Rutgers School of Engineering

Mechanical and Aerospace Engineering
650:467 Design and Manufacturing I

CRITICAL DESIGN REPORT

for

High Strength, Light-Weight Cylindrical Pressure Vessel with Fiber-Reinforced Composites

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EXECUTIVE SUMMARY

Under Pressure Incorporated is committed to crafting light weight cylindrical pressure vessels. Our vessels' design utilizes a carbon-fiber epoxy composite as its primary material. This fiber reinforced composite allows our vessel to be lighter and to out-strength its steel counterpart. According to a critical analysis of our design, we expect our vessel to easily withstand three-thousand (3000) psi, as it has a significantly larger limit. Due to our designs light weight and high tensile strength, it is an ideal product not only for aerospace applications, but also for the marine, energy, transportation, and the emergency preparedness industry.

The structural integrity of our vessel is achieved through our carefully engineered design process which entails the following: casting paraffin wax into a PVC pipe and two (2) hemispherical caps to create a cylindrical mold, inserting the nozzle with an attached hemispherical skirt to the end of the wax mold, wrapping the mold and nozzle skirt with multiple layers of an optimally woven carbon fiber mesh that has been pre-impregnated with epoxy resin, curing our vessel in an oven at approximately two-hundred fifty-five degrees Fahrenheit (255 F) while dispensing the liquefied wax contents into a dispense container, and attaching a hydraulic valve and a relief valve to the nozzle. The purpose of the hemispherical skirt on the nozzle is to distribute force away from the nozzle to prevent stress concentrations from causing fracture at that point. This hemispherical skirt is made of a carbon steel mesh and is supported to the nozzle with a spherical washer of the same material. The release valve attached in-between the nozzle and the hydraulic valve is another redundancy to prevent pressures exceeding three-thousand (3000) psi from compromising our vessel. Moreover, the carbon fiber woven mesh is angled at $45^0, -45^0, 0^0$ to optimize its strength. Note that these additional mechanisms do not add significant weight to our vessel and drastically improve our designs integrity.

After several months of research and planning, we are eager to see the fabrication of our design by ordering and assembling our required materials. After we successfully assemble our vessel, we expect to safely test its internal pressure limit- likely with hydrostatic testing.

STATEMENT OF THE PROBLEM

In a conventional household or major company, pressure vessels are used for storing liquids, gases and vapors at high pressures. These vessels have a broad range of applications, which can vary from a huge storage vessel used at a facility such as a power plant to store a specific gas, or an activity such as scuba diving. When looking at the products currently available on the market, we see a vast majority of pressure vessels that already exist have similar issues. Most vessels currently available are constructed from steel and other types of alloys. The problem with these kinds of vessels is they have a much lower strength to weight ratio, meaning these vessels weigh more while not being able to withstand as much pressure. Our goal is to construct a cylindrical pressure vessel that is fabricated from carbon fiber, which is a well known fiber reinforced composite. Our vessel will be able to provide our consumers with a lightweight solution that will have higher storage capabilities compared to its metal counterparts.

DESIGN OBJECTIVES

The purpose of this senior project is to design a composite reinforced cylindrical pressure vessel, and then manufacture it to be stronger and lighter than a steel pressure vessel of comparable dimensions. Carbon fiber and epoxy are used to accomplish this task.

A set of design objectives can be defined that will guide the manufacturing of the cylindrical pressure vessel. Following these objectives thoroughly will lead to the pressure vessel meeting design expectations. The carbon fiber cylindrical pressure vessel will:

(1) be able to withstand, minimally, a maximum internal pressure of 3000 psi.

(2) contain a mesh interface between the cylindrical washer and the carbon fiber layers, adding extra strength to the nozzle.

(3) be made up of no more than three layers of carbon fiber, each being oriented to specifically maximize pressure capacity.

The above objectives define our design parameters and the cost considerations as the project is designed and constructed.

DESIGN PROCESS

When coming up with a design for the pressure vessel, the major constraints that were assessed include weight, strength, and cost. All three of these constraints are connected to each other, and the final result is the best compromise of the three. The common materials used in pressure vessels today are steel and aluminum. These metals are readily available, easy to work with, and relatively cheap. The benefits of using metals are clear, however there are other options that better fit the constraints of the engineering applications in which pressure vessels are use. Composite materials such as carbon fiber, fiberglass, and kevlar reinforced polymers have high strengths and low weights compared to metals. In the case of carbon fiber, the strength to weight ratio can be as high as 20 times greater that of metals. This means that when incorporating carbon fiber into the structure of our pressure vessel, we can expect to see these improvements.

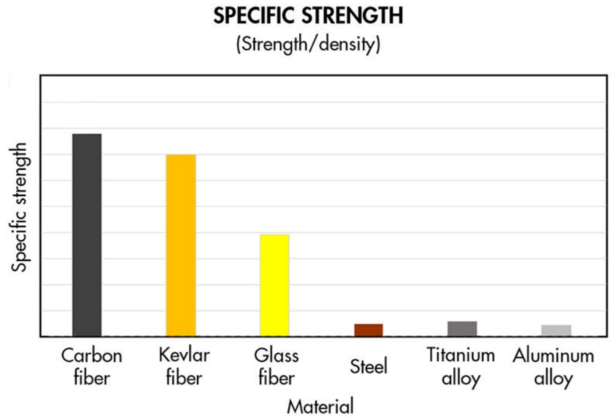

Figure 1. Comparing the strength to weight of composites to metals.

We chose to use carbon fiber over other types of fibers because it is the strongest available. Although carbon fiber is more expensive, less of it will have to used to reach our strength goal, which will help even out the cost when comparing each type of fiber.

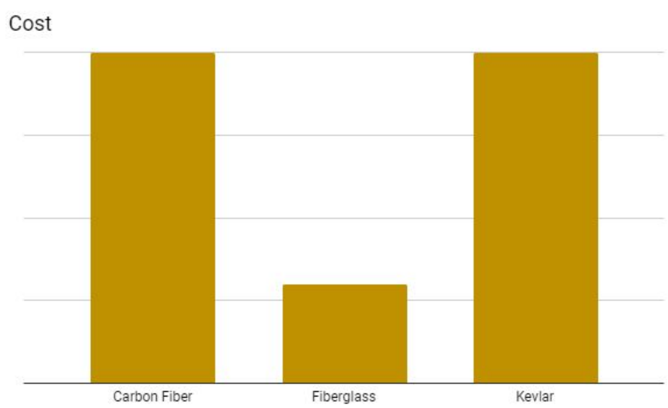

Figure 2. Comparing the cost of composites materials.

When planning on the mold design for the carbon fiber layup, it was decided that wax is the best option. Wax can be melted out of the vessel after the epoxy has cured. To make the wax mold, two of the options that were considered were foam and plastic pipe. The drawbacks of using foam are that it has to be carved out into the pressure vessel shape, and then treated before pouring wax into it. Using a PVC pipe is easier and more time effective because it already has a smooth cylindrical inside, so the sides would just have to be cut out so the hardened wax can be taken out.

The nozzle and valve part is one of the trickiest parts because of the absence of surface area on the valve for the carbon fiber to bond to. Solutions that were considered include using a spherical washer or a steel mesh to help better distribute the forces into the carbon fiber.

FINAL DESIGN

Cylindrical pressure vessels are straightforward when it comes down to the overall shape. There were a handful of features we had to take into consideration in order to come up with the most optimal design. Some of those included the overall dimensions of our vessel, whether the ends would be hemispherical or flat, the amount of carbon fiber layers to be used, and how we would install the nozzle onto the vessel. The objective that must be met for the pressure vessel is that it must be constructed to withstand 3000 psi. With this criteria we were able to use the governing equations for stress inside of pressure vessels, which is shown in the engineering analysis section, to determine the final dimensions of our pressure vessel as well as how many carbon fiber layers we would use. With this known, we determined the final dimensions to be 15 inches in height from the top to the bottom of the vessel. The radius from the outermost layer of the vessel to the center will be 3 inches.The height of the vessel does not include the height of the nozzle. The thickness of the vessel with 4 carbon fiber layers will be approximately .08 inches. All the dimensions can be referenced to our CAD, Solidworks, drawings at the end of the report. One of our biggest challenges was how to install the nozzle. Previous senior design groups had issues with their vessels failing at the nozzle. After a meeting with John Petrowski, we were able to come up with the idea to include a cylindrical washer under the carbon fiber layers with a metallic mesh integrated between the carbon fiber layers and the washer in order to provide the most structural integrity and avoid failure at the nozzle.

ENGINEERING ANALYSIS OF FINAL DESIGN

The overall dimensions and the thickness of a pressure vessel is important when trying to determine the theoretical stress it experiences. **Equation 1** and **Equation 2** below exemplify this.

$$\sigma_{longitudinal} = \frac{pr}{2t}$$

Equation 1: The longitudinal stress experienced due to internal pressure. Here, p is the internal pressure, t is the wall thickness, and r is the radius of the vessel.

$$\sigma_{hoop} = \frac{pr}{t}$$

Equation 2: Hoop stress experienced due to internal pressure.

These variables are outlined as follows in Figure 8.1 from Hibbler Mechanics of Materials:

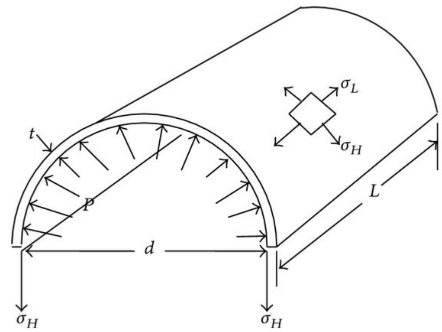

Figure 3: Hoop and longitudinal stress depicted on a visual model.

The three carbon fiber layers will be oriented in a specific direction. Theta represents the orientations of the carbon fiber layers with respect to the horizontal plane. This will result in a maximized pressure capacity for the vessel when all three are combined. It is intended to optimize the reinforced strength in longitudinal and hoop directions. A T-matrix is to be used to transform the stresses from the normal longitudinal and hoop directions to set of new orthogonal directions. To transform longitudinal and hoop directions equation four is used in conjunction with the T matrix shown in equation three, as seen below.

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix}$$

Equation 3: T matrix used for transformations

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{bmatrix} = [\boldsymbol{T}] \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix}$$

Equation 4: Using the T matrix to transform longitudinal and hoop directions to an orthogonal 1-2 direction.

Equations five and six will then be used to calculate the overall strengths in the hoop and longitudinal directions. In these equations, the superscripts 1 and 2 denote either the first or second layer.

$$\frac{1}{2}(\sigma_x^{(1)} + \sigma_x^{(2)}) = \sigma_x = \frac{pr}{2t}$$

Equation 5: Total longitudinal stress capacity from examining the individual stresses of layer 1 and layer 2

$$\frac{1}{2}(\sigma_y^{(1)} + \sigma_y^{(2)}) = \sigma_y = \frac{pr}{t}$$

Equation 6: Total hoop stress capacity from examining the individual stresses of layer 1 and layer 2.

Eventually MATLAB analysis will be able to yield what the maximum pressure a carbon fiber pressure vessel of our dimensions can hold as well as the orientation angle of the three layers. This can be done by analyzing an angle of fibers vs. maximum pressure graph. Even though MATLAB will show the optimal angle for orientation, it should be noted that this may be changed based on manufacturing difficulty. However the end goal of 3000 psi should not be compromised.

CONCLUSION

Composite materials have great potential in engineering applications to achieve a variety of results. Utilizing carbon fiber, an effective composite known for its strength, to tackle the problem of high pressure storage, resulted in the conception of the cylindrical composite carbon fiber pressure vessel. Designed to be low cost and lightweight, the pressure vessel is anticipated to hold 3000 psi with calculations predicting an even higher threshold for pressure storage capability.

Pressure vessels have use in several industries, however in many of these industries the most widely used type of pressure vessel is a traditional steel specification. Carbon fiber has a superior tensile stress compared to steel as well as it being lighter in comparison. These properties stage carbon fiber to make a large impact on the aerospace industry. With this in mind, design group W1 developed a cylindrical pressure vessel that will be formed using wax in the upcoming months, layered with carbon fiber, then cured with epoxy and be ready for use with an attached nozzle. Due to the most frequent failure of pressure vessels occurring at the nozzle, precise engineering has been integrated into the design of the nozzle that will feature several layers of security against fracture.

With a finalized parts list, W1 will move into next semester preparing a work space for fabrication and securing a strategy for in-house testing. Since it is dangerous to test pressure vessels because of their inherent application of storing high levels of pressure, the proper procedures must be followed in order to determine if the goal of 3000 psi of pressure held has been achieved. With the proper execution of the fabrication process, and the attributes of the composite material selected, carbon fiber, it is anticipated that the cylindrical pressure vessel will work as intended and showcase why it would be the most superior design to be used in aerospace applications compared to traditional pressure vessels.

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Appendix A1. PROJECT MANAGEMENT

Through the use of Gantt Charts, the team has been able to complete all identified deadlines. The Gantt Charts can be found in figure 1 and 2 below. Through the research and initial design of the pressure vessel, challenges regarding the mold and the nozzle was identified. However, the team was able to identify solutions for these concerns and then completed the full Computer Aid Drafting design of the pressure vessel. After completion of the the Logistics Director along with the Financial Officer, the parts order list has been identified and an order is ready to be made.

Furthermore, the development of the Gantt chart for Spring 2018 will provide access to concrete deadlines for the team. This will allow for a successful completion of the project. The mold design manufacturing is expected to be completed by beginning of February. Following the mold design, the Carbon Fiber and Epoxy will be wrapped around the mold and cured. One of the challenges that is expected during the manufacturing of the pressure vessel is finding an oven which is large enough. In order to resolve this, a list of available ovens on campus are being identified by size. Another significant challenge is the testing of the vessel. Since the vessel holds 3000 psi, it is dangerous to test it on campus. Therefore, alternative testing such as hydro testing will be done to demonstrate its functionality.

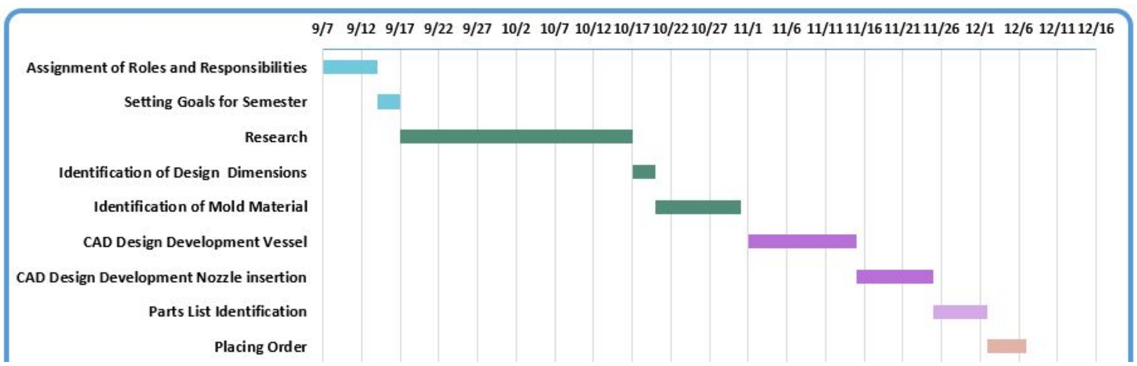

Figure 1: Fall 2017 Semester Gantt Chart where bars represent the progress of each activity on the right.

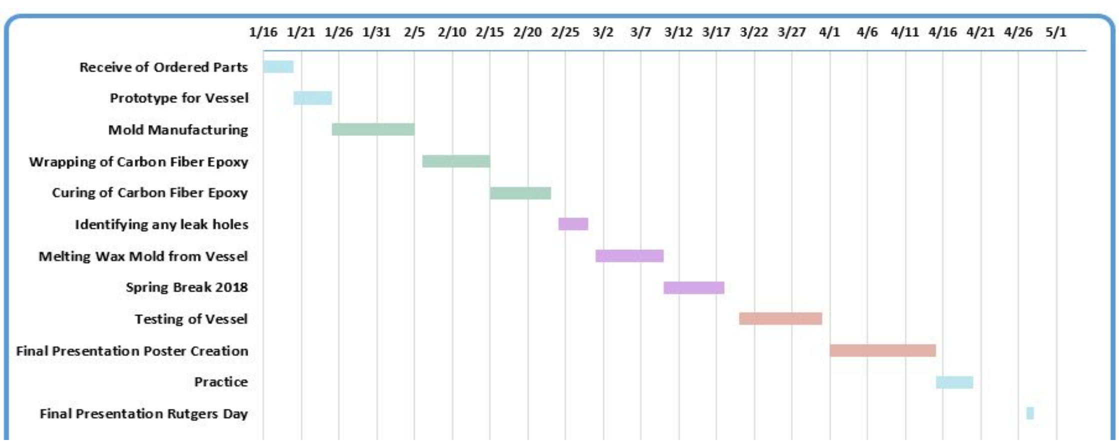

Figure 2: Spring 2018 Semester Gantt Chart where bars represent the progress of each activity on the right.

Appendix A2. BUSINESS MODEL CANVAS

The Business Model Canvas

Designed for: Text

Designed by: Text

On: 10/29/2017

Iteration #

Key Partners

Who are our Key Partners?
Who are our key suppliers?
Which Key Resources are we acquiring from partners?
Which Key Activities do partners perform?

Our key partners include the Rutgers School of engineering and mechanical engineering department that has agreed to allocate our project $650, covering shipping costs and placing the order for our materials; Section W2, who is working on a similar project and has agreed to purchase similar materials in bulk with us; Rutgers business school students who will be aiding us with our marketing plan next semester; and Home Depot (or other wholesalers/ department stores that would carry our required materials.

Key Activities

What Key Activities do our Value Propositions require?
Our Distribution Channels?
Customer Relationships?
Revenue streams?

The key activities required for our value proposition is the design and manufacturing of the Cylindrical Pressure Vessel. It is also required to properly market the product for the use in space missions.

Key Resources

What Key Resources do our Value Propositions require?
Our Distribution Channels? Customer Relationships?
Revenue Streams?

The key resources for our value proposition is the carbon fiber and epoxy supplies. We also require testing equipment for this product to ensure safety standards are being followed.

Value Propositions

What value do we deliver to the customer?
Which one of our customer's problems are we helping to solve?
What bundles of products and services are we offering to each Customer Segment?
Which customer needs are we satisfying?

We will deliver a lightweight cylindrical pressure vessel that can hold more than 20 MPa of pressure. This will provide easy usage in space missions.

Customer Relationships

What type of relationship does each of our Customer Segments expect us to establish and maintain with them?
Which ones have we established?
How are they integrated with the rest of our business model?
How costly are they?

Building robust relationship with NASA by developing contracts for our product.

Channels

Through which Channels do our Customer Segments want to be reached?
How are we reaching them now?
How are our Channels integrated?
Which ones work best?
Which ones are most cost-efficient?
How are we integrating them with customer routines?

Through the usage of contracts and participating in government bids for products.

Customer Segments

For whom are we creating value?
Who are our most important customers?

The customer segment for our project includes NASA for aerospace applications, aeronautical companies, marine and submarine companies, schools (for both educational and research applications).

Cost Structure

What are the most important costs inherent in our business model?
Which Key Resources are most expensive?
Which Key Activities are most expensive?

The most important cost inherent aspect of our business model is the carbon fiber, epoxy, valves,mold and equipment used for wrapping. Salary of the employees and marketing will also be a large part of the cost structure.

Revenue Streams

SEO $650 allocation to our project
Requested donations/ discount from a testing facility
Rental/purchase income from selling our pressure vessels
Design and Utility patent licensing
Possible NSF/ Govt grants

www.businessmodelgeneration.com

Appendix B. PARTS LIST/BUDGET

For the purposes of obtaining materials necessary for the construction of our pressure vessel, we have performed price comparisons between a multitude of vendors and have deemed the following materials to be the appropriate choices. Moreover, we are considering the option of purchasing some materials "in bulk" with section W2, as they are working on a similar project. For instance, we could purchase one (1) square yard of pre-pregnated carbon fiber with the other group and divide the cost, as we only require approximately 0.65 square yards. Moreover, we will contact each vendor in an attempt to receive a discount on any of the products that we require.

Table 1: Items & Funds for Initial Design

Item	Supplier	Catalog No#	Quantity	Unit Price	Total
High Pressure Valve	Grainger	1A049	1	$86.50	$86.50
Connector nozzle	Grainger	6W438	1	$2.61	$2.61
Release Valve	Surplus Center	9-6135-50-H	1	$44.95	$44.95
Carbon Steel Mesh	Amazon	B005H3AXKW	1	$21.56	$21.56
Spherical Carbon steel washer	Grainger	1JYJ1	1	$11.55	$11.55
Pre-pregnated Carbon Fiber (1 yard)	Fiberglast	3115-A	1	$175.95	$175.95
Paraffin Wax	Candles and Sup	WAX-130MP-SL	1	$25.50	$25.50
PVC Pipe (for mold)	Home Depot	100346975	1	$31.83	$31.83
Sphere Cap (for mold)	Amazon	B0000VZ3YM	1	$11.99	$11.99
				Total	$412.44

Appendix C. DRAWINGS