COMPARATIVE STUDY OF SMALL UAS FUEL

TANK FABRICATION METHODS

By

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Abstract: This paper will discuss the development, manufacturing, and testing of various fuel tanks intended for use in small unmanned aircraft with the intent of limiting weight, cost, and manufacturing complexities. The main goals of the research performed is the ability to manufacture multiple variations of fuel tanks in house that will allow for customization of fit and type for varying airframes. Investigated manufacturing methods were determined by the equipment available at the Oklahoma State University aerospace graduate student design lab, which includes composites, 3D printing, and thermoforming. Firstly, research and benchmarking were done to ensure the selected materials would not corrode or degrade over time when exposed to fuel or the operating environment. Selected materials consisted of Kevlar, fiberglass, a fuel safe epoxy, PETG, ASA, and Nylon. After materials were selected three experiments were performed in order to determine the viability of each material and manufacturing method. The first experiment consisted of creating disc samples of each material and pressure testing them in a small pressure pot submerged in water to identify leaks. Small samples were created with varying manufacturing specifications including differing layering for the composite fabrics with different epoxy ratios, multiple different settings for 3D printed parts such as infill density, top and bottom layers, and layer thickness. Both the second and third experiment tested 5.75” spheres that were made with the determined methodology. The second experiment consisted of pressurizing and submerging them in a tank of water to again look for small air leaks to study the effects of scaling up the manufacturing method. Results from the second experiment showed that some changes needed to be made to the composite and 3D printed parts as the increased surface area also resulted in an increase in pin holes, the thermoformed tanks only had small holes around the seam line. For the third experiment the spheres were dropped starting at four inches and increasing by four inches each time if the tank showed no signs of damage or leaks. Drop testing showed that all final manufacturing methods for the tanks are able be made with minimal or no leaks. Finally, with all testing complete and manufacturing methods finalized a cost and weight analysis was performed to compare the experimental tanks to ones available in today's market.

TABLE OF CONTENTS

Chapter | Page Number

Chapter Page Number

LIST OF TABLES

LIST OF FIGURES

Figure Page Number

Figure Page Number

CHAPTER I

INTRODUCTION

1.1 Introduction and Motivation

Within the aerospace industry research is always underway in order to further improve existing and create new technology. This is also true for the aerospace composite design and assembly lab at Oklahoma State University (OSU) where graduate and undergraduate students have the opportunity to design, manufacture, and test unmanned aircraft systems (UAS). Typically, the labs are used by students to create group 1 UAVs, weighing between two and fifty-five pounds, but on occasion larger planes have been built. Most undergraduate experience comes through the senior design challenge known as Speedfest, where students work together to design, fabricate, and test planes built in house to compete in specific challenges [1]. The first in-house fuel tank was made for one of these competitions when students were tasked with building a long-range reconnaissance UAV, this tank had a capacity of just over one gallon and was made from multiple types of fiberglass. The tank manufactured for the Speedfest competition can be seen in Figure 1. Two subsequent teams had also designed and built custom fuel tanks for their aircraft, one being made of fiberglass like the first and the other being 3D printed from PETG filament laminated with epoxy to fully seal it. All mentioned tanks were successful in retaining fuel without leaking, no definitive manufacturing method or testing procedure came from their production. Other teams over the many years of Speedfest competition have used multiple different items in attempts to have a fuel tank that efficiently uses the allotted space within their aircraft such as hard plastic bottles and bladder bags.

Figure 1: Oklahoma State Speedfest IX Fuel Tank

Many graduate research aircraft have used both standard off the shelf tanks as well as custom made composite. For example, the short takeoff and landing aircraft (STOL), Locust is shown in Figure 2, used multiple off the shelf DuBro brand fuel tanks for its hybrid propulsion system consisting of an internal combustion and turbojet engine. While other smaller form factor aircraft used composite tanks to better fit the unique interior configuration as well as to meet specific weight requirements for the airframe. It is desirable to be able to either prototype or manufacture fuel tanks in the OSU graduate student design lab that could fill similar roles as the tanks previously mentioned in order to provide more opportunities to future researchers and students to learn or expand a skill set in composite fabrication.

Figure 2: Oklahoma State STOL Aircraft – Locust

There are already many options for UAS and RC fuel tanks available on the market although improvements in weight and ease of manufacturing are always desired in both industry and hobbyist applications. Aircraft weight is one of the driving factors for most performance parameters including takeoff speed, max endurance, and many others which drives the need for lighter parts that do not increase the manufacturing difficulty. The purpose of the subsequent research is to better understand the manufacturing process behind making a fuel tank with desirable characteristics that can be produced by either researchers, students, composite manufacturers, or hobbyists. Desirable characteristics are defined by the figures of merit discussed in the next section.

1.2 Figures of Merit

For the research presented in this paper five figures of merit were determined to uniformly evaluate the tanks produced. These included the simplicity of manufacturing, the cost of the tank produced, the ability to resist leakage, the damage tolerance, and the volume to weight ratio. Simplicity of manufacturing includes the time to make molds or any tooling needed to produce the final part, the manufacturing time to either layup, print, or form the part, fixes that need to be made to the part to seal the tank, and the total assembly time. Manufacturing simplicity is very important to the overall cost, marketability, and feasibility of producing the part. The overall cost of the produced tank is a major factor as well since if the tanks produced are not cheaper or at least comparable to the price of the commercially available fuel tanks then there is not much use in manufacturing them in house. Cost estimates for the tanks tested are based on three main components which are the machining cost associated with making molds and jigs, the cost of the materials used, and the expense that is usually the highest being the labor hours used to produce the fuel tanks. Next the leak resistance of the tank without modifications after initial production is also important since if additional work is required to seal the tank it adds to the labor required to achieve the final product. Leak resistance also serves a critical role if the fuel system being designed is a pressurized system as the air will escape through holes that are much too small for the fuel particles to fit through. The damage tolerance of the final product is important as the tank must be strong enough to support the desired fuel load as well as the loads transferred from the aircraft to the tank through supporting structure. Finally, the volume to capacity ratio is significant as it symbolizes the ability to maximize usable fuel or payload volume while minimizing the weight added from the tank.

1.3 Available Manufacturing Methods

It is important that investigated manufacturing methods are ones available to both graduate and undergraduate students, or ones that can be done in a nonprofessional environment. The availability of equipment to students and hobbyist is important as the devised fuel tank production methods are intended for use in student research projects as well as the ability of a person interested in custom aircraft to produce their own tanks. Methods available at the Oklahoma State University Design and Manufacturing Lab (DML) consist of thermoforming, 3D printing, and composites. While the thermoforming equipment available to students at the DML is a professional level machine the same results can be obtained through the use of a standard household oven as the heating element is the most crucial part since the forming table can be made for relatively low cost. 3D printers can range in cost from a few hundred dollars to thousands of dollars but have become more readily available to the general public. It is also possible to make a model of the desired tank shape and have a company print the parts for you. Finally, the composite manufacturing is one of the more complicated methods and has the largest startup cost. Even though the startup cost is high it is still possible to produce composite parts in a nonprofessional setting.

1.4 Goals and Objectives

As previously stated, the goal of this thesis is to define manufacturing procedures for 3D printed, composite, and thermoformed fuel tanks. The following list will give an outline of the objective to meet this goal.

1. Conduct a literature review of current uses and manufacturing procedures for each method.
2. Design and assemble testing apparatus to apply a pressure load to small scale samples.
    a. Must be able to hold 3.75” sample disc
    b. Must be able to apply a load of 5 psi

3. Determine 3D printer settings and composite layup orientation.
    a. Find best 3D printer settings to achieve an airtight sample off the print bed
    b. Find composite layup orientation and epoxy ratio to achieve airtight samples
4. Design, build, and test large scale samples.
    a. Ability to produce similar parts from all manufacturing processes
    b. Be able to withstand 5 psi load
    c. Be able to withstand a minimum of a 4 inch drop at 80% volumetric capacity
5. Perform a cost analysis for the experimental tanks to be compared to products available on the current market.
6. Determine final manufacturing procedures for different methods
    a. Create guides to be able to replicate the process used to produce samples

CHAPTER II

BACKGROUND RESEARCH

2.1 Market Study

Presently there are a wide selection of fuel tanks for remote controlled and autonomous planes which vary widely in cost and capacity. These tanks can range from generic shapes such as rectangular or cylindrical and are usually molded plastic or are of Kevlar composite make, although when it comes to the composite tanks there are many companies that are willing to make custom fuel tanks for an increased cost. At the time of writing the aero assembly graduate student design team uses either pre manufactured plastic DuBro fuel tanks or JetTech Kevlar composite fuel tanks. The premade DuBro tanks range in capacity from 2 fl. oz to 100 fl. oz and have an average price per fluid ounce of \$0.92/fl. Oz, with the most cost-efficient tank being the 24 fl. oz with a price of \$0.49/fl. Oz [2]. Jet Tech has both a stock of premade tanks that are varying diameters of cylinder or made for specific model aircraft. These tanks have an average cost per capacity of \$2.03/fl. oz with the most cost-effective tank being a 150 fl. oz 5.5" diameter cylinder that cost \$1.3/fl. oz. While some custom tanks that have been ordered for specific research aircraft have cost between \$1.75/fl. oz to \$2/fl. oz making them comparable to the average cost of the pre-made tanks from Jet Tech [3]. Although it is desired for the tanks made in the lab to be a similar cost if not cheaper than the off the shelf counterparts it is not a requirement as the ability to reliably prototype and manufacture custom tanks is the desired outcome.

2.2 Federal Aviation Regulations

For manned aircraft the FAA code of federal regulations (CFR) lays out the testing and structural requirements for fuel tanks to get approved for use. This includes tank load factors as well as both pressure and drop testing where some requirements depend on placement of the fuel tank in the aircraft. Pressure testing requirements can be found in both chapter 25 and 27 of FAA regulations which define standard for cargo transport aircraft and normal rotorcraft. Chapter 27 requirements are defined for nonmetallic tanks supported by the structure of the rotorcraft in which it is installed. This test states that the tank must be able to withstand an internal pressure load of 2.0 pounds per square in (psi) [4]. Furthermore chapter 25 states that an internal pressure of 3.5 psi should be achievable as well as a 125% of maximum air pressure developed in the tanks from ram effect. It also states that the tanks should be able to withstand fluid pressure developed during the most adverse combination of airplane roll and fuel load, maximum limit accelerations, and deflections with a full fuel load. An additional requirement of chapter 25 pertains to hydrostatic pressure loading and states that the fuel tank must be able to withstand the loading dictated by equation 1, where K, ρ, g, and L are defined in Figure 3 [5].

$$P = K\rho g L \tag{1}$$

P = fuel pressure at each point within the tank
ρ = typical fuel density
g = acceleration due to gravity
L = a reference distance between the point of pressure and the tank farthest boundary in the direction of loading
K = 4.5 for the forward loading condition for those parts of fuel tanks outside the fuselage pressure boundary
K = 9 for the forward loading condition for those parts of fuel tanks within the fuselage pressure boundary, or that form part of the fuselage pressure boundary
K = 1.5 for the aft loading condition
K = 3.0 for the inboard and outboard loading conditions for those parts of fuel tanks within the fuselage pressure boundary, or that form part of the fuselage pressure boundary
K = 1.5 for the inboard and outboard loading conditions for those parts of fuel tanks outside the fuselage pressure boundary
K = 6 for the downward loading condition
K = 3 for the upward loading condition

Figure 3: Hydrostatic Pressure Equation Terms

Drop testing requirements in the CFR title 14 chapter 27 are defined as follows; a minimum drop height of 50 feet, the impact surface must be non-deforming, the tank must be filled to 80 percent of its normal capacity, the tank must be closed in the surrounding structure unless it can be proven that it is housed in a puncture free environment, the tank must drop freely and impact ±10° from horizontal, and finally there must be no leakage after testing [4]. For the cases the researched fuel tank is designed for some of the minimum drop height of 50 feet is a bit extreme and is being reduced to better simulate the landing scenario for most group 1 UAS as well as hobbyist fliers. All other requirements for fuel tank testing will be observed as stated in the federal regulations for commercial aircraft.

2.3 Chemical Compatibility of Materials

Another important factor that will determine the types of plastics used is the chemical compatibility of the plastics with different kinds of fuel. The fuels of interest being diesel, no ethanol gasoline, aviation low lead gasoline, and Jet A-1 aviation fuel. Plastics chosen for this study were ones that had the capability to be thermoformed even if they did not have the best properties to do so and ranked either “Good” or “Excellent” in compatibility with the desired fuels [6]. A study by Al-Lal, et al. investigated the structural properties of common materials used in the construction of commercial aircraft against the corrosiveness of Jet A fuel which is used in almost all modern jet aircraft. Testing included stress, strain, hardness, and dimensional variation, this testing found that the plastics used as well as the composite materials showed no insignificant changes, less than 10% different, in all tested properties [7]. As far as research on the corrosive effects of fuel and composites there is not much in that field, although the chemical compatibility charts for certain resins are available [8]. An internal study was previously conducted in the graduate student design (GSD) lab on the effects of long-term fuel storage in composite fuel tanks where a tank made of 3oz and 9.6oz fiberglass was used to hold Jet A fuel at 25% capacity for 6 months without leaks. A research team at Prusa, a 3D printer manufacturer, tested multiple 3D printer filaments, including the ones selected, against multiple different solutions to test the effect on both impact strength and impact toughness [9]. Unfortunately, fuels were not among the selected solvents that were tested though the ones that were show how diverse the chemical compatibility of common 3D printer filaments is. An additional study was also conducted by the 2020 Oklahoma State University Speedfest Orange Team on the plastic Tritan which is commonly used in the manufacturing of Nalgene water bottles. It was found that the plastic had good chemical resistivity and could contain the desired fuels without leaks.

CHEMICAL COMPATIBILITY

A: Excellent,
B: Good,
C: Fair to Poor,
D: Not recommended
- No Data

CHEMICALS	METALS					PLASTICS, ELASTOMERS & LEATHER																			
	Aluminum	Carbon Steel	Cast/Ductile Iron	304 Stainless Steel	316 Stainless Steel	Acetal	Buna	CSM (Hypalon)	EPR, EPDM	Fluorocarbon	Fluoroelastomer (FKM)	Geolast (Buna & Polypropylene)	Hastelloy C	TPE	Leather	Nitrile (TS)	Nitrile (TPE)	Nylon	Polychloroprene	Polypropylene	PTFE	PVDF	Santoprene (EPDM & Polypropylene)	UHMWPE	Urethane
Dichloroethyl Ether	B	-	-	-	-	-	D	-	-	-	-	-	-	-	-	D	-	-	-	-	A	-	-	-	-
Dichloroethylene	-	-	-	-	-	-	-	-	-	-	-	-	-	D	-	-	-	A	-	A	A	A	D	D	-
Dichloro-Isopropyl Ether	D	-	-	-	-	-	D	-	-	-	C	-	-	-	-	-	-	-	D	D	A	-	-	-	-
Dichloropenthane	-	-	-	-	-	-	-	-	D	-	A	-	-	-	-	D	D	-	D	-	A	-	D	-	D
Dicyclohexylamine	-	-	-	-	-	-	D	-	D	B	D	-	-	-	-	D	D	-	D	-	A	-	B	-	D
Diemethyl Formamide	A	-	A	A	-	C	-	-	B	-	D	-	A	B	-	C	C	-	D	A	A	D	A	A	D
Diemethyl Phthalate	A	-	A	A	-	-	-	-	B	-	A	-	A	A	-	D	D	-	D	A	A	A	A	-	D
Diesel Fuel	A	A	A	A	A	A	A	B	D	-	A	A	B	B	A	-	-	A	D	B	A	A	D	D	-
Diesel Oil (Fuel ASTM #2)	A	-	A	A	-	A	A	-	D	A	A	-	A	B	-	A	B	-	D	B	A	A	D	A	B
Di-Ester Lubricant Mil-L-7808	-	-	-	-	-	-	-	-	D	-	A	-	-	-	-	B	C	-	D	-	A	-	D	-	D
Di-Ester Synthetic Lubricants	A	-	A	A	-	-	-	-	D	-	A	-	A	D	-	D	D	-	D	-	A	-	D	-	D
Diester Synthetic Oils	A	-	A	A	-	-	B	-	D	A	-	-	A	-	-	-	-	-	D	-	A	-	-	-	-
Diethanol Amine	A	-	A	A	-	-	B	-	A	-	D	B	A	D	-	D	D	A	D	A	A	-	-	-	D
Diethanolamine	A	A	A	A	A	-	-	-	-	-	-	-	-	D	-	-	-	B	-	B	A	-	-	-	-
Diethyl Amine	B	-	D	B	-	-	C	-	C	D	D	-	A	-	-	C	D	A	C	A	A	A	C	-	C
Diethyl Aniline	-	-	-	-	-	-	-	-	B	-	C	-	-	-	-	D	D	-	D	A	A	A	B	-	D
Diethyl Benzene	-	-	-	-	-	-	D	-	D	A	A	-	-	-	-	D	D	-	D	-	A	-	C	D	D

Figure 4: Chemical Compatibility of Diesel Fuel **[6]**

2.4 Material Selection

Initial material selection began with the identification of what is available for the different techniques used to produce fuel tanks as well as the materials traditionally used in these procedures. Research showed that most fuel tanks on the commercial market available for RC and small scale UAS are either injection molded plastic or a Kevlar composite layup. Fuel tanks specifically investigated for market research are DU-BRO [3] plastic tanks and Jet-Tech [2] composite tanks which can be custom made to fit the desired aircraft.

Most plastic fuel tanks are made out of high-density polyethylene (HDPE) using either a thermoformed or blow molded method, although there are some cases of homemade fuel tanks where hobbyists are using polyethylene terephthalate glycol (PETG). Other plastics that could be used is Nylon as it has similar properties to both HDPE and PETG but is more resistant to wear as well as being a flexible material as well as chlorinated polyvinyl chloride (CPVC) a version of standard PVC that is better suited to thermoforming manufacturing. HDPE, PETG, and CPVC are good candidates for thermoformed tanks as they are resistant to fuel, UV corrosion, cheap, and easily obtainable. Nylon can also be thermoformed but the cost of the material needed for this method is significantly higher than the other possible materials. All the plastics that were considered for thermoforming were also researched for 3D printed manufacturing. While HDPE is the most used plastic when it comes to fuel storage it is not readily available as a 3D printing filament with all suppliers being out of stock or having a long lead time. These are the reasons why HDPE filament was no longer considered as a possible plastic for 3D printing. Both PETG and Nylon are readily available options that can be purchased from multiple vendors. When researching 3D printing materials, a fourth plastic, Acrylonitrile styrene acrylate (ASA) was found that is advertised as having good UV and chemical resistivity.

Composite material selection was somewhat limited as it was desired that the determined procedure could be performed in house as well as some market research that showed the most used material is generally a combination of Kevlar and Fiberglass. Specifically, two types of fiberglass, a 3 oz/yd^2 4H satin weave, a 9.6 oz/yd^2 plain weave, and a single variation of Kevlar, 5.3 oz/yd^2 plain weave. A plain weave refers to the standard one over one under pattern, there are varying types of satin weaves but the 4H refers specifically to a three over one under [10], different weave types can be seen in Figure 4. While there are many variations of weave and weight for composite materials these specific ones were chosen since they are readily available in the graduate student design lab.

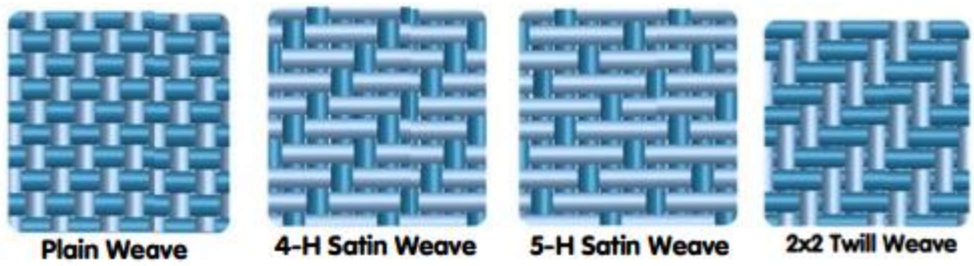

Figure 5: Woven Fabric Style Guide **[10]**

2.5 3D Printer and Filament Characteristics

As with most materials 3D printing filaments all have different structural and chemical properties as well as have varying manufacturing characteristics that play a part in the quality of the piece produced. Along with the subtleties in the printer settings each filament has a range of values for printing such as extruder temperature, bed temperature, extrusion speed, and cooling percentage.

When working with 3D printers each model has its own nuances that need to be worked out in order to get the best prints possible. The printers initially used in this study were a Dremel 3D45 and a Snapmaker A350 modular printer. These printers vary in a multitude of ways including the print size supported, the environment enclosure, customizable parts available, and most importantly the slicer that is used with each printer. 3D printer slicers are programs dedicated to the conversion of stereolithography, STL, files that are generated by modeling software's into g-code which is essentially turning the part into many small layers that the printer can use to build the part. Slicers for the 3D45 and the A350 vary widely in versatility and ease of use. While the Dremel 3D45 has a proprietary slicer that you must use for their printers, the Snapmaker A350 is designed to use a variety of slicers as long as they can export the g-code needed by the printer. Although the proprietary slicer for the Dremel is easy to use and nice for beginners it offers very little room for customization of print settings needed to better optimize the parts produced. The inability to customize some settings later led to the Dremel 3D45 no longer being used to produce test samples as it was not possible to get an uncorrupted slice when trying to mimic some custom settings of the A350 that allowed for solid layers of filament to be printed for a certain number of layers on the top and bottom of the sample. The 3D45 also seemed to have problems with the stringiness of PETG filament where it would gather plastic around the extruder head from wisp of plastic then it would deposit a large amount in a single area whenever it would get pulled of the extruder which led to inconsistencies in parts as well as some failed prints. Nylon filament also showed some issues when used in the 3D45 as the parts would either warp due to cooling too quickly or would print bed adhesion problems. An attempt was made to try and resolve the adhesion issues by trying different print bed temperatures as well as using stick glue, unfortunately neither of these options produced consistent results on the Dremel printer. After discovering these nuances and unsuccessfully trying to find ways around them using the Dremel printer it was decided that all prints would be done on the Snapmaker A350 as the sample parts produced on it seemed to be produced at a higher quality and the issues that were found on the Dremel were mitigated.

2.6 Composite Characteristics

Composites fabrics come in many different variations and composite parts can be made in a multitude of ways. Traditionally the Graduate Student Design (GSD) lab at Oklahoma state uses either a wet or prepreg layup technique with a female mold. Wet layup refers to laminating the fabric in the mold layer by layer while prepreg refers to laminating the fabric outside the mold then laying the wetted pieces into place. Molds can be either female or male which dictates whether the part desired intrudes or protrudes form the parting board. The molds used in this thesis were male as the part protruded from the base forming the interior of the created samples and made use of a prepreg laminating method. While this was an effective way to produce a small number of parts it is not ideal for larger scale manufacturing. Another way to produce fuel tanks as described in an RC hobbyist forum and YouTube video tutorial makes use of a subtractive manufacturing method using a positive Styrofoam mold with Kevlar fabric where after the epoxy had cured the Styrofoam was removed using gasoline as a solvent [11]. While this technique is affective in achieving a part it would be difficult to replicate the part as the mold vary as it would have to be manufactured for each tank. Composite fabrics can vary in weave as discussed in the previous section; they can also vary in fabric weight. Weave type mostly affects the flexibility and ease of use of the fabric while weight dictates the structural properties of the finished part.

2.7 Thermoforming Characteristics

Although thermoforming plastics is a relatively straightforward process there are still manufacturing characteristics of the plastic selected that need to be taken into consideration. These factors include the shrinkage rate of the plastic being used as well as the draft ratio of the part being produced. Shrinkage ratio is important due to the contraction the parts can have when they are being cooled which can lead to deformed parts or parts out of tolerance. Shrinkage ratio varies by specific plastic compounds and can be as low as 0.1% or up to 6% for some plastics and each plastic has a minimum and maximum shrinkage that is ambiguous over the total deviation of the compound. The shrinkage percentage that actually affects the parts being produced depends on many factors including; ambient temperature, mold temperature, plasticization temperature, low holding pressure, or short cooling time [12]. Another major factor to consider when thermoforming is the draft ratio of the part being manufactured. This is simply a ratio of the total surface area of the part divided by the footprint area and is generally accepted as a maximum ratio of 3:1. The ratio is important since it dictates the final thickness of the product due to the expansion of the plastic due to the drafting process. For example, if the desired final thickness of a part is 0.1" and has a draw ratio of 1.7 then an initial thickness of 0.17" is required [13]. Other than draw ratio and shrinkage of the material used only the standard plasticization temperature and the proper use of a thermoforming machine is needed to produce parts.

CHAPTER III

SMALL SCALE TESTING

3.1 Preliminary Testing Guidelines and Setup

After selecting which materials would be suitable for the intended applications a process for testing small samples of both the composite and 3D printed tanks was devised in order to further down select the layup composition as well as the 3D printer settings needed to ensure the tanks will be liquid tight without further modifications needed to achieve a proper seal. The thermoforming plastic was omitted from this testing as it was assumed that premanufactured sheets of a known chemically resistant plastic would be airtight. For this testing a small 3D printed pressure pot, shown in Figure 5 and Figure 6, was designed to fit a 3.75" sample disc which was loaded to 5 psi to check for small air leaks. A pressure of 5 psi was chosen to provide a safety factor of approximately 1.5 over the FAA CFR requirement of 3.5 psi for manned cargo aircraft fuel tanks. Experimental setup went as follows; a large container was filled approximately ¾ of the way with water, samples were placed between the top and bottom half of the pressure pot with a gasket on both sides to ensure a good seal, perimeter bolts were tightened by hand in an alternating pattern, a compressed air tank was attached to the pressure regular, the sample was then lowered into the tank of water, the regulator key was slowly turned until a pressure of 5 psi was achieved, once at testing pressure any air holes were noted.

3.2 Small Scale Testing Apparatus

The testing apparatus was specifically designed and built for the small-scale samples and went through two iterations which varied in compression points (number of mounting holes), thickness, and size. To construct the testing apparatus a simple 3D model was created in Solidworks and then printed as two components using ASA filament on the Snapmaker A350. The Snapmaker was used due to size of the printing areas as well as the higher quality of print that could be achieved. The first iteration consisted of four compression points at 0.5” thickness, a 0.25” wall thickness, a 0.5” flange, and was design to fit samples of 4.5” diameter. This iteration showed leaks around the flange as there was not an even distribution of force, as well as leaks through the main body as there was an instance of a non-fully bonded layer. The second and final iteration is shown in Figure 6 and Figure 7. The final pressure post consisted of eight compression points at a thickness of 0.875” for the main body and 0.625” for the lower portion, a wall and flange thickness of 0.375”, and fit the same 3.75” diameter samples. The top of the pressure pot was design to with a tap hole for a ¼” NPT thread, the piping and gauges used were selected to have the same ¼” NPT threading to limit the use of varying materials. A sheet of simple plumbing gasket was cut to shape to place on the top and bottom of the sample to create a better than the plastic-to-plastic contact between the sample and pressure pot.

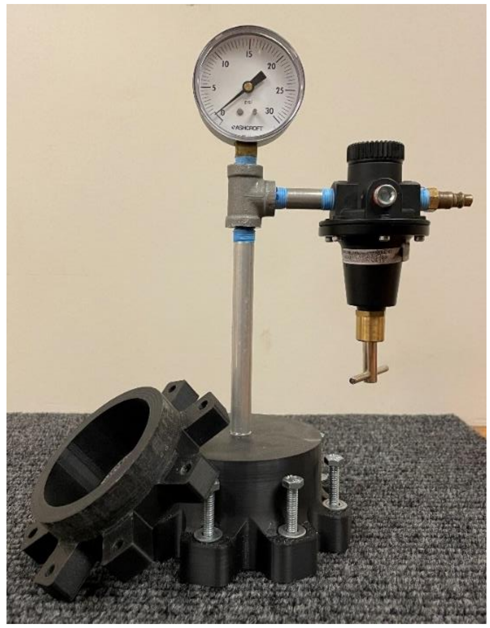

Figure 6: Pressure Pot – Front View

Figure 7: Pressure Pot – Internal View

3.3 3D Printed Samples

3D printed materials were tested with variations in both thickness and infill density with the goal being to find the thinnest the part could be with the least amount of infill and still be produced without leaks. Variations included thickness of 1/16th and 1/32nd of an inch with infill densities of 25%, 50%, and 100%. Initially two different 3D printers were being used for prototyping, a Dremel 3D45 and Snapmaker A350, after complications with the Dremel and the much more versatile slicer used for the Snapmaker it was decided to move all printing to the A350 after the initial Nylon and PETG disc prints from the Dremel both failed testing.

Table 1: Snapmaker Printer Settings

Material	Nozzle Temperature (°C)	Bed Temperature (°C)	Cooling Fan Speed	Print Speed (mm/s)
Nylon	255	95	0%	37.5
PETG	240	85	100%	50
ASA	250	90	0%	50

To better understand the reason behind these failures' samples produced by the Dremel printer were studied under a microscope. It was found that the slicer was staking the layers of filament directly on top of one another compared to the Cura slicer used for the Snapmaker which would slightly offset every layer. Figure7 and Figure 8 show the difference in layer orientation and adhesion between the two printers.

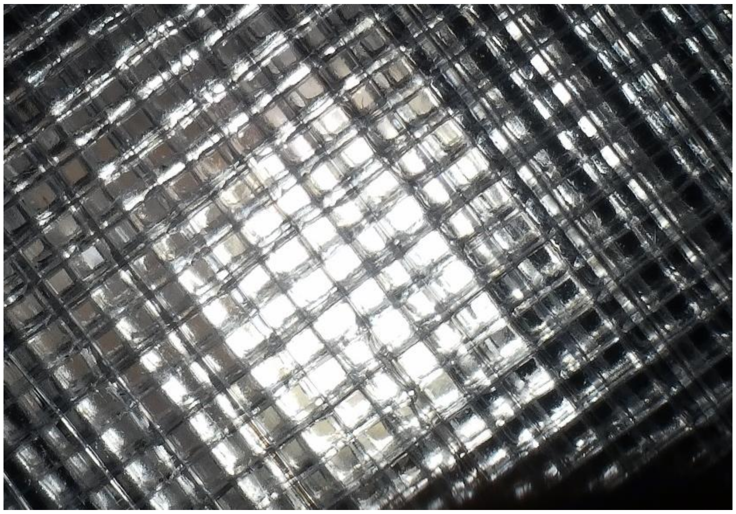

Figure 8: Dremel PETG 3D Print

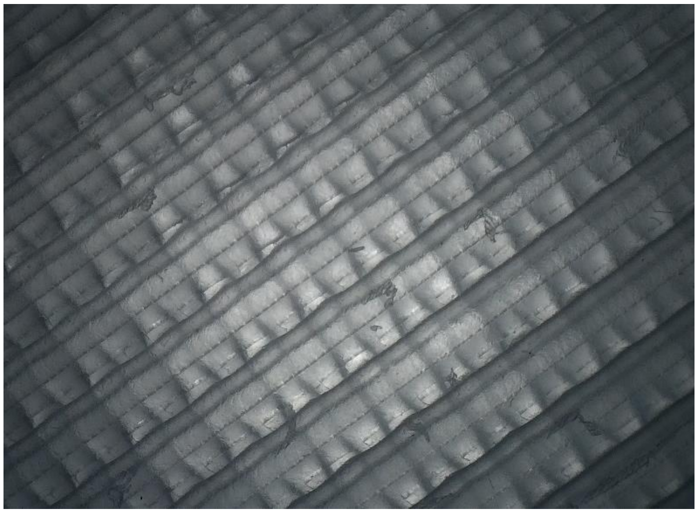

Figure 9: Snapmaker PETG 3D Print

The switch appeared to be justified after the initial Nylon and PETG prints were redone on the A350 and both passed with the same thickness and infill density as set on the 3D45. While these phenomena found in the 3D printed examples are easily seen under the microscope it is not known whether they are caused by the printer hardware itself or the slicing software used by each printer. After the final initial testing was done with the 3D printed materials it was found that the disc could be made in the thinnest and least filled combination and still be air tight when tested up to 5 psi.

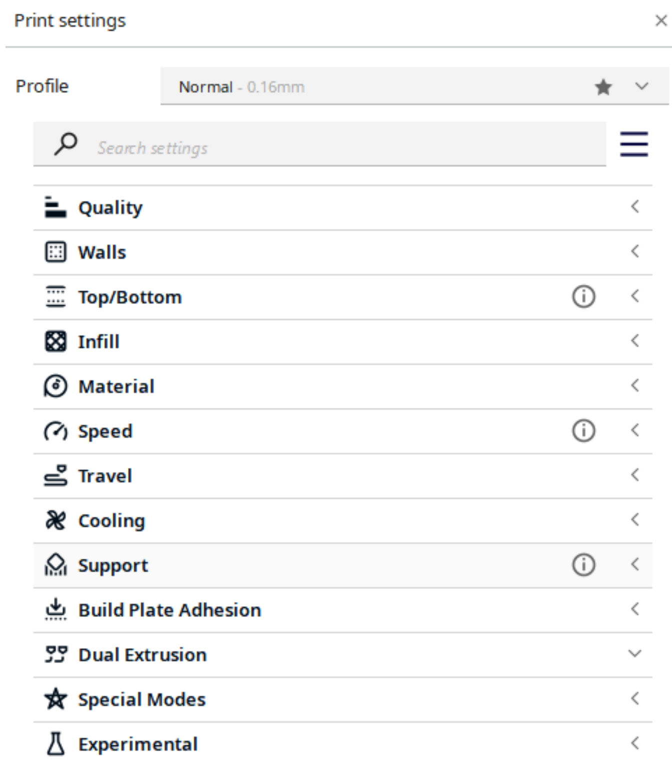

Figure 10: Cura Slicer User Interface

This shows that the availability of a more versatile slicer on the Snapmaker allowed for the settings to be tweaked in such a way that the top, bottom, and outside layers of the part could be printed in a variable number of solid layers before the infill is applied which in turned produced parts that were air tight right off the print bed.

Table 2: 3D Printed Small-Scale Sample Characteristics

Print Sample	Thickness (in)	Infill Density	Sample Results	Printer Used
Nylon 1	1/16	50%	Fail	Dremel
Nylon 2	1/16	100%	Fail	Dremel
PETG 1	1/16	50%	Fail	Dremel
PETG 2	1/16	100%	Fail	Dremel
ASA 1	1/16	50%	Pass	Snapmaker

ASA 2	1/32	100%	Pass	Snapmaker
Nylon 3	1/16	100%	Pass	Snapmaker
PETG 3	1/16	100%	Pass	Snapmaker
PETG 4	1/32	100%	Pass	Snapmaker
ASA 3	1/32	50%	Pass	Snapmaker
Nylon 4	1/16	25%	Pass	Snapmaker
Nylon 5	1/32	25%	Pass	Snapmaker
PETG 5	1/16	25%	Pass	Snapmaker
PETG 6	1/32	25%	Pass	Snapmaker
ASA 4	1/16	25%	Pass	Snapmaker
ASA 5	1/32	25%	Pass	Snapmaker

3.4 Composite Samples

Similar to the 3D printed sample the composite ones were made with varying amounts of epoxy and layers to study the impact of it had on the ability to be leak resistant. Initial layups consisted of two main techniques, one which was composed of painting epoxy directly onto the part then letting it kick or become "green" which just involved waiting a minimum of the working time plus 50% of that working time. For example, when using an epoxy with a 30-minute working time a minimum of a 45-minute wait time in addition to the working time is suggested. This layer of epoxy was then followed by multiple layers of fabric with varying types of fiberglass or layers of Kevlar and glass combined. The second method was more traditional as sheets of fabric were infused with epoxy stacked on top of one another then placed under vacuum to insure proper adhesion. Initial samples were made with a ratio of 125% epoxy weight to the weight of the fabric used for the piece. Samples that failed initial testing were not progressed to the next stage of testing where the epoxy ratio was reduced until the layups became undersaturated or the weight of the epoxy was lower than the weight of the fabric at a ratio of 90%. The composite samples were tested under the same procedure as the 3D printed ones where they are inserted into the pressure pot and the pressure is increased from 0 to 5 psi or until the sample began to leak. Similarly, to the 3D printed samples, composite discs were observed under a microscope in an effort to better understand the reason behind the failures. Contrary to 3D printed samples the composite samples did not have a clear reason as to why certain ones passed and others failed. When examining the samples, it can be seen that there are microbubbles within the layers of the layup, these bubbles appear in multiple layers not just the outer ones, as shown in Figure 9.

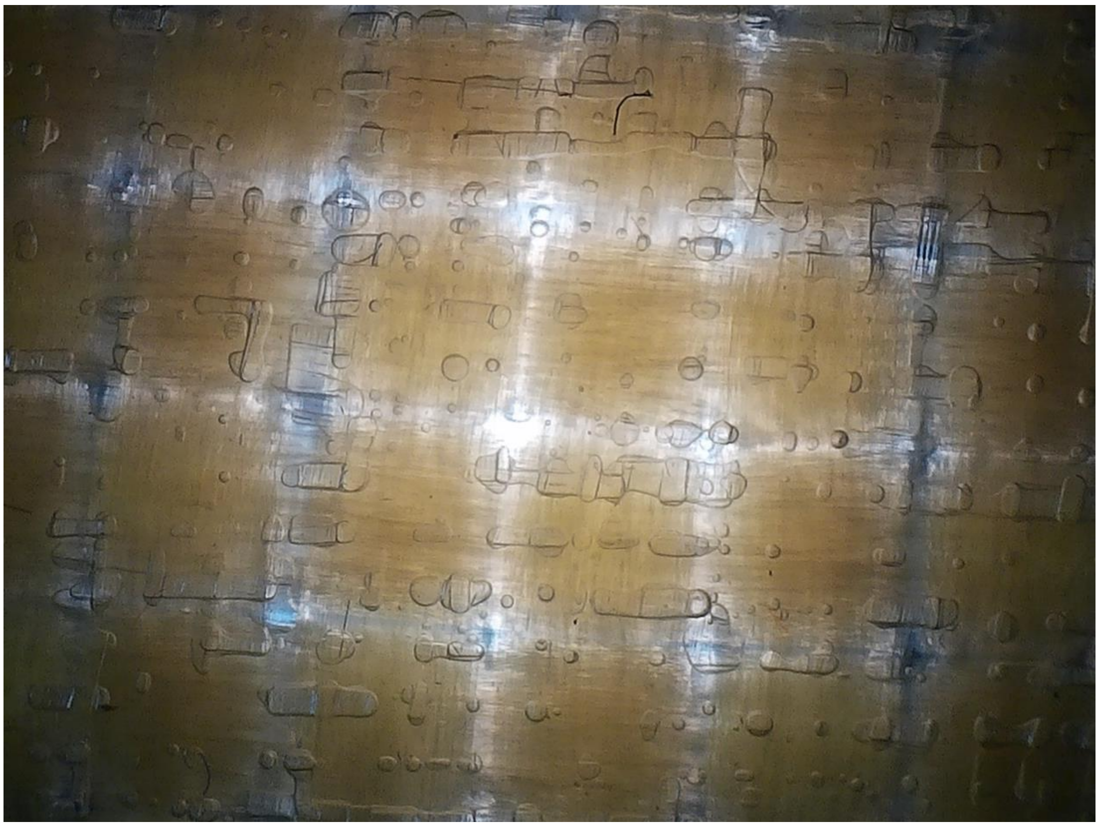

Figure 11: Kevlar Composite Sample Disc

It was hypothesized that bubbles formed when epoxy is mixed and spread might be one of the causes for air leaks in the composites. A simple experiment was performed using a vacuum chamber to degas the epoxy used in the layup which was then compared to the standard procedure used within the graduate student design lab. When using a vacuum chamber to degas epoxy it is imported to use a heat source, either a heat gun or blow torch, to pop the bubbles that come to the surface. To properly degas the resin, it is recommended to leave the already mixed epoxy under as complete of a vacuum as possible for a minimum of 15 minutes. This is important when considering the type of epoxy, you want to use as a resin with a shorter cure time may not be idle as the degassing processes will leave you with little time to perform the layup. Figures 10 and Figure 11 below show the aforementioned bubbles in the panels.

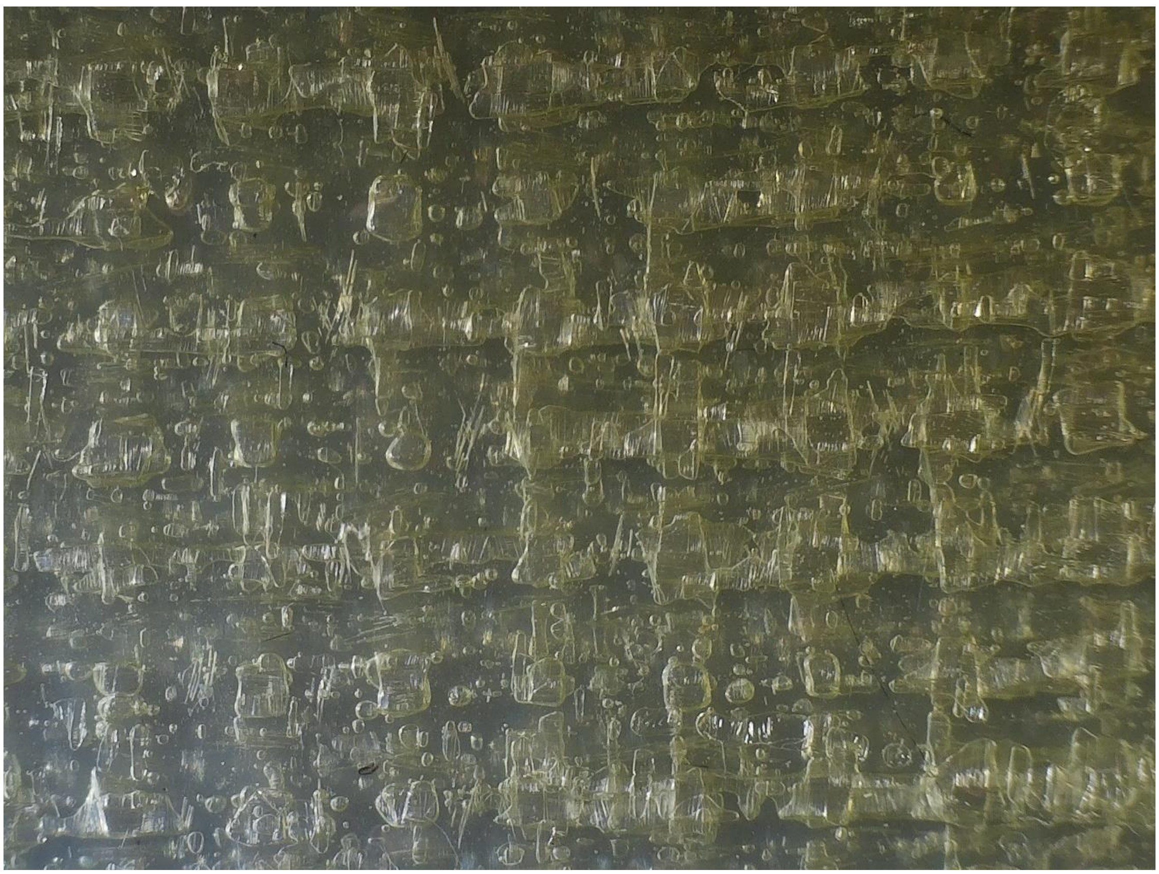

Figure 12: Standard Epoxy Mixing Procedure

Figure 13: Degassed Epoxy Mixing Procedure

The results from this experiment showed there was an indistinguishable difference in the number of microbubbles within the composite panels made. It is believed to be a result of the viscosity of the epoxy being too large for the buoyancy of the microbubbles to overcome. It is also reasonable to assume that the vacuum applied in the curing process does as much if not more than degassing the epoxy before laminating the fabric.

3.5 Preliminary Testing and Results

Preliminary testing had three main phases where the testing for each consecutive phase was designed to improve on or limit the samples from the previous phase in order to determine the minimum amount of material needed to produce an airtight sample. Phase 1 testing consisted of four composite layups, two fiberglass variations, two Kevlar ones, as well as six 3D printed samples, two from each type of plastic with thicknesses of 1/16th and 1/32nd of an inch with all samples having a 100% infill density. Shown below is the test matrix with the results of all phases for each material investigated. This matrix shows that both the fiberglass variations succeeded in passing the pressure test along with one of the Kevlar variations and the 3D printed ASA samples. In this phase it was noted that material samples that were printed on the Dremel 3D45 were faulty in a way that was inconsistent with the sample from the Snapmaker A350, at this point in the experimentation a comparison of the values used in the slicer software for both printers were compared and it was found that the Cura slicer used on the Snapmaker allowed for more versatility. When new PETG and Nylon samples were printed using the A350 and tested all samples were able to withstand the 5-psi load without leaking which allowed these materials to proceed to the next phase of testing. It was also noted that the Kevlar 2 sample, which was intended to be a less time-consuming variation of the Kevlar 1 layup and a comparison to the Fiberglass 2 sample, was also found to leak under the 5-psi load. After the Fiberglass 2 and Kevlar 2 layups did not have the same results and inference was made that there is a possibility the size of the composite sample was not a satisfactory size to compare to overall size of a full-scale fuel tank. For these reasons it was decided to scale up the size of the samples so that a minimum of four 3.75" disc could be obtained from a single flat plate layup. After adopting this method for manufacturing samples, the Kevlar 2 layup was produced on a 12"x12" sheet where 5 samples could be obtained and tested individually; all samples failed. With this development the layup for Kevlar 2 was discontinued from the rest of the experimentation. After the initial phase of testing was completed and with some of the nuances of working with the selected materials were discovered the optimization of the selected samples began. For the second phase of testing all 3D printed parts were made on the Snapmaker due to the discovery that the layer variation from the Dremel slicer allows for air to pass through. 3D printed samples for this phase were made at 1/16” thick for both Nylon and PETG plastics with an infill density of 100% while the ASA print was 1/32” with 50% infill density. All 3D printed samples proved to be air tight and had no leaks when tested up to 5psi. Composite samples were made in 12” x 12” sheets much like the retested Kevlar 2 layup so that multiple samples could be obtained from a single layup. These samples consisted of one fiberglass layup made of two layers of 3oz glass on the exterior with a layer of tooling glass in the center, two Kevlar layups one being the same method as Kevlar 1 and the second consisting of one layer of 3oz glass, a layer of Kevlar, and two more layers of 3 oz glass, all composite samples for this made were made with a 1:1 ratio of epoxy to fabric weight. Third phase samples consisted of the same composite samples used in the previous phase with the epoxy weight decreased to 90% of the total fabric weight, 3D printed samples were decreased to 1/32” thickness with infill densities of 100% and 25%. Similar to the second phase all samples passed pressure testing with no air leaks.

Table 3: Composite Sample Layup Layers and Results

Composite Sample	Layers	Epoxy Ratio (Fabric Weight : Epoxy Weight)	Sample Results
Fiberglass 1	2x Painted and Kicked Epoxy 1x 3oz Fiberglass 1x 9.6oz Fiberglass	1:1.25	Pass
Fiberglass 2	1x 3oz Fiberglass 1x 9.6oz Fiberglass 1x 3oz Fiberglass	1:1.25	Pass
Kevlar 1	1x Painted and Kicked Epoxy 1x 3oz Fiberglass 1x 5.3oz Kevlar	1:1.25	Pass

Kevlar 2	1x 3oz Fiberglass 1x 5.3oz Kevlar 1x 3oz Fiberglass	1:1.25	Fail
Fiberglass 3	1x 3oz Fiberglass 1x 9.6oz Fiberglass 1x 3oz Fiberglass	1:1	Pass
Kevlar 3	1x Painted and Kicked Epoxy 1x 3oz Fiberglass 1x 5.3oz Kevlar	1:1	Pass
Kevlar 4	1x 3oz Fiberglass 1x 5.3oz Kevlar 2x 3oz Fiberglass	1:1	Fail
Fiberglass 4	1x 3oz Fiberglass 1x 9.6oz Fiberglass 1x 3oz Fiberglass	1:0.9	Pass
Kevlar 5	1x Painted and Kicked Epoxy 1x 3oz Fiberglass 1x 5.3oz Kevlar	1:0.9	Pass

CHAPTER IV

FULL SCALE TESTING

4.1 Introduction

With the data collected from small scale testing a selection of materials and layups were selected to proceed to large scale testing. Large scale testing samples consisted of 5.75” spheres made using the methods investigated in previous testing. Spheres were chosen as the shape allows for a simplified analysis of the loads the tank is expected to withstand. This shape is also challenging for standard cartesian 3D printers due to the low bed adhesion area and the amount of overhang as the part is made. Spheres are also known to be complicated shapes to make out of composites using traditional methods as the curvature is difficult to lay stiffer fabrics such as plain weave Kevlar over without using relief cuts. Relief cuts refer to the user having to make a small or large cut along a fold in the fabric as it resists laying over or into the curvature of the mold. It is desired to minimize relief cuts in layups as the seams created can lead to holes in the finalized product. For large-scale thermoforming testing a single type of plastic was chosen as the methodology used can be applied to other materials with little to no modification. The chosen plastic for this testing being 3/32” thick PETG sheets. In the thermoforming process a sphere can cause complications in the form of webbing which describes the folding of the plastic onto itself. Spheres are also one the edge of what is deemed an acceptable draft ratio as a perfect sphere will have a ratio close to 1:1. Ratios over 1:1 can lead to non-uniform thickness over the area of the part making some areas weaker than others. Full scale testing consisted of two separate experiments, pressure testing and drop testing. Firstly, samples were pressure tested to identify any leaks that occur from the manufacturing processes discussed below. If leaks were found the process was changed to minimize and prevent leaks for future samples. Once spheres were able to hold pressure without leaking the determined process was then used to produce samples for drop testing. Experimentation was done in this fashion since the modifications made to create an airtight sample would affect the results of the drop testing. Drop testing consisted of filling the completed tanks to 80% of their maximum volumetric capacity then allowing them to free fall from designated heights to observe the damage taken from impact.

4.2 Fabrication

Subsequent sections will outline and define fabrication methods and techniques used to produce full scale samples for testing. Detailed manufacturing instructions will be outlined in future chapters. Table below details 3D printed sample settings and table shows composite layup layering and epoxy ratios.

Table 4: 3D Printed Sample Characteristics

3D Print Ball Sample	Thickness (in)	Infill Density	Sample Results
Nylon 6	1/16	50%	Fail
ASA 6	1/16	50%	Fail
PETG 7	1/16	50%	Fail
Nylon 7	1/8	50%	Fail
ASA 7	1/8	50%	Fail
PETG 8	1/8	50%	Fail
ASA 8	1/8 + Epoxy Coating	50%	Pass
Nylon 8	1/8 + Epoxy Coating	50%	Pass
PETG 4	1/8 + Epoxy Coating	50%	Pass

Table 5: Composite Sample Layup Layers and Ratios

Composite Ball Sample	Layers	Epoxy Ratio (Fabric Weight : Epoxy Weight)	Sample Results
Kevlar 5	1x Painted and Kicked Epoxy 1x 3oz Fiberglass 1x 5.3oz Kevlar	1:0.9	Fail
Fiberglass 4	1x 3oz Fiberglass 1x 9.6oz Fiberglass 1x 3oz Fiberglass	1:0.9	Fail
Kevlar 6	1x 3oz Fiberglass 1x 9.6oz Fiberglass 1x 3oz Fiberglass 1x Layer of Painted and Cured Epoxy	1:1	Pass
Fiberglass 5	1x 3oz Fiberglass 1x 9.6oz Fiberglass 2x 3oz Fiberglass 1x Layer of Painted and Cured Epoxy	1:1	Pass

4.2.1 3D Printed

3D printing the full-scale spheres seemed relatively straightforward but proved to be complicated with the length of print time, support structure needed, and high print temperatures for some of the selected materials. The spheres were printed in two halves with a print time of approximately 30 hours per half or 60 hours for a complete part. While this may not be the longest possible print time it does mean if at any time during the 30-hour print there was a problem such as a missed or skipped layer, clogged nozzle, power outage, or bed adhesion problem the part was lost and had to be restarted. The long print times and high print temperatures also caused issues when combined as parts were being made sequentially the printer started to fail. One issue being the wiring for a limit switch melted, the particular switch controlled the shut off in case the printer ran out of filament.

This of course caused the printer to shut off in the middle of a print even though there was more than an adequate amount of filament left on the spool. Unfortunately, there was no way to repair or change the part so the whole printhead assembly needed to be replaced. Another issue that was frequently encountered was the nozzle clogging during a print or the feeder stripping the filament so that it could not push anymore through the nozzle. These issues would cause the printhead to continue but it would not extrude any filament so the print would need to be stopped, a simple fix implemented and then restarted from the beginning. Filaments chosen also had unique characteristics that made the problems with the printer more plausible. For example, Nylon has a very high print temperature and low feed rate which made it more prone to stripping and advanced wear on the printer. The issue where the limit switch wires melted happened when printing multiple Nylon hemispheres sequentially. Nylon also had the most bed adhesion problems, this stemmed from printing the hemispheres as a bowl with the midline opening facing upward. This problem was simply solved by flipping the orientation of the part in the slicer and printing them as domes with the midline opening faced toward the print bed. Examples of failed Nylon prints are shown in Figure 12.

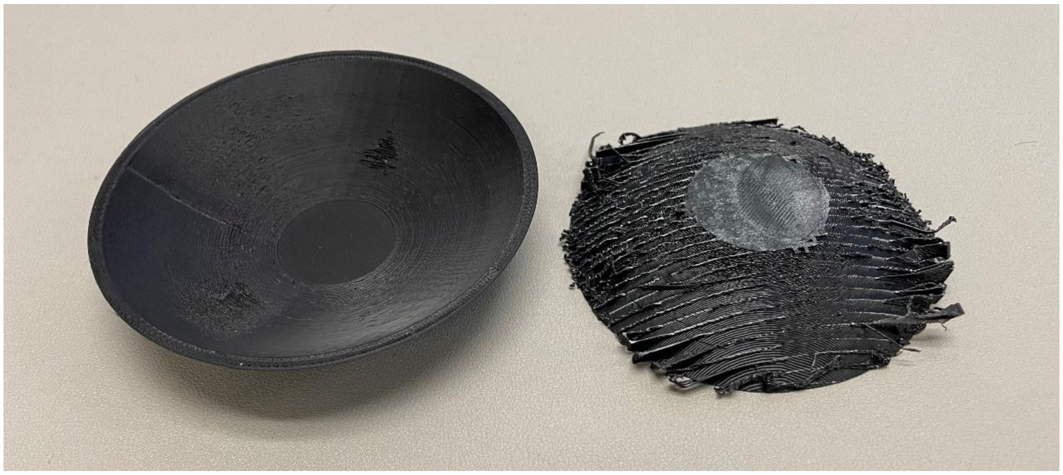

Figure 14: Top and Bottom View of Failed Nylon Prints

PETG failures mostly came from the nozzle clogging since when it prints it is very stringy, has a low print temperature, and requires cooling to be active. These printer settings led to the strings on the outside of the part sticking to the nozzle which can cause multiple problems while printing including; clogging, depositing large pieces of accumulated plastic within random layers, and in one case caused an entire prints worth of plastic to stick to the outside of the nozzle which made a large ball, Figure 13.

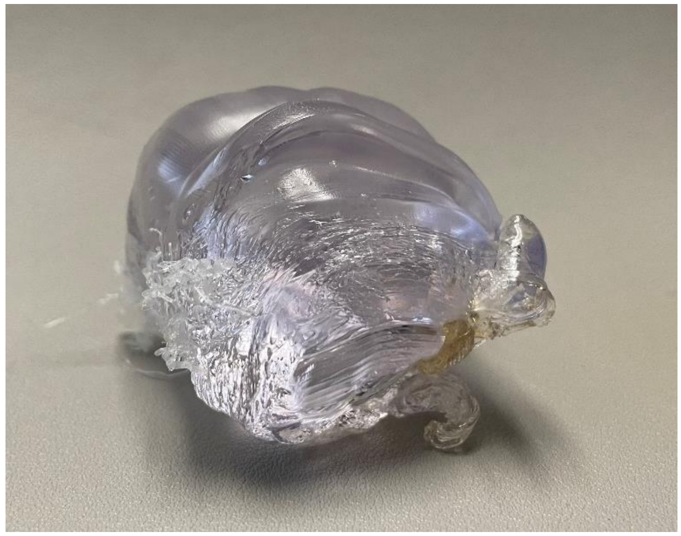

Figure 15: PETG Extrusion Failure

This last problem is extremely worrisome as it could cause the plastic to catch fire which on long unsupervised prints could lead it spreading and causing damage to the surrounding area. Using a dome orientation for PETG also helped reduce the strings produced while printing, leaving a better-quality print in the end. Of the selected materials the ASA filament proved to be the least problematic, issues were still encountered such as the nozzle clogging but nothing unique to the specific plastic. ASA does have the highest printing and bed temperature of the chosen filaments so caution should be used when printing multiple samples or for extremely long print times. Even with all the possible problems and problems that did occur it was still possible to print the samples needed to continue testing. Figure 14 and Figure 15 shows successfully printed parts. Table 1 in Chapter 3 shows the settings used for each material.

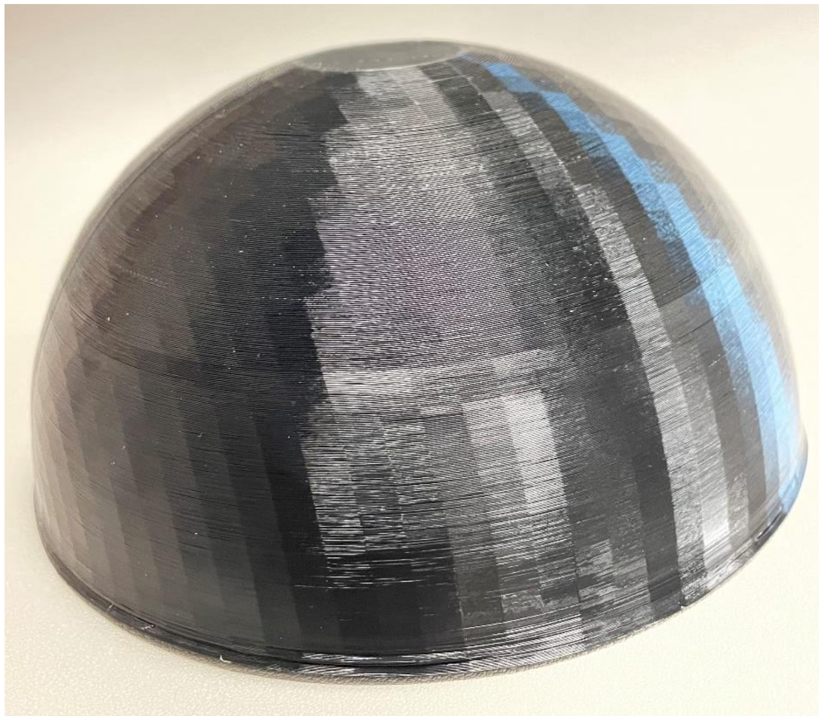

Figure 16: Successful ASA Half Tank Print

Figure 17: PETG Half Tank Print

4.2.2 Composite

In order to make the composite test pieces a mold must first be made. The mold is made out of a high-density foam just to shape on a CNC router. In this case eight hemispheres were machined, four for composite mold and four for thermoformed molds. While the thermoforming molds are good to use straight off the router the composite molds need to be prepped before a layup can take place. Machining took a total of one and half hours for the eight hemispheres, a 26”x16”x4” piece of high-density foam was used. To get the CNC foam pieces ready they must first be sanded with medium grit sandpaper, 220 grit in this case, to remove any tooling marks left by the bit. Once the tooling marks are removed the part is painted with multiple layers of a thin primer, two layers will usually suffice but up to three or four can be added, the point of the primer is to further smooth the surface of the foam. Once the layers of primer dry the mold part must be sanded with high grit sandpaper to further smooth the surface. The process of painting and sanding is repeated with multiple grits of sandpaper, traditionally starting with 220 grits, then 320 grit, 420 grit, and finally 600 grits. This can be continued with even higher grits of sandpaper if an even smoother finish is desired but for prototyping samples 600 grit sanding is more than sufficient. A smooth surface is crucial as any inclusions in the mold will show in the final part, inclusions can also lead to the part sticking to the mold which can damage the mold when the part is removed. This damage can be as simple as a small bit of primer being removed and as severe as entire pieces of the mold breaking. Once the desired finish was achieved the hemispheres were secured to a melamine board using epoxy and screws, Figure 16 below shows the finished mold.

Figure 18: Finished Composite Mold

With the molds completed the sample layups could begin. Samples were laid up as two individual hemispheres and then had to be bonded together after they had cured. Once the hemispheres were carefully demolded using a combination of wedges and compressed air. Flanges were then trimmed to approximately an inch in width to increase the bonding area for the halves. After trimming the flanges, the inside of the midline is lightly sanded then cleaned with alcohol. With area prepped a one-inch-wide piece of 3 oz fiberglass tape that is the length of the circumference of the hemisphere is wetted with epoxy then applied around the inside of one of the hemispheres. This strip of tape was allowed to cure until it reached the “green” stage before proceeding to the next step. Once it had reached the green stage the halves were bonded together using a colloidal thickened epoxy was applied around the perimeter, outside of the tape. A weight is used to put pressure on the halves to ensure a good bond while the epoxy cures. After the epoxy has cure the flanged is then trimmed as close to the part body as possible, for any excess flanged that cannot be trimmed a combination of manual sanding and a belt sander was used to remove the material. With the entirety of the flange removed another piece of one-inch-wide fiberglass tape is adhered to the outside perimeter over the seam line. It is important to prep the area by lightly sanding the circumference and cleaning with denatured alcohol before applying the tape. Once cured the outer tape can be wet sanded with either 220 or 320 grit sandpaper to achieve a smooth finish but this is not a necessary step.

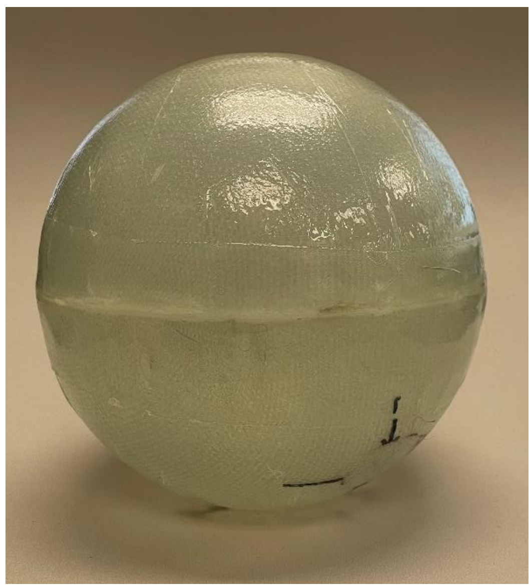

Figure 19: Completed Fiberglass Tank

4.2.3 Thermoformed

The process of making thermoformed parts is relatively straightforward and can be done without expensive equipment. To thermoform parts the only things required are an overhead heat source, a mold or form, a vacuum or downdraft table, and a medium to high flow rate vacuum. Molds for thermoforming were produced in the same CNC process as the composite molds as stated above, like the composite mold these were painted and sanded to achieve a smooth finish but not quite to the same standard. A custom vacuum table was made using ¾” plywood, this was a simple box design held together with brad nails, silicon was added to all the seams to ensure a tight seal. The table was sized in such a way that there was approximately an inch of space around the outside of the mold and was tall enough so that a hole for a wet/dry vacuum hose could be drilled. For this project a 6 horsepower Shop-Vac with a 1.5” diameter hose was used, this was found to be sufficient for forming the parts. In order to avoid some of the issues that can happen when vacuum forming parts it is important to consider a few key details such as the size of the vacuum table to the size of the part, how much the plastic should droop when heated, and how long it takes for the plastic to cool.

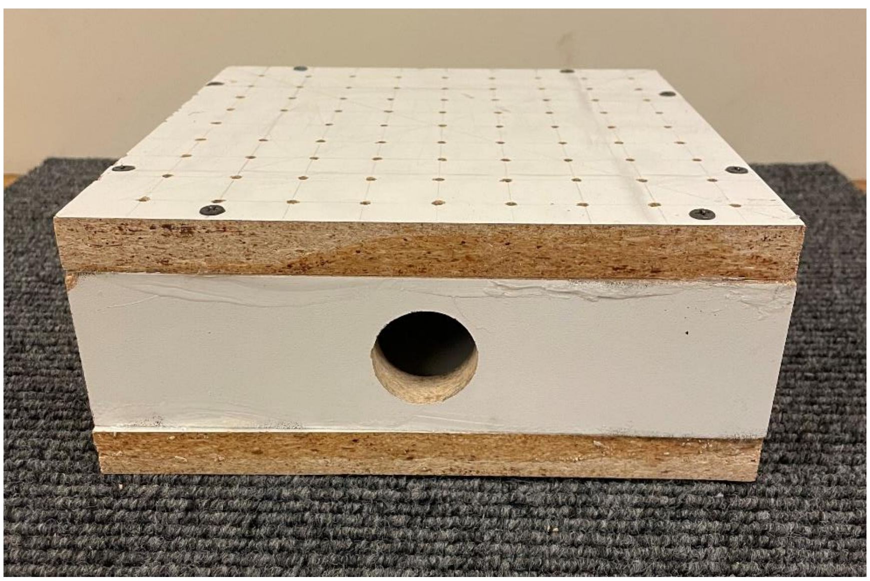

Figure 20: Thermoforming Table (Front Iso View)

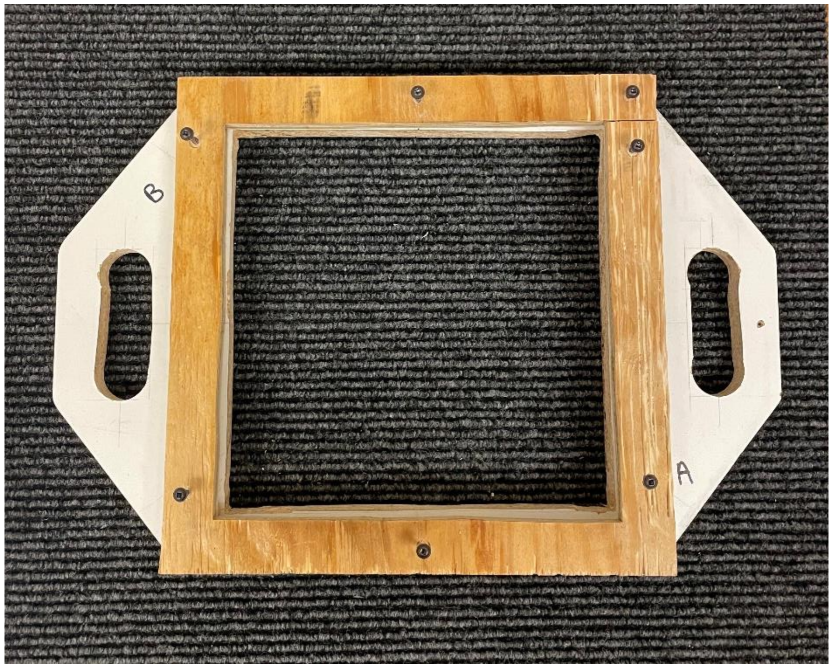

Figure 21: Thermoforming Material Holder

The size ratio of the vacuum table to the part is key to avoid plastic waste as well as webbing, or the folding over of the plastic onto itself. If the forming table is too large compared to the part, not only will an excess amount of plastic be used and scrapped but this excess will also cause the heated plastic to fold over and adhere to itself. It was found through research and testing that an inch of space around the mold for the vacuum table was more than sufficient to prevent webbing. When determining if the material is heated sufficiently to be formed the easiest way to tell is to see how much it has drooped. For the PETG sheets used in the experiment it was found that a deformation of approximately ¾" was ideal for forming. Any less than this and the plastic was not hot enough to be completely formed by the vacuum, if the droop reached or exceeded an inch it would be too hot and webbing or folds would appear. Unfortunately, there is no clear definition of how much sag each type or thickness of plastic should ideally have to be formed, this can only be determined through testing. The rate at which the plastic cools is crucial as this is what dictates the working time. Thinner stock will cool faster than thicker stock as the thicker stock will have more heat retention, different plastics will also cool at different rates based on the specific properties.

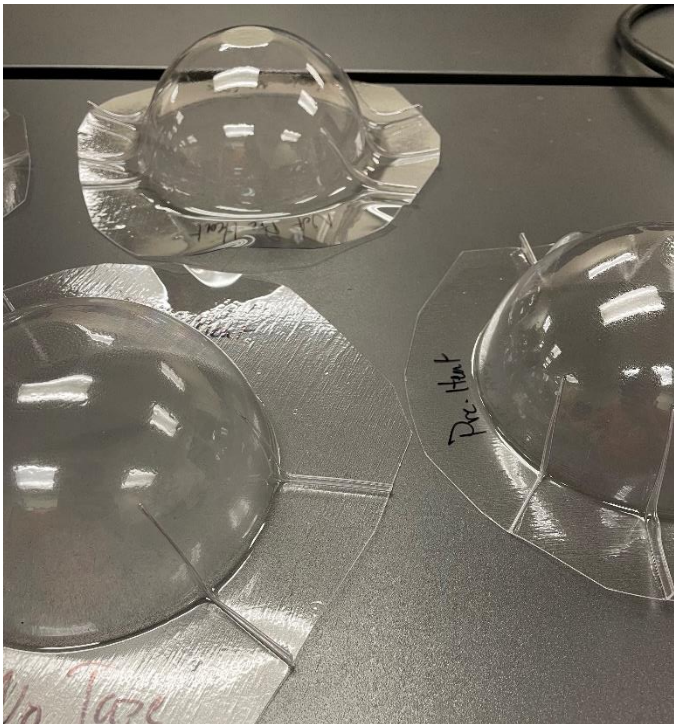

Figure 22: Example of Webbing in Thermoformed Parts

After several attempts, approximately ten, a thermoformed part was produced without webbing that could be used to make a complete tank. When the nuances of thermoforming parts were determined the halves for a tank could be produced in roughly five minutes. This is assuming the forming machine is preheated but accounts for fixing the plastics to the form, heating it to the correct temperature, allowing it to cool, and demolding the part. To separate the part from the excess plastic a hot knife was used to carefully cut around the seam line. When doing this it is important to wear proper safety gear, including glasses and an N95 mask, as well as be in a well-ventilated area.

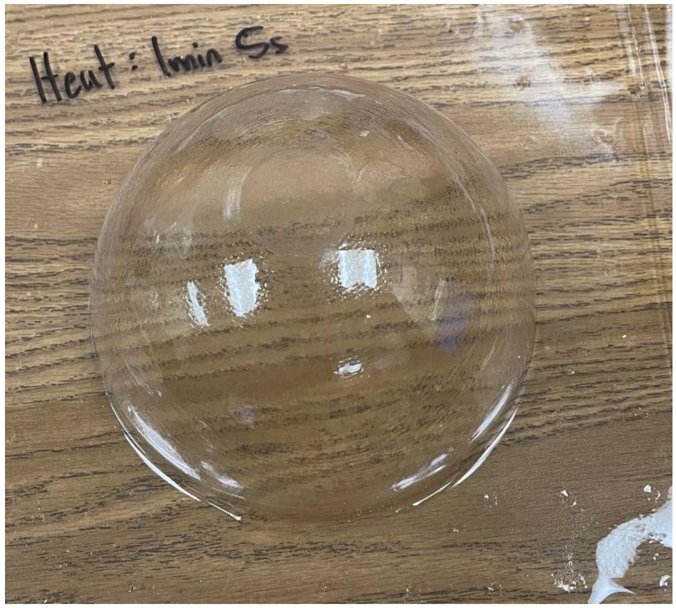

Figure 23: Successfully Thermoformed Part

Once the halves have been cut an electric hot plate was used to slowly bring the seam up to temperature, this was determined visually by watching for the plastic on the ends to begin to flatten. When they reached the proper temperature, the halves were then gently pushed together to form a chemical bond. During this process there was excess that squeezed out from the sides. A soldering iron, set to 725°F, was then used to slowly melt and read here the plastic back over the seam line to help strengthen the bond and fill any gaps.

Figure 24: Completed Thermoformed Fuel Tank

CHAPTER V

Testing and Results

5.1 Pressure Testing

Procedures for the large-scale samples include two different sets of testing; checking for leaks and drop testing. Testing for leaks is obviously important as it is undesirable for the tank to lose fuel during the flight as it shortens the overall range of the aircraft as well as risks damaging internal structure and electronics. To determine if the tanks are leak resistant a similar testing procedure to the sample disk is used where the manufactured spheres were pressurized to 5 psi and submerged in water which allows for the visual inspection of air bubbles escaping through microscopic pores or cracks. Samples were pressurized by using a two-port fuel stopper fitted to a hole that was drilled into the top of all the spheres. This was then attached to the same pressure regulator and gauge used in the small-scale testing via a tygon fuel tube. The primary samples also have a second pressure requirement that comes in the form of the hydrostatic pressure requirement from CFR § 25.963. Fuel pressure will be determined through the hydrostatic pressure equation defined in the CFR and discussed in chapter 2. The equation variables are defined as follows; ρ is the density of water, g is the acceleration due to gravity of $32.2 ft/s^2$, L is 5.75” as this is the diameter of the tank from the pressure reference point to the farthest boundary, and K will be set to 6 for a downward loading condition. Using the variables defined above a hydrostatic pressure of 1.25 psi is determined which is well below the 5-psi test point showing pressure loading from the fuel is not of concern.

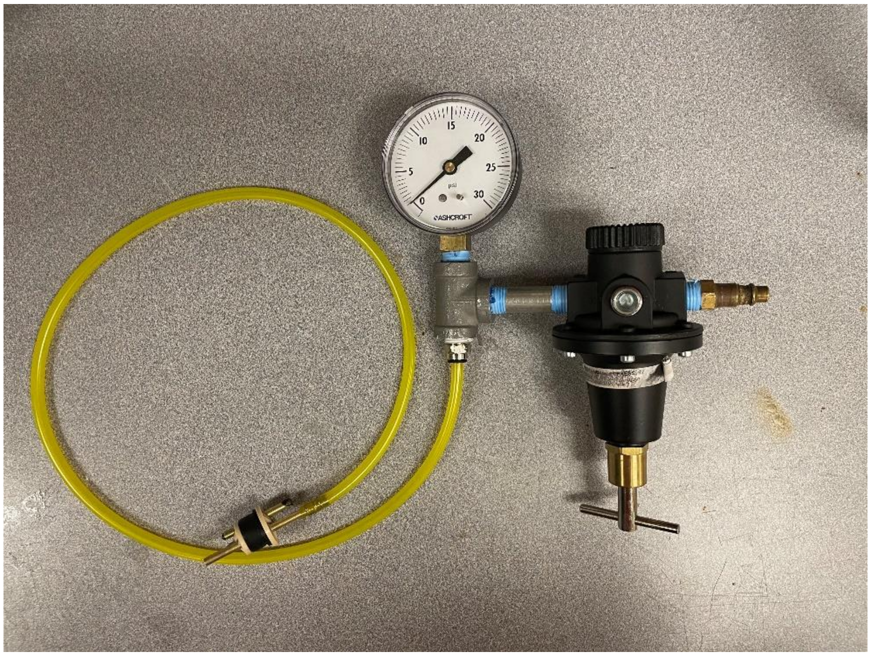

Figure 25: Full Scale Pressure Tester

5.1.1 Pressure Testing Results

The initial phase of large-scale pressure testing included parts with the following dimension and layering. 3D printed spheres were made with a 1/16" wall thickness and 50% infill density. Composite parts used the final layup orientation from the small-scale testing, for fiberglass two layers of 3 oz glass was used with a layer of 9.6 oz tooling glass in the center, the Kevlar layup consisted of a layer of epoxy painted onto the mold which was left to sit until it was green then one layer of 3 oz fiberglass and a layer of 5.3 oz Kevlar. All thermoformed parts were made with the aforementioned 3/32" sheets of PETG. Pressure testing the parts showed that when scaled up none of the parts were airtight. 3D printed parts had flaws around the entire surface but most prominently around the top and bottom area where the support material was removed.

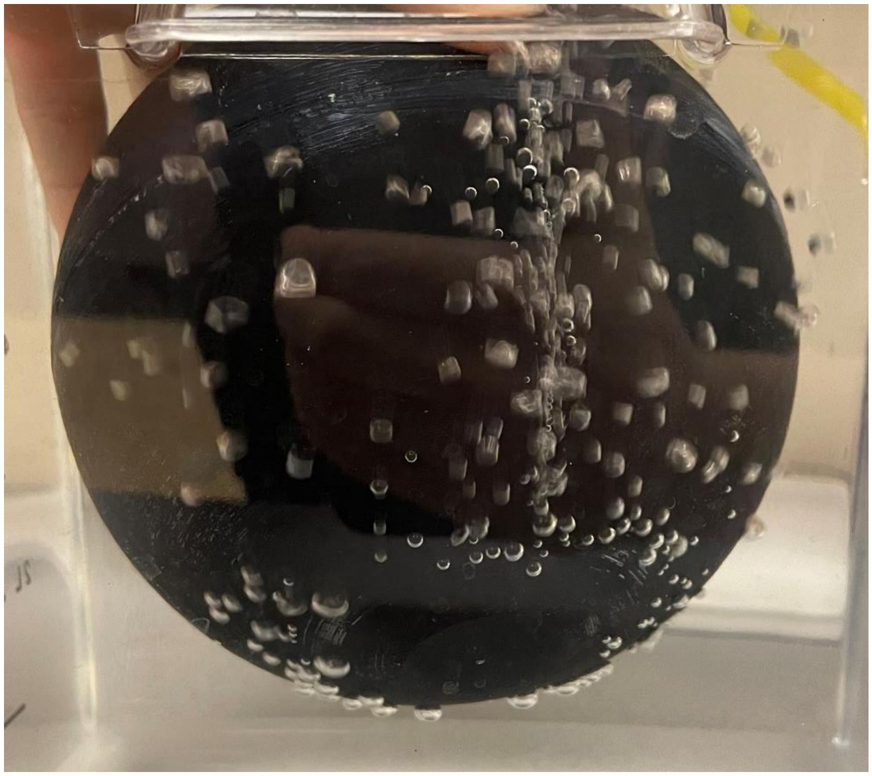

Figure 26: 1/16” Nylon Pressure Test

Composite parts had sporadic holes around the surface and had large holes and gaps around the seam line. Thermoformed parts only had small holes around the seam line which were fixed using a soldering iron to either add scrap plastic to the area or using the extra plastic around the seam using the method mentioned before. After this simple fix the thermoformed parts were able to withstand the 5-psi load without leaks.

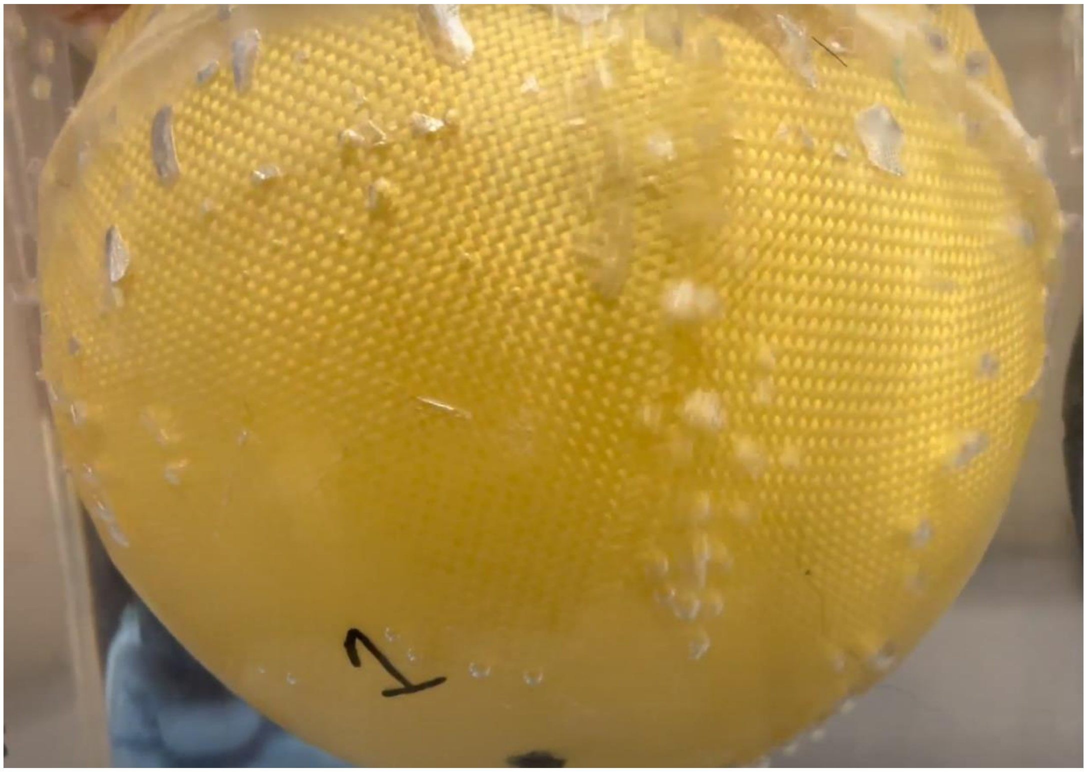

Figure 27: Kevlar 1 Pressure Test

For the second phase of testing 3D printed parts were made using a 3/32” wall thickness with a 50% infill. Fiberglass composite sphere used four layers in the orientation; single 3oz glass, single 9.6oz glass, and two 3oz glass. Kevlar parts were made with three layers; 3oz glass, 5.7oz Kevlar, 3oz glass. Both composite parts were made with a 1:1 epoxy to fabric weight ratio and were also additionally coated with a layer of epoxy brushed onto the inside of the part after they had cured, been demolded, flanged trimmed, and part cleaned. After the layer of epoxy had been brushed onto the inside it was allowed to cure to the green stage before adding the internal tape and sealing the halves. For this phase a second thermoformed part was made to both practice and better refine the methodology for making the tanks with this method. Like the initial large-scale testing all 3D printed parts failed to hold at the 5-psi threshold having multiple leaks throughout the entire part with a large number of holes around the top and bottom again. Unlike the first phase both composite parts succeeded in holding pressure without leaks. Similarly, the thermoformed sphere also had a few small holes around the seam line that were easily fixed with the use of a soldering iron. With both the composite and thermoformed parts able to withstand the 5-psi load without leaking, pressure testing was concluded for these materials. Continuing with testing the 3D printed tanks the next sample set was printed with a ⅛" wall thickness at 50% infill, like the composite tanks this time the 3D printed tanks were also internally coated with epoxy. Epoxy was left to cure to the "green" phase before continuing with sealing the two halves as normal. Unfortunately, the internal layer of epoxy was not enough to seal the tanks so a second external layer was added to all the tanks. With the addition of the second layer of epoxy all 3D printer fuel tanks were finally able to hold pressure without any leaks. Now that all methodology had been developed for all materials to achieve an airtight fuel tank pressure testing could be concluded and the passed samples could be drop tested.

5.2 Drop Testing

Drop testing allowed for the simulation of various types of loading the tanks will be expected to endure during miscellaneous points in the aircraft's flight profile. During a typical unmanned systems mission profile, the largest external loading is expected to happen during landing. To determine expected landing load conditions a simple energy calculation was done assuming a 6-degree glide slope with an approach speed of 60 knots. With these conditions it was determined that a vertical drop of approximately 4 inches would be sufficient to simulate minimum acceptable loading conditions. Samples were dropped with the seam line parallel to the ground to simulate an ideal scenario since most tanks will be placed in aircraft with load resistance in mind. This orientation is preferred for testing as it puts a majority of the loading through similar geometry without introducing the variability in the construction of the seam line for each tank.

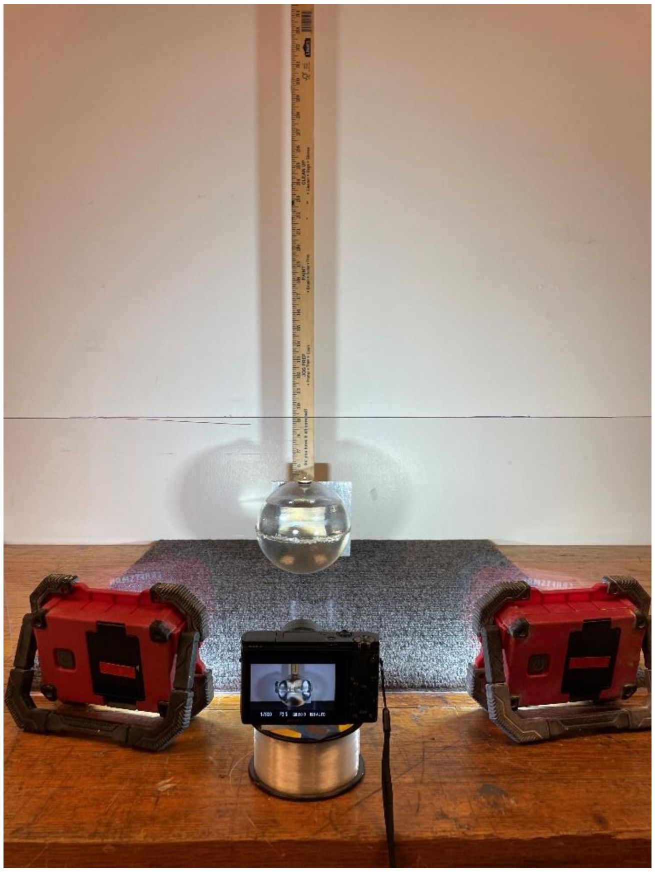

Figure 28: Drop Testing Experimental Setup

Drop testing started at 4 inches then was increased 4 more inches after pressure testing to ensure that no leaks developed from loading, this was continued till failure through either a crack, puncture, leak, or until a maximum height of 36 inches was reached. Tanks will be filled with water to 80% capacity to simulate fuel loading according to FAA standards for fuel tank testing, this equates to approximately 44.8 fl. oz or 2.9 pounds of water.

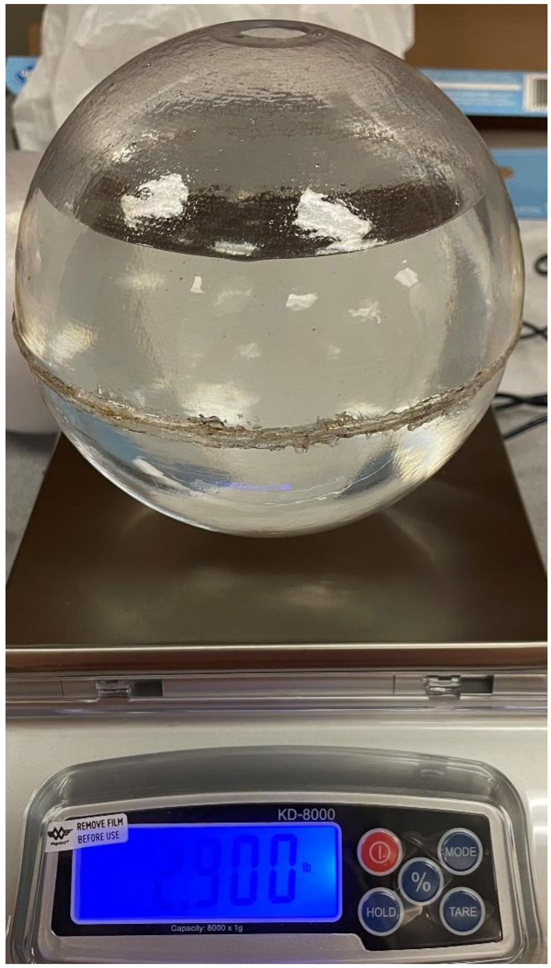

Figure 29: Thermoformed Tank with Drop Testing Load

5.2.1 Drop Testing Results

Results from drop testing showed that all tanks were able to survive the minimum expected load from the four-inch drop. As testing continued it was found that all tanks could be dropped from up to twelve inches before damage started to become noticeable. At sixteen inches the Kevlar fuel tank had developed substantial damage and was slowly leaking from the bottom, the fiberglass fuel tank had also acquired similar damage but it did not leak as much as the Kevlar one and could have easily been repaired at this stage. Drop testing the fiberglass tank continued even after the damage was noted as it was desired to know the height at which catastrophic failure would occur. A height of twenty-four inches was reached before a substantial leak developed from the stress cracks on the bottom of the tank that can be seen in Figure 30.

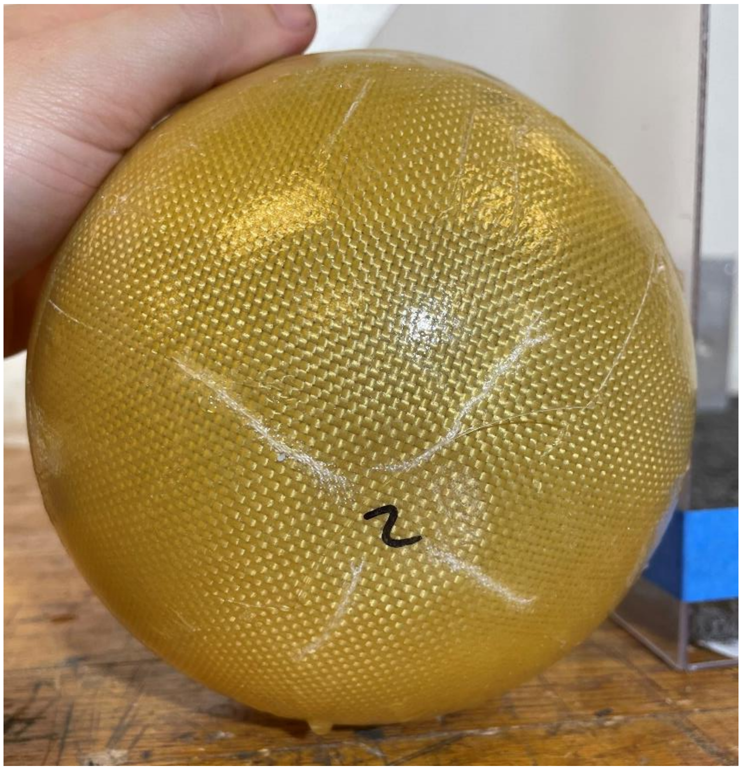

Figure 30: Sixteen Inch Drop Test Results (Kevlar)

Composite tanks failed in similar fashion as the bottom of the tanks suffered cracking from the increasing load, it is believed they failed in this way due to the relatively low compressive strength of the fabrics as well as the epoxy used in the layup. The thermoformed sphere did surprisingly well when dropped and reached a height of twenty-eight inches before failing due to the seam debonding and only failed in this way due to the tank bouncing approximately ten inches after the initial drop rotating in the air and then landing on the seam. Due to it failing in this way it would not be extremely difficult to reseal the seam line, check for leaks and then either continue testing or reimplement the tank into an aircraft. Thermoformed tanks were suspected to fail in this fashion as the seam line is the weakest area of the tank due to the low bonding area and the seal being purely chemical in nature. If the tank was able to be repaired and tested in a way to isolate the drop in such a way that it could not rotate after the initial impact it would most likely fracture in multiple places due to the brittleness of the PETG after it has been formed.

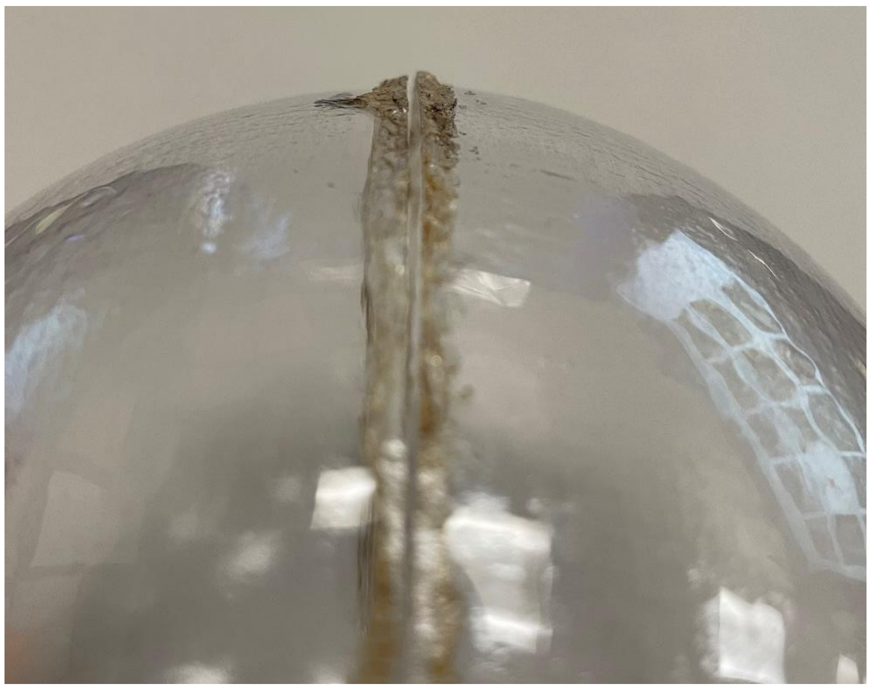

Figure 31: Thermoformed Fuel Tank Seam Line Split

Unexpectedly the 3D printed fuel tanks survived substantially higher drops than expected with the Nylon reaching a height of twenty inches before the bottom of the tank fractured as seen in Figure 32.

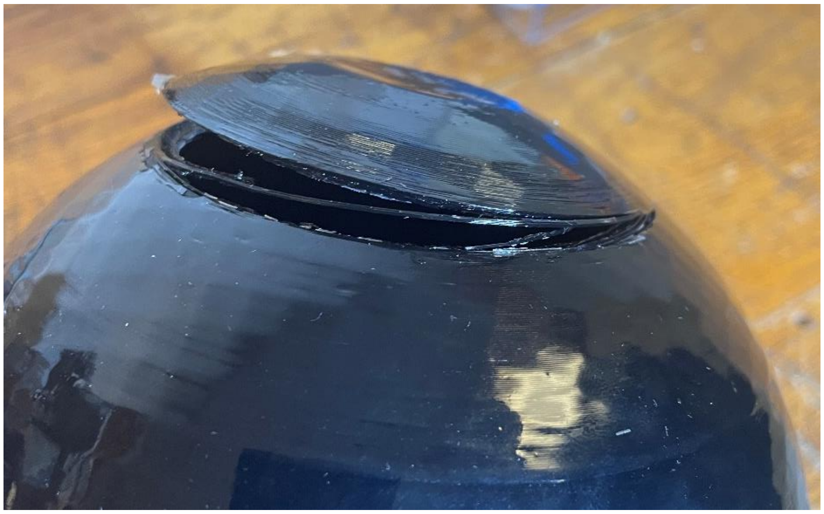

Figure 32: Nylon Tank Failure

The PETG tank reached a height of twenty-four inches before suffering from a catastrophic failure that left the tank unrepairable, the failure is shown in Figure 33 and Figure 34.

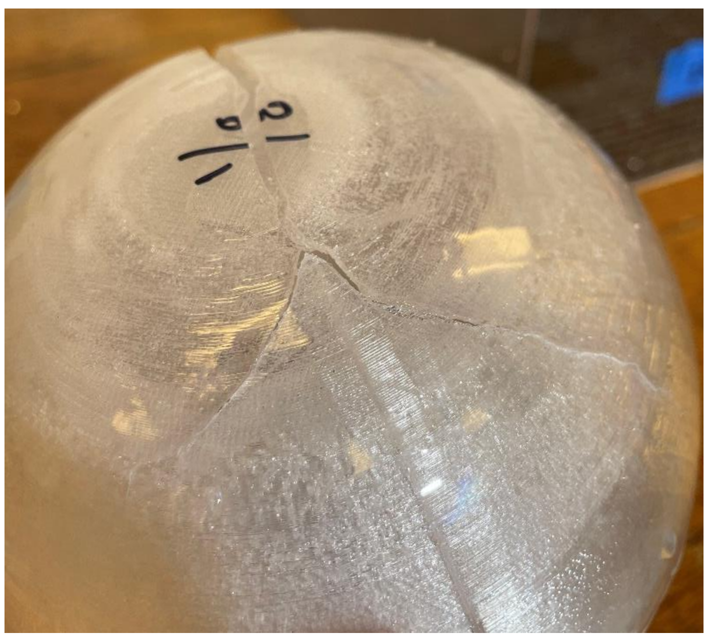

Figure 33: PETG Failure (Top View)

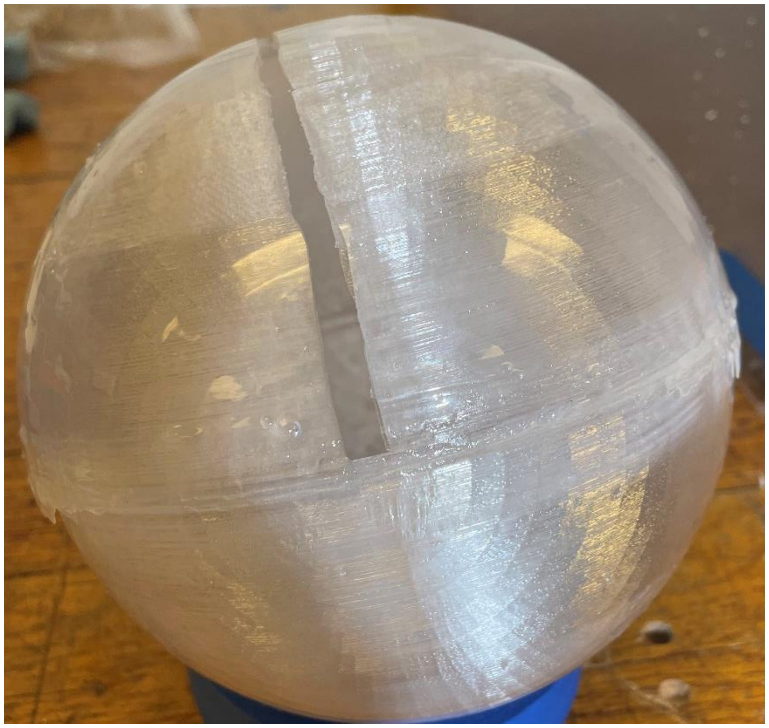

Figure 34: PETG Failure (Side View)

Finally, the ASA sphere was able to survive a drop from thirty-six inches without failing, some damage was seen around the bottom of the tank in the form of the epoxy coating starting to crack but when pressure tested afterward was still able to hold at 5 psi without any air leaks.

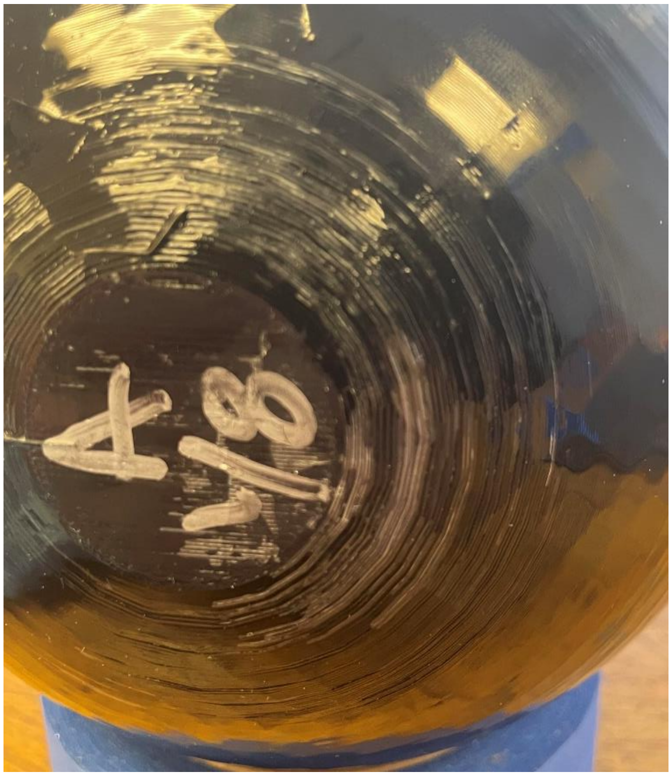

Figure 35: Damaged Sustained by ASA Tank (36in Drop)

While the nylon and PETG 3D printed tanks failed in different areas the mode of failure was similar, as they both failed in a way that suggests the quality of the print has an impact on the durability of the tank. As the nylon tank failed along layers that were not fully adhered to one another causing the bottom to cave in and delaminate from the rest of the tank while the PETG tank fractured due to the brittleness of the combination of epoxy and fully adhered solid plastic.

Table 6: Drop Testing Results

	Drop Height of Failure (inch)
Kevlar	16
Fiberglass	16
3D Nylon	20
3D ASA	N/A*
3D PETG	24
Thermoformed PETG	28**

* Did not fail at maximum drop height

** Failed due to rotation after initial impact

While the manufacturing methods used to produce these fuel tanks are adequate to achieve a tank that can withstand more than the expected load and are air tight, optimization can still be done in order to further reduce the weight, materials and equipment needed, and cost of the tanks. The overall cost of the tested fuel tanks is also a significant factor when considering which method would work best for the intended application.

5.3 Cost Analysis

With the final manufacturing methods decided on, a rough cost estimate for each tank can be determined for comparison to what is available on the open market. To determine the cost for each tank the overall surface area, part thickness or layer count, manufacturing time, post processing time, material cost, and tooling must be accounted for. All tank designs used the same epoxy which has an estimated cost of $47 per gallon of resin and $50 per gallon of hardener, man hours are estimated at $28 per hour as this is the pay rate for graduate research assistant at Oklahoma State University, and finally the CNC machining cost of approximately $95 per hour. To further break down the epoxy cost a gallon of resin is approximately 4220g which comes out to $0.011 per gram while the hardener is approximately 3840g per gallon with a cost of $0.013 per gram. With a mixture ratio of 100 parts by weight to 40 parts by weight the cost of each gram of epoxy comes out to be $0.0162 per gram.

3D printed tanks are the simplest to calculate as slicer used gives an estimate for printing material needed then the only other cost to account for are the cost of epoxy, the man hours spent setting up the printer, post processing on the print, applying the epoxy, and bonding the halves of the tank. 3D printed tanks required approximately 200g of material with the plastics costing $30 for a kilogram of ASA, $45 for 750 grams of Nylon, and $40 for 750 grams of PETG. Each tank used about 80 grams of epoxy with a cost of $1.30, this with the material cost of each material brings the total material cost of the tanks to $7.30 for ASA, $13.30 for Nylon, and $11.97 for PETG. Printer setup, part post processing, and assembly took roughly 1.5-man hours with a cost of $42 bringing the cost of the ASA, Nylon, and PETG fuel tanks to $49.30, $55.30, and $53.97 respectively. This represents the ideal cost of each tank and does not account for time needed to test tanks, repair holes, or to deal with complications with the 3D printer during the manufacturing process.

Composite test tanks were made with many varying layers but used pieces cut to 12”x12” so a cost can be estimated by taking the total cost of a roll and dividing the surface area of the roll by the fabric used. Kevlar used in experimentation has a cost of $49 per linear yard on a 50” wide roll coming to a cost of $3.92 per square foot (Ref - https://www.fibreglast.com/product/Kevlar_Plain_Weave_Fabric_2469). Costs for the 3oz fiberglass and 9.64oz tooling glass were calculated using the same method coming out to $0.72 per square foot and $0.65 per square foot respectively. Composite tanks also required specialized materials for vacuum bagging the parts while the epoxy cure which consisted of a separation material, a breather, and bagging. Bagging materials were cut at varying lengths; separation and breather material was cut in 16”x16” sheets, while the bagging was cut to 28”x36”. Breather material cost $0.1 per square foot, separation material cost $0.35 per square foot, and bagging cost $0.068 per square foot. With the estimated cost for all bagging materials the price for finishing materials for each tank comes to $1.28. Final Kevlar layup consisted of four layers of 3oz glass, two layers of Kevlar, 72 grams of epoxy for the layup itself, an epoxy coating of approximately 15 grams, and 30 grams of epoxy for bonding the two halves of the tank together. Material cost of the Kevlar fuel tanks is found to be $13.90 per tank. Final fiberglass tanks have a similar layup but use six layers of 3oz glass, two layers of 9.64oz glass, 120g of epoxy for the layup, and use the same amount of epoxy for coating and bonding. Using these figures, the material cost for the fiberglass tank is calculated to be $9.57 per tank. To help simplify the cost estimate it is assumed that both composite tanks require the same amount of man hours to complete and are estimated to approximately three hours with a cost of $84. Finally, the machining cost needs to be calculated and added, machining cost will be divided between the composite and thermoformed estimates as they made use of the same mold procured from the CNC. CNC cost consists of setup time, machine run time, and cleanup time which came out to be roughly 1.5 hours at $95 per hour is $142.5 or $71.25 per part type.

Machining time will be divided between the number of parts that can be made from a single mold and an estimated twenty parts for the life of the composite mold. With these assumptions it is found that the cost of molding is $0.89 per hemisphere or a total cost of $1.78 per fuel tank produced. Composite molds also required the machined parts to be sanded, painted, and attached to a base which added another two-man hours or a price of $56, like machining cost this is divided over a 20-part life expectancy for the mold coming to a cost of $2.80 per tank. Mold base was made out of a ¾” melamine board that cost $31, the board was also used to produce the custom vacuum table used for the thermoformed parts, board cost for the composite parts was $20 or $1 per tank. Considering all these factors the Kevlar and fiberglass tanks come out to a price of $104 and $99 respectively.

Thermoformed tanks are again relatively easy to calculate the cost of the tanks produced as it is the price of the overall sheet of plastic used divided by the number of tanks that can be made, plus man hours required, the mold machining cost, and the cost of manufacturing a custom vacuum table. PETG sheets used were 24”x48” and were approximately $22, it was possible to produce 3 full tanks per sheet with a material cost of $7.34 per tank. As stated, the custom vacuum table was made using the remains of the mold base for composite parts with a carryover cost of approximately $11 for materials and an estimated half a man hour for assembly at $14. Unlike the composite molds, the ones used for thermoforming are expected to last much longer with an estimated life of 50 parts or 25 completed fuel tanks while the base is expected to last a minimum of 100 parts of 50 completed tanks. With this life expectancy it is estimated that machining, tooling, and assembly costs are totaled at $1.21 per tank. Man-hours for thermoformed parts consisted of manufacturing and assembly. Manufacturing time consisted of set up and cleanup which only takes a few minutes and only need to be done once per run, this is estimated to be 0.25 man-hours for 3 completed tanks, and manipulation of the mold and plastic. Actual manufacturing time is similarly short as it consists of prepping the mold base, heating the plastic, applying vacuum, waiting for the part to cool, and demolding. This entire process takes approximately 0.75 hours per run, or per 6 tank halves made. Assembling the tank halves takes much longer than making them on the forming machine as the excess plastic needs to be trimmed from the flange, the halves must be heated at the seam and pushed together, and finally the excess flange must be heat formed back over the part. Assembly takes roughly 0.5 hours per tank. This brings the total amount of man hours per tank to just under one so for estimating the cost it will be assumed it takes a full hour. With factors stated above taken into consideration for the manufacturing of the thermoformed tanks it can be estimated that each tank cost of each tank is $37.

In order to compare the cost of the tanks produced during this study to ones currently available on today's market they must be normalized by the total volume of the tanks. As previously stated, the tanks produced have a volume of approximately 56 fl. oz. Using the volume of the tank to normalize the estimate cost the following values are achieved: 3D printed ASA $0.90/fl. oz, 3D printed Nylon $1.01/fl. oz, 3D printed PETG $0.98/fl. oz, Kevlar $1.89/fl. oz, Fiberglass $1.80/fl. oz, and thermoformed PETG $0.67/fl. oz. Benchmarked fuel tanks had an estimated cost of $0.63/fl. oz for the plastic DuBro tanks and $2.24/fl. oz for the composite JetTech tanks. It was reasonable to expect the DuBro tank to be cheaper than anything that is produced at a smaller scale but was interesting to find that the thermoformed tank has a similar price point. Also considering the DuBro tank used for comparison had the lowest cost per fluid ounce of all the fuel tanks available on their website. This shows that a prototype fuel tank can be produced at a similar cost to commercial off the shelf parts if that is a slight bit cheaper. 3D printed parts were expectantly much more expensive than the DuBro tank with the most expensive one coming in at 1.5x the cost and the cheapest being 1.33x the cost. Somewhat expectedly the cost of the studied composite tanks have a similar cost to the ones available from JetTech but are a decent amount cheaper. The Kevlar tank produced in this study 83% the cost of the benchmarked tank while the fiberglass one is only 79% of the cost. Considering the studied tanks are prototypes and would not likely have a large number produced unless desired by the manufacturer it would take a production run for the life cycle of the mold in order to achieve the pricing discussed.

5.4 Weight Comparison

Weight is a significant factor when designing aircraft as such the weight of the components is equally important. In order to normalize the weight of varying sizes of fuel tanks they will be compared based on the available capacity per gram of fuel tank. This ratio is used as it is generally desired to maximize fuel capacity while minimizing weight. Benchmarked JetTech and DuBro fuel tanks had capacity to weight ratios of 0.585 fl. oz/g and 0.481 fl. oz/g respectively. All 3D printed tanks came in under this margin with the following values; 0.337 fl. oz/g for Nylon, 0.367 for ASA, and finally the PETG had the lowest ratio of 0.296. These values show that 3D printed tank are not a preferred solution if weight is a main factor in the design of the aircraft. The thermoformed PETG tank had a ratio of 0.585 fl. oz/g which is equivalent the JetTech tank and greater than the DuBro tank. This shows that the thermoformed tank to be a viable option bases on a weight prospective. Finally, both composite tanks achieved a greater capacity to weight ratio than the benchmarked fuel tanks with values of 0.743 fl. oz/g for the Kevlar tank and 0.597 fl. oz/g for the fiberglass tank. While the composite tanks seem to be the best solution based on a weight analysis, they also are the least structurally resilient. All capacitate ratios for the tanks are shown in Table 7.

Table 7: Fuel Tank Capacity Ratios

	Capacity (fl oz)	Weight (g)	(fl-oz)/g
Jet Tech	120	205	0.585
DuBro	100	208	0.481
Kevlar	55	74	0.743
Fiberglass	55	92	0.598
3D Nylon	55	163	0.337
3D ASA	55	150	0.367
3D PETG	55	186	0.296
Thermofromed PETG	55	94	0.585

CHAPTER VI

FABRICATION

The following chapter will outline the fabrication procedure for each of the techniques used to produce test samples.

6.1 3D Printer

This method is devised for parts made in multiple pieces and it is unknown whether or not it will be as effective on single piece parts. Some instructions may be different based on the model of 3D printer and slicer software used. It is also recommended to create a joggle between the pieces of the part to create more surface area for bonding.

6.1.1 Printing

1. Prepare .STL file in the slicer of your choosing. Cura slicer was used with the settings shown in Table 8.

Table 8: Final Snapmaker Printer Settings

Material	Nozzle Temperature (°C)	Bed Temperature (°C)	Cooling Fan Speed	Print Speed (mm/s)
Nylon	255	95	0%	37.5
PETG	240	85	100%	50
ASA	250	90	0%	50

2. Prepare desired filament according to the printer instructions.
3. Prep print bed using a glue stick spread a layer of glue over the area of the print.
    a. This helps with bed adhesion issues

4. Start print.
5. Once finished remove any support material.
6. Sand areas where support material was located until area is no longer rough.
7. Clean sanded area with alcohol. Preferably 90% isopropyl or denatured.

6.1.2 Finishing and Bonding

1. Prepare work area by covering with painter's plastic or some material that will not bond to the epoxy.
2. Mix epoxy resin according to package instruction.
    a. The amount of epoxy needed will vary with the size of the printed part.
3. Using a small brush spread the epoxy on the interior of the part and allow to sit for a minimum of double the working time.
    a. Allowing to sit the full cure time is fine if timeline allows.
4. Mix a small amount of resin according to package instructions.
5. Spread the epoxy on the seam line or joggle of the printed pieces and fix them together.
    a. Fixation can either be done using clamps, weights, or tape depending on what works best for the shape of the part.
    b. Tested spheres were bonded together by simply placing one half on top of the other and using a small 1-pound weight to hold the pieces in place.
6. Allow the seam to fully cure before continuing to the next step.
7. After the seam has fully cured mixed a similar amount of epoxy resin as in step 2.
8. Using a brush spread the epoxy on the exterior surface of the part.

    a. It is important to make sure there are no dry spots as the epoxy is meant to fill and cover and holes in the print layers.

9. Finally, allow exterior epoxy to fully cure before any modifications are made to affix fuel pick up system.

6.2 Thermoforming

Thermoforming fabrication procedures are based off experience with 3/32" sheets of PETG. Other thicknesses or using a different material may affect timing sensitive processes such plasticization temperature and cooling time. It is recommended to have multiple pieces of material precut to the dimensions of your forming table.

6.2.1 Molding

1. Begin by powering on your heating element.
    a. A professional thermoforming machine was used in this research but the same result can be achieve using the broiler setting of an oven or a high-powered heat gun.
    b. Allow the heating element to preheat as this will help keep timing consistent between parts.
        i. This can take anywhere from a few minutes to tens of minutes.
2. Prepare forming table by placing it in an area close to your heating element as the plastic will cool quickly when moved from beneath the heating element.
    a. Insert wet/dry vacuum hose in the hole on the side of the forming box and plug in the vacuum.
    b. Place part mold in the center of the forming table.

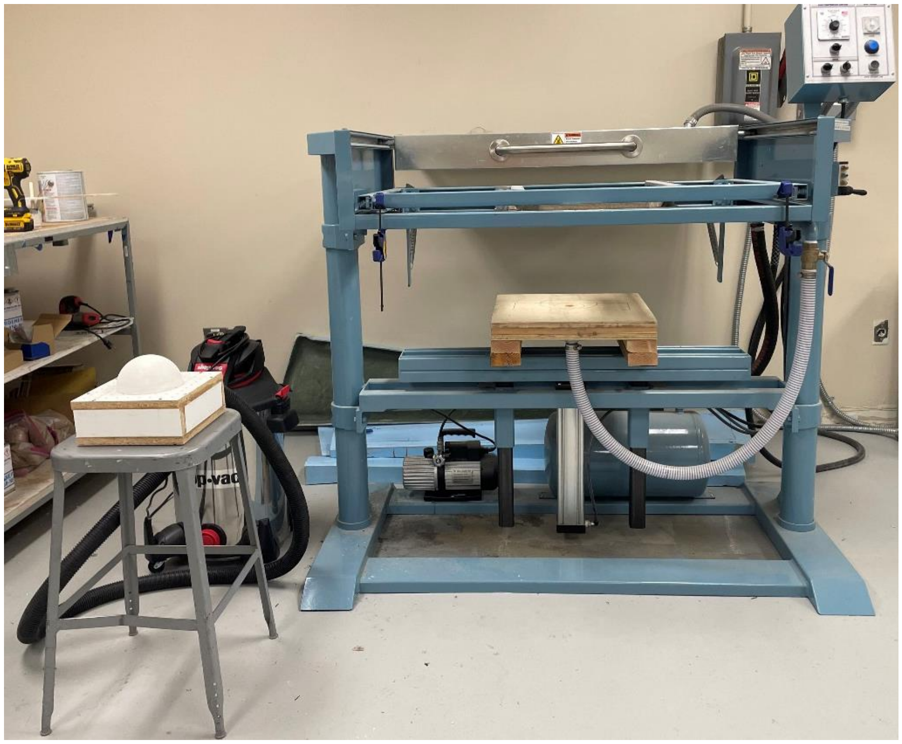

Figure 36: Thermoforming Fabrication Setup

3. While the element is preheating place and affix the material into something to secure it as it is heated.
    a. A simple form was made using particle board that sandwiched the material between two pieces and can be seen in Figure 21.
4. Once element is up to temperature place material under the heat and watch for the plastic to begin to sag.

Figure 37: Secured Material

5. For 3/32” of PETG it took approximately 60 seconds for the material to sag ¾”.
    a. After multiple attempts it was found that ¾” was ideal for forming the selected material.
6. When there is approximately 5 seconds left or the material is about to reach the appropriate amount of sag turn on the vacuum.
7. When the material has deformed ¾” remove from under the heating element and quickly place it over the mold and bring the form down over the table.
    a. The vacuum should pull the deformed material onto the mold and into the corners.

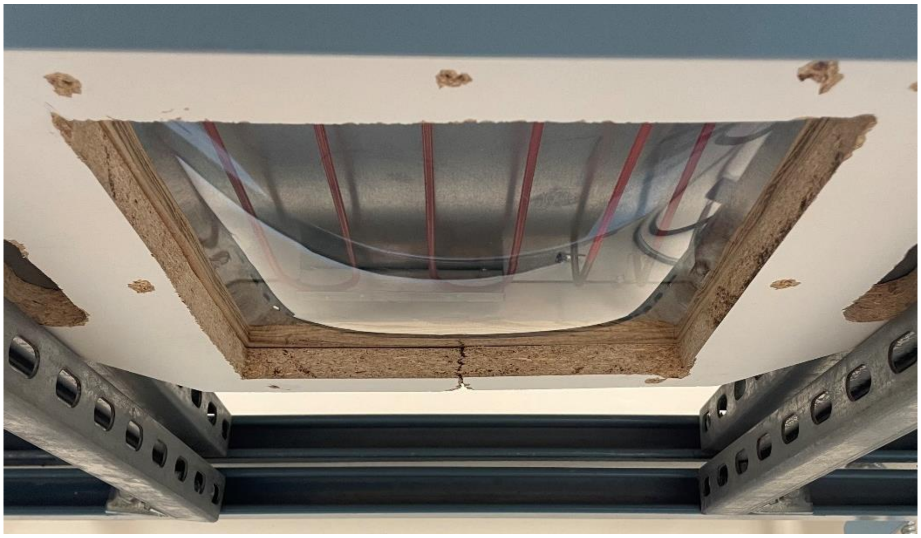

Figure 38: Deformed Material

8. To achieve clean corners over in your part, use a card or scraper to push the material into the corners while it is still warm.
9. Wait approximately 45 seconds for the part to cool before turning off the vacuum.

Figure 39: Formed and Cooled Part

10. Remove the molded part from the form and repeat steps 3 through 9 to make the second half of the tank.

6.2.2 Bonding

A hot knife was used to cut the molded parts from the excess flange, if access to a hot knife is not available it is possible to use a box knife or other sharp object. A hot knife is simply a small electric knife that can be set to different temperatures in order to smoothly cut foam or plastic. Also, an electric hotplate was used to heat the seam line of the material until soft in order to bond the halves together. It is also possible to use another type of heating element or even plastic specific epoxy to bond the halves together.

1. Prepare area where hot knife will be used.
    a. It is important to use the hot knife in a well-ventilated area as well as wear a mask and safety glasses while in use.
    b. A small plate of aluminum was place over a scrap piece of wood to create a surface that was safe to use the knife on.

Figure 40: Hot Knife Cutting Setup

2. Plug in the knife and allow to come to temperature.
3. Once the knife is at temperature, this should only take a minute or so, use the tip to slowly cut around the edge of the part to remove the excess.

a. Repeat this step for however many parts are available to expedite the fabrication process.

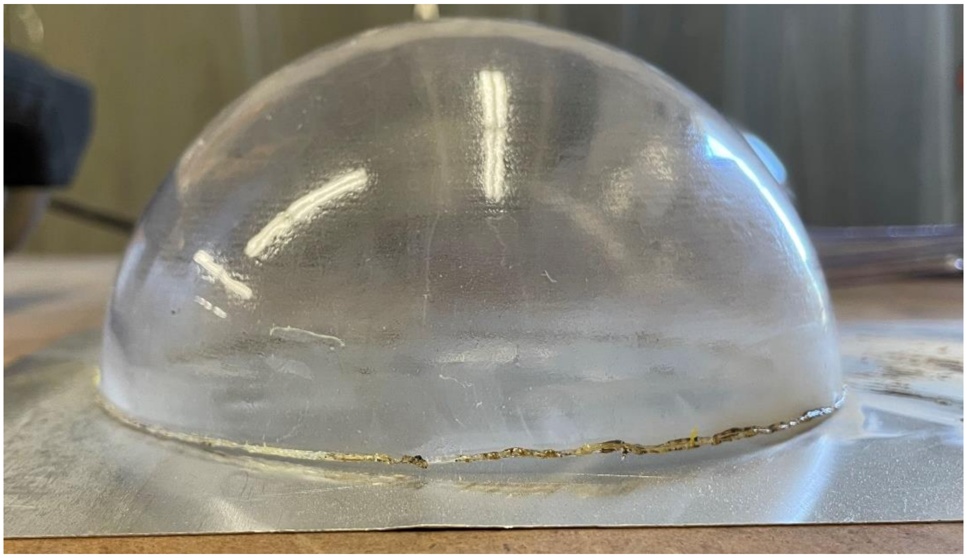

Figure 41: Cut Fuel Tank Half

4. Turn the hotplate or electric griddle to its maximum heat setting and cover with wax paper to prevent the plastic from sticking.
5. Put both halves of the tank seam side down on the hot plate and move them constantly so the seams heat up evenly.

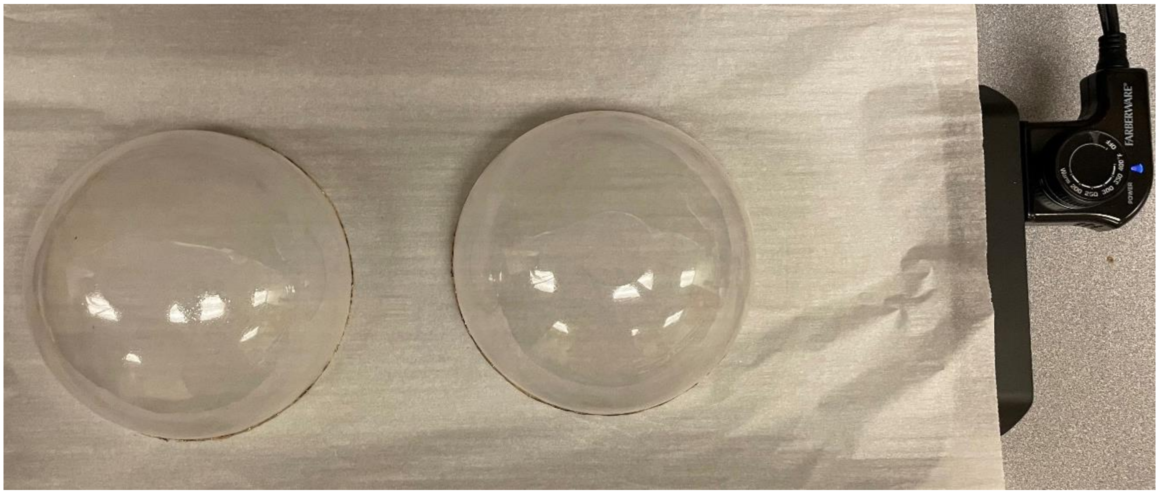

Figure 42: Thermoformed Parts Placed on Hot Plate

6. Once the plastic begins to deform remove them from the hot plate and carefully push the two halves together until a small amount of plastic is pushed out creating a flange.
    a. The flange should be less than 1/8”, preferably 1/16”.
7. Using a soldering iron set to 725°F or higher with a wide tip carefully melt the flange over the seam to create a better seal.
    a. Ventilation and a mask are highly recommended for this step.

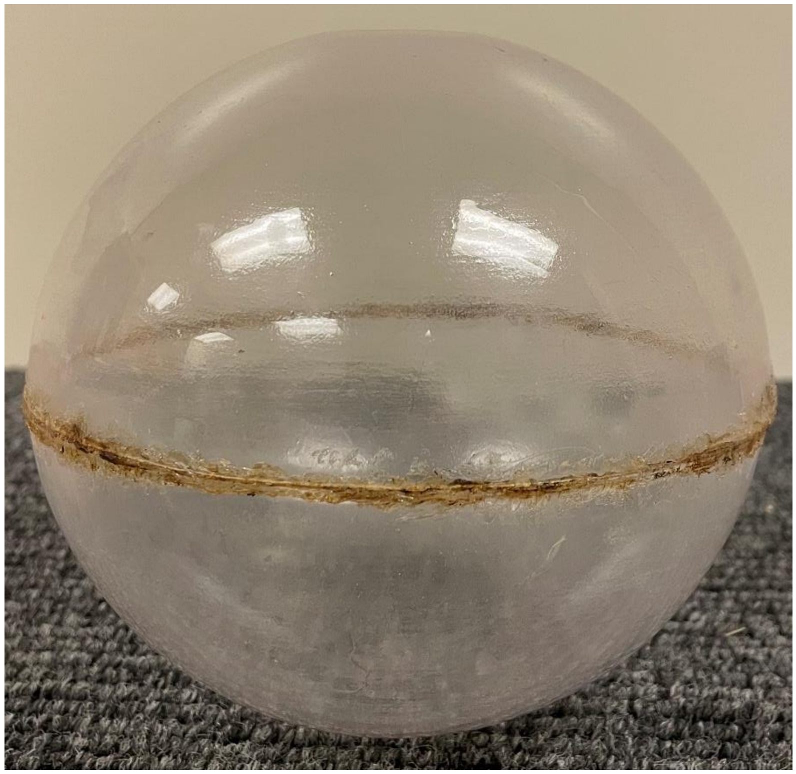

Figure 43: Bonded Halves

8. Allow flange to cool, approximately 30 to 60 seconds after being heated, before making modifications to affix fuel tank fixtures.

6.3 Composites

All composite fabrication was done using a 1:1 epoxy to fabric weight ratio. Fabrication procedure is the same for Kevlar and Fiberglass. Composite procedure can be modified to account for extra layers of fabric if desired. It is recommended to wear nitrile gloves while doing the layup, the use of a plastic scrapper is helpful but not necessary, finally denatured or isopropyl alcohol can be used to clean up any epoxy spills.

6.3.1 Layup Procedure

1. Cut bagging material. Includes separation material, breather, and bagging.

a. To find how much material you need find the dimension of your mold accounting for the outer dimension of the part. This will be the size of your separation and breather material.
b. Cut an additional piece of breather material to place under or around your vacuum hose to avoid sucking epoxy into the pump.
c. Bagging material will be this dimension plus the height of your parts multiple by the number of parts along that dimension.

2. Prepare layup area
    a. It is recommended to cover a section of a table that is much larger than the fabric to be cut to be able to infuse the fabric. This will make cleanup much easier.
    b. Secure the painters plastic with tape to ensure it does not move around while applying epoxy.
3. Prepare the mold for the layup
    a. Using 1inch tape, cover the exterior perimeter of the mold to prevent release from curing there.

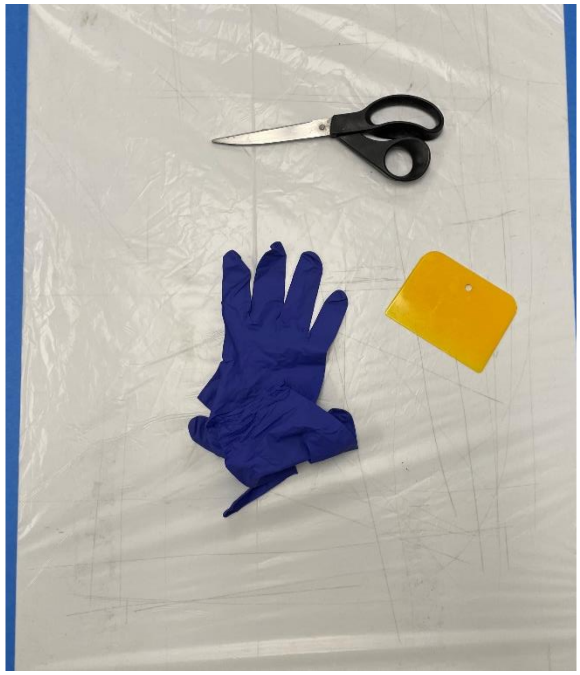

Figure 44: Prepared Layup Area with Equipment

b. With a mold release wax, Partall Paste #2 is recommended, apply and then remove the wax according to the package instructions. Repeat his process according to the package instructions.

c. Next apply two coats of mold release, Partall Coverall Film is recommended, according to the package instructions.

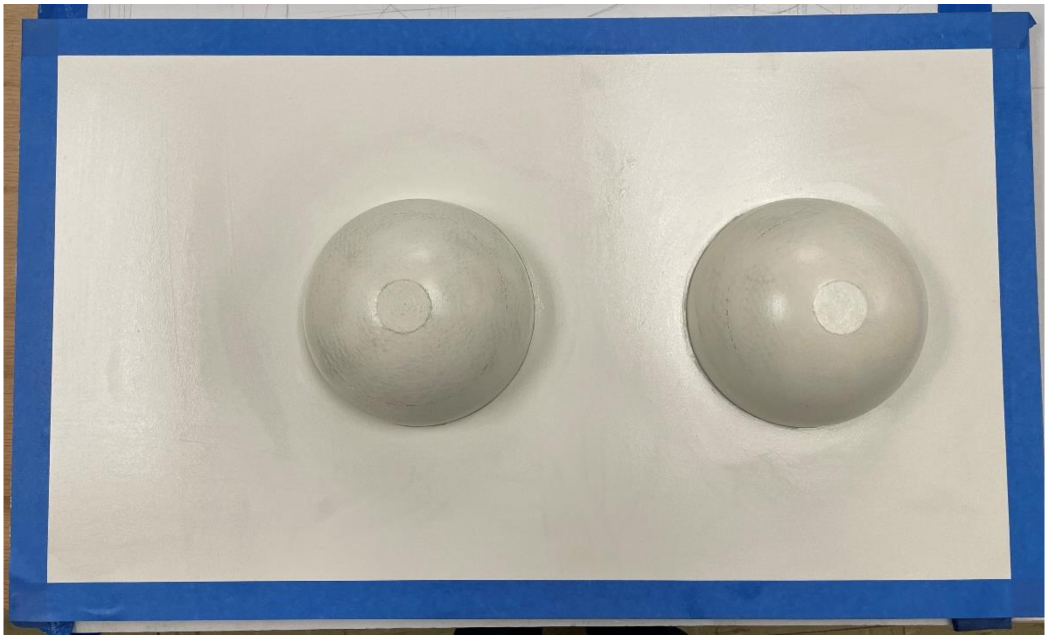

Figure 45: Released Mold

4. While the release film is drying cut layup material.
    a. It is recommended to cut layup material so that at least 1 inch of flange will be created around the perimeter of the part.
    b. Weight fabric after it has been cut and record the weight in grams.
5. Once release has fully cured the actual layup can begin.
6. Start by mixing the epoxy by weight to match the weight of the fabric, or as close as can be made within the mixture ratio of the resin.
7. Lay the first piece of fabric in your prepared area and pour a reasonable amount of the epoxy overtop.
    a. Use the plastic scrapper or your hands to spread the epoxy over the fabric until saturated.

Figure 46: Dry (Left) and Wetted (Right) Fabric Comparison

8. Once the fabric is saturated lay it over your part mold and smooth it down with the goal of removing all the wrinkles.
    a. If there are some wrinkles that are too difficult to smooth out due to the geometry of the part a relief cut can be used to make the process easier.
    b. If a relief cut is used a small patch can be laid over it to reduce the chance of creating a potential leak.
9. Repeat the previous step with all fabric layers.
    a. Be careful to not use to much epoxy as this does not improve the leak resistance of the part but will increase the weight.

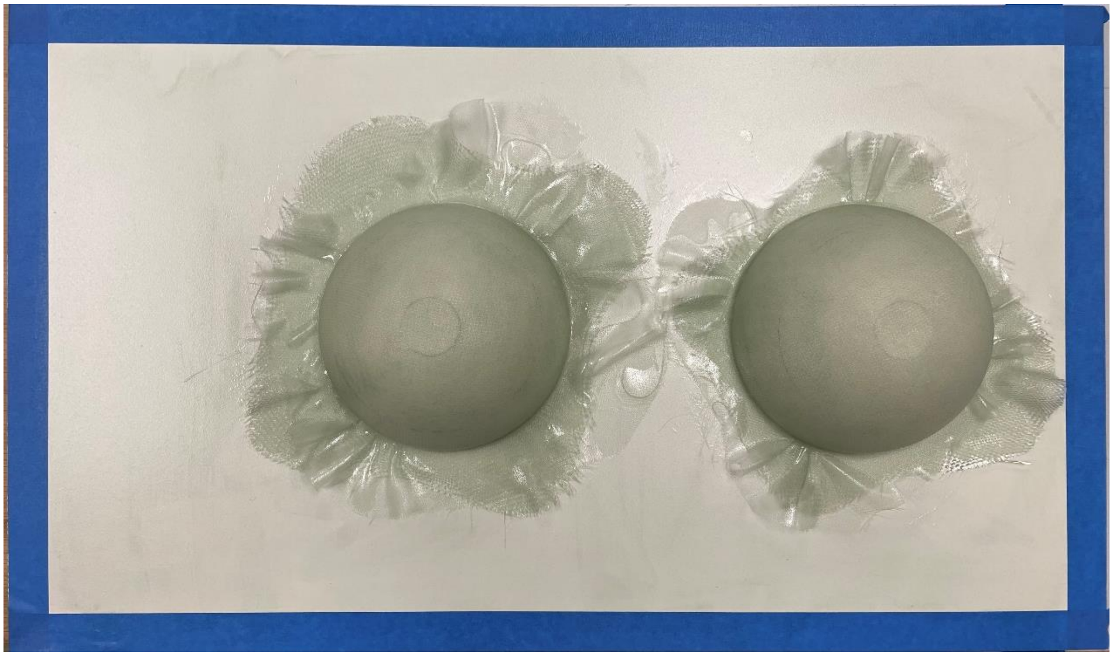

Figure 47: Applied Wetted Fabric

10. After the last layer of fabric has been applied the bagging process can begin.
11. Begin by laying the separation material, a released perforated film was used, and then the breather material, a thin cotton fabric, over the entire part.
    a. Be sure to push the separation into the corners of the part otherwise when vacuum pressure is applied it can move the material and fabric creating creases.
12. Remove the tape from around the perimeter of the mold. Replace this with a layer of chromate or "tacky tape." This is used to secure the bag and create an airtight seal.
    a. An envelope bag can also be used to avoid having to use chromate and eliminate the single use vacuum bagging material, these can be purchased online from multiple retailers.

13. If using a medallion fitting fold, the extra breather material over itself 3 times and place it under the bottom of the fitting.
    a. If using a tube, wrap the breather material around the end of the tube and place it on the side of the mold.

Figure 48: Chromate (Boarder), Separation Material (Right), Breather (Middle), Medallion (Left)

14. Starting in one corner apply the bagging material to the chromate move along the shorter side until you reach the next corner.
    a. A dog ear will need to be applied along the midline to allow for excess bag to form around the part. A dog ear refers to an extra piece of chromate that extrudes off the mold to add bagging material to the mold surface.
15. Continue down both long sides of the mold applying dog ears where extra bagging material is need to fit the contours of the mold part.

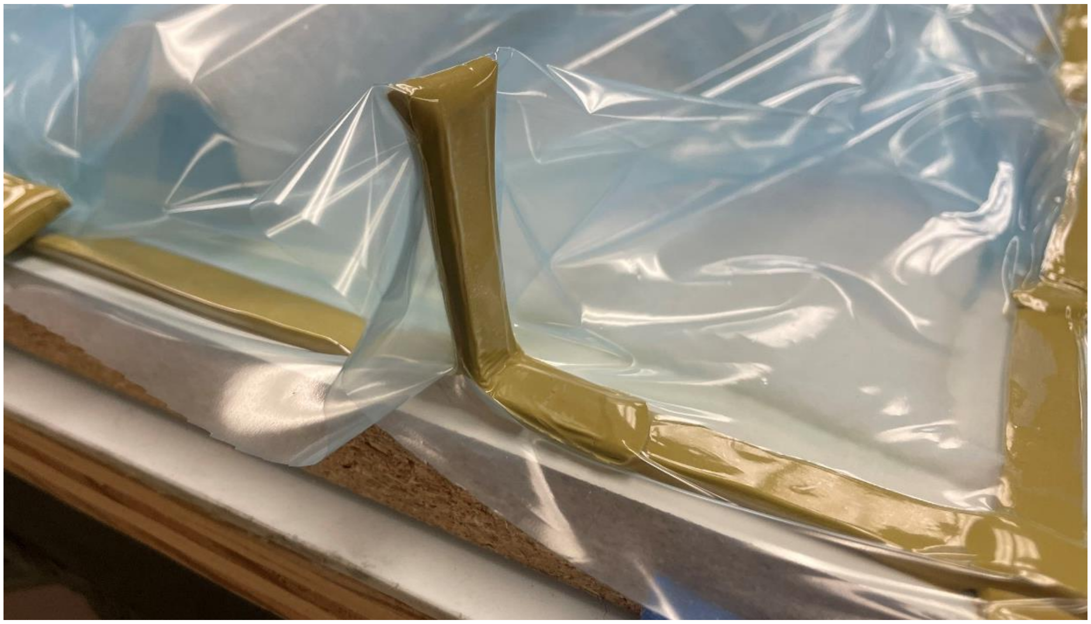

Figure 49: Example of Dog Ear

16. Once the perimeter of the mold is sealed attach the top part of the medallion fitting by cutting a small hole in the bag over the bottom part of the fitting and applying according to the manufacturer instructions.
    a. If using a tube, it is easiest to place it at the base of a dog ear or by putting a piece of chromate around the tube and firmly pressing it into the chromate below and around the tube.

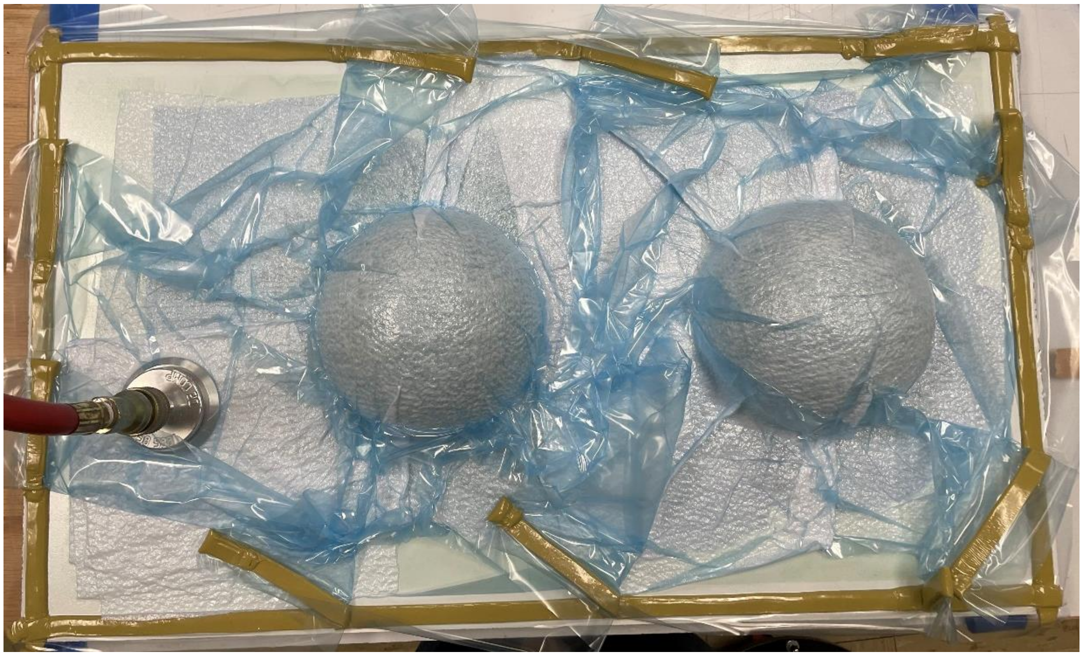

Figure 50: Example of Completed Bag at 24in-Hg

17. Turn on and attach vacuum pump to mold or medallion fitting. A minimum vacuum pressure 20 in-Hg is recommended. To achieve this is may be necessary to check the corners of the mold and were dog ears are place for small leaks. These can generally be heard if listening closely for the sound of air moving through the holes.

Figure 51: Medallion Vacuum Fitting

18. Once the minimum pressure has been reached be sure to use a clean scrapper or a thin rolling tool to firmly push down the corners of the mold. This ensures the part comes out with sharp features.
19. Allow to sit under vacuum for the full cure time of the epoxy resin used.
    a. Make sure to clean tools and the layup area with alcohol to ensure the longevity of your working area.
20. Once the part is fully cured remove the vacuum bagging, breather, and separation material. Clean the inside of the part with water to remove any leftover release film. Remove all but ½” of the flange with either scissors, a band saw, or by any reasonable means.

6.3.2 Bonding

With the initial layups complete the process of bonding the pieces together can begin.

1. Lightly sand the inside of the part with 220 grit sand paper.
    a. Clean with alcohol afterwards.
2. Mix a small amount of epoxy resin and apply to the inside of the part using a brush.
    a. Make sure the entire surface is adequately covered.

Figure 52: Laminated (Left) vs Unlaminated (Right) Composite Fuel Tank Halves

3. Allow epoxy resin to cure for a minimum of twice the working time.
4. Cut a 1-inch strip of fiber glass the length of the perimeter of the part.
5. Once the epoxy has set, infuse the 1-inch-wide strip of glass with the epoxy and apply it to the inside perimeter of the part.
    a. Allows this to fully cure before moving to the next step.

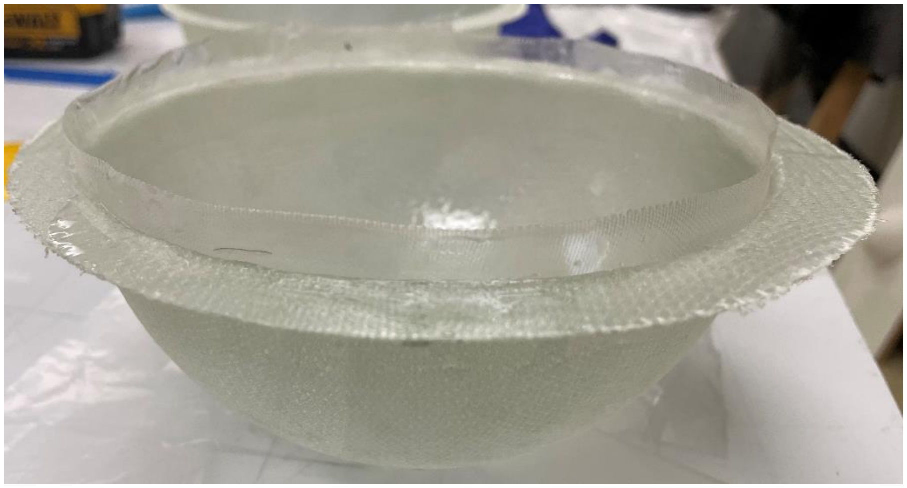

Figure 53: 1 inch Strip of Fiberglass Tape

6. Mix the volume of epoxy needed to cover the flange of the part. Add thickener to the epoxy till an icing like texture is achieved, colloidal silica was used.
7. Apply the thickened epoxy around the exterior perimeter of the part alongside the strip of fiberglass.

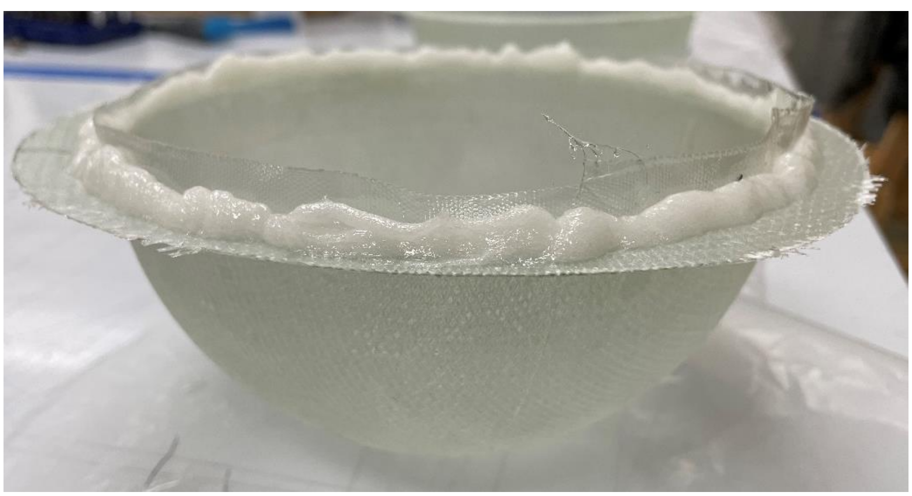

Figure 54: Thickened Epoxy Applied Along Exterior Perimeter

8. Place the other tank half over the one with the thickened epoxy and secure them together through reasonable means. Check to ensure halves are aligned properly.

a. Allow the epoxy to fully cure before moving to the next step.

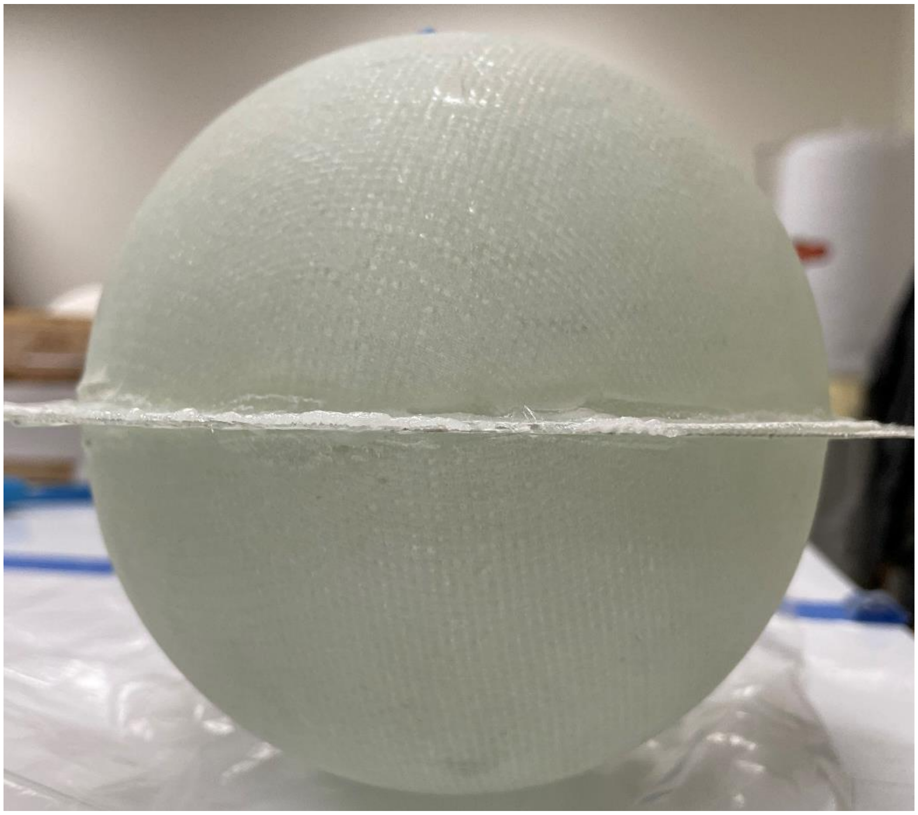

Figure 55: Bonding Halves

9. Remove the remaining flange.
    a. A band saw was used to remove a majority of the flange.
    b. Using a belt sander and sanding by hand the flange was removed to the part surface.
    c. Clean the part with alcohol when finish.
10. Cut a 2-inch-wide piece of fiberglass tape the length of the exterior of the part.
    a. Infuse the glass with epoxy and apply to the exterior of seam line of the part.
11. If desired once the epoxy is fully cured wet sand the edges of the exterior tape until a smooth finish is achieve

CHAPTER VII

SUMMARY, CONCLUSION, AND FUTURE WORK

In this chapter of summary of work done, knowledge gained, goals achieved, and future work will be discussed.

7.1 Summary

The purpose of this thesis was to determine if the manufacturing methods available to students at Oklahoma State University were viable ways to produce fuel tanks for small to medium unmanned aircraft systems. In this thesis, available manufacturing processes are discussed, material properties were consideration, current marketed tank prices were investigated. Next initial small-scale samples for each method were produced, they were pressure tested for air leaks, methods were adjusted for results, air tight samples were produced from small-scale testing results. Afterward, 5.75" spheres were produced with the final small-scale testing results, they were pressure tested for leaks, when leaks were present the production procedure was changed to reduce or eliminate leaks, after air tight spheres were made, they were dropped at varying heights to observe the damage tolerance or the tank. Additionally, a cost analysis of the tanks produced was conducted in order to compare the value of them to ones available in the commercial market. Finally, this research provided questions about thermoforming materials that could be used, further optimizing composite layups and techniques; 3D printer hardware, software, and setting optimization.

7.2 Conclusion and Recommendation

In order to determine the most fitting manufacturing technique for the desired situation the figures of merit for all designs must be evaluated. To do this a simple function was determined that weighted four of the main design and manufacturing factors; price/fl. Oz, labor hours required, maximum drop height without leaks, and the capacity ratio for each material are also noted in Table 9. The purpose of Table 9 is to aid in making a final decision for the desired design scenario by listing the aforementioned major factors as well as the strength and weaknesses for each material. Based on the following table it is recommended to use a composite layup if viable, although the composite layups take the most time and skill as well as have the lowest drop height survived, they have the highest capacity ratio which is debatably the most significant factor. A thermoformed tank would be recommended if the weakness of the seamline could be reduced or eliminated through different bonding techniques or reinforcement. 3D printed fuel tanks are not recommended as they offer the lowest capacity ratio along with the long print times, epoxy cure times required to achieve a seal, and the lower cost does not off set the other weaknesses. A 3D printed fuel tank is only recommended if it is the only manufacturing method available or if durability is desired above all else.

Table 9: Final Comparison

	Price / Fl. Oz	Labor Hours	Drop Height	Capacity Ratio (fl. oz/gram)	Strengths	Weaknesses
Kevlar	1.89	3	16	0.743	• Lightweight • High Capacity to Weight Ratio	• High Cost • Low Durability • Moderate-High Skill
Fiberglass	1.80	3	16	0.598	• Lightweight • Moderate Capacity to Weight Ratio	• High-Moderate Cost • Low Durability • Moderate-High Skill
3D Nylon	1.01	1.5	20	0.337	• Low Skill	• Moderate Cost • Moderate Durability • Low Capacity to Weight
3D ASA	0.90	1.5	36	0.367	• Low Skill • Moderate-Low Cost • High Durability	• Low Capacity to Weight
3D PETG	0.98	1.5	24	0.296	• Low Skill	• Moderate Cost • Moderate-High Durability • Low Capacity to Weight
Thermoformed PETG	0.67	1	28	0.585	• Moderate Skill • Quick Production Time • Moderate-High Durability • Moderate Capacity to Weight Ratio	• Durability dependent on loading

7.3 Goals Achieved

As stated in Chapter 1 the goals of this thesis were to design, test, and determine manufacturing procedures for multiple production methods in order to reach the goals stated.

1. Conduct a literature review of current uses and manufacturing procedures for each method.
2. Design and assemble testing apparatus to apply a pressure load to small scale samples.
    a. Must be able to hold 3.75” sample disc
    b. Must be able to apply a load of 5 psi
3. Determine 3D printer settings and composite layup orientation.
    a. Find best 3D printer settings to achieve an airtight sample off the print bed
    b. Find composite layup orientation and epoxy ratio to achieve airtight samples

4. Design, build, and test large scale samples.
    a. Ability to produce similar parts from all manufacturing processes
    b. Be able to withstand 5 psi load
    c. Be able to withstand a minimum of a 4 inch drop at 80% volumetric capacity
5. Determine final manufacturing procedures for different methods
    a. Create guides to be able to replicate the process used to produce samples
6. Perform a cost analysis for the experimental tanks to be compared to products available on the current market.

In order for the research to be considered a success the above goals needed to be met. The first objective was met in Chapter 2 and led to the specific selection of materials for each production method. Objectives 2 and 3 were achieved within Chapter 3 through the use of small-scale testing. These experiments showed that samples could be made using each investigated method that satisfied all sub objectives and could have possibly endured a larger load form the pressuring testing. Full scale testing and results discussed in Chapters 4 and 5 completed objectives 4 and 5 as well as objective 6. It was found during the final stages of testing that in order to meet the requirements for objective 4b that tanks ended up being over designed for the next objective, 4c. While this isn't necessarily a negative outcome it does show that more work can be done in order to further optimize the final designs.

7.4 Future Work

While the research presented lays out an initial procedure for testing and fabrication there is much that can be done in the future to further understand the processes behind each method. Even though all final fuel tanks produced met the discussed objectives future research can be done to further optimized the individual manufacturing methods. For example, 3D printing techniques and settings vary widely between printers, software, and filaments. Composite fabrication could be further optimized by investigating different fabrics, resins, layup techniques, and layup orientations. Finally, thermoforming fabrication could be further expanded by researching other materials than the ones discussed and also by discerning more replicable ways to produce tanks. Thermoforming manufacturing would also benefit by looking at ways tanks could be produced as a single piece or better ways of sealing multiple pieces together. With the research presented in this thesis it is possible to build a fuel tank that can be used in future aircraft research projects at Oklahoma State University, other universities, or hobbyist and enthusiast-built planes.

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