2019

Waterproofing 3D-Printed Parts

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Recommended Citation

Freitas, Allen; Carroll, Zachary; Robinson, Holly; and San Angelo, Alyssa, "Waterproofing 3D-Printed Parts" (2019). *Mechanical Engineering Capstone Design Projects.* Paper 50.
https://digitalcommons.uri.edu/mechanical-engineering-capstones/50

WATERPROOFING 3D-PRINTED PARTS

TEAM 1

Operation: Watertight

Final Design Report

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May 6th, 2019

Abstract

Team Operation: Watertight has been given the task to design a technique for printing or a post process application for treating fused deposition modeled parts to become impermeable to water. The final design report shows the progress made over the past academic year in order to create this process.

In the fall, the team brainstormed many possible solutions and was able to narrow them down with the support of our sponsors, accompanied by a lot of research. This research consisted of many literature searches and patent searches to ensure there was not a process already designed for this application. Last semester, four concepts were selected and tested: resin injection, resin vacuum infiltration, XTC-3D, and Gelcoat. Each concept was applied to 3D printed ABS parts and then submerged in water. The change in mass after submersion for varying lengths of time allowed for the evaluation of each process.

From the results seen, XTC-3D and resin injection proved to be the most promising out of the four. With this knowledge, the two methods were combined and tested in the Spring semester. They were not only tested by submergence, but pressure and strength tests were done as well. The original goal for the pressure test was to create a vessel to withstand 100 psi. With the methods applied, this goal was surpassed by 200 psi. The strength test was completed to see the effects of each method on the structural integrity of the 3D printed part.

Contents

List of Acronyms

3D	Three-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
FDM	Fused Deposition Modeling
GD/EB	General Dynamics/Electric Boat
MEKP	Methyl Ethyl Ketone Peroxide
POC	Proof of Concept
PPE	Personal Protective Equipment
psi	pounds per square inch
QFD	Quality Function Deployment
Resin/XTC-3D	Resin injection and XCT-3D combined process
URI	University of Rhode Island
USPTO	United States Patent And Trademark Office
UV	Ultraviolet
BPA	Bisphenol A
VOC	Volatile Organic Compound

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1 Introduction

With the increase in popularity of 3D printing, there comes a drive to make the most out of the prints created. Tasked by General Dynamics Electric Boat (GD/EB), our goal was to do just that. Currently, non-metallic 3D printed parts made by this method of fused deposition modeling (FDM) are permeable to water. At Electric Boat, water is an unavoidable factor in many of their projects. Having a part that absorbs or leaks water is not ideal, whether it be a piece for a ship or a scale model for proof of concepts. Typically, voids are created within the piece during the printing process. These voids allow water to enter, therefore changing the initial density of the part. The first challenge presented was to make 3D printed fused deposition modeled parts impermeable to water. Once solutions were conceived and narrowed down, test pieces were designed. Then the best solutions were found to waterproof a 3D printed part, the next step was to create a pressurized vessel that can withstand pressures up to 100 psi. The goal was to simulate the pressure felt during submergence underwater and see if the designed processes increased the ability of ABS to withstand such pressure. The last step to evaluating the best methods to waterproof 3D printed parts was to perform strength testing. It was crucial to see how the different processes affected the ABS material. To develop this process to make FDM 3D printed parts completely waterproof, to design a pressure vessel, and to complete strength testing, Electric Boat provided a generous budget of $10,000.

With this proposal, there was freedom to create a process through either printing or treatment techniques. This prompted the research of many different options, ranging from different infill levels to several different coatings. Ultimately, our team ended up testing two methods. The two methods being the following: applying an XTC 3-D coating and injecting resin on the inside of the test piece while also applying XTC-3D to the outside surface.

2 Research

2.1 Patent Searches

One of the first steps in designing a process is to ensure that there are no patents issued for the process one plans to implement. Once the initial research into waterproofing 3D printed parts was done, the patent searches were then narrowed into four separate topics. The four different topics were resin and fill materials, waterproof coatings, ABS properties, and 3D printers and each team member was designated to one topic. Searching patents helped to see what other people have done to prevent the absorption of water into 3D parts and to ensure that our process development would not infringe on any relevant patents. Since our team was not developing a new material or type of 3D printer there were very little patents that pertained to this process. A couple notable patents are listed below and pertain to a surface treatment of FDM parts using a chemical vapor treatment. Specifically they include a certain mixture of the chemicals used and different vapor vessel modifications. Since a vapor treatment was considered as an aspect of the design process at one point, the team made sure these patents will not be infringed upon since a specific vapor chamber will not be used and only acetone will be tried for the chemical composition for the vapor.

Patent Number: 8,765,045

Patent Name: Surface-treatment method for rapid-manufactured three-dimensional objects

Patent Date: July 1, 2014

Inventors: Zinniel; Robert L.

Patent Description: A method for forming a surface-treated, three-dimensional object, comprising: solvent smoothing an exterior surface of a rapid-manufactured, three-dimensional object, and media blasting at least a portion of the solvent-smoothed exterior surface. The vapor smoothing step reduces a porosity of the three-dimensional object at the exterior surface. The solvent vapor uses a solvent selected from the group consisting of methylene chloride, n-propyl bromide, perchloroethylene, trichloroethylene, acetone, methyl ethyl ketone, dimethylacetamide, xylene, toluene, water, alcohols, and combinations thereof. The media blasting comprises blasting with sodium bicarbonate abrasively removing at least one surface blemish from the solvent-smoothed exterior surface.

Patent Number: 8,123,999

Patent Name: Smoothing method for layered deposition modeling

Patent Date: February 28, 2012

Inventors: Priedeman, Jr.; William R. Smith; David Thomas

Patent Description: A method for making a three-dimensional object comprising the steps of: providing an object built from a modeling material using a fused deposition modeling technique, wherein the modeling material comprises a thermoplastic resin, wherein the built object has an object surface formed of the modeling material, the object surface having at least one surface effect due to the fused deposition modeling technique that extends substantially across an entirety of the object surface, wherein the at least one surface effect comprises a stair step effect, striation, or a combination thereof, and wherein the object exhibits porosity due to the fused deposition modeling technique; placing the object in a vessel; exposing substantially the entire object surface to vapors of a solvent that transiently softens the modeling material at the object surface while the object resides in the vessel in a solvent vapor zone present below cooling elements in the vessel; reflowing the softened modeling material to reduce the at least one surface effect and to reduce the porosity of the object at the object surface; observing condensation of the solvent vapors on the object surface while reflowing the softened modeling material; discontinuing the exposure of the object surface to the solvent vapors after the condensation of the solvent vapors stops; and drying the object after discontinuing the exposure, wherein the object surface of the dried object is substantially free of the at least one surface effect and is substantially free of the porosity. The solvent is selected from the group consisting of methylene chloride, an n-Propyl bromide solution, perchloroethylene, trichloroethylene, and a hydrofluorocarbon fluid.

2.2 Literature Searches

Before starting research into the problem of waterproofing 3D printed parts, it first had to be determined what printer and type of material was going to be used. GD/EB typically uses a Fortus 360mc fused deposition modeling (FDM) printer with m-30 Acrylonitrile Butadiene Styrene (ABS). For this reason a basic understanding of these processes and material were researched. ”Development of rapid tooling using fused deposition modeling: a review” [1] was a good starting point and discussed how additive manufacturing (AM) is used, what materials are available, and how the 3D FDM printing process works. This article also mentions common finishing techniques and it is where vapor smoothing was first mentioned. Further information was gathered about the slicing techniques along with additional finishing techniques in the article ”Pre and post processing techniques to improve surface characteristics of FDM parts: a state of art review and future applications” [2].

The research clearly led to the use of vapor smoothing as a possibility and there were multiple articles dedicated to this topic. The vapor smoothing process involves placing the part in a chamber with a chemical that slightly melts the outer layer of the part. The melting of the outer layer can allow the ABS printed part to become less porous due to the reduction in any printing imperfections. Two of the articles found were Investigation for Surface Finish Improvement of FDM Parts by Vapor Smoothing Process [3] and ”Temperature-Dependent Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modeling and Vapor Smoothing,” [4]. The first of these articles discusses the methods of vapor smoothing and it’s effects on surface finish. The second one details how vapor smoothing changes the mechanical properties of ABS. From these articles it was determined that due to the lower mechanical and temperature effects from vapor smoothing that it would not be the ideal process to make a part waterproof and maintain the mechanical properties but could be used in addition to another process.

There are a few commercially available products specifically designed to be brushed on to 3D printed parts and one of them was selected to use in the project: XTC-3D. This product is a two part epoxy that is used to coat the part. The epoxy idea was researched more and a technique was used to strengthen 3D printed parts by filling the parts with resin. This process and the material property results are seen in the article ”Strengthening of 3D Printed Fused Deposition Manufactured Parts Using the Fill Compositing Technique” [5]. This article did not explore waterproofing the part but it would make sense that the part would most likely resist water infiltration since the inside cavities were filled with resin.

Similarly, the article ”Strength- ening of Plasma Treated 3D Printed ABS through Epoxy Infiltration” [6] goes into depth about vastly strengthening 3D FDM models by injecting resin into the walls. This was one of the reasons resin injection was selected as one of the waterproofing solutions. This method could be used in conjunction with a waterproof coating in order to strengthen and waterproof the part. This could prove especially useful next semester when the team will be testing 3D-printed pressure vessels.

Another method that came up with researching this project was from a study done at The University of Texas at El Paso. Their study ”Analysis of Sealing Methods for FDM-fabricated Parts” [7] consisted of brushing on and vacuum sealing a pressure vessel to see how much pressure could be held by each of their processes. This paper goes into detail about the types of sealers that were used, dimensional changes, and the performance of each method. The results looked promising and the vacuum infiltration method was determined to be a viable option.

3 Evaluation of Competition

When the team was proposed with the challenge of designing a process to waterproof 3D printed ABS parts the first thing that was performed was research. As the time went on, the team searched through patents and read over many articles pertaining to the finish of 3D printed parts. It was soon discovered that no one had come up with any specific process that someone can follow in order to achieve a waterproof 3D printed part. As seen above, multiple patents have been made pertaining to the finish of the 3D printed parts. The use of acetone vapor for smoothing the surface has been used many times but has never been tested to see the affect it has on making a 3D printed part waterproof. The product XTC-3D is also used to finish 3D printed parts. Since this product is designed specifically for this application, unlike gelcoat, it instantly became a top choice for one of our processes.

A strategy in order to promote the use of XTC-3D for waterproofing 3D printed ABS parts would include publishing research on our findings and encouraging the company to advertise it as a waterproofing product. This may require a more intensive study on how XTC-3D reacts with water on a molecular level. Once this research is public knowledge and Smooth-On Inc. is made aware of the true capabilities their product has, they can advertise on their website. Since their company is well known in the industry of finishing 3D printed parts they will have a lot of influence on the general public. These are a couple of ways that our processes could become public knowledge.

4 Specifications Definition

When a design concept is started, a set of parameters needs to be determined for the product or in this case the process to meet. These parameters were determined and prioritized through discussions with our sponsors at GD/EB. The first priority was to make the 3D printed parts waterproof. The sponsor also asked for secondary specifications such as: the ability to be submerged for one to three months, a weight change of less than 10%, the ability to withstand 100 psi, and a strength increase. The team had also looked into testing resistance to heat, chemicals, and UV light. These specifications were deemed non-essential, and therefore not explored due to the limited time of one academic year.

The team had determined that the best way to quantify the waterproof specification was to measure the mass gain from water on a 3D printed piece. The data was normalized for a max allowable gain of 1 gram of water per surface area of the test specimen which was about 87.1 cm^2. The life cycle of one to three months was tested by submerging the specimen for 60 days and the test pieces were weighed once a week to observe the mass change over time. The mass of each waterproofing process was determined by comparing the mass before and after the application of the process. A pressure vessel was created with a 3D printed cylinder and aluminum end caps. Using a hydrostatic pump, they were pressurized to see what the waterproofing methods can withstand. The initial objective of withstanding 100 psi was surpassed, and each of the cylinders with the waterproofing process applied withstood 300 psi. The increase of strength was quantified by finding the yield strength of the control. This was then used as the comparison for the methods to see whether strength was added or lost.

The 3D printed parts, once waterproof, would be used in both saltwater and freshwater mostly for prototype designs. The market demand for this process could extend far out from GD/EB since there are many marine industries and companies in need to waterproof 3D printed objects that could make the parts ready to enter the market as a final product. Currently about 36% of the 3D printing market uses FDM and 57% of 3D printing is for the first phase of product development. In comparison only 22% of 3D printed parts are used as final product which might be increased if the final process of this project is achieved [10]. The design specifications can be seen in Table 1.

Design Specifications	
Mass Gain*	<1 g
Mass Difference**	10%
Pressure	100 psi
Yield Strength	>30.86 MPa
Life cycle	60 days

Table 1: Quantified design specifications.

*Mass gain was determined for 1 gram per surface area of 87.1 cm^2

**Compares mass before and after application

5 Conceptual Design

Last semester, each team member had to devise 30 concepts each for this part of the project. Many had to do with coating the part but it also explored printing options as well as numerous fill options. The sponsor GD/EB did not want only coating options but wanted every possible avenue explored to come up with a viable solution. Since this was an individual project some of the same process designs may be mentioned more than once. Once the individual assignment was completed the four best options were chosen to test in the proof of concept phase: gelcoat, XTC-3D, resin injection, and vacuum resin infiltration. These initial process ideas did not explore the print options that were later determined to go along with each process.

5.1 Allen's Design Concepts and Evaluation

1. **Chemical smoothing** – Dipping the part in acetone to melt the surface and close any gaps in the material. This process would cause the part to lose dimensional tolerances and possibly create holes in the part.

2. **Vacuum** – Immersion in epoxy resin and use vacuum to infiltrate part. Resin will fill in any of the air gaps left by the printing process. This was chosen as one of the final processes and will be discussed further.

3. **TC-1614 a/b** – Epoxy resin designed to penetrate porous surfaces, can withstand temperatures up to 350 degrees, working time of 2 hours and tack free in 12 hours and cost $147 per gallon. This product was expensive, the availability to order it was questionable, and the idea was rejected.

4. **Gelcoat** - sand part down with 300 grit sandpaper and clean, then spray or brush gelcoat on part and allow to dry. Layer thickness should be about 0.02 inches. $60-160$ per gallon, is chemical resistant, smooth surface if sprayed or sanded after brushed. This was one of the final concepts as well and will be further explained in the report.

5. **Resin resin injection 1** – print 3D part with a 70% fill on the inside and then inject epoxy resin into the part to fill the remaining 30%. Part printing must take into account the holes needed to inject the resin and allow air to escape while doing so. This is relatively close to one of the process designs chosen but the infill was changed to 0%.

6. **Heating** – Placing the 3D printed part in an oven in an attempt to bond the part together better and close the gaps from the overlays. This option would cause the dimensions of the part to change too much.

7. **Feedstock** –A matrix material dispersed with one or more susceptor structures can be formed into a feedstock for an additive manufacturing process. The one or more susceptor structures can be excited by an energy field such as an electric field, a magnetic field, an electromagnetic field, or any combination thereof, to produce heat. The heat that is produced can be transferred to the matrix material that surrounds the one or more susceptor structures to provide heat treatment to the matrix material. The heat

treatment can improve the material and mechanical properties of three dimensional objects formed from the feedstock. The 3D printers may not be able to handle the feedstock with the prescribed material and could have damaged the printers.

8. **Vapor smoothing** – Setting the 3D printed part in a chamber with acetone soaked rags to melt the outer layer and seal and gaps on the surface. This maintains the dimensional accuracy better than the dipping method. This method may be used as part of a process in the spring but right now it is not a process that stands out on its own. It has been shown through the research that it does help reduce porosity.

9. **Thicker layers** – using thicker layers reduces the amount of air gaps in a material and help keep water from seeping through but Difficult to get tight tolerances. Many print options were considered but most of them such as this will reduce the strength of the 3D printed part.

10. **Resin injection 2** – Before printing the part it would be necessary to adjust the part to have a gap just inside the whole outer layer of it with support to ensure the part remains as one. Then resin would be injected into the region on the inner wall to seal off the inside from getting any water absorption. The part may need to incorporate many injection points and allow for air to escape each chamber to ensure a proper fill. This process was similar to the resin injection and still may be utilized pending the results of the resin fill process. It still needs to be determined if some parts can be made with a thin internal layer that will allow resin to flow throughout.

11. **Plasma** – using plasma to obtain individual qualities as the 3D part is being printed. This would consist of an applicator being attached to a 3D print head and administer the plasma to the layer either before or after it is put down, or both. This could be tailored to waterproofing or scratch resistance depending on the plasma layer. Due to the limited 3D printers supplied it was determined to not be feasible to try and implement this process.

12. **Print options** – Using a crisscross pattern to build the 3D part and overfilling the air gap as each layer is put down. This is done by changing the printer options and setting it for a negative air gap. Again the printer options are limited and the patterns are often difficult due to the program being used.

13. **Lacquer** – Part must be lightly sanded then apply a lacquer that is either brushed or sprayed on, multiple coats may need to be applied. This process would not be very resistant to scratching and if a scratch broke through the laquer easily it would not work to keep water out.

14. **Wax** – Melting wax and applying it to the part that needs to be waterproof, remove any excess that may be on it and wipe smooth. The wax would be to fragile and if it scratches easily it would not be durable enough.

15. **Electroplating** – Copper, gold, or nickel plating can be applied by metallizing the ABS and allow a thin film to be applied to the surface. The cost to impement would be extremely high and much training would be required.

16. **Dichtol** – WF49 product #1849, after part is cleaned the product can be dipped, sprayed, injected or brushed on and uses capillary action to impregnate and fill in pores. Cures in a short amount of time but takes 7 days to be fully chemical resistant. Availability was the main issue with this idea since it could not be easily ordered.

17. **Pressure** – Increase the pressure inside the 3D printer build area when part is being constructed. This may help layer to layer adhesion and may help limit the size of air gaps. The requirements to make the 3D print area hold pressure would have proved difficult and the printers were in high demand throughout the semester.

18. **Waxing filament** – Coat the ABS filament with a layer of wax before it is melted to print the part. Doing this may allow the wax to fill in the air gaps left by the build

process. This most likely would not work due to the temperature of the 3D print nozzle and the wax would just run down the side of the part instead of staying on each layer.

19. **Flex Seal** – Apply Flex Seal is a liquid rubber seal coating that can be applied to the outer surface and allowed to dry. UV resistance was a factor in not choosing this as well as the adhesive problems that may be faced and the flex seal not sticking to the ABS.

20. **Vinyl** – Create a vinyl wrap covering and attach to part by way of adhesive and using a heat gun to attach to plastic part. It would be hard to get the wrap on without a gap from the ends of the vinyl meeting which would allow water to infiltrate the part.

21. **Perimeter** – Increasing the outside layer perimeter to create more of a barrier between the inside and outside shell. Then using an acetone vapor to help seal the outer layer. This is a combination of two previous ideas. This would have a similar effect as just the vapor treatment and may be used as a part in the process but not for a process by itself.

22. **Ceramic** – Apply a ceramic coating to outside of part. This would make the part fragile if impacted and the cost would be too high.

23. **XTC-3D** – Another commercially available product meant for the purpose of waterproofing 3D parts by brushing the product over the surface. This was chosen as one of the final process designs.

24. **Nanocoating** – A specifically designed nanocoating that imparts superhydrophobic properties to repel water. High cost and availability prevented this process from being explored.

25. **Bond-o** – Use of an automotive filler to skim over the entire surface of the part. The filler is then sanded to get a smooth finish and then a coat of lacquer is applied over the

top of it for finishing and more protection. This would not be resistant to chemicals and the bond-o could crack if exposed to heat and UV light.

26. **Adhesive** – Use a hot melt adhesive (hot glue) to inject a partially infilled 3D built part. The hot glue would not give the proper flow characteristics to ensure all the gaps were filled.
27. **Silicone** – Coating the outside of the part in a layer of silicone. Silicone can not be sanded down and has a hard time adhering to some material.
28. **Polyurethane** – Used for treating wood and can infiltrate the pores of the part being coated. This material is not heat resistant and may lose its ability to protect the part if exposed.
29. **Epoxy Clay** – This is mold-able clay that can be spread over the part and hardens completely in about an hour. The part would have to be sanded to a smooth finish and would add considerable thickness. The added thickness would be hard to control since the clay is thick and it would have to be spread out by hand.
30. **Foam** – filling the inside of the part with a liquid expandable foam. Care would have to be taken as not to cause too much pressure on the inside of the part. Completely filling the gaps may not be attainable and the pressure from the foam expanding could break the part.

5.2 Zachary's Design Concepts and Evaluation

1. **Hydrophobic spray** – Spray print in super-hydrophobic spray. The coating is waterproof and would provide a watertight boundary. This product is not durable enough to be used in the applications required by the design specifications.
2. **Wax dip** – Heat up wax with a heat gun, evenly apply the wax to the entire 3D-printed part. This method would not be durable enough to be used in any real applications.

3. **Waterproof paint** –Paint the print with waterproof paint, let cure and check dimensions. Due to the difficulty of getting the paint to properly adhere, this method was not used.

4. **Submarine paint** – Paint print with submarine paint, accounting for the thickness of the paint in order to keep dimensions in line. This could be a good option for large simple 3D printed parts, but it would be quite difficult to apply to complex architectures.

5. **Sealant infiltration** – Fill a tank with sealant, submerge the entire part into the sealant and lightly pressurize the tank to impregnate the ABS, remove the part. This method could work, but it is quite similar to the vacuum resin infiltration in concept 24.

6. **Sealant spray** – Spray the outside of the part with a sealant, the inside probably wouldn't be able to be coated since spraying limits what can and cant be reached. That is why this method of waterproofing was not chosen.

7. **Acetone application** – Carefully paint on a thin layer of acetone, let the acetone lightly dissolve the part. Once the acetone evaporates, the part will have an even waterproof surface. This method was not chosen since painting on the acetone would most likely apply too much acetone to the piece.

8. **Higher quality ABS** – Change ABS plastic to a higher quality ABS. This potentially could have better layer adhesion. This method was not chosen since GD/EB would like to keep using the same filament they have been.

9. **Silicone dip** – Dip the print into a tank of silicone, pressurize the tank, and then remove the waterproofed part. This method lacks the durability required by the design specifications.

10. **XTC-3D** – Apply XTC-3D 2-part epoxy to the exterior of the part. Let the part cure and it will self-level. XTC-3D does not melt the plastic so tolerances wont be affected. It fills in the striations typically encountered with 3D parts printed with FDM. This method was chosen since it is proven to be effective in waterproofing 3D-printed parts.
11. **Clear coat** – Spray exterior of part with clear coat and let dry. Apply 2nd coat if necessary. This method does not meet durability or longevity requirements.
12. **Heat gun** – Melt top layer of ABS with a heat gun. The layers will adhere better when under heat. This method will not be tested since it is time-consuming and it will deform the 3D-printed parts.
13. **Acetone vapor bath** – Put the part in an acetone vapor bath. The part will receive an even layer of acetone to create a uniform layer. This method was tested with the intention on using it later on for use in conjunction with the other selected methods.
14. **Resin application** – Sand the print to show crack locations, then fill the exposed cracks with resin. This method is too time-consuming and will most likely compromise the structural integrity of the parts.
15. **Change print orientation** – Print the cup using a different orientation, either sideways or diagonally to promote better layer adhesion. This method was not tested during the first semester, but it could possibly be introduced into testing for the spring semester.
16. **Higher definition print** – Print the cup using thinner layers, which translates to a higher definition print. Higher definition could mean closer tolerances. This method was not used because ABS plastic exhibits hygroscopic properties, meaning it would still absorb water.
17. **Lower definition print** – Print a cup using thicker layers. Thicker layers mean fewer

incidences of a seam exposed to water. Much like printing using a higher definition, using a lower definition print would not solve the problem of the ABS absorbing water.

18. **Print temperature adjustment** – Alter the print temperature to promote better layer adhesion. This adjustment was used in order to get the ABS filament to print properly, but this is more of a calibration than a concept for waterproofing the parts.
19. **Heat treatment** – Put the print into an oven to melt the layers together. This method would most likely deform the part and cause large tolerancing issues.
20. **Increase perimeters** – Increase the number of perimeters in the walls to create a more watertight layer. This method would be good at limiting the amount of water reaching the center of a 3D-printed part, but the part would still absorb water.
21. **Solid infill** – Print using a solid infill in order to create a solid border to block the water. This method was not chosen because the ABS plastic will still absorb water.
22. **Different print process** – Switch to a different print process. SLA produces watertight parts with little to no post-processing. This method would work very well to waterproof 3D-printed parts, but the team has to stick to the guidelines provided by GD/EB which states 3D printing must be accomplished using a Fused Deposition Modeling printer.
23. **Wall width modification** – Modify the wall width to be a multiple of nozzle extrusion width. This concept is more of a calibration step in order to get a well-functioning printer rather than a waterproofing method.
24. **Vacuum infiltration** – Use vacuum infiltration to inject waterproof resin within the layers of the 3D-printed part. This method was chosen to be tested because it is not just another waterproof coating, it is a technique that impregnates the ABS with waterproof resin that also strengthens it.

25. **Gentoo coating** – Apply Gentoo waterproofing compound to create a waterproof surface. This method was very close to being chosen, but the team decided it was too similar to other concepts being tested.

26. **Plastic spray paint** – Spray part with a specialized plastic spray paint to ensure proper adhesion. This method does not meet required durability or longevity standards.

27. **Different color ABS** – Print using a different color ABS to compare the levels of water intrusion. This method was deemed ineffective, since all ABS will absorb water. It would not be an effective use of resources.

28. **Cyanoacrylate coating** – Apply superglue (cyanoacrylate) to the outside of the part to form a seal. This method would not be able to be used since superglue dissolves in water.

29. **Gelcoat** – Apply Gelcoat, a hydrophobic coating that is used on boats. It has very good longevity and will last years. This product was chosen to be tested because it is cost-effective and cures relatively quickly.

30. **Ceramic Pro Plastic coating** – Apply Ceramic Pro Plastic coating and let cure. The part will have a super-hydrophobic coating that is durable and UV resistant. This product is not cost-effective and may have trouble bonding to the ABS plastic.

5.3 Holly's Design Concepts and Evaluation

1. **Flex Seal**– Spraying the part in Flex Seal would allow for the small impurities of the 3D-printed part to be filled in. The spraying process might make it hard to tell when there is complete coverage. Also, the adhesion of this product to the ABS was a big concern.

2. **Plasti Dip** – Dipping the part in Plasti Dip would create a smooth rubber like surface on the outside of the part. This product is fairly cheap but might not be ideal for complex geometry.

3. **Acetone Vapor** – Setting the 3D printed part in a chamber with acetone soaked rags to melt the outer layer and seal and gaps on the surface. It is hard to control dimensional tolerances during this process. This method may be used as part of a process in the spring but right now it is not a process that stands out on its own. It has been shown through the research that it does help reduce porosity.

4. **Wax** – - Melting wax and dipping the part that needs to be waterproof, remove any excess that may be on it and wipe smooth. Unfortunately, the wax isnt durable enough and would easily scratch off the part.

5. **Smooth On epoxy resin** – This commercially available product is a typical epoxy that can be brushed on to the part. This product wasnt chosen but a similar epoxy was used instead.

6. **Gap Filling** – This is a process that was found online that someone had tried to intermittently fill in gaps during the printing process with what seemed to be a resin. This idea was rejected due to the tedious task of watching the part as it printed for hours.

7. **Priming and Painting** –This process would involve sanding the 3D printed part to ensure a smooth surface. The part would then be primed and painted with some type of marine paint. This process wasnt chosen but aspects of it were used in some the final choices.

8. **Changing the percent infill** – The percent infill of a 3D printed part effects many different things. One of the major things it effects is how long it takes for the part to print. During our final processes the percent infill was changed according on what

process was being applied to the part. The plan for next semester is to see how infill alone effects how parts react in water.

9. **Epolam epxoy** – This product is another epoxy on the market that is commonly used for marine applications. A different epoxy resin was found for the final concepts.
10. **XTC-3D** – This is a commercially available product specifically made for the purpose of finishing 3D printed parts. The product is self-leveling and gives the part a nice shiny finish. This product was chosen as one of the final concepts due to its established name in the 3D printed parts industry along with being very affordable.
11. **Increasing layer thickness** – The layer thickness of any 3D printed part is very small. If the thickness was increased in even the smallest way this would allow for less layers and ultimately less unwanted spaces to be made.
12. **Adding more perimeters** – Adding more perimeters or shells while printing would create more layers that the water would need to permeate. Unfortunately, it also means more layers to waterproof and more time spent printing.
13. **Enviro 700 PUR Waterproofing Membrane** – This is another product that can be applied to the outside of the part with the intention of making it waterproof. This was more expensive compared to many products therefore it was not chosen as an option.
14. **Enviro 200P Ultra-Waterproofing Membrane**– This product was pretty expensive when compared to other products so it was not chosen.
15. **HydroBan Waterproofing Membrane** – This membrane was one of the cheaper options when compared to other similar products. It was highly considered when making the final choice but was ultimately not chosen.

16. **Minwax Sanding Sealer**– The part would need to be sanded prior to the use of this product. The product itself does have a wax like consistency which was decided to be too risky if the 3D printed part needed to have some scratch resistance.

17. **Higher print temperature** – Increase the printing temperature to increase layer adhesion. The use of ABS filament has made it hard to maintain a high temperature without the print failing.

18. **Slicer Settings** – The slicer settings on the Raise 3D program can be adjusted for each print. These different options allow for the part to be printed in a way that benefits the specific process chosen. This has been used throughout the semester.

19. **Pressure Vessel** – The idea of printing a pressure vessel has been chosen as a task for next semester. This concept was generated with the thought of our sponsor in mind.

20. **Epoxy Clay** – This is mold-able clay that can be spread over the part and hardens completely in about an hour. The part would have to be sanded to a smooth finish and would add considerable thickness. The added thickness would be hard to control since the clay is thick and it would have to be spread out by hand

21. **Pressure** – Increase the pressure inside the 3D printer build area when part is being constructed. This may help layer to layer adhesion and may help limit the size of air gaps. The equipment provided for this project does not allow this to be a feasible option.

22. **Resin Infill** – This concept would involve injecting the resin into the part. This concept was chosen and has been shown to be slightly successful. After the long term testing is complete, the team would like to further analyze the parts that have been injected with resin by cutting them in half.

23. **Polishing and Sanding** – The process of sanding has been used during many processes this semester. The idea of polishing is going to be implemented next semester

with the acetone vapor.

24. **Vacuum Infiltration** – A 3D printed part is soaked in resin and then placed in a vacuum bag for multiple hours to ensure the resin has traveled throughout the entire part. This concept was chosen but has seem to be unsuccessful.

25. **Combination of processes**– The combination of vapor treating along with some type of coating to ensure the part becomes fully impermeable to water. As a team, acetone vapor was avoided due to its tendency to get rid of dimensional tolerances.

26. **Simple Mug Design** – The use of 3D printed cup would allow for the testing of whether or not water can be held in by the 3D printed part or not. The final design can be seen in the appendix. When printing the dimensions were scaled down by sixty percent.

27. **Fully Enclosed Cube** – The immersion of this 3D printed part design would allowed the testing of whether or not water is kept out. The final design can be seen in the appendix.

28. **Complex Design** – The design of a 3D printed part that incorporates different things such as screw threads and o-ring to see how the processes work when these elements are present. This a goal for next semester.

29. **Different printer** – The use of ABS throughout this project is a design specification from our sponsor. If a different printer was purchased that could use a waterproof filament it would eliminate the need for any other process.

30. **Heat** – Subject the 3D printed part to a certain amount of heat just below it melting point to help the layers of material combine together. This option wasnt chosen due to the potential of the part losing tolerances.

5.4 Alyssa's Design Concepts and Evaluation

1. **Gentoo Coating** – This is a superhydrophobic and abrasion resistant coating. It provides a resistance to UV exposure, salt spray and chemical exposure. This can be applied in different fashions including HVLP sprayed, dip-coated, brushed, or flow-coated. The coating is lightweight and thin, approximately 4-6 microns. Compared to other options, this is relatively expensive at around $400. Before testing had commenced, the company was contacted, and discovered this coating is not available to the general public right now due to it being a new release.

2. **GlideCoat** – A nano-ceramic coating that is superhydrophobic. It adds corrosion, chemical and UV resistance to the piece. The coating lasts for 18 months. This is usually used on boats over a gelcoat. It is around the same price as the Gentoo coating, at $400 for the kit.

3. **XTC-3D** – A commercial product available made to finish 3D printed parts. This is a process with two parts of liquids mixed together and then brushed onto part. Once applied, it takes a minimum of two hours to cure at room temperature. A con to this coating is that it can only be applied in one fashion. This product costs approximately $26 for a 24 oz container. This concept was selected to be tested.

4. **Amazing GOOP Coat-it Waterproof Epoxy Sealer** – This product is formulated with ceramic beads, graphite, and Kevlar fiber, to give it abrasion resistance, slip and toughness respectively. Dries a light tan/gray color. The cost is around $25 for a gallon.

5. **Valspar Clear Gloss Enamel** – Essentially a clear coat spray paint. This would make the sprayed item water, UV, and scratch resistant.

6. **Flex Seal Liquid** – This product can be poured, brushed, or rolled on. Creates a waterproof coating that will last for years, adding UV and chemical resistant. This is

safe around animals and plants when fully cured. It has a shelf life of 24 months. To full dry, it takes 24-48 hours. It is not recommended to seal flammable liquid tanks. It costs about $80 for a gallon.

7. **Nano Ceramic Project** –This is a hydrophobic nano coating. In addition to making the piece waterproof, it adds scratch and UV resistance. It costs $115 for 80 mL.
8. **Percenta Nano Coating for Plastic** – Another hydrophobic coating, that can last up to 1 year. It adds UV resistance and helps protect from bacteria growth. This product is $15 for 100 mL.
9. **Ceramic Pro Plastic** – This is a durable superhydrophobic coating. Also makes the piece UV and wear resistant. The cost is approximately $80.
10. **Acetone Vapor Bath** – This process creates a higher resistance to water, and strengthens the integrity of the piece. When done correctly, the acetone melts the piece just enough to finish it. This is a time sensitive process, since the piece cant be left vapor too long or it will deform.
11. **Acetone Wipes** – Like the acetone vapor bath, this would seal the voids of the exterior layer created while printing. This is also time sensitive, but gives more control compared to the vapor bath.
12. **Vacuum infiltration** – This would fill the voids created, making the piece waterproof. This process provides impact resistance, but no UV resistance. A vacuum system would be needed to complete this process. This concept was selected to be tested.
13. **Resin Infill** – This would be done by syringe infusion, filling the voids present. The resin would be injected into the open infill of the printed part. With the injection, different infill patterns and levels can be modified as well. This concept was selected to be tested.

14. **Wax** – This is a simple process,just melting wax and applying to the part. This would only make the part waterproof, with no improvement of durability.
15. **Slicer Settings** – By adjusting the 3D printers slider settings, the filament can be over-extruded. This would fill the gaps normally created while printing by FFF method
16. **Thickness Settings** – Increasing the thickness of the filament used would fill the gaps normally created by the FFF method.
17. **Handheld Hairdryer** – Using a hairdryer can melt the ABS plastic just enough to seal the cracks made when printing. This may, however, create an uneven result or deformations.
18. **Hooded Dryer** – This can provide a more even heat around the piece, preventing some deformations. It is very time sensitive, as the heat can deform the part.
19. **Epoxy Resin** – This is usually a two-component kit composed of a seal coat and a flood coat. Creates a durable, waterproof seal about 1/8 inch thick.
20. **Thompsons WaterSeal Multi-surface Waterproofer** – A spray-on sealer to make any porous material resistant to water. A spray can costs about $13. Adds nothing to the part other than water resistance.
21. **Duralux Marine Paint** – A clear varnish. Makes the piece UV and abrasion resistant. Typically, this varnish is used on boats. It can only be brushed on, with a 240-minute dry time. This costs $50 a gallon.
22. **Gelcoat** – A product typically used on marina vehicles. It adds UV resistance while making the part waterproof. Also provides an increase of durability. This concept was selected to be tested.
23. **Rust-oleum NeverWet** – A kit that creates a superhydrophobic barrier. It is fast drying and durable. This kit costs around $20.

24. **Sally Hansen Triple Strong** – A clear coat of nail polish that is water and wear resistant. Essentially is a flexible epoxy.

25. **Infill Patterns** – While 3D printing, different patterns of infill can be selected. Choosing from the different options, one design can create less voids than another.

26. **Infill Levels** – This setting controls the infill percentage. To increase the infill level may fill the voids while printing, making the piece waterproof.

27. **Weld-On 4 Acrylic Adhesion** This is a plastic to plastic cement. The bond it creates between plastics is done by softening the surfaces then fusing them together. For waterproofing purposes, the gaps of the printed pieces can be coated in this, and they will be essentially melted shut. This is an adhesion method, so care would need to be taken.

28. **Dichloromethane** – This is the solvent found in the Weld-On 4 glue that does the softening. Can be used to melt the voids created, without the worry of adhesion mishaps.

29. **Waterproof Paint** – Using a product made specifically for plastic pieces, this paint can possible seal the holes made while printing.

30. **Combination of Concepts** – The solution may be a combination of concepts listed. For example, a printed part wiped down by acetone before being coated by another can make the piece waterproof.

5.5 Evaluation of Final Concepts

Once every team member completed the individual concept generation assignment the 120 ideas had to be narrowed down. Individual Pugh charts were made for the concepts and concepts were narrowed down based off of the design specifications that each process could achieve. The choices were narrowed down to four processes that included gelcoat, XTC-3D, resin injection, and vacuum resin infiltration. Table 2 shows the initial comparison between the four processes chosen and how they were expected to perform for the given criteria. These assumptions were based off of the research that was conducted through the beginning of the academic year.

From the results seen in the testing completed in the Fall semester, the four initial concepts were narrowed down even further to just XTC-3D and resin injection.

Table 2: Initial Design Process Comparison

Engineering Criteria	Gelcoat	XTC-3D	Resin Injection	Vacuum Resin Infiltration
Waterproof	✓	✓	✓	✓
Scratch Resistant	✓	-	-	✓
Weight ±10%	✓	✓	-	✓
Heat Resistant	✓	✓	✓	✓
Impact Resistant	-	-	✓	-
Chemically Resistant	✓	-	-	✓
UV Resistant	✓	-	-	-
Cost	$	$	$	$$

6 QFD

A QFD analysis was performed and can be seen in Figure 22. It made it possible to see how the final three processes of XTC-3D, Resin Injection, and a combination of the two compared to one another. The ultimate goal is to make a 3D printed ABS part waterproof with the secondary goals of scratch resistance, the ability to withstand pressure, heat resistance, strength improvement, etc. These can be seen in the left hand column of the chart. Each of these customer requirements were weighted. The most important requirement of making the part waterproof was given the largest weight. On the top row there are quality characteristics which are different aspects that would change with each process. The triangle on the top of the chart shows the correlation between these characteristics. Each process has their advantages and disadvantages but with these different quality characteristics and requirements being analyzed XTC-3D seems to be the best option. This can be seen by looking at the graph on the right side of the chart. Since the XTC-3D line is all the way to the right, the QFD analysis evaluated it as the best option.

7 Design for Waterproofing Process

During the design of the waterproofing process, several considerations were made in order to ensure the product would be the best solution to the problem GD/EB wanted solved. These considerations helped narrow down which waterproofing processes the team wanted to test further. These considerations include: safety, cost, manufacturability, reliability, and environmental impact.

7.1 Safety

When searching for waterproofing compounds, the team would review the Safety Data Sheets to ensure the product was suitable for storage and application without the use of large amounts of additional safety equipment. After finding the four initial waterproofing processes the team wanted to test, the team followed the safety protocols outlined in the Safety Data Sheets as well as any instructions included with a product. An outline of the personal protective equipment needed and application instructions can be found in Section 9.

7.2 Cost

The sponsors at GD/EB encouraged the team to try to find various different waterproofing methods to test. One of the initial methods was Vacuum Resin Infiltration, which required special equipment that can be expensive to purchase. Our sponsors told us that non-recurring engineering was not as large a concern as running costs. This changed which processes were determined to be the most cost-effective. Our final waterproofing concept, XTC-3D, ended up being quite cost-effective as 1 oz can cover around 100 square inches and 1 gallon can be purchased for under \$140. This equates to about \$1.05 to coat the exterior of a cube with side lengths of 4 inches.

7.3 Manufacturability

One of the deciding factors between our two final concepts, XTC-3D and resin injection, was the ease of manufacturing for the processes. XTC-3D needed almost no prep work aside from some light sanding before application. XTC-3D is self-leveling so once it is brushed on, it just needs time to cure. On the other hand, Resin Injection requires the user to create an internal geometry inside the part to control the amount of resin injected into the part. Otherwise, the entire part would have to be filled with resin which adds a significant amount of mass. This extra step is time-consuming and it is not feasible for complex geometries. For this reason, XTC-3D was chosen as the optimal waterproofing solution for it's ease of application and superior waterproofing performance.

7.4 Reliability

In order to test for reliability, each of the four initial waterproofing processes were placed in water for about 2 months. The design specification for waterproofing states that the processes should be able to withstand being submerged for 60 days while not gaining more than 1 gram of water per 87.1 cm^2 of surface area. XTC-3D and Resin Injection both passed this design specification. In order to further bolster our results, the team decided to test the waterproofing concepts a second time for another 60 days. The XTC-3D and resin injection test pieces both outperformed the uncoated control test pieces just as they did during the first tests.

7.5 Environment

One of the benefits of 3D printing is the reduced environmental impact when compared to CNC machining. [14] In order to continue these benefits, the team needed to have a waterproofing solution that would have minimal impact on the environment. When searching for a waterproof coating, the team researched the chemicals used in the products to ensure they wouldn't adversely effect the environment. XTC-3D does not contain any volatile organic compounds (VOCs), phtalates, or phosphates which are known to be bad for the environment and unhealthy for humans to come into contact with. Total Boat's epoxy resin that is used for the resin injection does contain Bisphenol A (BPA), which is an endocrine disruptor and can cause negative health effects if properly mishandled. Bisphenol A has a low solubility, therefore if an accidental spill were to occur it would be an isolated incident that could be cleaned up easily.

8 Project Specific Details & Analysis

This section will detail why 3D printing is beneficial for a company to utilize and the type of space they need to implement the process design developed in this project. The advantages of subtractive manufacturing are the use of better materials and the cost efficiency of mass production. When using traditional processes, the cost of set up and tooling molds and machines for an assembly line are the most complex part. After the molds and machines are set up they are very efficient and can produce an abundance of products in a short amount of time. Injection molding and CNC machines produce a high-quality finish and can utilize a variety of materials. Plastic forming is widely used for large items with low complexity and is cheap for production. CNC machines are costly, about $2000-150,000$ but can use any material by using different attachments. The more advanced machines can make extremely precise parts, tolerances within 25 micrometers where 3D printers are only capable of 100 micrometers. Traditional manufacturing materials are stronger, more diverse, and can provide more consistent quality and strength.

The biggest disadvantage of traditional manufacturing is setup time. This is time spent to produce the molds and configure machines that are used in production of a product. The time frame to get the production line going may take anywhere from 2 weeks to 2 months depending on the product. If the production run is short, it can be very costly to get the process setup and the cost may be more than what you can make from the product. If the product is in production and needs to be changed because of a design flaw there will be time and money spent to retool the molds and equipment Wasted material is another drawback of the subtractive manufacturing process since you are removing pieces from a solid block, a lot of material is wasted in forming the part. Recycling of the material being removed may be an option but is also an added cost. Complex parts are hard to manufacture with traditional methods due to the limited methods of removing the material. Milling by a CNC machine is time consuming and is mostly used for working prototypes and engine or machine parts. Internal features and undercuts are also difficult for a CNC machine to produce. [11]

The major technological advantage to 3D printing is that a part can be made with intricate details inside of the part. This would be impossible to reproduce by any other traditional manufacturing process. As an example, a 3D printer can make a pathway through a part that curves in any direction but with traditional manufacturing processes only a straight hole would be able to be drilled. Additive manufacturing also reduces the amount of waste used to make an object which assists in cost and eliminates the need to recycle unused material. Many companies can also take advantage of the minimum set up time to create a product from a 3D printer. A company just needs to create or upload a file for a part and let the printer do the rest. Low volume production and highly customized parts are easier with a 3D printer over traditional manufacturing due to setup time. 3D printing provides an ability for quick analysis of a part design to determine if it meets all the specific needs. Therefore if a prototype needs to be tested underwater without the buoyancy or weight changing using a 3D printed part there needs to be a process to ensure it stays waterproof for a period of time.

The cost curve of a product is the price over the volume of products being made. 3D printers have the ability for a part to cost the same amount no matter how many products are made. The cost curve for a 3D printed product is a straight line, where a traditionally manufactured product costs more at first and decreases in price when more products are produced. The added increase is from the set up and tooling but for long production runs becomes more efficient. Figure 1 shows the cost curves for each process and a company must find out when one process will be more economical than the other by analyzing these curves [12].

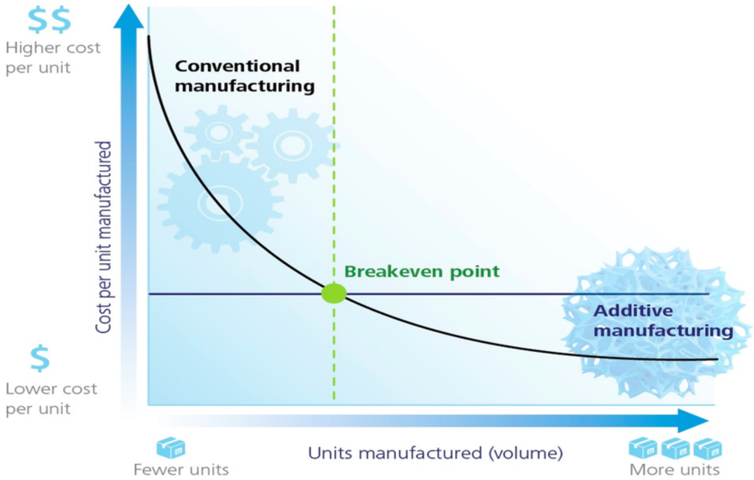
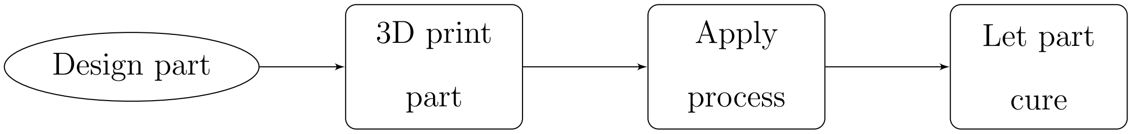


Figure 1: Break even analysis comparing conventional and additive manufacturing processes. Source [Cotteleer Dupress.Deloitte.com]

This project is specific towards 3D printing parts with a Fused Deposition Modeling printer using ABS. The regulations for these processes are safe in accordance with federal regulations and all handling and use of any chemicals must follow the Safety data sheet guidelines. All chemicals should be stored in a fireproof cabinet that will be grounded at all times. The area for these processes would not take up much room but should be located in an area that can be ventilated, have a table to work on, available fireproof storage cabinet, power outlets, and a secure place to store all materials needed. Due to the heating of epoxy resins a metal trash can would be required to dispose of the extra resin in the mixing container where it could not ignite any other trash. Below is a simple flow chart of the overall process with the application process being one of the two final concepts of XTC-3D of the resin/XTC-3D. Each process application is laid out in the next section. The part design must also take into account which process will be used because the part may have to be modified if using the resin injection process.



9 Detailed Process Design

The four process designs that were chosen for proof of concept testing were: gelcoat coating, XTC-3D coating, resin injection, and vacuum resin infiltration. Using four different methods to test the proof of concept on was vital because the team did not want to limit the available options since experimentation is needed to see if the method will work. In order to try and maximize the effectiveness of each process, each 3D print was specific to the process being applied. The Ideamaker program was used to slice the part files for the 3D printer to build. Many options are available to change but most were set on the default settings. The exterior shells were set at 2 and layer height was 0.1 mm for all printed parts. The processes described are generic and can be followed for any 3D printed part. The two different test specimens that were decided on was a cube and a small mug. The two different shapes would give a better idea of how the printer quality was effected by the shapes and to allow the design processes to cover these different shapes as well. These parts with dimensions can be seen in appendix C and D figures 23 and 24. Due to the print time for the mugs, the size was reduced to 60% of the dimensions listed. A detailed cost analysis will be discussed in section 15 of this paper.

9.1 XTC-3D Process

The 3D printed part was the same as the gelcoat process with a 15% infill with grid pattern. The following procedure was used in the application of XTC-3D.

Personal Protective Equipment (PPE)

- Nitrile gloves
- Safety glasses

Materials Needed

- Sandpaper - 320 grit
- Denatured alcohol
- Lint free cloth
- Mixing container
- Mixing stick
- XTC-3D
- Foam brush

WARNING - Use Denatured alcohol in a well ventilated area and wear all proper PPE. See Safety Data Sheets for more information.

Process Steps:

1. Sand part with 320 grit sandpaper until part is smooth to the touch.
2. Clean part by applying Denatured alcohol to lint free cloth and gently wiping part.
3. Mix XTC-3D with a 2 to 1 ratio of resin to hardener. XTC-3D has a 10 - 15 minute working time.
4. Brush XTC-3D on part ensuring complete coverage of the part. Layers should be 1/64 of an inch thick. If another layer is desired, wait until the previous layer is slightly cured and then apply another 1/64 inch layer.
5. Let part dry for 2 hours to be tack free and 4 hours to be fully cured.

9.2 Resin Injection Process

When developing this design process, a new part file had to be made that included cavities inside the parts so that resin could be injected into the part to fill all of the empty space. With the original solid part files, the Ideamaker program could not provide a support structure within the part if the infill was set to zero. With all the infill patterns there would have been multiple small cavities in the part and it would have been nearly impossible to ensure each one was filled with resin. When the parts were redesigned to have the cavities in them, the Ideamaker program would recognize this and then supports could be added for the bottom of the cup and top of the cube. The support pattern could be set to a specific distance away from the wall in a zigzag pattern which would allow resin to flow throughout. This support pattern can be seen in figure 2 in yellow at the center of the parts.

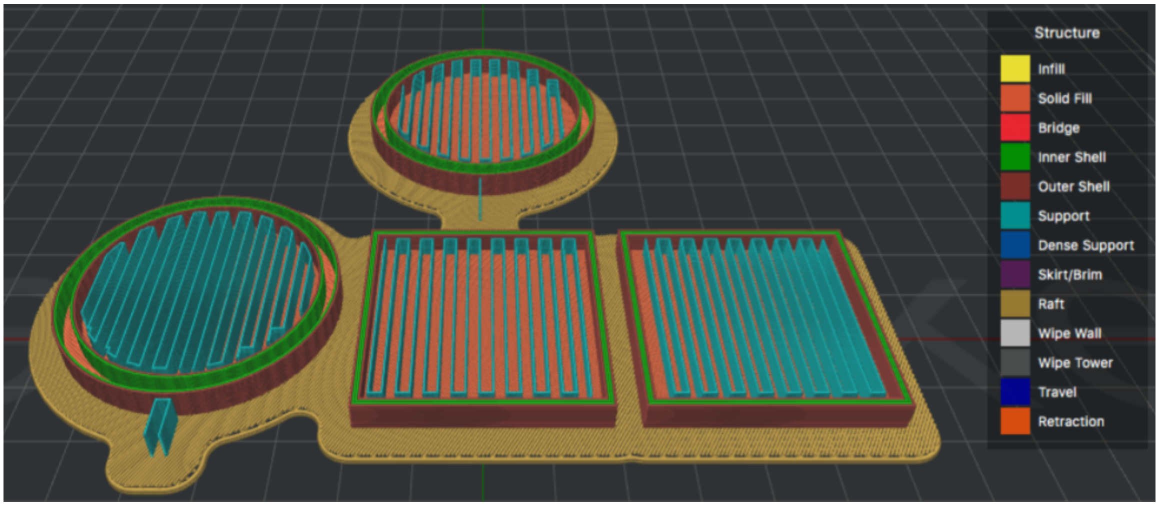


Figure 2: 0% Infill With Support

Personal Protective Equipment (PPE)

- Nitrile gloves
- Safety glasses

Materials Needed

- Denatured alcohol
- Lint free cloth
- Mixing container
- Mixing stick
- Total Boat 2:1 resin epoxy
- Resin syringe

WARNING - Use Denatured alcohol in a well ventilated area and wear all proper PPE. See Safety Data Sheets for more information.

Process Steps:

1. Build part with cavities that will allow resin to flow throughout part. This may need to be accomplished by using the 3D printer slicer options to have 0% fill with a support structure that will not prohibit resin flow in cavity.

2. Drill at least two holes into cavity to be filled 3/32 inch or larger depending on the part. One hole will be to inject resin into and the other allowing air to escape.

3. Mix resin with 2 parts resin to 1 part hardener in mixing container and stir thoroughly for 2 - 3 minutes ensuring to scrape along the sides for even mixing. Working time will be about 20 - 25 minutes.

4. Cut the tip of the syringe to desired size. With the plunger of the syringe fully depressed, put the tip of the syringe into the resin and pull plunger up to fill syringe with resin.

5. Inject resin into part allowing air to escape through the additional hole until resin fully fills the cavity. Allow a small bubble of resin on top of the hole since the resin will shrink slightly while curing.

6. Resin will be tack free in 3 - 4 hours and fully cured in 36 hours.

7. Wipe off any runoff of resin lightly with a lint free cloth with Denatured alcohol on it.

10 Engineering Analysis

The FDM 3D printing process builds a part layer by layer and with the round filament it can leave voids in between layers. The printing process may also cause layers do not adhere properly to the layer beneath it. Through many hours of printing the team was able to reach optimum printing setup with temperature, layer, infill, and support adjustments. Figure 3 shows what the voids between the layers may look like and also shows what can happen if layer adhesion is not correct. With a layer width of 0.1 mm used on the 3D printed parts the possible void area could be up to 0.2146 μm but is also limited by printer setting by slightly overfilling each layer. It is these voids and adhesion problems that allow water to infiltrate 3D printed parts. Through each of our processes these gaps and layer adhesion should be filled by the outside or inside coatings.

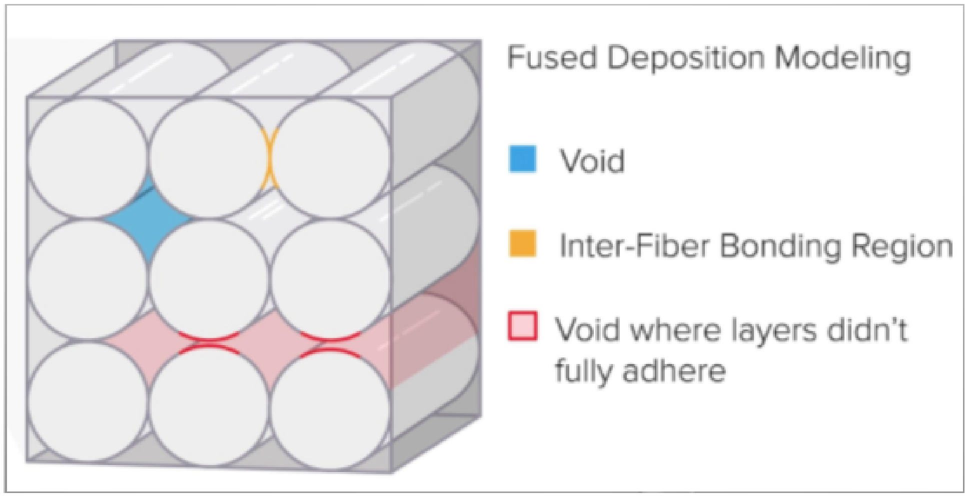


Figure 3: 3D printing layer process

The engineering analysis involved finding the thickness added and mass gained by each waterproofing method. This analysis will be used, in part with other data obtained, to help determine which method is the best at waterproofing 3D-printed parts. The layer thickness was found by comparing the initial measurements to the measurements after application and finding the difference between the two. A similar calculation was used to determine the mass gained from each method. The results from this analysis can be seen below in Table 3 for the cube test pieces and Table 4 for the cup test pieces.

Table 3: Mass and Thickness Gained By Each Process - cube

Method	Layer Thickness (mm)	Mass gained (g)
Gelcoat	0.28	1.68
XTC-3D	0.06	0.58
Resin injection	0	35.72
Vacuum resin infiltration	0.07	0.09

As you can see in Table 3, Gelcoat has the thickest layers at 0.28 mm and resin injection added no thickness at all since the application is completely internal. Vacuum resin infiltration added just 0.09 grams and resin injection added 35.72 grams. The resin injection added such a large amount of mass because the walls were completely filled with resin.

Table 4: Mass and Thickness Gained By Each Process - Cup

Method	Layer Thickness (mm)	Mass gained (g)
Gelcoat	0.24	3.29
XTC-3D	0.04	0.95
Resin injection	0	16.10
Vacuum resin infiltration	0.06	0.56

The values obtained in Table 4 were similar to the results obtained in Table 3. This shows there is consistency in the application method which is important for accurate results. With the redesign of two layers of XTC-3D and the resin/XTC-3D combination the layer thickness and mass gain are listed in table 5. it is important to note here that the control and XTC-3D coated cylinders are 100% infill and the resin injection process only adds 8 grams compared to the control cylinders. This value is important since it conforms with our design specifications of added weight of less than 10%.

Table 5: Mass and Thickness Gained By Each Process - cube

Method	Layer Thickness (mm)	Mass gained (g)
2 Coats XTC-3D	0.238	2.40
resin/XTC-3D	0.238	8.00

Other aspects that were tested were pressure testing of 3D printed cylinders, strength tests and submersion tests. The details of each of the tests are discussed in further detail in the testing section along with the results.

11 Build/Manufacture

The process designed throughout the past two semesters cannot be manufactured into a prototype. Electric Boat requested a method to waterproof 3D printed parts. Due to the fact of not having security clearance, the team was not told what specific application they wanted this solution for. Ultimately, the solution that was designed can be applied to many different 3D printed parts allowing for versatility. In the end, the hope is that the process that was designed could be applied to one of their products that is being mass produced within their company.

12 Testing

12.1 Proof of Concept Testing

For the proof of concept, it was decided to use control specimens along with the process applied specimens. The control specimens would create a good baseline to prove that the processes being applied will work at waterproofing the given part. This consisted of 3D printing a control mug and control cube for each different type of infill; 15% grid pattern, 0%, and 70% rectilinear. Then, each process was applied and the parts were submerged in water inside a Tupperware container. At intervals of 0.5, 1.5, 24.5, 48, 72, 192, and 1440 hours, 60 days total, each parts was wiped down with a cloth to dry the outside and weighed. The data collected for these tests are listed in appendix E figure 25. This weight change would indicate whether or not water was absorbing into the 3D printed parts.

3D printing often has some flaws in the part being produced and it is difficult to get the same quality every single time. This is one of the downsides of 3D printing and our data also supports this idea. For the uncoated control parts with a 15% infill, the data shows that the cube absorbed much less water than the mug and this may have been attributed to the shape of the object itself. This disparity in water absorption could be from the rounded shape of the mug and handle or possibly even the location of the support structure that was needed for the mug handle. Even for the different infills, the 15% control cube performed better compared to the other control cubes which could be due to the grid pattern creating chambers that are more difficult for water to penetrate. Due to the inconsistencies in print quality, the proof of concept definitely shows a need for the parts to be waterproofed if they're going to be submerged in water.

Figure 4 shows the data collected from weighing the gelcoat process parts and the control parts with 15% infill. Gelcoat was expected to be the top performing process when the team was coming up with the design process ideas. This data shows that is not the case and it is performing worse than all the other test parts. The treated cup absorbed twice as much water than the control mug and the cube absorbed 16 times as much as the control cube. The reason this may have happened could be from the gelcoat chemical composition and specifically the MEKP hardener. The application process could have caused a breakdown or melting of the ABS when the gelcoat was curing and actually created more gaps for water to penetrate through. At the end of the 60 day testing period, the gelcoat was peeling off the part and did not adhere properly to the ABS.

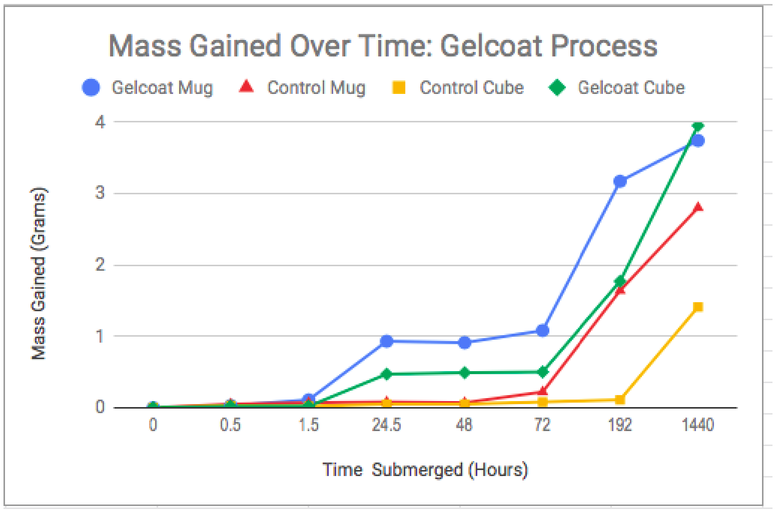


Figure 4: Mass Gained over Time in Test Specimens for Gelcoat Process

The graph below shows that the parts treated with XTC-3D gained less mass over time than the control specimens, therefore these can be considered favorable results. In the end, both the control mug and XTC-3D mug gained more than the cubes. The XTC-3D cube gained 0.11 grams where the XTC-3D mug gained 0.64 grams after 1440 hours of submersion. The results for all the specimens can be seen in Figure 25 which is located in the Appendix.

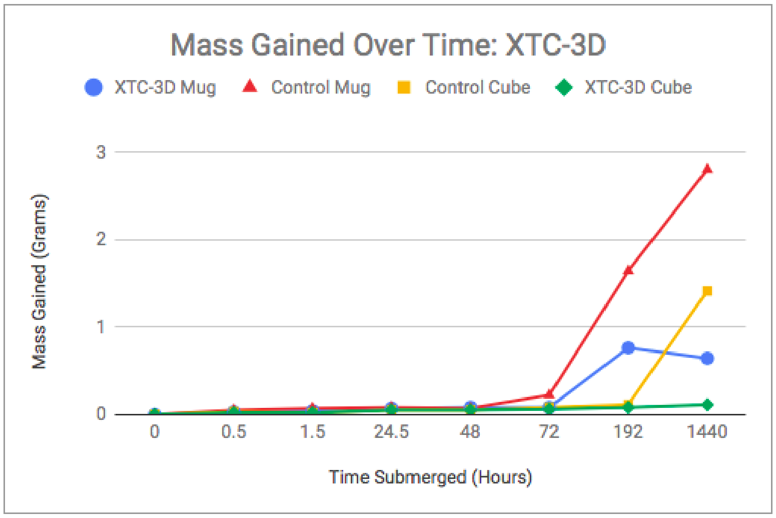


Figure 5: Mass Gained over Time in Test Specimens for XTC-3D Process

The resin injection process results in figure 6 shows that both the mug and the cube absorbed much less water than the control parts. Over the 192 hours of submerging time, the resin injected mug performed the best with a mass gain of only 0.55 grams and the resin injected cube only gained 0.28 grams of water. The outside of the part was not coated and only the interior of the parts were affected by the resin injection process.

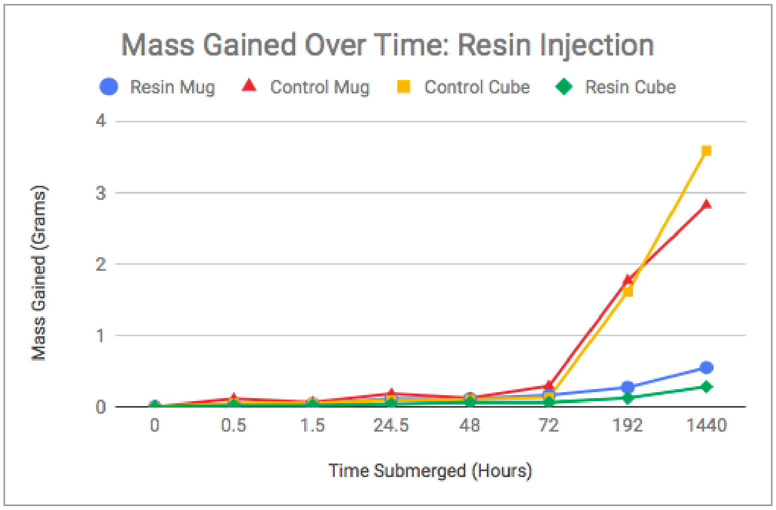


Figure 6: Mass Gained over Time in Test Specimens for Resin Injection Process

The vacuum resin infiltration results, as seen in Figure 7, show that the process did not have much of an effect on the amount of water being absorbed. The specimens treated with resin in the vacuum bag gained about the same mass than the control specimen for the mug and only slightly less than the control cube. These results are the opposite of what was expected. Unlike resin injection, vacuum infiltration allows for the resin to be on the outside as well as the inside of the part.

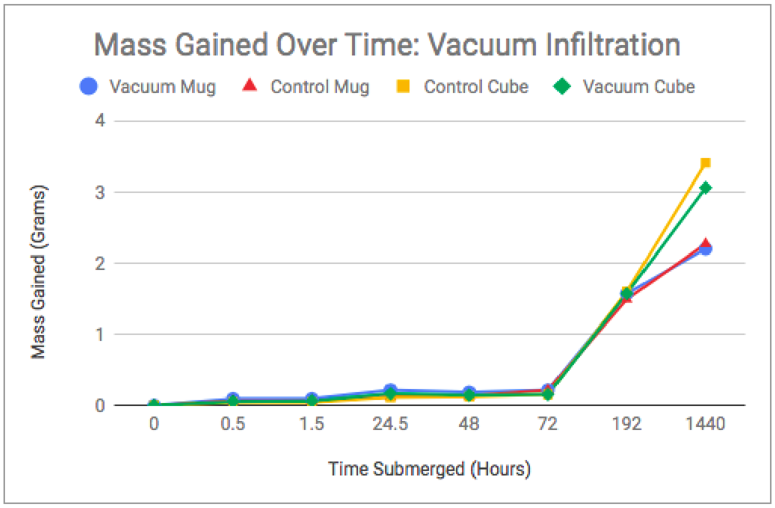


Figure 7: Mass Gained over Time in Test Specimens for Vacuum Resin Infiltration Process

In addition to the processes listed, an acetone vapor treatment process was applied to a mug that was accidentally printed with the wrong dimensions. The process was performed by placing the mug in a wire cage, placing an acetone soaked rag around the cage, and covering the whole setup under a plastic container for 15 minutes. A control mug was also used as a reference and they were subjected to the same water submersion tests as the test specimens for the other processes. It was found that using an acetone vapor treatment did not affect the water absorption rate and both mugs performed about the same. During the vapor process, the mug was right side up and the inside appears that it did not achieve the smoothing treatment as much as the outside of the mug did.

12.2 Final Design Testing

For the final design, a two layer coating of XTC-3D was used as well as a combination of the resin injection process along with two coats of XTC-3D which will be discussed in Section 13. Once the final process design was determined, the methods for testing the process to see if they met the design specifications had to be devised. The three test parameters that were most important were: the amount of water infiltration into the 3D printed part, the max pressure the process could withstand while still remaining waterproof, and the effect of the processes on the strength of the 3D printed part. The team decided that another submersion test would be accomplished over 60 days to see if the part would gain less than 1 gram of water per 87.1 square centimeters of surface area. Next a pressure vessel was be made with a 3D printed cylinder to see if the part would leak with an internal pressure of up to 100 psi. Finally, a dogbone strength test was conducted to find the yield strength and ultimate strength of 3D printed ABS with and without the two processes applied. The results of each test can be seen in table 6 and will be discussed further in detail.

Table 6: Test Matrix

Submersion Test	**Trial**	**Test**	**Parameters**	**Results (after 60 days)**
	Control 1	Mass gain over a duration of time	60 days of submersion, weighed once a week for mass gain	0.63 g
	Control 2			0.38 g
	Control 3			0.28 g
	Control 4			0.31 g
	XTC-3D 1			0.16 g
	XTC-3D 2			0.14 g
	XTC-3D 3			0.13 g
	XTC-3D 4			0.14 g
	XTC-3D/Resin 1			0.27 g
	XTC-3D/Resin 2			0.28 g
	XTC-3D/Resin 3			0.31 g
	XTC-3D/Resin 4			0.29 g
Pressure Test	**Trial**	**Test**	**Parameters**	**Results**
	Control 1	Ability to remain waterproof at simlulated depth	100 psi internal pressure, gradually increasing until max pressure of 300 psi or until failure	Failed after 15 minutes at 100 psi
	Control 2			Failed immediately at 100 psi
	Control 3			Failed immediately at 100 psi
	XTC-3D 1			Passed, no leaks for duration of test
	XTC-3D 2			Passed, no leaks for duration of test
	XTC-3D 3			Passed, no leaks for duration of test
	XTC-3D/Resin 1			Passed, no leaks for duration of test
	XTC-3D/Resin 2			Passed, no leaks for duration of test
	XTC-3D/Resin 3			Passed, no leaks for duration of test
Strength Test	**Trial**	**Test**	**Parameters**	**Results**
	Control 1	To find the yield and ultimate strength of dogbones with the respective processes	To have an increase in yield strength compared to the control of the test, using ASTM 638-14	Yield = 27.04 MPa Ultimate = 33.80 MPa
	Control 2			Yield = 27.63 MPa Ultimate = 31.02 MPa
	Control 3			Yield = 34.05 MPa Ultimate = 37.35 MPa
	Control 4			Yield = 34.70 MPa Ultimate = 37.49 MPa
	XTC-3D 1			Yield = 27.24 MPa Ultimate = 29.50 MPa
	XTC-3D 2			Yield = 30.26 MPa Ultimate = 32.02 MPa
	XTC-3D 3			Yield = 31.30 MPa Ultimate = 31.79 MPa
	XTC-3D 4			Invalid test
	XTC-3D/Resin 1			Invalid test
	XTC-3D/Resin 2			Yield = 33.26 MPa Ultimate = 33.26 MPa
	XTC-3D/Resin 3			Yield = 31.25 MPa Ultimate = 35.54 MPa
	XTC-3D/Resin 4			Yield = 34.64 MPa Ultimate = 37.84 MPa

12.2.1 Submersion Tests

For this round of submersion testing the main focus was on how well the XTC-3D and resin/XTC-3D performed without the infill being a factor. Another aspect that was taken into account was reducing the weight of the resin filled cube in which it was decided to design a cube within a cube. This design makes it possible to leave an interior cavity in the part that would be waterproof. For the 3D printer to print this a support structure had to be made in order to support both the inner cube and the top of the outside cube. As seen in figure 8, inside the outer cube there are a series of slats to provide support for the inner cube and allow proper flow of the resin throughout. These supports continue throughout and then also continue on the outer top portion of the inner cube. Cube dimensions are in appendix F.

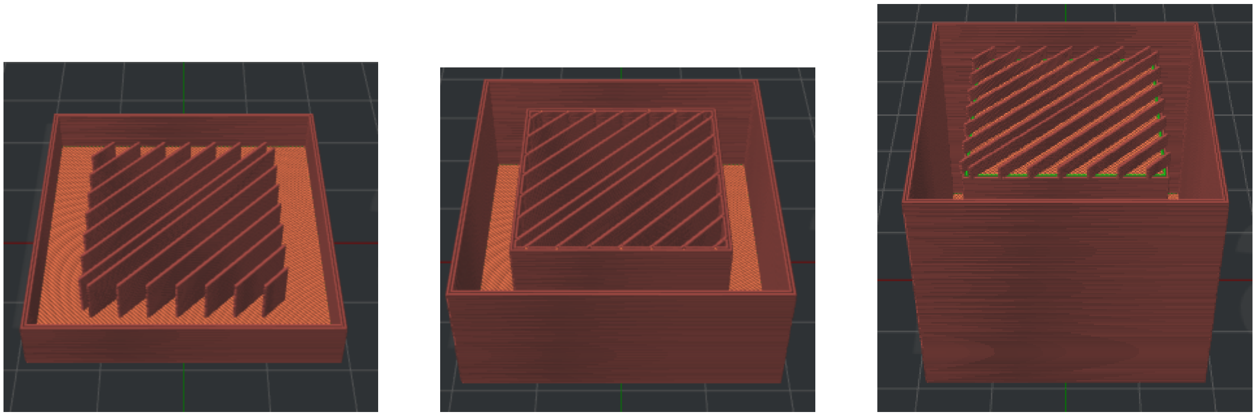


Figure 8: Interior structure of Cube design

The cube features two outer shells and was printed with 0% infill. The outer portion is 1/4 inch wide and was filled with resin for four of the cubes and then coated on the outside with XTC-3D. Four more cubes were only coated with XTC-3D and then four were left untreated. All 12 cubes were then weighed and submerged under a foot of water. The cubes were measured periodically throughout 60 days to determine the amount of water infiltration. This test did not take any water flow over the parts into account.

The results for the submersion test can be seen in the first part of the test matrix, table

6. Two of the control cube gained the most from water infiltration and two of the cubes matched the resin/XTC-3D combo. The XTC-3D alone performed the best in this test. The tests for the treated parts were very consistent with a 0.02 gram difference between all the XTC-3D cubes, a 0.04 gram difference between the resin/XTC-3D combo cubes, and the control cubes varied 0.32 grams between tests. From the average results in figure 9 XTC-3D performed the best with an average gain of 0.14 grams, resin/XTC-3D combo was second best with an average of 0.29 grams, and last was the control untreated ABS with an average gain of 0.40 grams. The XTC-3D leveled off after only seven days and then remained fairly constant since the XTC-3D most likely reached it's saturation point. With the combo of resin/XTC-3D there is a slow gradual curve that increases and this is most likely from the interior resin not reaching its full saturation point at 60 days. The saturation of the resin and XTC-3D don't necessarily mean that water is leaking through the part but any imperfections on the surface and water going into the material pores.

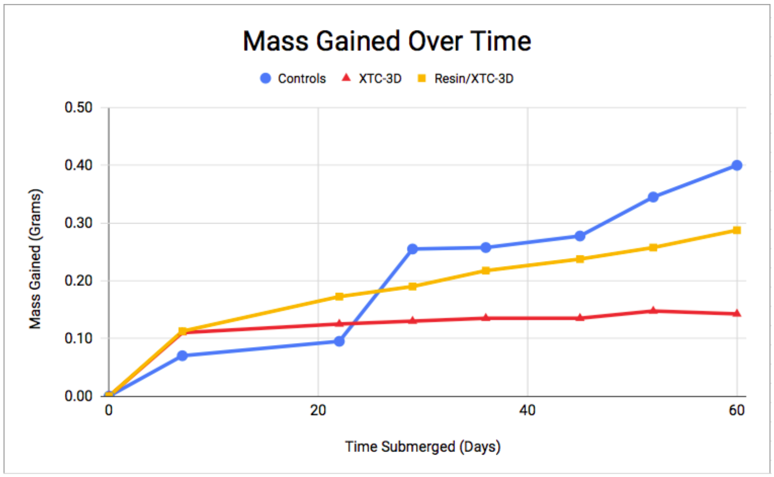


Figure 9: Average mass gain for cube submersion test

Figure 10 represents the mass gains for the control untreated ABS cubes and it shows the progression of the water infiltration. At the beginning all test cubes gained about the same and then cube 1 had a large spike while the others steadily increased. Then after about 45 days cube 2 had a large spike as well compared to cubes 3 and 4. This variation in the results for the control cube shows the lack of repeat-ability in 3D printed parts.

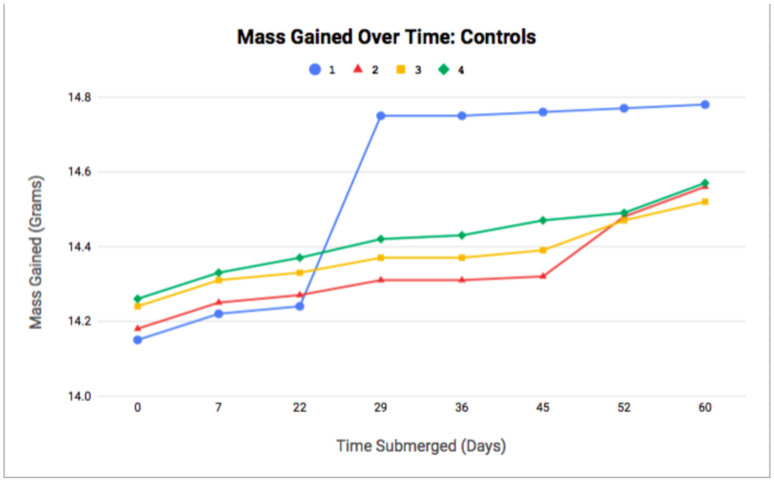


Figure 10: Mass gain for control cube submersion test

12.2.2 Pressure Tests

The intent of the pressure test was to find out of the applied processes would be able to keep water from leaking through the part while it was submerged at a depth of at least 230 feet. The best way to accomplish this was to create a cylinder that was 3D printed and make end caps that would allow for the inside of the cylinder to be pressurized with water. The cylinder and end cap drawings are located in 27 and 28 in appendix G. Then by adding blue dye to the water it would be easy to see if water was penetrating the white 3D printed part. The first step was to design the 3D printed cylinder and end caps that would use to make the pressure vessel.

For the 3D printed part to be structurally safe 100% infill was used for the control and XTC-3D cylinders to be tested and the Resin injection/XTC-3D cylinders would be 0% infill that would then be filled with resin. Although the design specifications were to make the part waterproof under 100 psi of pressure, testing was accomplished up to 300 psi which was the limit of the hydraulic pump that was ordered. With knowing the inside pressure would go up to 300 psi the design of the 3D printed cylinder could begin and Barlow's formula for minimum wall thickness, equation 1, was used. Where t_{min} is the minimum wall thickness, P_i is the inside pressure, D_o is the outside cylinder diameter, and S_y is the yield strength of ABS. With an outside diameter of 3 inches, inside pressure of 300 psi and a yield strength of 4351 psi, the minimum thickness of the cylinder wall had to be 0.103 inches. A safety factor of over 2 was implemented and the final wall thickness was made to be 0.25 inches thick. Due to the resin injection process the calculations would not be valid for that process but since the yield strength of the resin is greater than ABS it was assured that the cylinder treated with the resin injection process would be strong enough for the testing to be accomplished.

$$t_{min} = \frac{P_i D_o}{2S_y} \tag{1}$$

The hoop stress was also found by using equation 2 for a thick walled cylinder to ensure it would be structurally safe to test. The circumferential stress is denoted as σ_c, P_O and P_i are the outside and inside pressures, and r_o and r_i are the outside and inside radius. With an internal pressure of 100 psi the hoop stress was 555 psi and with an internal pressure of 300 psi it was 1664, which both are well below the yield strength of ABS.

$$\sigma_c = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} + \frac{r_o^2 r_i^2 (P_o - P_i)}{r_i^2 (r_o^2 - r_i^2)} \tag{2}$$

Once the 3D printed cylinder was designed, the end caps were then designed to fit the cylinder. One inch thick aluminum bar stock with a diameter of 6 inches was used on each end of the cylinder. Each end cap was milled to have a recess of 1/2 of an inch for the cylinder to sit in and a quick disconnect for the hydraulic hose was attached to the center of one end cap and a shutoff valve attached to the outside of the second end cap. The shutoff valve was used to ensure that the cylinder was filled with water and all the air was removed prior to testing the part. Each end cap also had three holes drilled on the outer rim of the cylinder recess that were spaced equally apart so that 3/8 inch threaded rods could be used to attach the two end caps and then tightened down with lock nuts. Figure 11 shows the assembly diagram for the pressure vessel and figure 12 shows the Hydrostatic pump with the actual assembled pressure vessel.

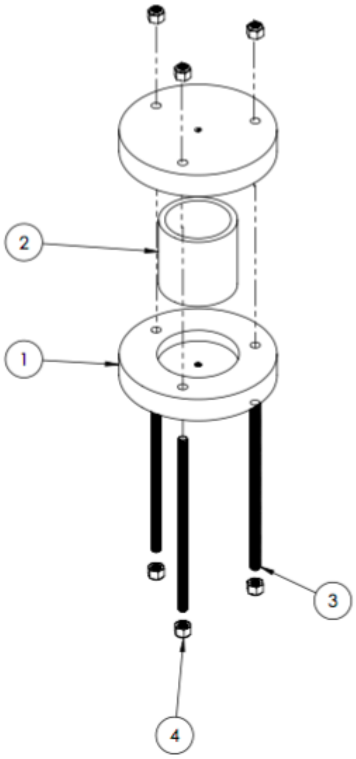


Figure 11: Pressure vessel assembly

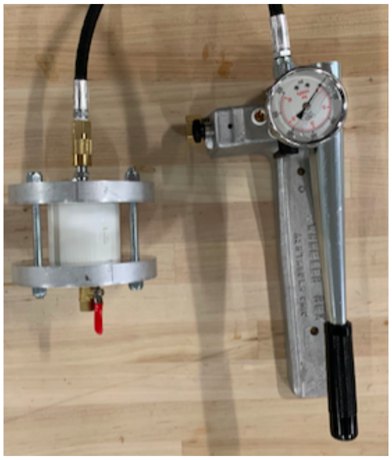


Figure 12: Pressure vessel and hydrostatic pump

Nine cylinders were 3D printed so that 3 would be the control tests with no process applied, another 3 cylinders treated with two coats of XTC-3D on the inside, and 3 cylinders that were injected with resin and then treated with two coats of XTC-3D on the inside. With the pressure cylinder parts designed and fabricated a testing process then had to be developed. The following steps were used in each test of the cylinders.

1. Weigh cylinder before test
2. Apply butyl tape in the two recesses of the end caps
3. Insert 3D printed cylinder in one of the end caps
4. Insert the three threaded rods with the lock nuts on the outside of the end cap

5. Line up second end cap with the threaded rods and insert over the top of the cylinder
6. Install the lock nuts on the other end of the threaded rod and tighten in a circular pattern until each nut is snug
7. Open shutoff valve on end cap and attach the pumps hydraulic hose to quick disconnect fitting
8. Insert pump suction hose into jug with blue dyed water
9. Pump handle on hydrostatic pump until water escapes the shutoff valve and no more air is present in the cylinder and close the shutoff valve
10. Pump handle until pressure reaches 100 psi
11. Let pressure vessel sit ensuring 100 psi is maintained for 20 minutes
12. After 20 minutes increase pressure by 50 psi for 10 minutes and repeat until pressure is at 300 psi for 10 minutes.
13. Test is over when the 300 psi is maintained for 10 minutes or the part is visually seen leaking
14. Disassemble the end caps, clean butyl tape off of the cylinder, weigh cylinder to determine if any water infiltrated the part

Results from the test, which can be seen in table 6, proved that 100% infill for a part will not make it waterproof and all three of the control cylinders leaked. Control cylinders 2 and 3 leaked immediately when pressure was applied to the inside and control cylinder 1 took about fifteen minutes to leak with an internal pressure of 100 psi. The leaking that occurred is clearly shown in figure 13. The cylinders that were treated with XTC-3D and resin/XTC-3D both performed well and no leakage was seen when the internal pressure was at a max value of 300 psi.

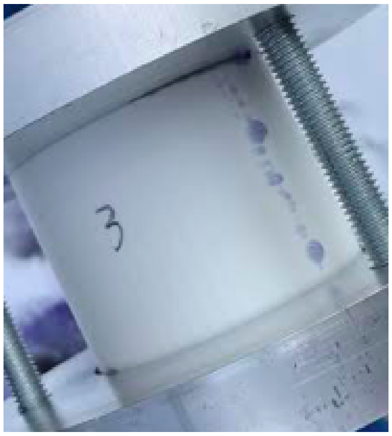


Figure 13: Control cylinder leaking

The control cylinders gained substantial weight from water infiltration with an average of 2.26 grams, while the 6 treated cylinders had an average of 0.043 grams. Figure 14 shows the results for each cylinder and from the control cylinders it is easy to see that it gained the least amount of mass from water and lasted the longest for the pressure test. This would suggest that the 3D print for that cylinder was of better quality than the other two control cylinders. The resin/XTC-3D combo cylinder 2 showed the most mass gain from the pressure testing, however once the test was completed and the cylinder was being removed from the endcaps some of the material tore off the part and could have led to an inaccurate measurement.

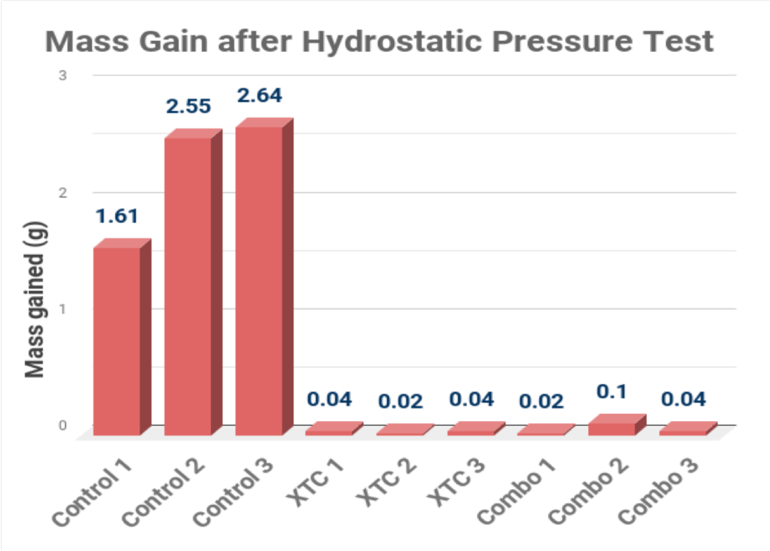


Figure 14: Mass gain after hydrostatic pressure test

12.2.3 Strength Tests

The strength tests were conducted using [13]. Following ASTM D683 - 14 type 4 test dogbone dimensions were established and four dogbones for each process were 3D printed with the control and XTC-3D dogbones printed with 100% infill and the resin/XTC-3D combo printed with 0% infill. The two processes were then applied to four dogbones each and set to fully cure. An Instron 5582 testing machine and attached computer software was used to get the raw data from each test and then analyzed to find the yield and ultimate strength of each dogbone. The testing process consisted of placing the dogbone in the jaws of the Instron tester and attaching an elastometer to the thin part of the dogbone to measure strain. The machine and elastometer were then zeroed out and the test began with the Instron moving at a rate of 4 millimeters per minute until the dogbone broke. The strain and amount of force were measured from the computer software and downloaded so it could then be analyzed. To find the yield strength a 0.2% offset from the slope of the line was made and where it crossed the original path was determined to be yielding point.

The results of each test can be seen in table 6, where the yield strength and ultimate strength are listed. Two of the tests were invalid due to the results not being consistent and is most likely from the jaws of the Instron tester slipping on the dogbone. The control Yield strengths varied about 7 MPa between the tests where the treated test were a little more consitant with a difference of 4 MPa between the XTC-3D test and 3 Mpa between the resin/XTC-3D combo tests. Since the results from the test vary, they were averaged out to give a better idea of where the true yield and ultimate strengths are compared to each other and are shown in table 7 and figure 15. The control dogbones had more elongation after the ultimate strength point and demonstrates how the processes make the part more brittle once applied. The dogbones that had the two processes applied broke just after the ultimate strength point and did not stretch the plastic out. This is due to the properties of the XTC-3D and resin being non-elastic in nature. With the XTC-3D treated dogbones the yield and ultimate strength are lower than the average of the control and Young's modulus appears to be slightly lower. This change in Young's modulus may have something to do with the XTC-3D effecting the chemical properties of the ABS and would require more testing to determine. With the resin/XTC-3D combo the same brittleness occurs but the yield and ultimate strength is improved due to the larger amount of resin on the inside of the part.

Table 7: Average Strengths

	Average yield strength (MPa)	Average ultimate strength (MPa)
Control	30.86	34.92
XTC-3D	29.60	31.10
Resin/XTC-3D combo	33.05	35.55

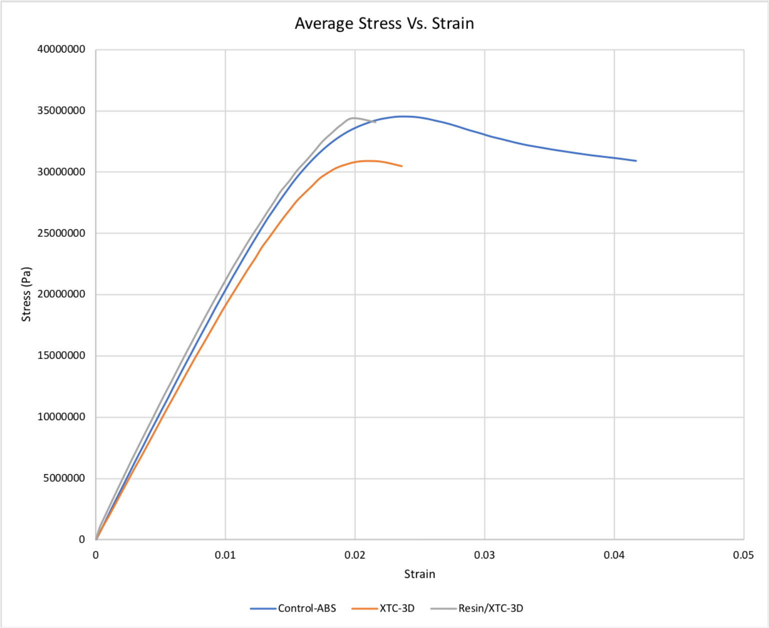


Figure 15: Average stress vs. strain curves

13 Redesign

From the proof of concept testing it was clear that the XTC-3D and resin injection processes worked the best. The poor results of the gelcoat and vacuum resin infiltration lead to the team ultimately dismissing those two processes as an option. The first testing also showed that an infill of a 15% grid pattern performed better with the cube submersion test but made no difference in the mug testing. For the redesign the team wanted to test the the coatings the most and not include the infill as a factor since the coatings should prevent the water from infiltrating the part.

Looking at the XTC-3D results, applying two coats instead of one was done to see if that would improve the effectiveness. With the resin injection process the team wanted to see if the combination of the XTC-3D on the outside of a resin injected part would keep the water from penetrating into the voids of the ABS outer layer. Another aspect to explore was the weight reduction technique for the cube where there would be an inner cavity not filled with resin. Along with lowing the weight the flow characteristics of the resin traveling through the part needed to be addressed so that there would be fewer gaps in the resin injection fill. The redesigned cube also helped to reduce 3D print time by 50 minutes per print over the 0% fill cube used for the proof of concept testing. For the submersion tests a cube was designed to have a layer of resin a quarter inch thick inside the outer printed layer and to design better supports to allow a better flow of resin. These designs are discussed in further detail in the final design submersion test section.

It was also suggested that the team try using Flex-seal to try and waterproof the part as well. The team 3D printed a cube and mug at 15% infill like the ones used for the proof of concept testing and dipped the parts in Flex-seal, scraped off the excess, and let the parts dry. Before the initial submersion testing started it was discovered that the Flex-seal did not adhere very well to the ABS and could be scraped off easily just by rubbing the coating. Since the overall design should resist coming off with surface contact the Flex-seal idea was abandoned.

14 Project Planning

At the beginning of the academic year, the team devised a high-level overview of what needed to be accomplished based on GD/EB's problem definition and engineering challenge. Clarifying questions were posed by the team to GD/EB during the first conference call in order to ensure the problem would be solved as efficiently as possible. Also during the conference call, a recurring meeting time was established in order to keep GD/EB up-to-date with all pertinent information. The first semester was divided into three main milestones: research, concept generation, and testing. Each of which had separate smaller milestones to ensure everything was completed on-time or ahead of schedule. These deadlines were put into a Gantt chart format using Microsoft Project. The Gantt chart can be found in appendix 22.

The team most often accomplished the ground work for assignments after Capstone ended on Tuesdays and Thursdays. This time was selected due to the convenience of having everyone in the same place. On any given week, the team could have met from one to four times, depending on the circumstances and availability. An average of one and a half hours were spent working on the project after each Capstone class. Each of the assignments completed brought the team one step closer to achieving GD/EB's goal of waterproofing 3D-printed ABS parts. Our sponsors at GD/EB provided invaluable insight throughout the entire project.

The first semester was meant to take the concepts generated and narrow them down into the most optimal waterproofing solutions. Preliminary testing was conducted on the waterproofing solutions and these results will be used next semester accompanied by further testing. Once all the tests are conducted, modifications will be made to the concepts to see if they can be improved further.

14.1 Research

The first step in any project where a problem has to be solved is to see if others have solved a similar problem. This is very important because a lot of time could be wasted trying to solve a problem that already has an answer. That is why the team conducted a patent search using the United States Patent and Trademark Office (USPTO) website. The results of the patent search can be found in Section 2.1. Each team member was tasked with researching a certain aspect of Waterproofing 3D-printed ABS parts. For example, 3D printers, waterproofing ABS plastic, ABS water absorption, and 3D printing using ABS.

The second step during the research phase involved a literature search. This involved searching through peer-reviewed papers for research findings and other information relevant to the project. The literary search yielded more relevant findings than the patent search because most of the information needed was not able to be patented.

14.2 Concept Generation

The concept generation method used involved each member creating 30 independent concepts in order to waterproof 3D-printed ABS parts. Each team member took the 30 concepts and put them into a Pugh chart in order to find the best solutions by comparing them to a reference concept. The top 4 solutions were put into a Quality Function Deployment (QFD) chart in order to see which method should work the best according to specific engineering criteria.

14.3 Preliminary Design

The four best solutions were Gelcoat, XTC-3D, Resin Injection, and Vacuum Resin Infiltration. These solutions were tested until the start of the second semester. Preliminary results obtained after the test pieces were submerged for about a week shows that XTC-3D was absorbing the least amount of water out of the four solutions. The results were preliminary, therefore judgment will be suspended until testing has been finalized. Further testing will be conducted in the Spring semester in order to determine the most optimal solution to waterproof the 3D-printed parts. The 3D-printed test shapes were chosen to be a cup and a cube. This was due to the simplicity of the parts for more accurate measurement as well as incorporating curved and sharp edges into the test pieces.

14.4 Building

A Raise 3D N2 printer was used to create the cups and cubes to be used as test pieces. The test pieces were printed using white ABS filament purchased from Raise3D's website to ensure the highest quality printing. Each test piece was very cost effective to print and required little setup time once the printers were correctly calibrated. Before the printer was properly calibrated, a lot of time went into reprinting parts that didn't print correctly. The first obstacle was getting the ABS to adhere to the heated print bed. This was solved by increasing the heat bed temperature from 100^oC to 110^oC. The second obstacle with the 3D printing involved the inner support material of the part, known as the infill. The infill was not adhering to the base of the part which resulted in a printing failure. This issue was solved by reducing the vertical infill offset to 0. Once these issues were solved, printing became much easier and more low maintenance.

14.5 Testing

During the first semester, the team decided to focus on the main objective which was to make the 3D printed test pieces waterproof. To test how waterproof each method was, the team took initial weight measurements of each piece and then completely submerged the pieces in water. Weight measurements were taken at a half-hour, one hour, one day, two days, three days, and eight days. These test pieces should be able to remain waterproof while being submerged for weeks to months at a time to meet GD/EB's design specifications.

14.6 Redesign

During the Spring semester, the team took the final measurements for the first round of submergence testing that was started on 11/30/18. The results from this testing can be seen in Section 12.2.1. The results from the submergence testing revealed that Gel coat and Vacuum resin infiltration did not perform as well as XTC-3D or resin injection. The team decided that the two lowest performing waterproofing solutions should be removed from further testing. This allowed the team to focus on XTC-3D and resin injection for the strength and pressure tests. This decision saved the team hours that would have been wasted printing test pieces for waterproofing processes that the team knew wouldn't succeed.

14.7 Secondary Testing

After completing the first submergence test, the team decided it would be beneficial to redo the submergence test with XTC-3D, resin injection + XTC-3D combination, and control test pieces. This retesting would provide more assurance that these coatings performed the best. After the submergence test began, the team decided to start the pressure testing. This involved 3D printing 9 cylinders, 3 for XTC-3D, 3 for XTC-3D + resin injection combination, 3 for control test pieces. The team decided the time would be best spent splitting up the work load. the team accomplished this by having three team members apply coatings to the 3D printed cylinders while one person would machine the aluminum end caps for the pressure vessel at the machine shop. Only one person was sent to the machine shop because machining can only be done by one person and adding a second person would not make it go any faster. This is one of the ways the team optimized the time to be as efficient as possible.

15 Financial Analysis

The total budget that was provided from GD/EB for this project was $10,000. Overall the team has spent $614.67 for materials to 3D print, application of processes, and for testing. Since every 3D print is different and the surface area and volume change with each given part it is difficult to give an exact value for price and time to complete each process. In the following analysis an average surface area of 645 square centimeters (100 square inches) and average volume of 245 cubic centimeters (15 cubic inches) was used for cost and time analysis.

15.1 Process time

Printing time and process time can become a factor if there are time constraints that need to be met. Printing time can vary greatly depending on the type of part, size, and infill density. When using the resin/XTC-3D process 3D print time and amount of material used may be reduced but at a cost of longer process application time. As an example the 3D cylinders used in the pressure testing took 20 hours and 13 minutes to print and used $3.57 worth of material for 100% infill . The 0% fill cylinder took only 6 hours and 34 minutes to print and used only $0.97 worth of material. For the resin/XTC-3D process the part could be printed and have the resin injected in one shift, wait a minimum of 24 hours to cure (using a fast hardener), and then coated on the third day ready to use by the end of shift. With the XTC-3D process with 100% infill it takes almost one day to print and then on the second day the coating could be applied and be ready to use by the end of shift. The time differs by one day on these two processes for this particular part. However if there is a large part that needs to be printed the resin/XTC-3D process may actually be just as fast or faster if the 3D printing time is reduced by a significant amount of time.

XTC-3D application takes about two hours as long as the temperature is at least 70 degrees and low humidity due to the effect on drying time between coats. The working time with XTC-3D is about 15 minutes which gives able time to coat an object. at least one hour is required before the second coat and then 4 hours should be allowed for the XTC-3D to cure. The time for the resin injection process takes about an hour or even less possibly to drill into the cavity and inject the resin into the part. The cure time for the resin used is 36 hours for a complete cure. Cure time for the Total Boat epoxy resin is due to the hardener used which allows for a longer working time which was needed for the vacuum resin infiltration. A different hardener could be used for the resin injection process that would shorten the cure time by at least 12 hours. Although the directions say that it takes up to 36 hours to cure, when the testing was being accomplished the resin was solid and not tacky after just 12 hours.

15.2 Cost

Many factors must be taken into account when trying to determine the cost of a process due to the differences that exist between two different parts. Materials, process application time, and start up cost must be taken into account. This is assuming that the company already has a 3D printer and a place to store chemicals. If these products still need to be purchased the start up cost would be much higher. Material cost was based on the list of materials stated in the detailed process design section along with ABS to print the part and again using an average surface area and volume of 645 square centimeters and 245 cubic centimeters respectively. Application cost was determined from an application time of 2 hours for two coats of XTC-3D, additional 1 hour for the resin/XTC-3D combo, and based on a single person getting paid $15 an hour. Training would be fairly simple for each process and would only require a person to see and help execute the process one time to replicate and therefore was not included in this analysis.

Table 8 shows how much each process will cost for the average size stated. Since the Resin/XTC-3D has two processes combined it costs more than double for the application of the two. XTC-3D would be the cheapest method to apply and unless added strength was needed for the part XTC-3D would be the most economical to use.

Table 8: Cost for Each Method

	XTC-3D	Resin/XTC-3D combo
Material Cost	7.73	$19.62
Application cost	$30	$45
Total Cost	$22.73	$49.62

Even though the total cost of this project was just over $600 if all the factors were taken into account such as time invested by the group, materials, shop use, electricity, the cost would have been substantially greater. The total cost over the two semesters were calculated to include many factors shown in table 9 which would be closer to the actual cost a company may incur if they were to tackle this project. The majority of the cost is from the students time while performing activities for the class, such as assignments and meeting with each other during class time.

Table 9: Total cost of project

	Hours	Cost per hour	Total cost
Materials	N/A	N/A	$614.67
3D-printer	390	$4	$1,560.00
TA and Student Assistance	4	30/20	$90.00
Machine shop use	10	$40	$400.00
computer use	30	$5	$150.00
Lab equipment usage	4	$100	$400.00
Sponsor time	8	$120	$960.00
Members Hours	1017.8	$20	$20,356.00
		Total	**$24,530.67**

15.3 Human Resource Allocation

Time management is an important aspect of any project. The teams time throughout the semester was broken down into ten different sections which include research, design, assignments, team meetings, sponsor meetings, 3D printing, application of processes, testing, analyzing data, and machining parts. These times can be seen in figures 16 - 19.

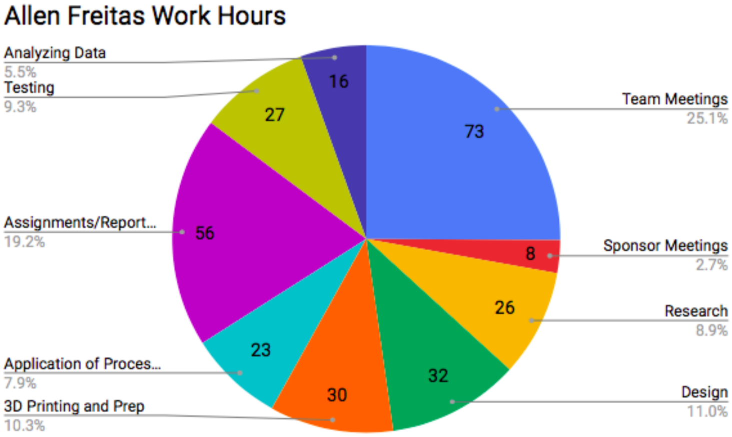


Figure 16: Allen Freitas's Work Hours

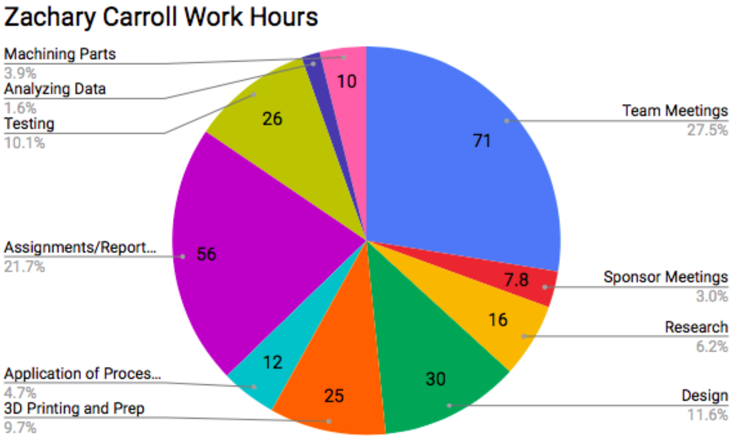


Figure 17: Zachary Carroll's Work Hours

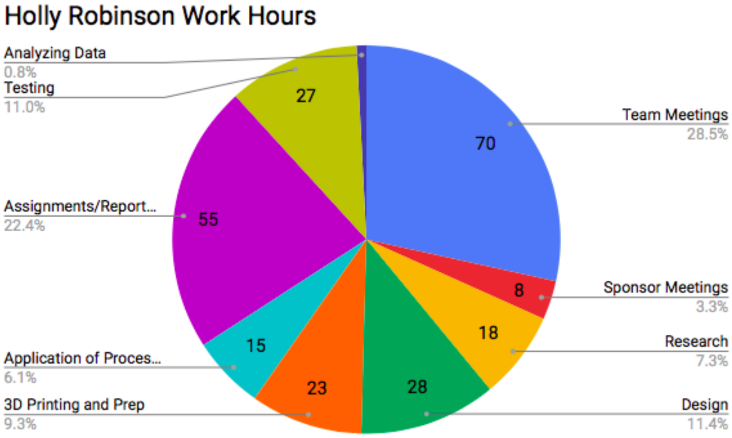


Figure 18: Holly Robinson's Work Hours

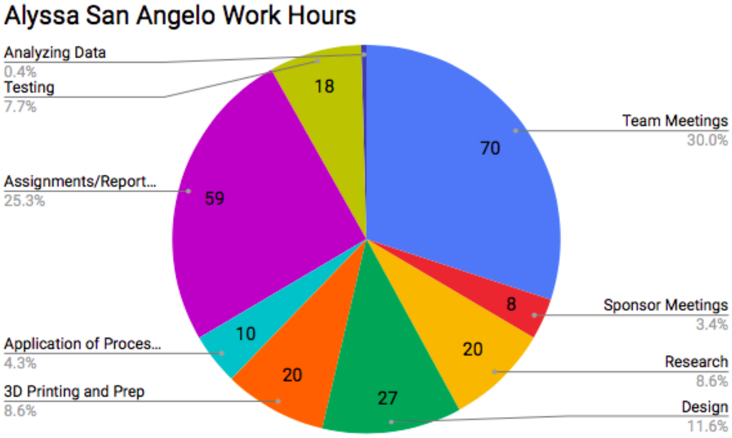


Figure 19: Alyssa San Angelo's Work Hours

16 Operation

Due to this project being a process rather than a product, the steps for each application process can be found in detail in Section 9. Once the processes are applied, the part can be used for the intended purpose, whether that is underwater or ground applications.

17 Maintenance

Once the process has been applied to the 3D printed piece, little maintenance is required. If the part is submerged for a longer duration of time, some organic build up might occur. To resolve this, wipe the part off with an alcohol wipe and clear the build up. The team also cautions about exposing the piece to UV light, since this was not a design specification that was tested. While not explicitly tested, if UV light will be a factor, adding a coat of UV resistant paint to the piece is advised. This additional layer can help protect from the UV rays.

The printing material, ABS, is recyclable. However once each process is applied it would no longer be recyclable and would need to be disposed of in the trash.

18 Additional Considerations

As engineers, we must take responsibility for the things we create and the impacts they have on the world around us. In order to do so for this project which is waterproofing 3D printed ABS parts, the team had to take the following into consideration: Economic impact, Societal and Political impact, Ethical considerations, Health and Safety considerations, and Environmental and Sustainability considerations.

18.1 Economic impact

The team was tasked with waterproofing 3D printed parts and it was sponsored by General Dynamics Electric Boat. GD/EB encountered 3D printed parts that were absorbing water and changing the buoyancy of things they were testing. The sponsors made it clear that they were looking to solve a general problem of water intrusion, though mainly for prototyping situations. The economic impact that could come from this project would be due to GD/EB purchasing large amounts of XTC-3D to coat a large amount of parts per year. The vast amount of 3D printing done at a place as large as GD/EB could very positively effect XTC-3D's parent company, Smooth-On.

18.2 Societal and Political impact

GD/EB has been the primary builder of US Navy submarines for over 100 years. Because of this, GD/EB can have strong societal and political impacts. This project is primarily going to be used for prototyping and test fitting parts which will not significantly change the way GD/EB conducts business. Therefore, it is reasonable to assume there will be no societal or political impact brought forth by this project.

18.3 Ethical considerations

As mentioned previously, GD/EB is mainly planning on using the waterproof coating to prototype and test fit parts. In spite of this, it is not out of the realm of possibility for GD/EB to use this waterproof coating to 3D print and waterproof weaponry that could be used to harm others. Therefore, the team had to consider this possibility during the design process.

18.4 Health, ergonomics, safety considerations

As mentioned in Section 7.5, Total Boat's epoxy resin contains Bisphenol-A (BPA) which is known to cause upper respiratory irritation and may affect the liver, kidney, and bladder when inhaled. BPA has also been recognized as a possible endocrine disruptor. [15] This is one of the reasons the team chose XTC-3D as the most optimal waterproofing solution. XTC-3D does not contain BPA, nor does it contain Volatile Organic Compounds (VOCs), Pthalates, or Phosphates.

In order to make the application process as easy as possible for the end user, the team had to consider the ergonomics of the process. Ergonomic is defined as "relating to or designed for efficiency and comfort in the working environment". Resin injection requires the user to custom create an internal geometry inside the part in order to control the amount of resin injected into the part. After this, the user would then have to drill holes into the exterior of the part, mix the epoxy resin, put it into a syringe, and inject it into the part. This method is not only inefficient, but also not enjoyable for the end user. Conversely, XTC-3D does not require any prep work, though the team decided light sanding could improve adhesion to the part. Then it's as simple as mixing the 2 part epoxy and brushing it onto the exterior of the part.

Each waterproofing compound the team found had the Safety Data Sheet printed out as soon as it was determined to be a viable solution. This allowed the team to find all of the necessary Personal Protective Equipment (PPE) and safety precautions to safely handle them. An outline of the safety equipment and application instructions can be found in Section 9.

18.5 Environmental impact and Sustainability considerations

One of the benefits of 3D printing is the reduced environmental impact when compared to CNC machining. [14] The team wanted to be sure that the process evaluated wouldn't negatively effect the environment. The chemicals used were researched in the waterproof coatings to ensure they wouldn't adversely effect the environment. As mentioned in Section 18.4, XTC-3D does not contain any VOCs, Pthalates, or Phosphates which are harmful to humans and the environment.

19 Conclusions

Throughout the year, several different processes were tested with the intention of waterproofing 3D printed ABS parts. These processes range in many variables such as application involvement, cost, and effectiveness. They were evaluated by first 3D printing controls and test specimen for each method tested, for all individual specification tests: submersion, pressure, and strength. These specimen were then weighed before and after each of the three tests. The change in mass allowed us to see the effectiveness of each method.

Last semester, it was found that the most successful methods were XTC-3D and resin injection. When these processes were applied to the specimen, they gained significantly less water than the control specimens. These results led to the team combining the methods, and completing new tests. In each of the three tests, there were specimen that were coated with XTC-3D, injected with resin and coated with XTC-3D, and controls. A submergence test was done with cubes over a two month period, which tested both the mass gain from water and the life cycle of the method. With the pressure test, it was seen that both methods were able to withstand 300 psi of internal pressure, surpassing the objective of 100 psi. The strength test resulted in the combination of resin injection and XTC-3D showing an increase in yield strength, while XTC-3D alone was reduced. This decrease was hypothesized that the XTC-3D on the ABS created a chemical change and made the piece more brittle.

XTC-3D was determined to be the most viable option due to ease of application and relatively low cost. The resin injection method with the XTC-3D would be applicable only when additional strength is absolutely necessary. This method proved to be very involved, needing specific geometry and custom supports inside the piece. In addition to this drawback, this method increases the weight of the piece significantly and was expensive. In the end, the team was in successful in designing a process that prevented water absorption in 3D printed ABS parts.

20 Acknowledgments

Team Operation: Watertight would like to thank The University Of Rhode Island for providing the opportunity and resources to complete this project and to Dr. Nassersharif for his guidance. We would also like to thank our sponsors, Evan LaBras and Kurt Hamel from General Dynamics/Electric Boat for their valuable guidance and input throughout the year during this project. In addition, Timothy Pickard gave us valuable advice for designing the pressure vessel and Brian Cheney assisted with the strength testing.

21 References

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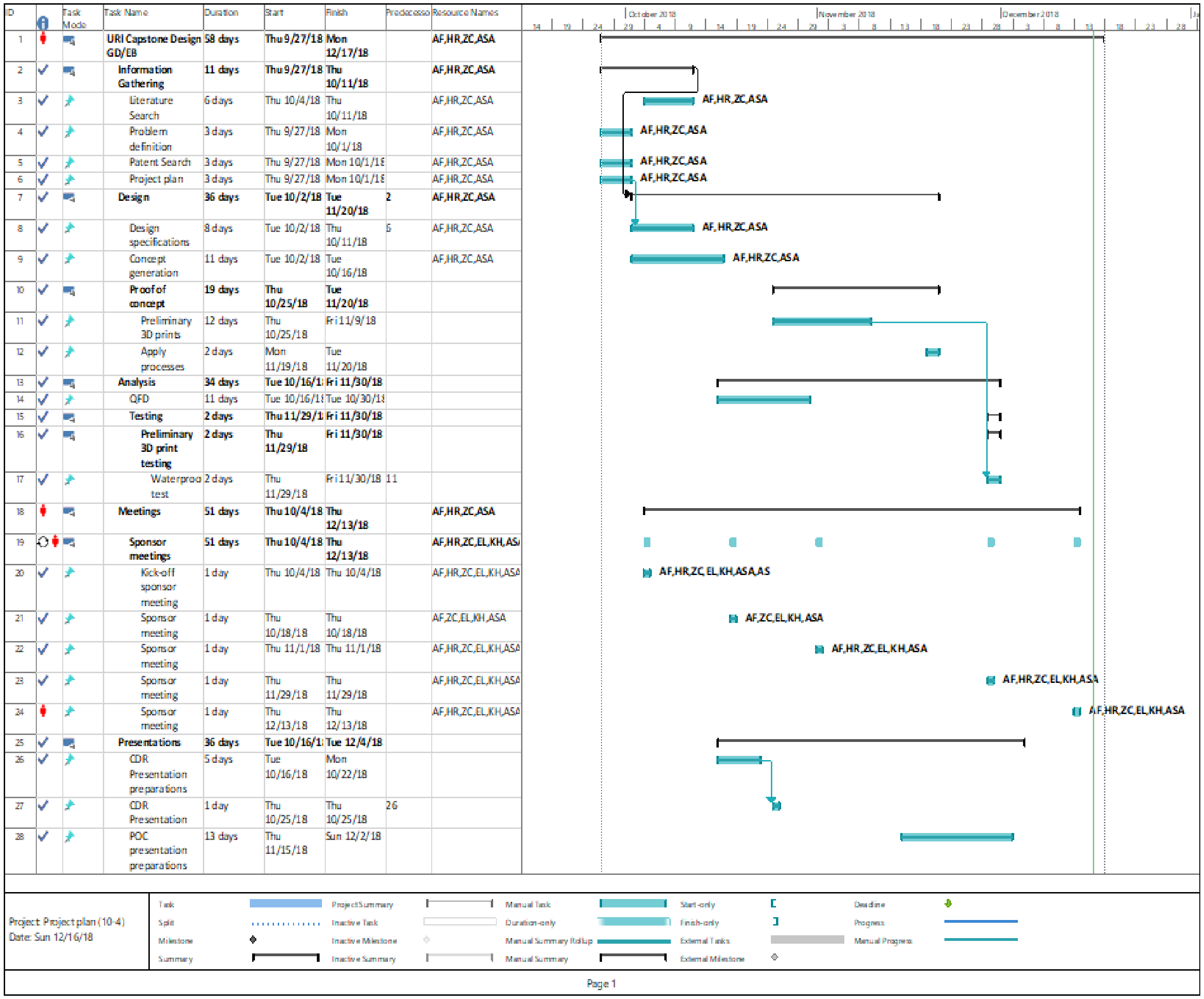
22 Appendices

Appendix A: Project Plan

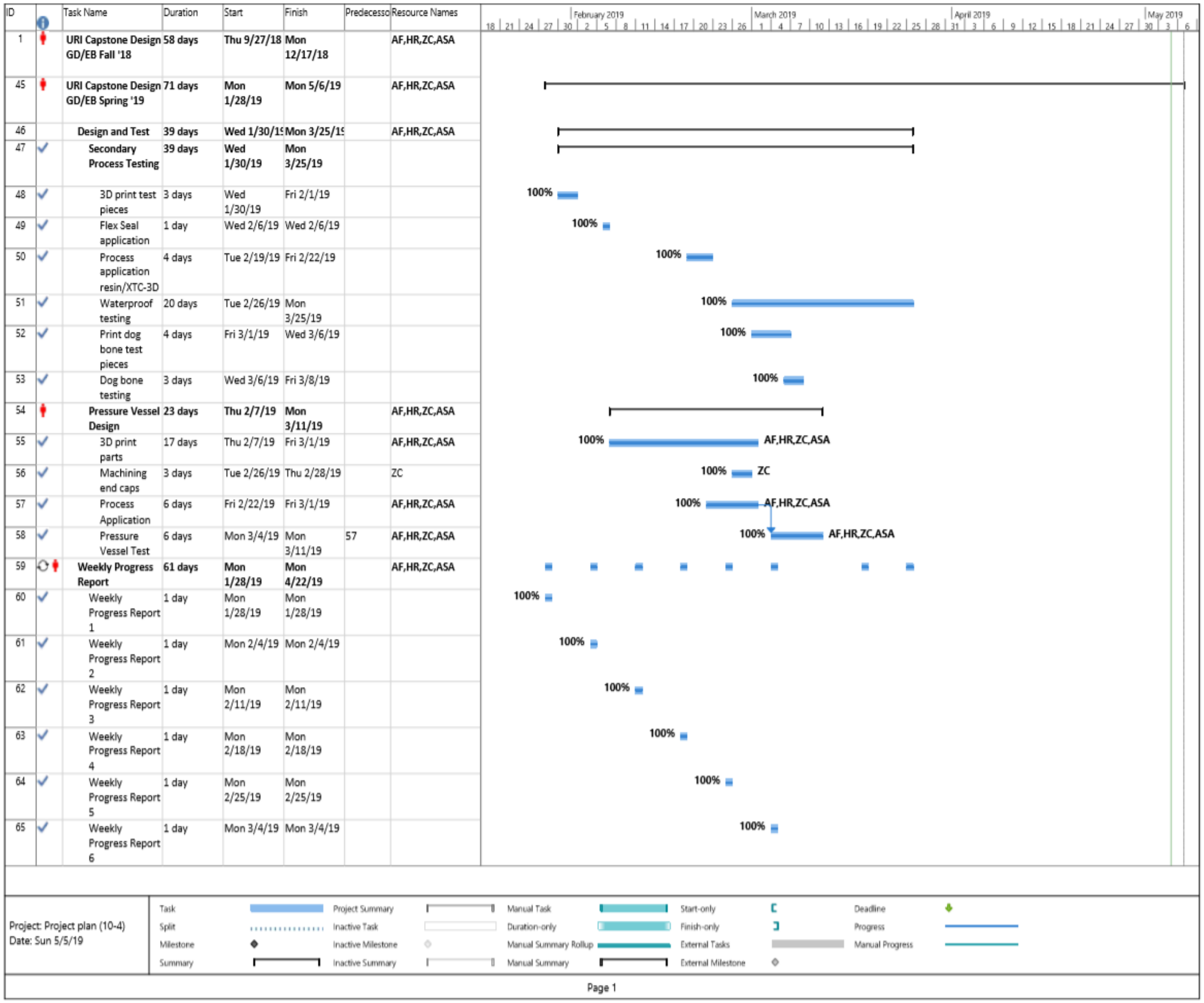


ID		Task Mode	Task Name	Duration	Start	Finish	Predecesso	Resource Names
1			**URI Capstone Design GD/EB**	**58 days**	**Thu 9/27/18**	**Mon 12/17/18**		**AF,HR,ZC,ASA**
2	✓		**Information Gathering**	**11 days**	**Thu 9/27/18**	**Thu 10/11/18**		**AF,HR,ZC,ASA**
3	✓		Literature Search	6 days	Thu 10/4/18	Thu 10/11/18		AF,HR,ZC,ASA
4	✓		Problem definition	3 days	Thu 9/27/18	Mon 10/1/18		AF,HR,ZC,ASA
5	✓		Patent Search	3 days	Thu 9/27/18	Mon 10/1/18		AF,HR,ZC,ASA
6	✓		Project plan	3 days	Thu 9/27/18	Mon 10/1/18		AF,HR,ZC,ASA
7	✓		**Design**	**36 days**	**Tue 10/2/18**	**Tue 11/20/18**	**2**	**AF,HR,ZC,ASA**
8	✓		Design specifications	8 days	Tue 10/2/18	Thu 10/11/18	6	AF,HR,ZC,ASA
9	✓		Concept generation	11 days	Tue 10/2/18	Tue 10/16/18		AF,HR,ZC,ASA
10	✓		**Proof of concept**	**19 days**	**Thu 10/25/18**	**Tue 11/20/18**		
11	✓		Preliminary 3D prints	12 days	Thu 10/25/18	Fri 11/9/18		
12	✓		Apply processes	2 days	Mon 11/19/18	Tue 11/20/18		
13	✓		**Analysis**	**34 days**	**Tue 10/16/1**	**Fri 11/30/18**		
14	✓		QFD	11 days	Tue 10/16/1	Tue 10/30/1		
15	✓		**Testing**	**2 days**	**Thu 11/29/1**	**Fri 11/30/18**		
16	✓		**Preliminary 3D print testing**	**2 days**	**Thu 11/29/18**	**Fri 11/30/18**		
17	✓		Waterproo test	2 days	Thu 11/29/18	Fri 11/30/18	11	
18			**Meetings**	**51 days**	**Thu 10/4/18**	**Thu 12/13/18**		**AF,HR,ZC,ASA**
19			**Sponsor meetings**	**51 days**	**Thu 10/4/18**	**Thu 12/13/18**		**AF,HR,ZC,EL,KH,AS**
20	✓		Kick-off sponsor meeting	1 day	Thu 10/4/18	Thu 10/4/18		AF,HR,ZC,EL,KH,ASA
21	✓		Sponsor meeting	1 day	Thu 10/18/18	Thu 10/18/18		AF,ZC,EL,KH,ASA
22	✓		Sponsor meeting	1 day	Thu 11/1/18	Thu 11/1/18		AF,HR,ZC,EL,KH,ASA
23	✓		Sponsor meeting	1 day	Thu 11/29/18	Thu 11/29/18		AF,HR,ZC,EL,KH,ASA
24			Sponsor meeting	1 day	Thu 12/13/18	Thu 12/13/18		AF,HR,ZC,EL,KH,ASA
25	✓		**Presentations**	**36 days**	**Tue 10/16/1**	**Tue 12/4/18**		
26	✓		CDR Presentation preparations	5 days	Tue 10/16/18	Mon 10/22/18		
27	✓		CDR Presentation	1 day	Thu 10/25/18	Thu 10/25/18	26	
28	✓		POC presentation preparations	13 days	Thu 11/15/18	Sun 12/2/18		

Project: Project plan (10-4)
Date: Sun 12/16/18

Page 1

Figure 20: Project Plan Fall 2018



ID	Task Name	Duration	Start	Finish	Predecessors	Resource Names
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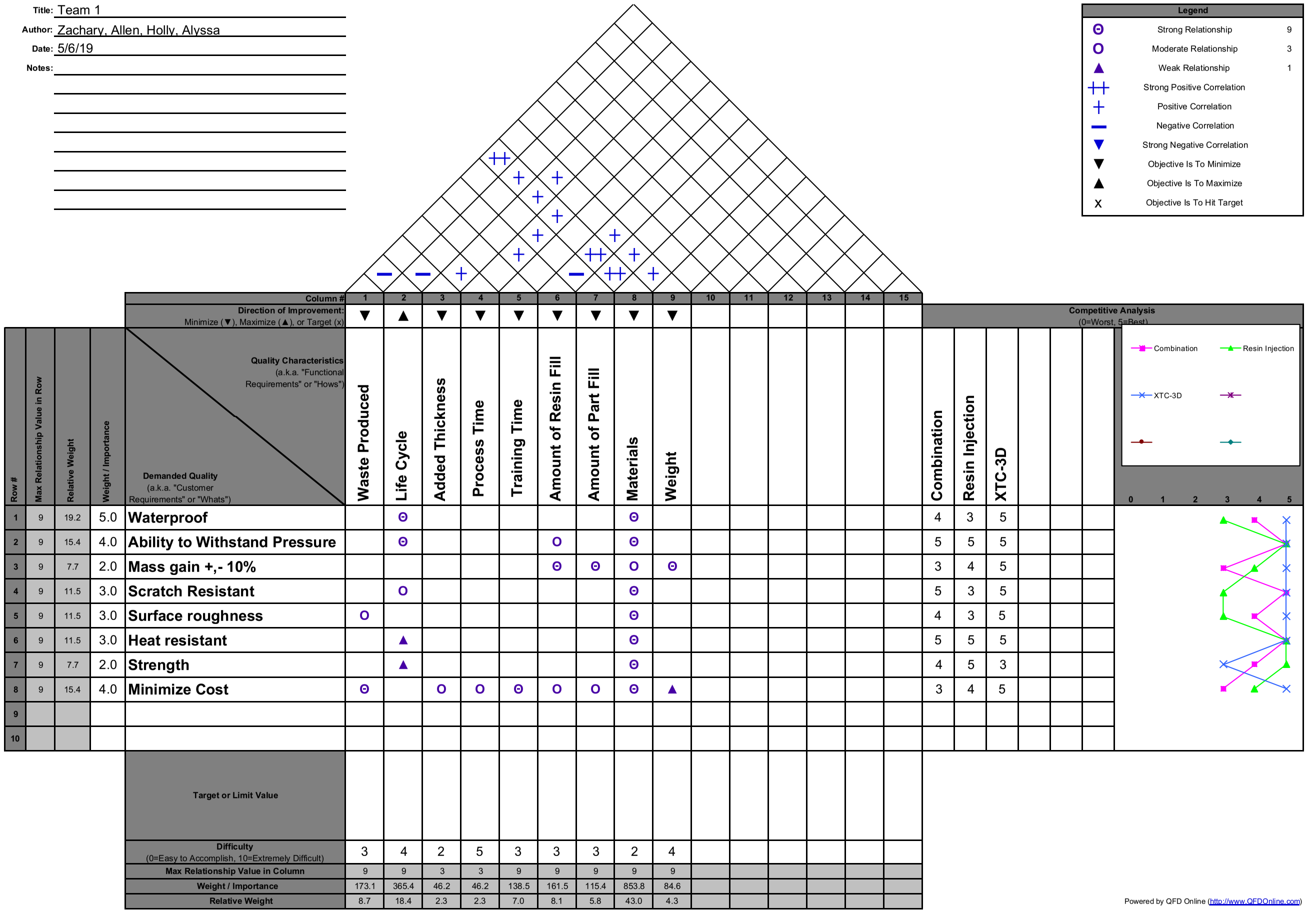
45	**URI Capstone Design GD/EB Spring '19**	**71 days**	**Mon 1/28/19**	**Mon 5/6/19**		**AF,HR,ZC,ASA**
46	**Design and Test**	**39 days**	**Wed 1/30/1**	**Mon 3/25/1**		**AF,HR,ZC,ASA**
47	**Secondary Process Testing**	**39 days**	**Wed 1/30/19**	**Mon 3/25/19**		
48	3D print test pieces	3 days	Wed 1/30/19	Fri 2/1/19		
49	Flex Seal application	1 day	Wed 2/6/19	Wed 2/6/19		
50	Process application resin/XTC-3D	4 days	Tue 2/19/19	Fri 2/22/19		
51	Waterproof testing	20 days	Tue 2/26/19	Mon 3/25/19		
52	Print dog bone test pieces	4 days	Fri 3/1/19	Wed 3/6/19		
53	Dog bone testing	3 days	Wed 3/6/19	Fri 3/8/19		
54	**Pressure Vessel Design**	**23 days**	**Thu 2/7/19**	**Mon 3/11/19**		**AF,HR,ZC,ASA**
55	3D print parts	17 days	Thu 2/7/19	Fri 3/1/19		AF,HR,ZC,ASA
56	Machining end caps	3 days	Tue 2/26/19	Thu 2/28/19		ZC
57	Process Application	6 days	Fri 2/22/19	Fri 3/1/19		AF,HR,ZC,ASA
58	Pressure Vessel Test	6 days	Mon 3/4/19	Mon 3/11/19	57	AF,HR,ZC,ASA
59	**Weekly Progress Report**	**61 days**	**Mon 1/28/19**	**Mon 4/22/19**		**AF,HR,ZC,ASA**
60	Weekly Progress Report 1	1 day	Mon 1/28/19	Mon 1/28/19		
61	Weekly Progress Report 2	1 day	Mon 2/4/19	Mon 2/4/19		
62	Weekly Progress Report 3	1 day	Mon 2/11/19	Mon 2/11/19		
63	Weekly Progress Report 4	1 day	Mon 2/18/19	Mon 2/18/19		
64	Weekly Progress Report 5	1 day	Mon 2/25/19	Mon 2/25/19		
65	Weekly Progress Report 6	1 day	Mon 3/4/19	Mon 3/4/19		

Project: Project plan (10-4)
Date: Sun 5/5/19

Figure 21: Project Plan Spring 2019

Appendix B: QFD Analysis



Title: Team 1
Author: Zachary, Allen, Holly, Alyssa
Date: 5/6/19
Notes:

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Waste Produced	Life Cycle	Added Thickness	Process Time	Training Time	Amount of Resin Fill	Amount of Part Fill	Materials	Weight							Combination	Resin Injection	XTC-3D
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)		
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▲	▼	▼	▼	▼	▼	▼	▼									
1	9	19.2	5.0	Waterproof		Θ						Θ								4	3	5
2	9	15.4	4.0	Ability to Withstand Pressure		Θ				O		Θ								5	5	5
3	9	7.7	2.0	Mass gain +,- 10%						Θ	Θ	O	Θ							3	4	5
4	9	11.5	3.0	Scratch Resistant		O						Θ								5	3	5
5	9	11.5	3.0	Surface roughness	O							Θ								4	3	5
6	9	11.5	3.0	Heat resistant		▲						Θ								5	5	5
7	9	7.7	2.0	Strength		▲						Θ								4	5	3
8	9	15.4	4.0	Minimize Cost	Θ		O	O	Θ	O	O	Θ	▲							3	4	5
9																						
10																						
				Target or Limit Value																		
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	3	4	2	5	3	3	3	2	4									
				Max Relationship Value in Column	9	9	3	3	9	9	9	9	9									
				Weight / Importance	173.1	365.4	46.2	46.2	138.5	161.5	115.4	853.8	84.6									
				Relative Weight	8.7	18.4	2.3	2.3	7.0	8.1	5.8	43.0	4.3									

Powered by QFD Online (http://www.QFDOnline.com)

Figure 22: QFD Analysis

Appendix C: Design of Cube

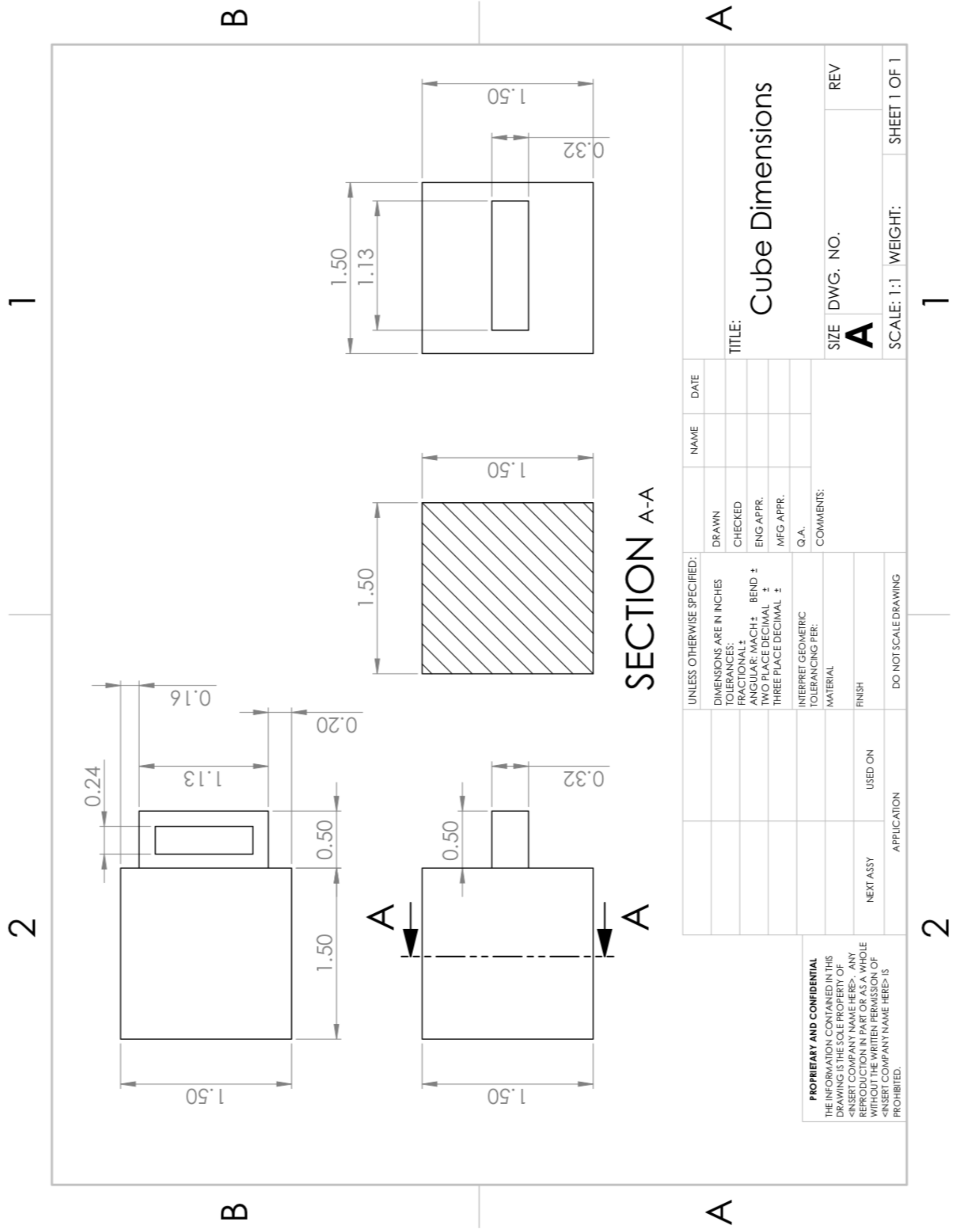


Figure 23: Dimensions of Cube in Inches

Appendix D: Design of Mug

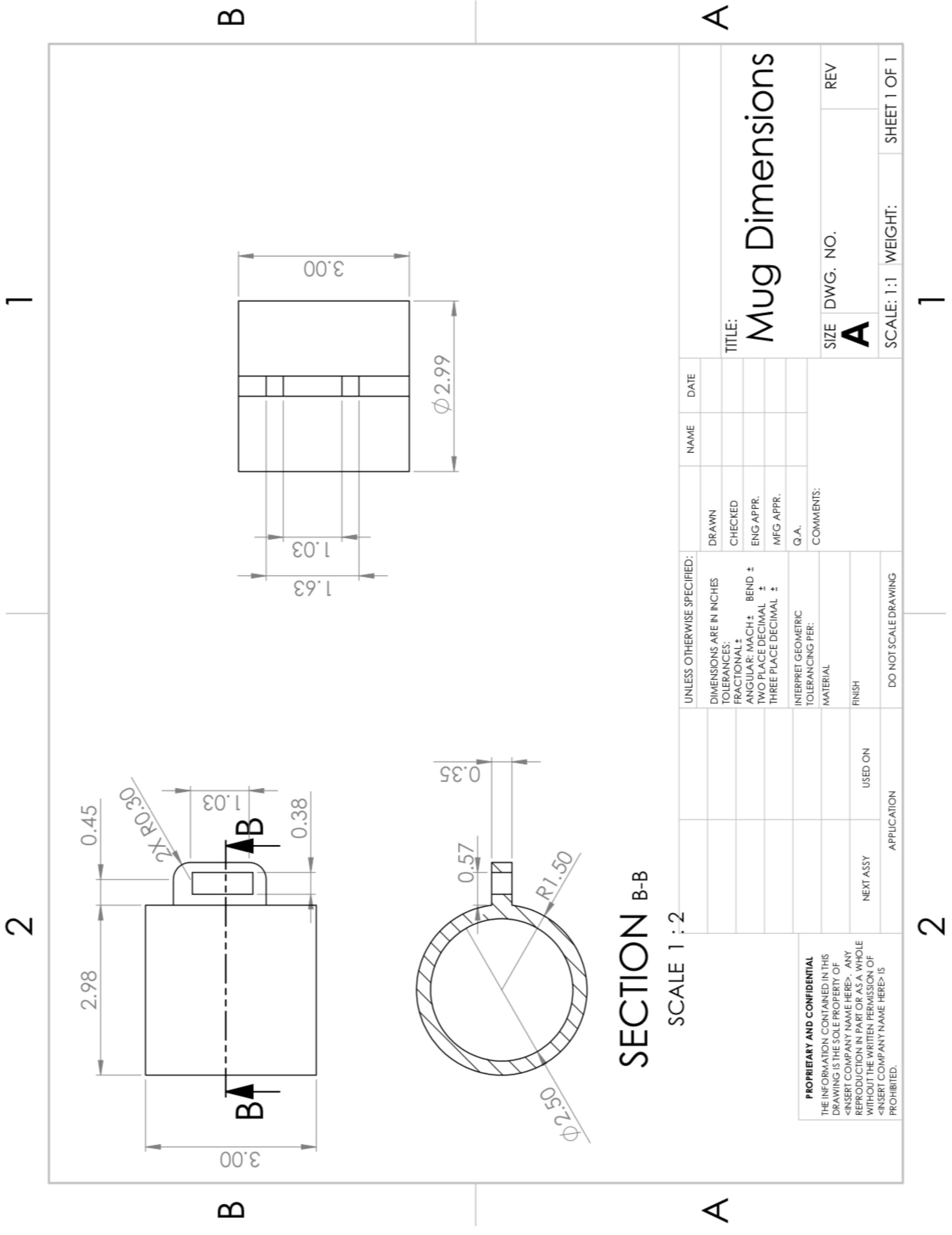
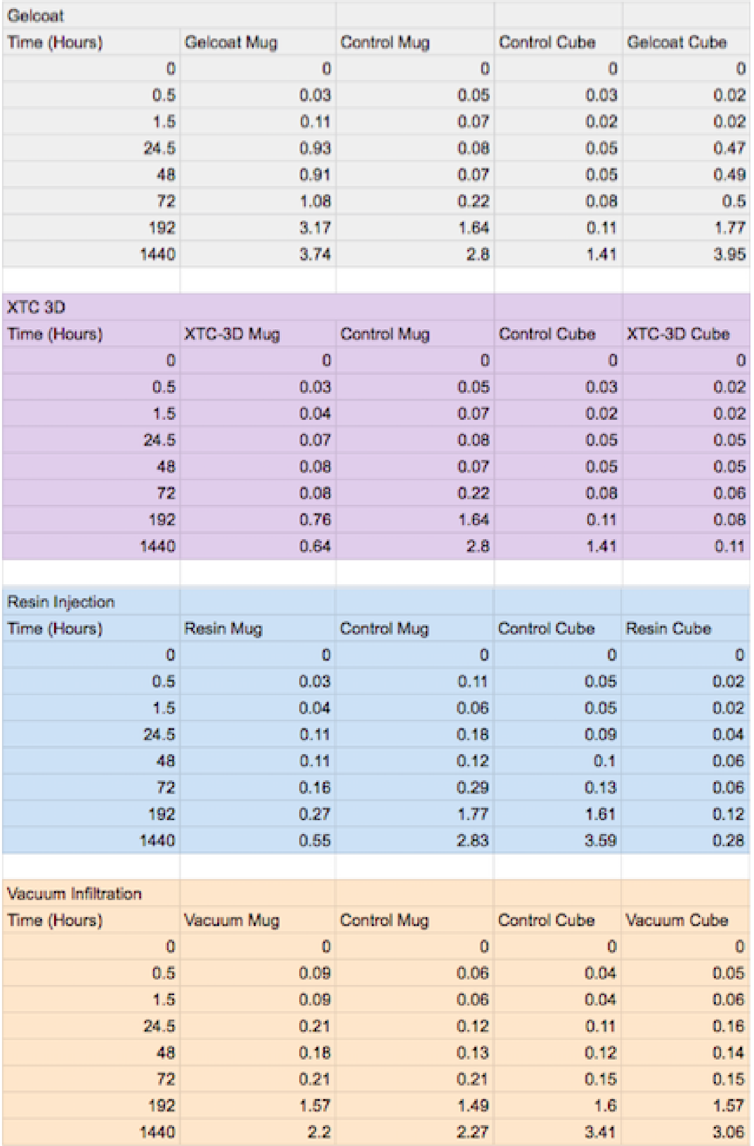


Figure 24: Dimensions of Mug in Inches

Appendix E: Part Data



Gelcoat				
Time (Hours)	Gelcoat Mug	Control Mug	Control Cube	Gelcoat Cube
0	0	0	0	0
0.5	0.03	0.05	0.03	0.02
1.5	0.11	0.07	0.02	0.02
24.5	0.93	0.08	0.05	0.47
48	0.91	0.07	0.05	0.49
72	1.08	0.22	0.08	0.5
192	3.17	1.64	0.11	1.77
1440	3.74	2.8	1.41	3.95

XTC 3D				
Time (Hours)	XTC-3D Mug	Control Mug	Control Cube	XTC-3D Cube
0	0	0	0	0
0.5	0.03	0.05	0.03	0.02
1.5	0.04	0.07	0.02	0.02
24.5	0.07	0.08	0.05	0.05
48	0.08	0.07	0.05	0.05
72	0.08	0.22	0.08	0.06
192	0.76	1.64	0.11	0.08
1440	0.64	2.8	1.41	0.11

Resin Injection				
Time (Hours)	Resin Mug	Control Mug	Control Cube	Resin Cube
0	0	0	0	0
0.5	0.03	0.11	0.05	0.02
1.5	0.04	0.06	0.05	0.02
24.5	0.11	0.18	0.09	0.04
48	0.11	0.12	0.1	0.06
72	0.16	0.29	0.13	0.06
192	0.27	1.77	1.61	0.12
1440	0.55	2.83	3.59	0.28

Vacuum Infiltration				
Time (Hours)	Vacuum Mug	Control Mug	Control Cube	Vacuum Cube
0	0	0	0	0
0.5	0.09	0.06	0.04	0.05
1.5	0.09	0.06	0.04	0.06
24.5	0.21	0.12	0.11	0.16
48	0.18	0.13	0.12	0.14
72	0.21	0.21	0.15	0.15
192	1.57	1.49	1.6	1.57
1440	2.2	2.27	3.41	3.06

Figure 25: Mass of parts for each process over time measured in grams

Appendix F: Redesigned cube

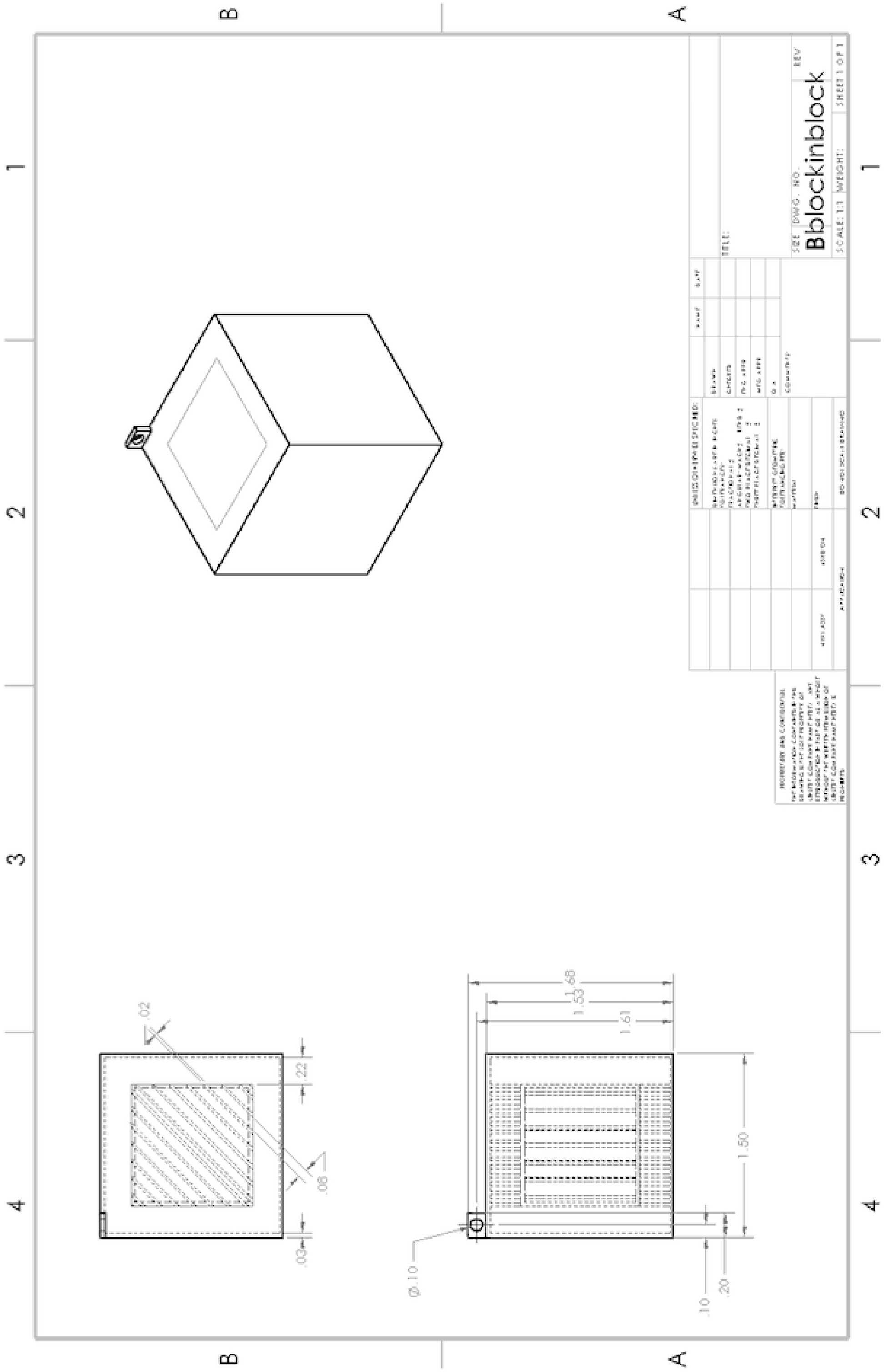


Figure 26: Dimensions of redesigned cube

Appendix G: Design of Pressure Vessel End Caps and Cylinder

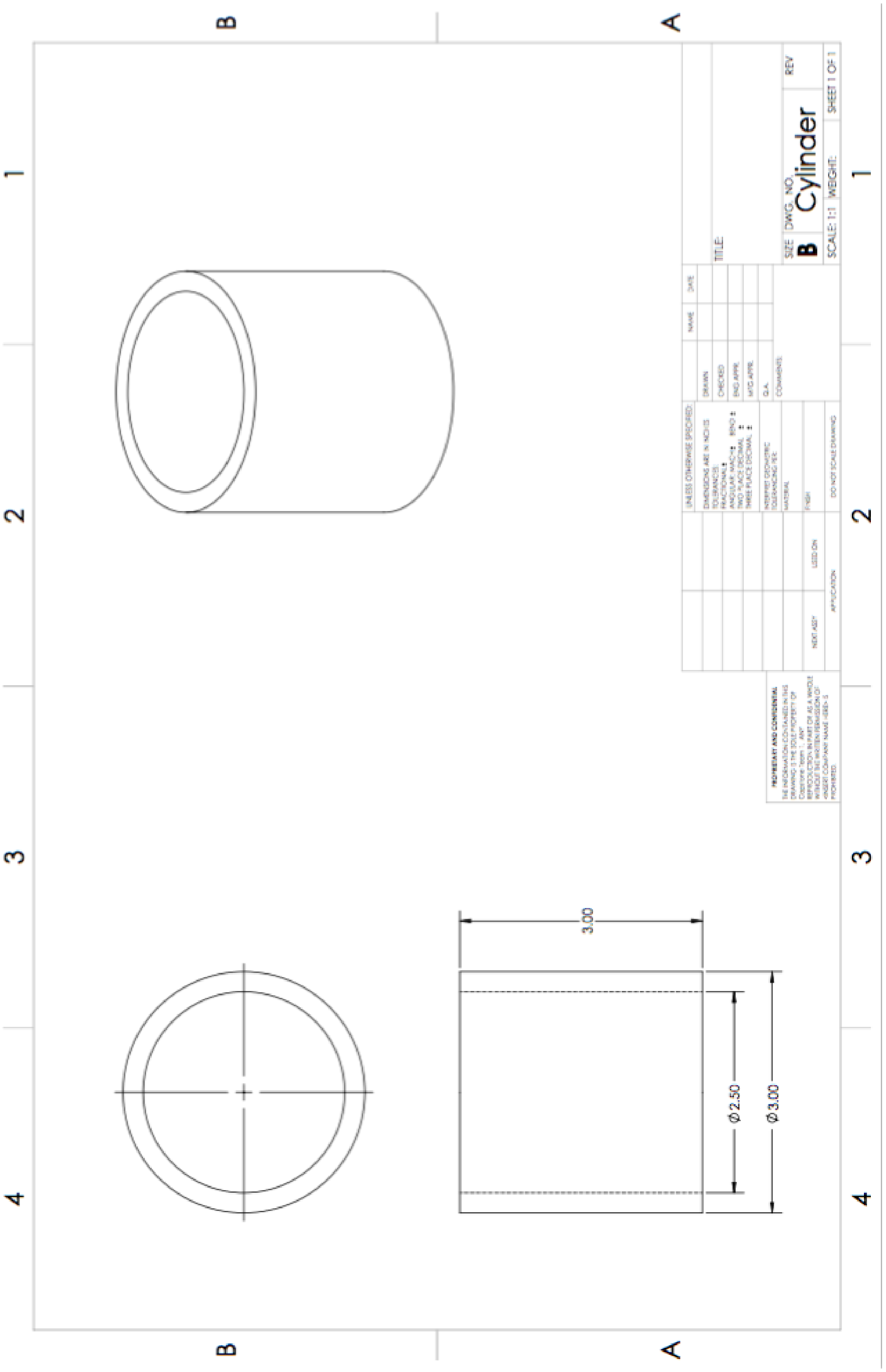


Figure 27: Dimensions of Cylinder in Inches

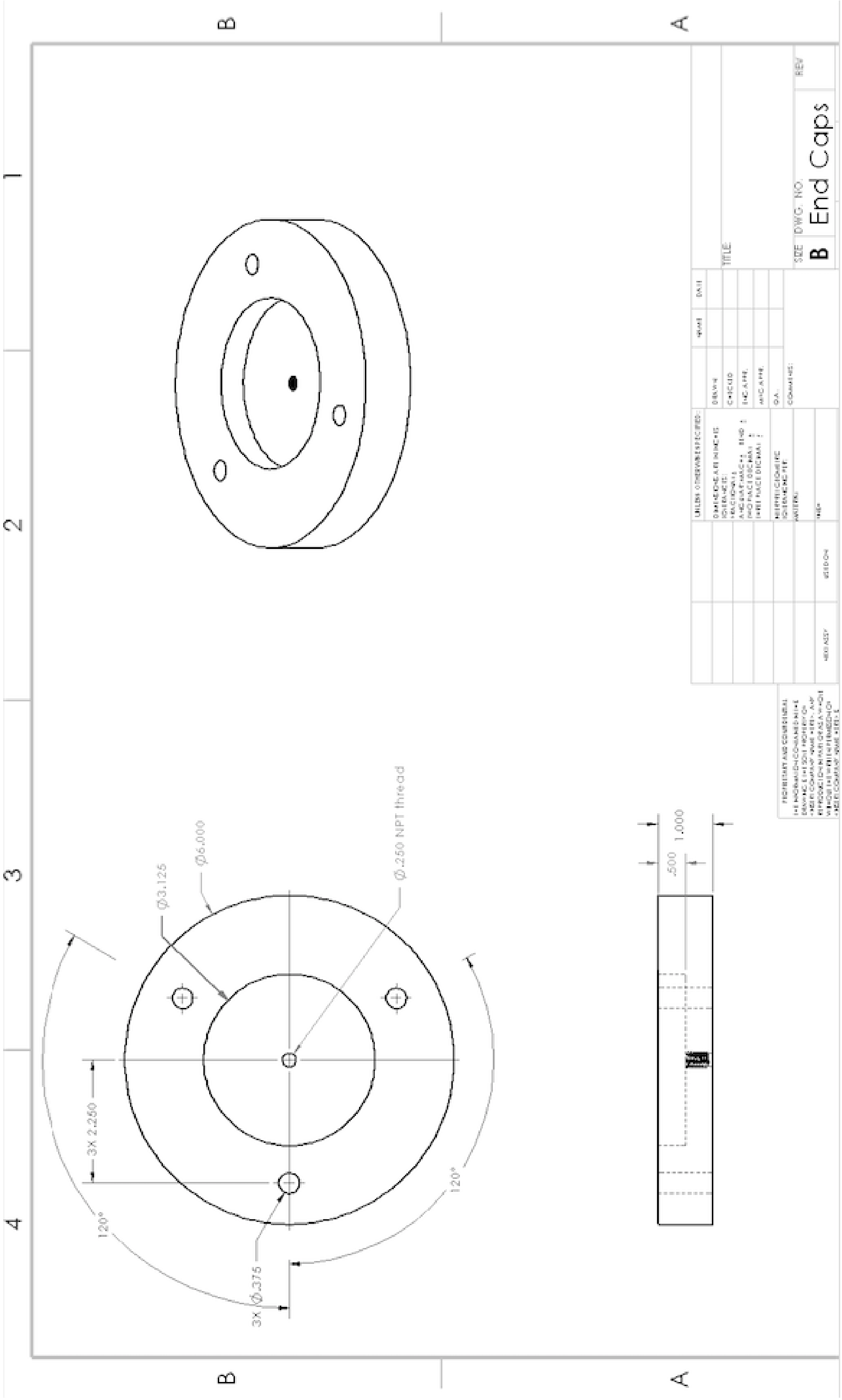


Figure 28: Dimensions of End Caps in Inches