carbon fiber: Cut one layer CF using “outer layer” template, cut roughly 2 fibers oversized. Cut one layer CF using “inner layer” template, same oversizing objective.
6. Nomex: Cut one layer from the ” thick Nomex using “inner layer” template. Cut one layer from the ¼” thick Nomex using the “outer layer” template.
7. METLBOND: Cut two layers using “outer layer” template, three layers using “inner layer” template. Cut 2 strips using “ring” template.

Aluminum Rings and End Caps:

1. Use the 320 grit sandpaper to sand the outer edge of the end cap until it fits easily into position in the mating ring (check this with the end cap upside down to avoid getting the shrink-fit portions of the design stuck together).

2. Sand the interior and exterior surfaces of the lapping section of the mating rings progressing from the 320 grit to the 800 grit and then to the 1500 grit sandpaper removing the tooling marks from machining.
3. Using the 1500 grit paper only, sand the interior shrink-fit surface of the mating rings (this is a precise fit so be careful to not remove much material, the goal is to smooth the surface in order to negate the chance of a leak path developing in the seal)
4. Repeat step 3 on the exterior of the shrink-fit portion of the end caps.
5. Clean the mating rings and end caps using acetone and paper towels.

Mandrel:

1. Wrap the mandrel with a single layer of the release film using the Kapton tape to secure in place. Refer to the liner machining procedure for instructions on mandrel creation and preparation.

Fabrication Process:

Mating Rings:

1. Remove the orange backing from the METLBOND and adhere the adhesive to the inside of the lapping portion of the mating rings. (In general, the heat generated by pressing and rubbing the adhesive should be enough to hold it in place. If you use the heat gun, be careful as this can cause it to adhere very strongly to the white backing.)
2. Remove the white backing from the METLBOND.

PTFE Liner Placement:

1. Slide the liner into position on one of the mating rings (use a tongue depressor or another similar tool if needed to keep the adhesive in place as you mount the liner in position).
2. Slide this arrangement onto the mandrel.
3. Using similar methods to the first step, mount the second mating ring.

Lay Up Procedure:

1. Pull the working layers from the freezer, and double-check that all layers are accounted for before beginning.

   - 2 Layers of carbon fiber
   - 2 Nomex honeycomb core layers (0.125″ for inner layer, 0.25″ for outer layer)
   - 5 layers METLBOND adhesive film (2 outer layers and 3 inner layers)

   Be careful in the application of these layers to apply them as straight and evenly as possible. Best practice is one person holding the layer straight and pressing it into place while a second holds the mandrel firmly and rolls it slowly. Place the seams so they are not all aligned in the same location on the layup.

2. Peel the orange backing off of the Metlbond and adhere to the exposed surface of the PTFE using the heat of your hand to help it remain in place. Stop with about 1″ gap to remove white backing before lapping adhesive layer.
3. Remove the white backing pressing firmly on any areas that seem to be lifting. Use the heat gun briefly if necessary.
4. Using the heat gun on a lower setting (350F) warm the adhesive while carefully pressing the ″ Nomex layer into place. It is easiest to wrap around and adhere the seam first, then compressing in place around the remainder of the module.
5. Repeat steps 2 & 3 on the exterior of the Nomex layer.
6. Peel one side of yellow backing from the inner carbon fiber layer and carefully adhere in place.
7. Remove the yellow backing from the carbon fiber.
8. Repeat steps 2 & 3 carefully placing the next layer of the METLBOND adhesive.
9. Repeat step 4 using the ¼″ Nomex layer.
10. Repeat steps 2 & 3.
11. Repeat steps 6 & 7.
12. Repeat steps 2 & 3 one last time.
13. Wrap a layer of release film around finished layup and secure with Kapton tape
14. Wrap shrink tape across the length of the module so that it overlaps itself (50%) on each pass. Start the wrap on the mating rings, securing it well with the kapton tape. Use a similar 2-person application process as that employed earlier. Make sure to tension the shrink tape so that it is taught, but not tight, as too much tension will put too much compression on the layup during curing. Wrap to the other mating ring and secure using kapton tape.

Vacuum Bag Seal:

1. Create vacuum bag using with breather cloth and Goop tape, leaving one end open.
2. Insert tank module.
3. Seal with Goop tape, leaving a small section with the backing still attached through which the vacuum hose can be inserted when placed in the oven.

Curing Process:

1. Insert vacuum bag with secured layup into the oven, and connect vacuum hose into open slot in the bag. Seal with Goop tape.
2. Connect vacuum hose to vacuum pump (or other source of vacuum pressure) and open valve to create vacuum seal. Check carefully for a complete seal.

3. Turn on the oven.
4. Ramp up 50F every 20 min, until max temp of 350F is reached.
5. When 350F is achieved, hold at temperature for 2 hours.
6. When cycle is complete, turn the oven off and allow to return to ambient room temperature slowly.
7. When ambient temperature is reached, remove vacuum bag and module from the oven.
8. Remove module from vacuum bag and mandrel. It may be necessary to hammer the module off of the mandrel. Although some force may be necessary, this shall be done carefully so as to not damage the aluminum rings or cause any unnecessary stress to the module.

E.3 Assembly Procedure

Place the completed module back into the oven. Turn the oven on and set the temperature to 250F. While the oven is ramping up to temperature, fill a styrofoam cooler with LN_2 to a depth of about 3” and place end caps inside cooler before replacing the lid. When the oven reaches temperature, remove the module (wear gloves to protect from the heat) and place on working surface. At the same time, have another team member (wearing gloves to protect from the cold) use tongs to remove one of the end caps from the cooler. Use the keyways to ensure placing it in the correct position on the module. Once in position, use a mallet to quickly insert into position on the mating ring. Be certain the end cap is fully inserted and seated evenly. Place the module back in the oven allowing it to come back to temperature. Repeat this procedure for the remaining end cap.

F Test Procedures

F.1 6-Stage General Testing Procedure:

We have devised a six-phase testing procedure that is designed to identify as many design problems as possible before spending large amounts of resources on the manufacturing of tanks. Any design must pass each phase, in order, before moving to the next phase. The following is a summary of the procedure.

Phase 1:

Flat test coupons exhibiting the same material layers and thicknesses as the current design concept are made and tested. The first test is a room temperature tensile test in which aluminum tabs simulate the rings and function as gripping areas for testing apparati. A drawing of an example coupon is shown in Figure . This test is to get a baseline strength of the bond between layers. The second test is to place coupons into a liquid nitrogen bath and remove them 10 times, allowing them to reach thermal equilibrium each time. The pass criteria for this test is a lack of any evidence of cracking or delamination as a result of the thermal cycling. The third test is the same as the first, but using a specimen that has passed the thermal cycling test. A comparison of the strength of the coupon after each test will be made. The purpose of this test is to determine the minimum lap area necessary to keep the rings attached to the cylinder, with a factor of safety of 2, and learn what layering configurations will work.

Phase 2:

Simplified physical layups are made. In this phase, we see whether the configurations that passed Phase 1 will survive the lay-up process. In other words, It will show whether or not our proposed lay up process will work. To save on materials and time, these prototypes will not include end caps, gaskets, or fasteners, and may be made with rings that lack features such as bolt holes.

Phase 3:

Tank designs that pass Phase 2 will get gaskets and end caps. One end cap will have an inlet, allowing the tank to be filled with water using a hand pump. We will increase the pressure until the tank leaks or bursts, and record the pressure. To pass this test, the tank must have a fail pressure of at least 6 atm.

Phase 4:

Test designs that pass Phase 3 will be thermally cycled by filling with liquid nitrogen, like the thermal cycling at the coupon phase, but using a geometry that is representative of the actual tank design. These tests can be done with only one end cap. Tanks pass this phase by exhibiting no visible evidence of cracking or delamination.

Phase 5 - End of Capstone Project:

A tank that survives the cryogenic liquid fill cycling will be fitted with a gasket and end cap featuring a fill port and will undergo a second pressurization test to see if thermal cycling reduced the strength or integrity of the tank. It must pass this phase by having a failure pressure of at least 6 atm.

Phase 6 - Future Work:

Any tank design that has passed the previous 5 phases is ready to be filled with liquid oxygen. A pressure relief valve set to 3 atm will be added to the end cap with the fill port. The time it takes for the oxygen to boil off and the tank to empty itself (until it contains only oxygen gas) will be measured. Any tank that takes longer than 20 minutes to empty (and does not catch fire) is ready to be presented to PSAS.

F.2 Hydrostatic Test Procedure

To perform the hydrostatic test a hand pump was used to pressurize the the tank. Place a plug in one of the end caps of the test tank module. Fill the tank with water. Place the supply hose for the hand pump in a bucket of water. Prime the pump by pumping until water come out of the discharge hose. Attach the discharge hose to the other end of the tank. Place tank on a stand. Set up a camera so that the pressure gauge and tank are in view. Pressurize tank while watching for any leaks. Take note of what pressure leakage occurs and from what source. Be aware that if no leakage occurs and the tank fails structurally there is a possibility of rapid disassembly and injury.

F.3 Cryo-Compression Test Procedure

Place a plug in one of the end caps of the test tank module. Fill a styrofoam cooler with enough LN_2 to completely submerge the test tank module. Place module in cooler allowing LN_2 to fill the module. Replace cooler lid and allow the module to reach cryogenic operating temperatures. While the module comes to testing temperature, check to be sure that the hydraulic press is properly set up. Use spacers to ensure that there is not too much travel before the press is able to engage with the module.

Begin logging test data. Use a block of known size to calibrate the displacement sensor. Using a set of tongs, remove the module from the LN_2 and place on the stage of the hydraulic press.

Be certain to center the module on the stage to ensure the pressure is applied evenly throughout the test procedure. Begin operating the hydraulic press, continuing to build compression pressure until failure occurs.

G Bill of Materials

G.1 Total Project Expenditures:

Date	Item	Qty	Price	Shipping	Total	Link	
3/12/2017	Hydrostatic Test Pump (1000 psi)	1	$ 254.00	$12.90	$ 266.90	grainger	
3/12/2017	Virgin PTFE molded cylinder, 6" OD, 5.625 ID, 7" length	1	$ 50.00	$13.82	$ 63.82	enflo	
3/12/2017	Kapton Tape (1/2" x 36 yd)	2	$ 17.00	$10.15	$ 44.15	uline	
3/12/2017	Clauss Titanium Shears (9 in)	1	$ 8.53	$0.00	$ 8.53	amazon	
3/12/2017	Acetone (1 gallon)	1	$ 13.97	$0.00	$ 13.97	PSU Chem. Dept	
3/19/2017	UCR compressible PTFE Gasket Material (15" x 15" sheet)	1	$ 155.00	$0.00	$ 155.00	mcmaster	
3/19/2017	Steel Phillips Flat Head Screw 50 pk (82 degree countersink angle, 0-80 Thread size, 1/4" long)	1	$ 7.80	$0.00	$ 7.80	mcmaster	
3/19/2017	320 grit waterproof sandpaper 5pk (9"x11")	4	$ 5.70	$0.00	$ 22.80	mcmaster	
3/19/2017	600 grit waterproof sandpaper 5pk (9"x11")	4	$ 5.70	$0.00	$ 22.80	mcmaster	
3/19/2017	1500 grit waterproof sandpaper 5pk (9"x11")	4	$ 6.11	$9.44	$ 33.88	mcmaster	$ 242.28
3/19/2017	Tritan 6" ABS Inch/metric digital caliper	1	$ 46.80	$0.00	$ 46.80	fastenal	
3/19/2017	4" round 6061-T6511 Aluminum Extruded, 24" length	1	$ 140.44	$20.00	$ 160.44	Metal Supermarket	
3/30/2017	Honeycomb Core Material, AHN 4120 3/16 3.0 OX, thickness 0.25", width 39", length 91"	1	$ 375.00	$306.00	$ 681.00	http://www.ahtinc.com/	
3/30/2017	Economy Heat Gun, item#: 32605K55	1	$ 57.05	$0.00	$ 57.05	https://www.mcmaster.c	
3/30/2017	Heat gun nozzle set, item#: 32605K77	3	$ 15.90	$0.00	$ 47.70	https://www.mcmaster.c	
3/30/2017	Mark On Plastic Bags 9" wide, 12" high, 6 mm thick, item#:14555T14, 10pk	2	$ 5.99	$0.00	$ 11.98	https://www.mcmaster.c	
3/30/2017	Heavy Duty Precision Knife item#: 38995A71	2	$ 4.41	$0.00	$ 8.82	https://www.mcmaster.c	

3/30/2017	Precision Knife Replacement blades, Type P, 15pk, item#: 38995A82	1	$ 7.20	$8.49	$ 15.69	https://www.mcmaster.	$	141.24
3/30/2017	Sterilite 17918004 3 Drawer Unit, White Frame with Clear Drawers 4 pack, item#:B002BA5F2A	1	$36.00	$0.00	$ 36.00	https://www.amazon.cor		
3/30/2017	Sterilite 19658604 Deep Clip Box, Clear with Blue Aquarium Latches 4 pack, item#:B004QJM0DG	1	$21.96	$6.70	$ 28.66	https://www.amazon.cor		
3/30/2017	Kapton Tape (1/2" x 36 yd)	4	$ 16.00	$10.15	$ 74.15	uline		
4/6/2017	3.25" outer diameter, 3.0" inner diameter, 5.25" long PTFE tube	5	$ 46.00	$27.27	$ 257.27	Queen City Polymers,See		
4/6/2017	Virgin PTFE Sheet-Etched 1 sided 0.031 x48x48	1	$282.00	$0.00	$ 282.00	http://www.professional		
4/13/2017	0.375" Thick, 1" width 6061T6 Aluminum Flat Bar (12" long cut size)	4	$2.50	$0.00	$ 10.00	Metal Supermarket		
4/13/2017	0.063" Thick, 6061T6 Aluminum Sheet (4"x4" cut size) 10	10	$ 1.17	$0.00	$ 11.69	Metal Supermarket		
4/13/2017	0.032" Thick , 6061T6 Aluminum Sheet (2"x6" cut size)	5	$ 0.85	$22.32	$ 26.55	Metal Supermarket	$	48.24
4/13/2017	Through-wall Straight Adapter, Pipe Size (A) NPT Female1/4", Threaded size (B) 3/4"-16, item#:50785K273	1	$ 8.23	$0.00	$ 8.23	McMaster Carr		
4/13/2017	Passivated 316 Stainless Steel Hex Drive Rounded Head Screws, 1/4" long, 50 pk, item#:98164A422	1	$ 12.06	$6.21	$ 18.27	McMaster Carr	$	26.50
4/13/2017	Scott Shop towels rolls (case of 12)	1	$ 34.79	$0.00	$ 34.79	Amazon		
4/13/2017	Gojo Natural Orange Pumice Hand Cleaner (1 gal)	1	$ 11.43	$0.00	$ 11.43	Amazon	$	46.22
4/18/2017	WR Meadows Poly-Jet LOX Sealant, 11oz cartridge, item#:4340111	1	$ 25.53	$7.83	$ 33.36	http://www.sealantexper		
4/18/2017	Modified PTFE bag 7"x6", 2.5 mil	10	$ 5.35	$13.15	$ 66.65	http://www.fluorolab.co		
4/18/2017	Modified PTFE 1 gallon pail liner 12"x12", 1 bag	1	$ 9.50	$0.00	$ 9.50	http://www.fluorolab.co	$	76.15
4/20/2017	Clear Cast Acrylic sheet item#: 8560K259	1	$ 23.82	$0.00	$ 23.82	https://www.mcmaster.c		
4/20/2017	PTFE Teflon Tube 3.5" OD, 3" ID, 1/4" thick, 12" long item#:8556K15	1	$ 165.40	$22.60	$ 188.00	https://www.mcmaster.c	$	211.82
4/20/2017	Tongue Depressor (100pk)	1	$ 7.99	$0.00	$ 7.99	https://www.amazon.cor		

4/25/2017	End Cap rev 1	4	$ 118.42		$ 473.68	Proto labs	
4/25/2017	Mating Rings rev 1	4	$ 194.71		$ 778.84	Proto labs	$ 1,252.52
4/25/2017	3-48 Stainless steel hex drive rounded head screws, item#: 92949A325	1	$ 6.98	$6.21	$ 13.19	McMaster Carr	
05/03/2017	Liquid Nitrogen (per gallon)	3	$ 10.11	$0.00	$ 30.33	Portland State Chemistry	
05/12/2017	Through-wall Straight Adapter, Pipe Size (A) NPT Female1/4", Threaded size (B) 3/4"-16, item#:50785K273	1	$ 8.23		$ 8.23	McMaster Carr	
05/12/2017	Plug with external hex drive, 1/4" NPTF, item#: 50925K389	2	$ 0.73		$ 1.46	McMaster Carr	
05/12/2017	Teflon PTFE Tube 12" long, item#: 8556K18	2	$ 165.40	$8.51	$ 339.31	McMaster Carr	$ 349.00
05/12/2017	Nitrile Powder Free Gloves, 5 mil, size large	2	$ 10.25		$ 20.50	amazon	
05/12/2017	Nitrile Powder Free Gloves, 5 mil, size medium	2	$ 7.99		$ 15.98	amazon	
05/12/2017	Nitrile Powder Free Gloves, 5 mil, size x-large	1	$ 7.99	$3.00	$ 10.99	amazon	$ 26.97
05/16/2017	Aluminum Endcaps (1/8" liner, shrink design)	4	$ 172.90		$ 691.60	Protolabs	
05/16/2017	Aluminum Main Ring (1/8" liner, shrink design)	4	$ 213.65		$ 854.60	Protolabs	$ 1,546.20
05/17/2017	Hook and Loop Thermocouple, type K	1	$ 34.95	$6.19	$ 41.14	McMaster Carr	
05/24/2017	Liquid Nitrogen (per gallon)	4	$ 10.11		$ 40.44	PSU chem dept.	
05/31/2017	0201-C_Main Ring	6	$ 225.25		$ 1,351.50		
05/31/2017	0301-C_End Cap	6	$ 174.11		$ 1,044.66		$ 2,396.16
05/31/2017	PTFE Teflon Tube 3.5" OD, 3" ID, 1/4" thick, 12" long item#:8556K18	2	$ 165.40		$ 330.80	Mcmaster	
05/31/2017	18-8 Stainless Steel Hex Drive Rounded Head Screw, 3-48 Thread Size, 1/4"	1	6.98	14.37	$ 21.35		$ 352.15
				Total Spent	$ 8,866.09		

G.2 Approximate Tank Cost (Final Tank Design):

Table 3: Current Per Tank Cost (excluding donated materials and tools)

Material	Cost
1/4” PTFE Tube	$165
Aluminum Mating Rings (x2)	$854.60
Aluminum End Caps (x2)	$691.60
Stainless Steel Hex Screw (x12)	$0.50
Total Cost:	$1,711.70

H Additional Resources

For complete design documentation and control code go to the Documentation Page: https://github.com/psas/composite-propellant-tank.