Progress Report for Conceptual Design

Portland State Aeronautics Society's Composite Cryogenic Fuel Tank Capstone Team

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March 21, 2017

1 Executive Summary

Portland State Aerospace Society (PSAS) has determined that in order for its next generation LV4 rocket to reach its goal altitude of 100 km, it will require an increase in the chemical energy density of its propellant, and a reduction in the rocket's dry mass relative to the current design (LV3). Our goal is to design a composite tank that is less massive than an alternative aluminum tank, and can hold cryogenic propellant.

We have secured funding for the project through a $8,863 grant from the Oregon Space Grant Consortium, and gained access to said funding and placed our first order on March 14. Our PSAS contact developed an optimization program which predicted that an 11 inch diameter, liquid propellant rocket with a 25 inch long fuel tank can reach an altitude of 100 km. We decided to roughly match this length to diameter ratio and set our prototype tank length to 6.75 inches with a 3 inch inner diameter. Basic design decisions were made based upon cost, time constraints, availability of materials, manufacturing processes, and scalability. An initial design concept has been selected, and we have begun to move into the engineering analysis and prototyping phase of the project. We have developed a six-tiered testing procedure, beginning with the most basic requirements, so that prototypes can be tested quickly and cost effectively. A configurable CAD model has been developed that includes the features we expect to have in our first prototype. General stress and heat transfer analyses have been performed for multilayered, cylindrical pressure vessels so that parameters can be easily changed for future calculations. Basic oxygen permeability analysis of PTFE has been done to find a minimum liner thickness for the tank. We have also included a static stress analysis for the adhesives and fasteners of the current design concept at maximum expected load. After performing tensile test on the composite-aluminum and PTFE-aluminum interfaces, we determined that the structural adhesive used to adhere the materials is not the critical failure mechanism.

In order to complete the project by June 2017, we will begin building and testing prototypes as soon as we receive our first etched PTFE liner. Over the following 12 weeks, we will build and test at least one prototype per week, and make necessary design changes to pass test stages at a rate of one every other week. The PTFE Liners have a minimum lead time of 3 weeks, which means that any changes to liner design take top priority between prototypes. All other parts have shorter lead times or will be manufactured at PSU.

Approved by Dr. Jun Jiao, March 18, 2017

Jun Jiao

2 Conceptual Design Summary

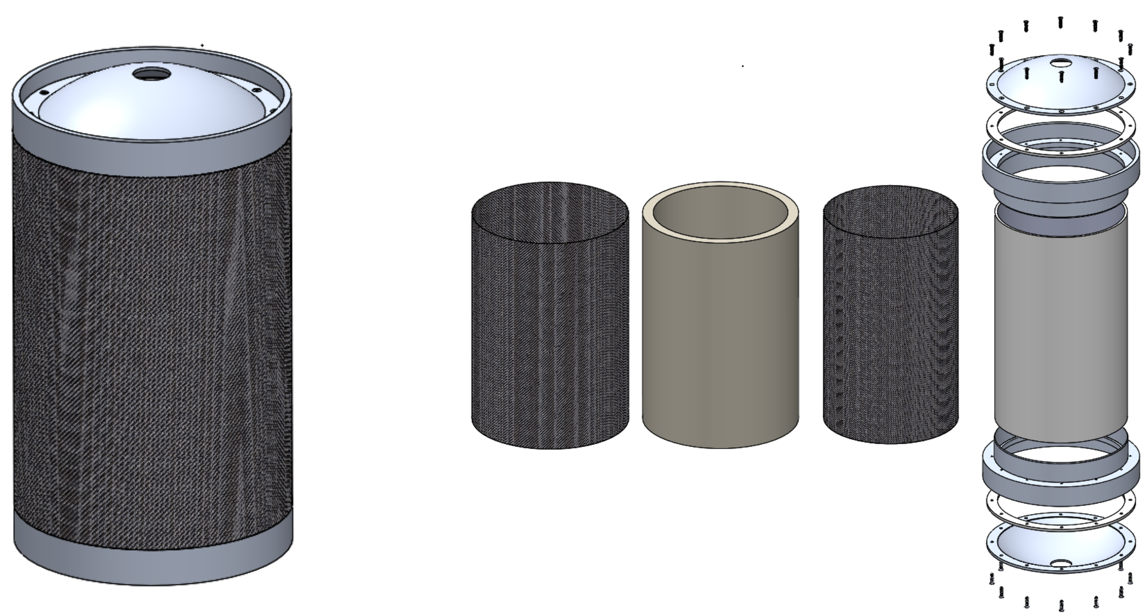
Concept Selection Process:

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 in detail the current design of individual components, other designs that were considered, as well as justifications for our final design decisions. All subsystem and whole system requirement matrices can be found in Appendix G.

Sub-System Decomposition:

CAD Model

Figure 1a is our most up-to-date CAD drawing of the tank assembly. Figure 1b shows an exploded view of all the components and how they fit together. Figure 2 shows a cross sectional view of the layers and interfacing features of the tank assembly.



(a) Tank Assembly Exterior View

(b) Tank Assembly Exploded View

Figure 1: Current CAD Models of Cryogenic Tank

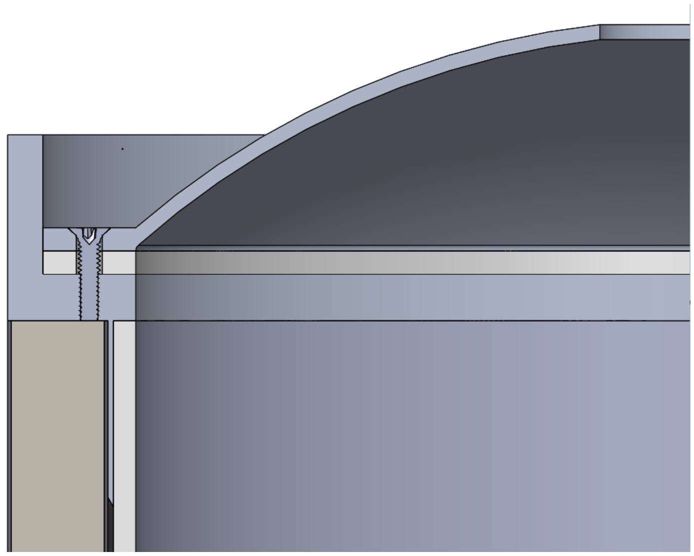


Figure 2: Cross Sectional View of Tank Interfaces

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 ℃ below that boiling point of oxygen, where PTFE has a permeation rate similar to most thermoplastics, and remains ductile at working temperature (-183 ℃), and according to Dupont, as low as -268 ℃. PCTFE has the highest strength, but also has the highest glass transition temperature at 45 ℃, 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 endcaps 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 have learned that the minimum thickness of an affordable 3" ID x 5.25" tube is 1.5 mm. We are waiting on quotes from our vendors, but we expect the tube itself will cost approximately $200, and the etching will cost approximately $100. Since 1.5 mm is 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. This analysis is found in Appendix D. The approximate volume of oxygen at 3 atm 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, we 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[1].

Tank Layers

To build upon the work of previous capstone teams the outer layers of the tank will have a design similar to the skin of the rocket. We have 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 are not overhauling the general lay up design. The current design includes 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 multilayered 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 ℃. The temperature of the tank's PTFE inner layer is assumed to be at equilibrium with the liquid oxygen at -183 ℃. 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 cm^3 tank with 680 g of fuel, the approximate time to boil off all of the liquid oxygen was determined to be 1 hour. Calculations and material

[1]http://www.compositesworld.com/articles/an-update-on-composite-tanks-for-cryogens

properties can be found in Appendices C & E. 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 multilayered 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. A table of material properties and the general equation development is included in Appendix B. An initial calculation was done for the materials and layer thicknesses of the current 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.

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, 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 uses fasteners oriented in the axial direction and sandwiches a gasket between the endcap and mating ring. The second uses threaded surfaces and teflon tape. Drawings of these two concepts are shown in Figure 3. 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.

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 learned from 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

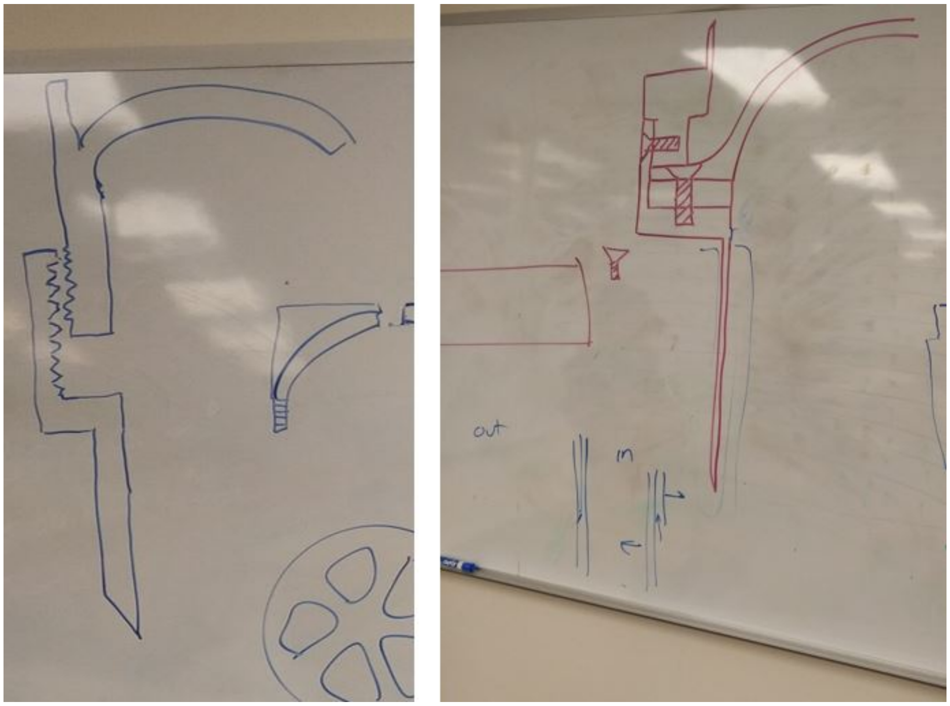


Figure 3: Initial Tank Concept Drawings

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. A cross section view to clarify these features is shown in Figure 4.

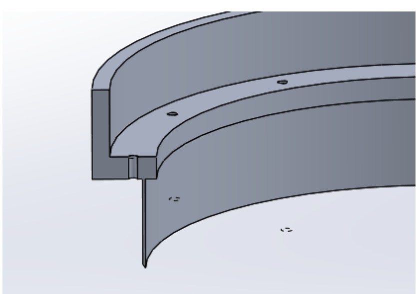


Figure 4: Cross-section of Ring Design

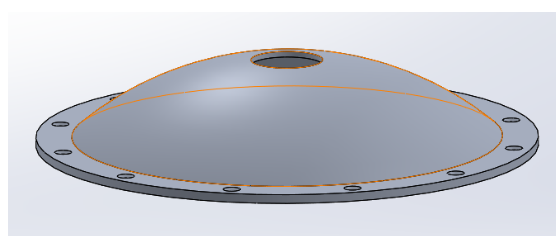


Figure 5: End Cap Design

End Caps

The current end cap design, shown in Figure 5, 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 are currently discussing other options, 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

The interface between the end caps and the rest of the tank must seal completely. To address this, we designed a simple PTFE gasket, shown in Figure 6. PTFE was elected as the material for this gasket for the same reasons as the liner. We plan to make these gaskets ourselves, by purchasing PTFE in sheet form and cutting them on a CNC router. The exact type of PTFE selected may vary from the liner material, as compressibility will have to be factored into the selection process.

Fasteners

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 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 Appendix F.

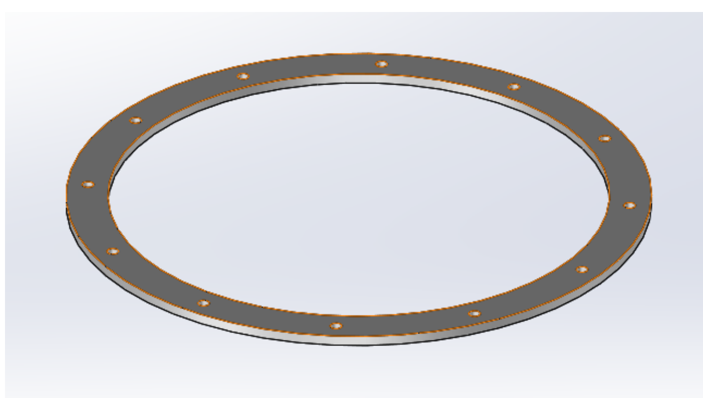
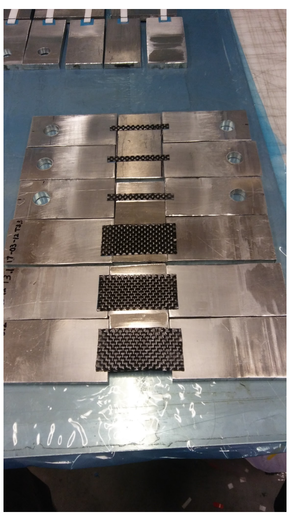


Figure 6: PTFE Gasket Design

Shear Adhesive Experiment (to justify aluminum lap length)

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 was completed by designing two different experiments, a manual tensile test performed by ourselves, in addition to a tensile test performed in Maseeh College's materials lab by a tensile testing apparatus operated by a trained engineer. 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 7.



(a) CF - Aluminum

(b) PTFE - Aluminum

Figure 7: Tensile Test 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. The complete testing apparatus can be seen in Figure 8.

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.

Figure 8: Manual Testing Apparatus

3 Updates on Performance Measures

Assessment of Progress
As we have learned more about our project, the plan has evolved significantly. At the time of the project contract, we were flying blind. Design is an iterative process and so is planning for design. In our project contract, we outlined a list of constraints, success measures, and key deliverables. Many of these have been revised significantly. We will be designing and building 3-inch prototypes, as opposed to 4-inch and 6-inch. This was recently advised by our PSAS contact in order to save money, materials, and time.

There is not a weight limit on this prototype, but instead, the tank must be designed such that it can be scaled up for a future 11-inch-diameter rocket. PSAS has informed us that we should not burden ourselves too heavily with weight concerns because it is their belief that any carbon fiber tank design will be superior to the current alternative, which is to buy an aluminum pressure vessel and machine down the outer diameter. We will provide weight estimates for a scaled up version of our design for the sake of comparison.

We have learned that fueling the rocket is one of the very last things done before the rocket is launched, and that teams can be called upon in the future to design frangible insulation to be employed on the launch pad. This means that mitigating heat transfer into the tank is also no longer a constraint, but rather a performance measure to be documented for future use. We have also been informed that we do not need to design mating details. Our design just has to allow module mating features to be added later. The following is a revised list of project constraints:

- Tank must carry liquid oxygen at a pressure of 3 atm without leaking (this includes oxygen permeation through the liner), for a flight duration of 3 minutes.
- Tank must withstand 15 G acceleration, approximately 4000N, for the full-scale tank.
- All design criteria must incorporate a factor of safety of 2.
- Tank must be constructed from previously acquired composite material.
- Design concept must be applicable to an 11-inch diameter tank.
- Design must allow module mating features to be added.

Our original estimates for the value of the donated materials turned out to be grossly under-quoted, but our final tank cost should still fall under our previously stated bill of materials success-measure of less than $1000. The cost of the carbon fiber and structural adhesive for an 11-inch-diameter tank is approximately $55.00 per tank. We have not obtained a quote for a machined and etched PTFE liner for the full size tank, but based on the quotes we have received, we expect the liner and the etching to increase linearly with the size of the tube. Now that we have reduced the amount of detailed features required, we can machine aluminum parts ourselves, which places an estimation of the cost of detailed future parts outside the scope of our project.

We have committed ourselves to providing enough documentation of the materials and manufacturing procedure to allow future rocket enthusiasts to copy our design. We have not yet finalized the deliverable documentation format (likely a Jupyter notebook) but through the use of Github, we have been documenting design decisions and iterations in excel, word, and image documents.

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. We will perform another strain analysis that includes the aluminum lap layer, and compare the strains at each interface to those calculated for the unlapped layer area. This should provide insight into the likelihood of failure in this region.

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.

As we refine the design, we will also refine the analyses we have performed so far. The heat transfer analysis will include the end caps. The initial lap length of the aluminum ring extensions will be driven by the data we receive from the coupon tensile tests. A study of gasket theory will be done to find the ASME recommended clamping force needed to provide a good seal.

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 9. 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.

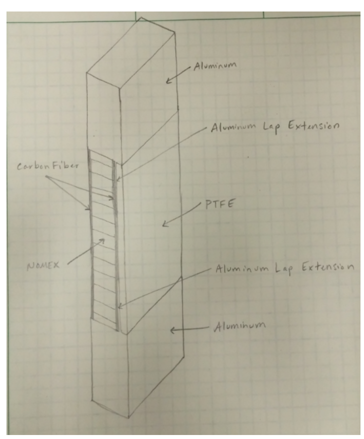


Figure 9: Example Test Coupon

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 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 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.

4 Planning Update

Designing and building a rocket capable of reaching 100km is very expensive, and requires many different areas of expertise. To ensure our success and allow design flexibility, procuring additional funding for our portion of the project was deemed necessary. PSAS informed us of an opportunity to apply for a grant from the Oregon Space Grant Consortium (OSGC). We put significant time and effort into this endeavour, and were awarded $8,863. The application required an essay, budget, schedule, and proof of 2-to-1 fund matching through other fund-raising means. This forced us to learn the value of all previously donated materials that we planned to use for this project and apply them as matching donations. We are not expecting any further funding from other agencies, including PSAS. The OSGC dollar amount represents our total budget, and we have not allocated any of it to specific areas of the project other than the few purchases we have made so far. This unexpected time allocation caused us to alter our timeline slightly. Our new gantt (see Appendix A) chart reflects these changes and the pace of progress we expect to see in the upcoming quarter.

In our project contract, we claimed we would have an initial design for end caps, rings, and liner by the 20th of February. We had some ideas by then, but we settled on a design for the first prototype nearly three weeks later. Somehow, we thought we could have three design iterations for these features completed before making our first prototype, which was not realistic without test data to inform our design improvements. We do, however, have a CAD model of our initial full prototype design complete ahead of schedule. Understanding that it is early in the design process, the CAD model was designed to be easily adjustable to accommodate design changes by making part dimensions driven by a layout sketch within the tank assembly.

We were expecting to have a lay up procedure developed by the 20th of March, but since we have not begun to build tank prototypes yet, we do not know which of our fabrication ideas will work. The lay up process will be developed iteratively.

We initially planned to use a three-point bending test on a layered coupon matching our materials and their respective thicknesses immediately after submerging them in liquid nitrogen. Upon further consideration, we have concluded that the tank will not fail in bending, as there is not an associated loading condition during tank filling or rocket launch, and that a tensile test would be more useful as the tank ends will experience up to 4000N of force during launch, when fully scaled. We believe the most likely feature of the tank to fail is the interface between the aluminum and PTFE. We have performed room temperature tensile tests of the structural adhesive bond between aluminum and carbon fiber, as well as between aluminum and etched PTFE, which showed that the PTFE fails before the adhesive. We plan to test with liquid nitrogen during the week of March 20.

We have selected vendors for the PTFE liner and the etching process. We have ordered our first liner, a hydrostatic test pump, some fasteners, and some aluminum rod and tube stock, from which we will machine end caps and rings. These purchases were expected to be made by March 30.

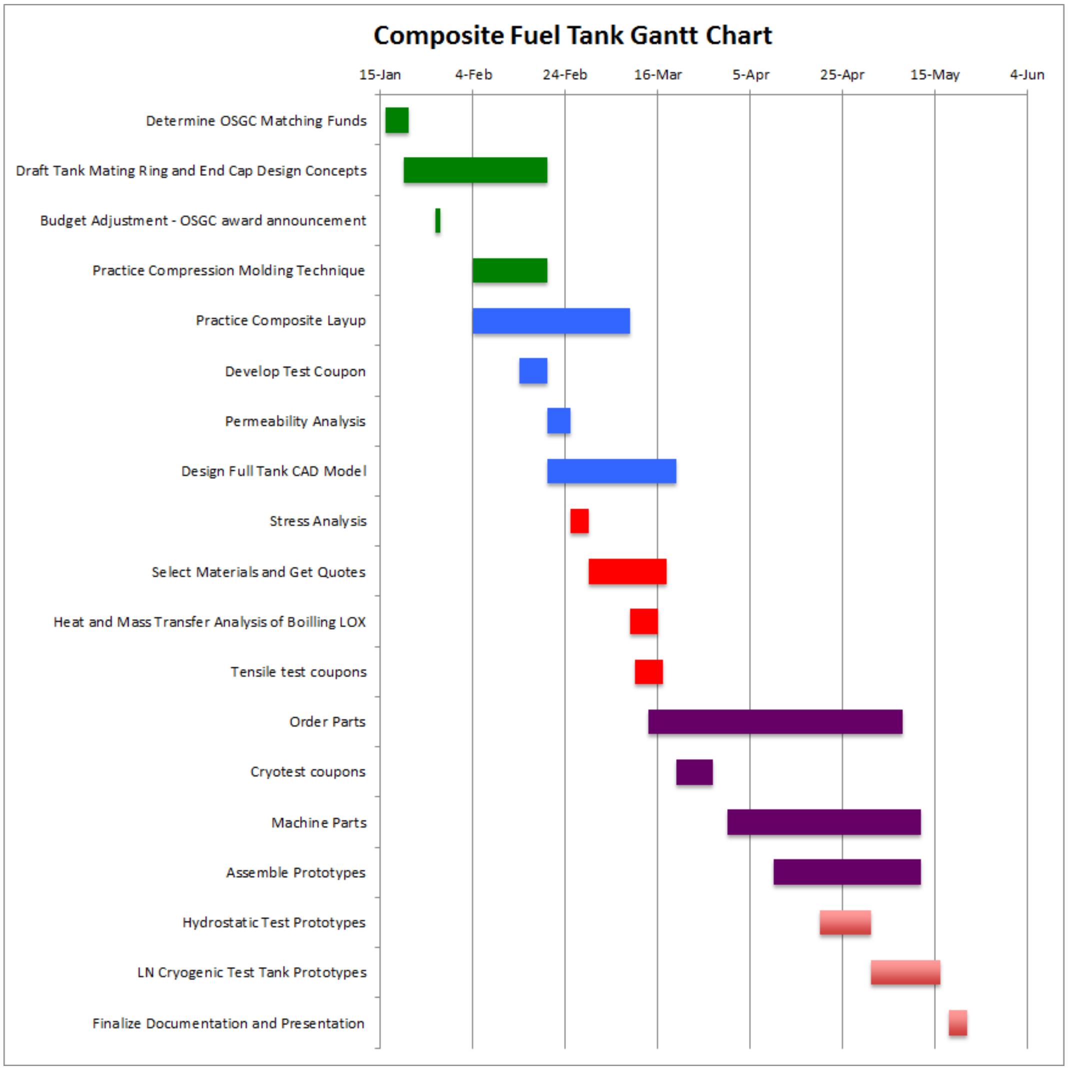
Given the new list of constraints, and a better understanding of the project, we believe we are on schedule to reach our final goal. We have also gained a better sense of the amount of work that remains to be done.

After creating a testing procedure, it was determined that prototypes must pass many simpler design tests before it is necessary to test them with a cryogenic fluid fill. Liquid nitrogen is much easier to obtain and has a lower boiling point, so it will be used to test the assembly's resistance to thermal stresses and cycling. That being said, we have not selected a vendor for liquid nitrogen, but PSU's chemistry department, whom we have already contacted, is a likely supplier. Filling the tanks with LOX will be among the very last tests performed, and it is expected that the first several prototypes will not make it to the LOX stage, and so the procuring of LOX has been moved to a later date.

Appendices

A Gantt Chart

Task Name	Start	End	Duration (days)
Determine OSGC Matching Funds	1/16/2017	1/21/2017	5
Draft Tank Mating Ring and End Cap Design Concepts	1/20/2017	2/20/2017	31
Budget Adjustment - OSGC award announcement	1/27/2017	1/28/2017	1
Practice Compression Molding Technique	2/4/2017	2/20/2017	16
Practice Composite Layup	2/4/2017	3/10/2017	34
Develop Test Coupon	2/14/2017	2/20/2017	6
Permeability Analysis	2/20/2017	2/25/2017	5
Design Full Tank CAD Model	2/20/2017	3/20/2017	28
Stress Analysis	2/25/2017	3/1/2017	4
Select Materials and Get Quotes	3/1/2017	3/18/2017	17
Heat and Mass Transfer Analysis of Boilling LOX	3/10/2017	3/16/2017	6
Tensile test coupons	3/11/2017	3/17/2017	6
Order Parts	3/14/2017	5/8/2017	55
Cryotest coupons	3/20/2017	3/28/2017	8
Machine Parts	3/31/2017	5/12/2017	42
Assemble Prototypes	4/10/2017	5/12/2017	32
Hydrostatic Test Prototypes	4/20/2017	5/1/2017	11
LN Cryogenic Test Tank Prototypes	5/1/2017	5/16/2017	15
Finalize Documentation and Presentation	5/18/2017	5/22/2017	4

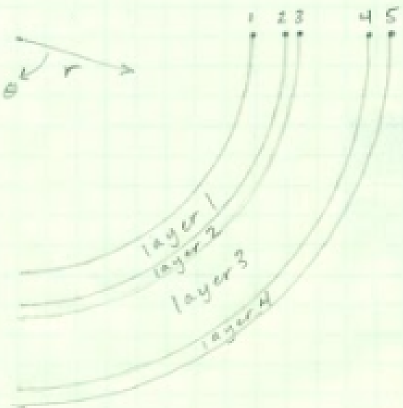


Composite Fuel Tank Gantt Chart
15-Jan
4-Feb
24-Feb
16-Mar
5-Apr
25-Apr
15-May
4-Jun
Determine OSGC Matching Funds
Draft Tank Mating Ring and End Cap Design Concepts
Budget Adjustment - OSGC award announcement
Practice Compression Molding Technique
Practice Composite Layup
Develop Test Coupon
Permeability Analysis
Design Full Tank CAD Model
Stress Analysis
Select Materials and Get Quotes
Heat and Mass Transfer Analysis of Boilling LOX
Tensile test coupons
Order Parts
Cryotest coupons
Machine Parts
Assemble Prototypes
Hydrostatic Test Prototypes
LN Cryogenic Test Tank Prototypes
Finalize Documentation and Presentation

B Important Material Properties

Material	O_2 Permeability at 25 °C ($cm^3cm/(cm^2Pa*s)$)	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

C Generation of Layer Stress Relationship and Calculations



r_1 refers to the radial distance to point 1, and p_1 refers to the pressure at point 1, etc.

Stress Analysis of Multilayer Pressure Vessels Under Thermal Loads

Stress due to pressure in the n^{th} layer is given by the equation:

$$\sigma_n = \frac{p_n r_n^2 - p_{n+1} r_{n+1}^2 - r_n^2 r_{n+1}^2 (p_{n+1} - p_n)/r^2}{(r_{n+1}^2 - r_n^2)} \qquad [1]$$

According to Hooke's Law, $\sigma = E\varepsilon$, and thus the strain due to pressure is found by dividing Eq. 1 by the material's elastic modulus:

$$\varepsilon_{n,p} = \frac{p_n r_n^2 - p_{n+1} r_{n+1}^2 - r_n^2 r_{n+1}^2 (p_{n+1} - p_n)/r^2}{E_n (r_{n+1}^2 - r_n^2)} \qquad [2]$$

Thermal strain is simply the product of the material's coefficient of thermal expansion and the change in temperature

$$\varepsilon_{n,T} = \alpha_n \Delta T \qquad [3]$$

The total strain is then the sum of Eq. 2 and Eq. 3

$$\varepsilon_n = \frac{p_n r_n^2 - p_{n+1} r_{n+1}^2 - r_n^2 r_{n+1}^2 (p_{n+1} - p_n)/r^2}{E_n (r_{n+1}^2 - r_n^2)} + \alpha_n \Delta T \qquad [4]$$

Assuming that the materials are bonded at the interfaces, have isotropic properties, and that their change in thickness is negligible compared to change in their circumference, the strain equations can be equated to each other at the interfaces. Substituting known values and solving the system of equations reveals the pressure at each interface. These values can then be substituted back into Eq. 4, and both sides multiplied by the elastic modulus. The maximum stress in a cylindrical pressure vessel occurs at the innermost fiber, so the maximum stress in each layer is then found by:

$$\sigma_{n,max} = \frac{p_n r_n^2 - p_{n+1} r_{n+1}^2 - r_{n+1}^2 (p_{n+1} - p_n)}{r_{n+1}^2 - r_n^2} + E_n \alpha_n \Delta T \qquad [5]$$

Finally, this can be compared with the yield stress of the material to obtain a factor of safety for each layer:

$$FOS = \frac{\sigma_{n,y}}{\sigma_{n,max}}$$

After applying values associated with our current tank design, and solving the system of equations, the following table was made:

Layer	Maximum Stress (psi)	Factor of Safety
PTFE Liner	-680.968	23.5
Inner CF	-298857	1.67
NOMEX	2818.64	unknown
Outer CF	63510.0	3.42

D Oxygen Permeability of PTFE Calculations

PTFE oxygen permeability @ 25°C : $3 \times 10^{-13} \frac{cm^3\,cm}{cm^2\,Pa \cdot s}$

Liner surface area : $2\pi(1.5\,in)(5.25\,in) = 49.5\,in^2 \approx 320\,cm^2$

Assuming 3-minute flight duration : 180 s

working pressure : 3 atm = 303975 Pa

PTFE thickness : 0.15 cm

Volume of O_2 that will pass through the liner:

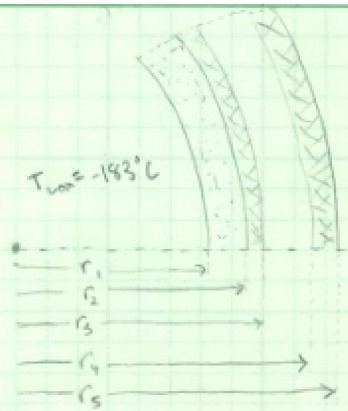
$$\left(3 \times 10^{-13} \frac{cm^3\,cm}{cm^2\,Pa \cdot s}\right)(180\,s)(303975\,Pa)(320\,cm^2)/(0.15\,cm) = 0.035\,cm^3$$

Permeability is temperature dependent, and follows this relationship:

$$P = P_o e^{-\frac{E_p}{RT}}$$

This means the permeability will be much lower at the working temperature, which is why we believe it can be neglected.

E Heat Transfer Through Cylinder Layers



$T_\infty = 38\ ^\circ C$

PTFE

Nomex

carbon fiber

Objective: Determine a rough estimate of the time it takes for a 3" diameter 5.15" long cylinder of liquid oxygen to boil off on a hot summer day in Brothers, OR ($T_\infty = 38°C$)

Assumptions:
- The temperature of the outermost carbon fiber layer is equal to the ambient air temperature. $T_5 = T_\infty$
- The temperature of the innermost (PTFE) layer is equal to the liquid oxygen (LOX) temperature. $T_1 = T_{LOX}$
- The Nomex honeycomb layer is considered to be composed of mostly air.
- Convection and radiation effects are neglected
- Material properties are constant.

<u>Conductivity</u> (engineeringtoolbox.com, Cengel, Tian)

$k_{air} = 0.026\ W/m\cdot K$

$k_{PTFE} = 0.25\ W/m\cdot K$

$k_{CF,Transverse} = 0.5 - 0.8\ W/m\cdot K$

<u>Dimensions</u>

$r_1 = 1.5'' = 0.0381\ m$

$r_2 = 0.0381 + 0.0015 = 0.0396\ m$

$r_3 = 0.0396 + 0.000254 = 0.0399\ m$

$r_4 = 0.0399 + 0.0047625 = 0.0446\ m$

$r_5 = 0.0446 + 0.000254 = 0.0449\ m$

$L = 5.15'' = 0.13081\ m$

<u>Fluid Property</u>

$\rho_{LOX} = 1141\ kg/m^3 \qquad T_{LOX} = -183°C$

$h_{e,oxygen} = 214\ kJ/kg$ (latent heat of vaporization)

The following analysis was performed using steady heat conduction analysis of multilayered cylinders (cengel, pg 156). The heat transfer rate is given by:

$$\dot{Q} = \frac{T_S - T_1}{R_{total}}$$, where R_{total} is the total thermal resistance

expressed as:

$$R_{total} = R_{PTFE} + R_{CF} + R_{air} + R_{CF}$$

$$= \frac{\ln(r_2/r_1)}{2\pi L k_{PTFE}} + \frac{\ln(r_3/r_2)}{2\pi L k_{CF}} + \frac{\ln(r_4/r_3)}{2\pi L k_{air}} + \frac{\ln(r_5/r_4)}{2\pi L k_{CF}}$$

Solution:

Thermal Resistance: $$R_{total} = \frac{1}{2\pi(0.13081)}\left[\frac{\ln\left(\frac{0.0396}{0.0381}\right)}{0.25} + \frac{\ln\left(\frac{0.0399}{0.0396}\right)}{0.8} + \frac{\ln\left(\frac{0.0446}{0.0399}\right)}{0.026} + \frac{\ln\left(\frac{0.0449}{0.0446}\right)}{0.8}\right]$$

$$= 1.217\,[0.1544 + 0.009434 + 4.283 + 0.00838]$$

$$R_{total} = 5.42\ \mathrm{K/W}$$

Heat Transfer rate: $$\dot{Q} = \frac{38 - (-183)}{5.42}$$

$$\dot{Q} = 40.77\ \mathrm{W}$$

The energy balance on a thin layer of liquid at the surface is expressed by

$$\dot{Q}_{transferred} = \dot{Q}_{latent,absorbed} \quad \text{or} \quad \dot{Q} = \dot{m}_v h_{e,oxygen},$$ (cengel, pg 841)

where $\dot{m}_v$ is the rate of evaporation. Solving for $\dot{m}_v$ gives us:

$$\dot{m}_v = \frac{\dot{Q}}{h_{e,oxygen}} = \frac{40.77\ \mathrm{J/s}}{214{,}000\ \mathrm{J/kg}} = 1.905 \times 10^{-4}\ \mathrm{kg/s}$$

The mass of liquid oxygen is given by:

$$m = \rho V = 1141 \cdot \pi(0.0381)^2(0.13081) = 0.68\ \mathrm{kg}$$

Finally, the amount of time that it takes for all 0.68 kg of LOX to boil off is:

$$t = \frac{0.68\ \text{kg}}{1.905\times10^{-4}\ \text{kg/s}} = 3572\ \text{s} = \boxed{59.5\ \text{min}}$$

F Bolt Stress Analysis

Screw stress : 0-80 × 0.25"

Nominal Tank Pressure : 45 psi

acting area : $\pi (1.5\,in)^2 = 7.07\ in^2$

Force : PA = 318.09 lb

Force per screw : 26.5 lb = P

Tensile stress area : 0.00180 in²

screw stress : $\frac{F}{A}$ = [illegible] psi (stress due to internal pressure only)

McMaster-Carr → tensile strength : 60,000 psi

$$P_b = \frac{k_b P}{k_b + k_m} \qquad (8\text{-}24d)\ p.\,428$$

$$k_t = k_b = \frac{A_t E}{l_t} \qquad (8\text{-}16)$$

$$A_d = \pi (0.03\,in)^2 = 0.002827\ in^2$$

$$A_t = 0.00180\ in^2$$

$$E = 29 \times 10^6\ psi$$

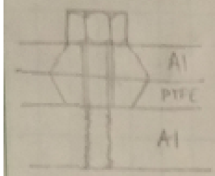
$$l_t = 0.125\ in$$

$$l_d = 0.125\ in$$

$$k_b = \frac{(1.8 \times 10^{-3}\,in^2)(29 \times 10^6\,lb/in^2)}{(0.125\,in)} = 417600\ lb/in$$

$$\frac{1}{k_m} = \frac{1}{k_{Al}} + \frac{1}{k_{PTFE}} \qquad (8\text{-}18)$$

$$k = \frac{0.5774\pi E d}{\ln \frac{(1.155t + D - d)(D + d)}{(1.155t + D + d)(D - d)}} \qquad (8\text{-}20)$$



$D = 0.112''$ (McMaster-Carr)
$d = 0.06''$ (Shigley's, Table 8-2)

$$k_{Al} = \frac{0.5574\pi\,(1\times10^{7}\ \mathrm{lb/in^2})(0.06\ \mathrm{in})}{\ln\left[\frac{(1.155(0.125\ \mathrm{in}) + 0.112\ \mathrm{in} - 0.06\ \mathrm{in})(0.112\ \mathrm{in} + 0.06\ \mathrm{in})}{(1.155(0.125\ \mathrm{in}) + 0.112\ \mathrm{in} + 0.06\ \mathrm{in})(0.112\ \mathrm{in} - 0.06\ \mathrm{in})}\right]} = 277481\ \mathrm{lb/in}$$

$$k_{PTFE} = k_{Al} \cdot \frac{8.01\times10^{4}\ \mathrm{lb/in^2}}{1\times10^{7}\ \mathrm{lb/in^2}} = 2222.63\ \mathrm{lb/in}$$

$$k = \left[\frac{1}{277481\ \mathrm{lb/in}} + \frac{1}{2222.63\ \mathrm{lb/in}}\right]^{-1} = 2205\ \mathrm{lb/in}$$

$$P_{b,pressure} = \frac{(417600\ \mathrm{lb/in})(26.5\ \mathrm{lb})}{(417600\ \mathrm{lb/in} + 2205\ \mathrm{lb/in})} = 26.36\ \mathrm{lb}$$

Assuming the tank is subjected to a maximum acceleration of 15 G, while containing approximately 2.6 lb of LOX, an additional 3.28 lb is applied to each bolt

$P_b = 29.64$ lb

Assuming we preload the bolts to 5 lb each, to ensure a good gasket seal (analysis will come later)

$F_i = 5$ lb

$F_b = P_b + F_i = 34.64$ lb

Stress in each screw: 19243 psi

yield stress of steel screws: 33 ksi

Factor of Safety: 1.71

G Requirements Matrices

G.1 Full System Requirement Matrix

System requirement-measurements for Cryogenic Tank

		Units	in	in	lb	atm	y/n	$	% (hours of manufacturing)	$	cubic cm	min
		Performance measures	Tank Length	Tank Diameter	Tank Weight	Burst Pressure	Evidence of microcrack	Cost of tank after development	Percentage of tank manufactured at PSU	Cost of machined parts	Working Volume	LOX Boil Off Time
	Target design requirements for Cryo-Tank		1	2	3	4	5	6	7	8	9	10
1	The Tank can hold liquid oxygen without bursting in	9				x	x					x
2	The Tank is affordable	3	x	x	x			x	x	x		
3	The Tank is reproducable	9	x	x				x	x	x		
4	The Tank doesn't leak	9				x	x					x
5	The Tank is made of donated composite material	9			x		x	x	x			x
6	The Tank weighs less than conventional aluminum	3			x						x	
7	The Tank shall withstand strains resulting from	9	x	x	x	x	x				x	
8	The Tank is scalable for larger rocket design	9	x	x	x		x	x	x	x	x	
			30	30	33	27	45	30	30	21	21	27
		Lower Acceptable	5.75	3	-	6	Composite material microcracks but doesn't cause failure during flight	-	50	-	596	20
		Ideal	6.75	-	2	10	Composite material doesn't microcrack at cryogenic temperature	1000	100	0	-	60
		Upper Acceptable	13.00	6	5	-	-	2000	-	2000	2371	-

G.2 Rings Subsystem Requirements Matrix

Subsystem requirement-measurements for mating ring

	Units		in	%	in	sq. inch
	Performance measures		Mating ring inner diameter	Percentage of parts manufactured at PSU	Mating ring length available to mate with airframe modules	Mating ring surface area available to adhere composite material
	Target design requirements for Aluminum components		1	2	3	4
1	Components can be modified to mate tank with airf	3	x		x	
2	Components allow for compression molding on ma	9			x	x
3	Components are affordable	9	x	x		
4	from pressure and body loads	9				x
5	Components have a short lead time	3	x	x		
6	The components are reproducable	9	x	x	x	
7	The components are scalable for larger rocket desi	9		x	x	
			24	30	30	18
	Lower Acceptable		3	50	0.75	1.75
	Ideal		6	100	1	-
	Upper Acceptable		11	-	1.25	5

G.3 Liner Subsystem Requirements Matrix

Subsystem requirement-measurements for Liner Material

		Units	Degree F	Degree	psi	$	in	in
		Performance measures	Material Lower Service Temperature	Material Upper Service Temperature	Maximum tensile load on liner aluminum interface	Cost of liner for 1 tank	Maximum liner height available for purchase	Maximum liner diameter available for purchase
	Target design requirements for tank Liner		1	2	3	4	5	6
1	The Liner will serve as an impermeable layer between the LOX and composite	9	x		x			
2	The Liner will adhere to aluminum parts	9		x	x			
3	The liner can withstand temperature and pressure loads expected during	9	x	x	x			
4	The size of the liner available for purchase is scalable for larger rocket design	9				x	x	x
5	The liner is affordable	1				x	x	x
			18	18	27	10	10	10
		Lower Acceptable	-	350	77	-	12	10
		Ideal	-200.00	375.00	88	0	25	11
		Upper Acceptable	-195.00	-	-	300	-	-

G.4 Composite Layers Subsystem Requirements Matrix

System requirement-measurements for Composite Layers

		Units	min	psi	y/n	$	# of Cycles	mm	lb
		Performance measures	LOX Boil off time	Carbon Fiber Tensile Strength	Evidence of microcrack	Money Spent on Composite Material	Cryogenic Thermal Cycles to Failure	Composite Layer Thickness	Compressive Load to Failure of Composite Module
	Target design requirements for Composite Layers		1	2	3	4	5	6	7
1	The composite materials are affordable	3				x		x	
2	The layup process is reproducable	9				x			
3	The composite doesn't allow LOX to leak	9	x	x	x		x		
4	The composite layers are strong enough to produce a reuseable tank	1		x	x		x	x	x
5	The Composite shall withstand temperature,	9	x	x	x		x	x	x
6	The layup process is scalable for larger rocket desig	9			x	x	x		x
			18	19	28	21	28	13	19
		Lower Acceptable	20	77	material microcracks but doesn't cause tank failure during flight	0	4	-	337.5
		Ideal	60	88	Composite material doesn't microcrack at cryogenic temperature	More Donations	10	7	450
		Acceptable	-	-	-	500	-	8	-

G.5 End Caps Subsystem Requirements Matrix

Subsystem requirement-measurements for End Cap

		Units	in	lb	atm	y/n	$	% (hours of manufacturing)	$	y/n	min	psi
		Performance measures	Tank Diameter	Tank Weight	Burst Pressure	Evidence of LOX leakage	Cost of tank after development	Percentage of end cap manufactured at PSU	Cost of machining	Ease of removability	LOX Boil Off Time	Bolt Strength
	Target design requirements for End Cap		1	2	3	4	5	6	7	8	9	10
1	The endcap is mounted to tank, independent of o	9								x	x	x
2	The endcap is affordable	3	x				x	x	x			
3	The endcap is acceptably insulative	3	x								x	
4	The endcap doesn't leak	9			x	x					x	x
5	The endcap shall withstand strains resulting	9	x	x	x	x					x	x
6	The endcap is scalable for larger rocket design	9	x	x			x	x	x	x		x
			24	18	18	18	12	12	12	18	30	36
		Lower Acceptable	3	-	6	Leakage visible at operating pressure *	-	50	-	End caps can't be added to tank layup w/o modification or damage	20	77
		Ideal	-	2	10	No visible leakage before burst	1000	100	0	End caps can be added and removed from tank layup w/o damage	60	88
		Upper Acceptable	6	5	-	-	2000	-	2000	-	-	-

G.6 Gaskets Subsystem Requirements Matrix

Sub-System requirement-measurements for Gasket

			Degree F	in	atm	$	min	y/n
		Units	Degree F	in	atm	$	min	y/n
		Performance measures	Gasket Lower Operating Temperature	Gasket Inner Diameter	Burst Pressure	Cost of gaskets for 1 tank	LOX Boil Off Time	Machinability
	Target design requirements for Cryo-Tank		1	2	3	4	5	6
1	The gasket is affordable	3				x		
2	The gasket can withstand cryogenic temperature	9	x		x		x	x
3	The gasket is reproducable	3		x		x		
4	The gasket will prevent LOX leakage	9	x		x		x	x
5	The gasket can fits between the end cap and mat	9		x	x			
6	The Gasket is scalable for larger rocket design	3		x		x		
			18	15	27	9	18	18
		Lower Acceptable	-	3	6	-	20	The gasket material is not machinable and end cap/mating ring must be modified to fit an off the shelf seal
		Ideal	-200	-	10	0	60	The gasket material is machinable and will fit a custom end cap and mating ring design
		Upper Acceptable	-190	6	-	50	-	-