Senior Capstone Design

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Green Ellipsis- Splicing of PET Plastic

Final Report

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Acknowledgments

We would like to thank our sponsors at Green Ellipsis, Brian Alano and Jane Kang. We greatly appreciate their guidance and knowledge which have helped make this project what is. We recognize and appreciate the trust they have put in us to see this project through.

We would also like to express our deepest gratitude to our professors Dr. Aceros and Dr. Stagon, whose mentorship and expertise have been instrumental in guiding us through the engineering process. We appreciate how they always made time in their schedules for us and answered any question no matter how small. Without them, we wouldn't be able to push our ideas into reality and strive to bring about the best work imaginable.

We would also like to extend our thanks to all our fellow students and peers in the class who were always open to giving advice and support throughout the semester. We'd also like to thank all the other professors we've had over our time at UNF, without them we wouldn't have the knowledge to pursue this project.

Team Value Statement

As members of the Green Ellipsis team, we pledge to work hard, to be respectful to each other, and open to all ideas. We will keep each member of the team accountable to themselves as well as the group. Disagreements between group members won't be taken personally and will be resolved quickly so the work can continue without suffering. We are committed to making sure that we each do our fair share and that no singular member is overburdened. When a team member has hardships outside of the group, the other members will compensate as much as possible to help lessen their load. Above all, our goal is to work as a cohesive team to complete the project and produce a viable solution.

As requested by our sponsor, all design components will use the metric system of measurements. When possible, open-source software and platforms will be used for easy adoption by the community. Our working motto will be to test early and test often to find problems early before they propagate into the design.

We also pledge to follow the credo of the company we are working with, Green Ellipsis. We will put health and safety concerns above all else. We hope to work in a way that supports the environment and community. All processes we use in the design and production of our project will consider environmental impacts and attempt to have a positive impact.

Printed name	Signature
Allison Wolfson	
RYAN HUNTER	
Christopher Zervos	
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Executive Summary

Green Ellipsis is a small innovative company working to create a complete process of upcycling PET plastic soda bottles into 3D printer filament that can be adopted and recreated by small community organizations. The current process is unsustainable due to the minimal amount of filament produced from such a labor-intensive undertaking. The goal of this project was to optimize the ratio between the cost of production and the overall value of the end product. For the product to be viable, the filament must have a diameter of 1.75mm and withstand the stress of spooling and 3D printing. The raw material that makes up the filament should continue to be from plastic bottles, without any major additives, and the process should be environmentally friendly. Since the goal is for the process to be recreated by others, it should be reliable, safe, cheap, and simple to reproduce. The budget for this project was $1,000.

The ratio of production to selling value could be decreased by either increasing the profit of the filament produced or by decreasing the cost of labor that goes into production. Initially ideas were pitched to decrease the labor costs by automating one of the subprocesses of the already created machine. Ideas were developed to automate the cleaning, pultrusion, or spooling process. It was then decided that it would be more beneficial to focus on increasing the value of the filament through splicing multiple pieces of filament together to form a single 1kg spool. Since the team discovered that splicing was a major problem that had yet to have a solution, it was deemed to be the most beneficial way to increase the cost/value ratio of production.

Seven potential splicing techniques were brainstormed, fleshed out, designed, and created to attempt to join the end of one filament to the next. These methods were tested based on their ability to create a stable joint that could hold itself up, withstand a tensile force of 30 Newtons, withstand a 45-degree bend across a 5mm radius, and successfully create a print in a 3D printer without clogging or defects. After these tests, two of the methods showed promise in creating strong joints that could move through a 3D printer without clogging. One method uses a tight-fitting silicone sleeve to hold two ends of filament together while a soldering iron applies enough heat to join the filaments. The other successful method uses nichrome wire to quickly heat the ends of two filament pieces and join them together.

The silicone sleeve method is better as a quick handheld solution for hobbyists while the nichrome method could be useful for larger scale production. It is further recommended that these designs are iterated upon and optimized so the produced splices can meet the constraints more consistently. Initial final prototypes have been created to give directions and suggestions of how this can be done.

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Background

Green Ellipsis is a company focused on fostering a more sustainable future for all. To advance this mission, they have chosen to concentrate their efforts on recycling two-liter plastic bottles, primarily Pepsi brand, into filament that can be used by a 3D printer for a multitude of projects and can be infinitely recycled. Single use plastics are a growing problem, not just in the US but worldwide. Almost 400 million tons of plastic are produced worldwide each year with more than two thirds of that thrown away into dumps or the ocean [1]. Although plastic recycling is not free, the cost of returning the materials back into the production cycle can in many cases be an economical and environmentally friendly alternative to the cost of disposal [2].

Going from two-liter bottles to usable filament requires multiple sub processes as can be seen below in Figure 1:

1. Bottle preparation: Before the bottles can be processed, they must first be prepared in several ways. The labels need to be removed, the label adhesive needs to be removed, the plastic needs to be cleaned, and the bottles must be dried.
2. Cutting: After the bottles have been prepared, they are cut into 8mm wide strips. A previous UNF senior design team automated this process.
3. Threading/Pultrusion: After being cut into thin strips, one end needs to be fished through an extruder nozzle. This is currently done by hand and can be difficult to do. Once fished through, the strip is heated to reform into the desired shape of a 1.75 mm strand. This strand is pulled through the hot nozzle in a process called pultrusion. The strand is attached to a spool and continues to be pulled until the entire strip obtained from the bottle is formed into the desired filament.
4. Winding/Packaging: The filament is unwound from the spool on the machine and packaged in a way that it can be stored before use/sale. This is currently done by hand and must be done for each individual bottle which can bottleneck the process.

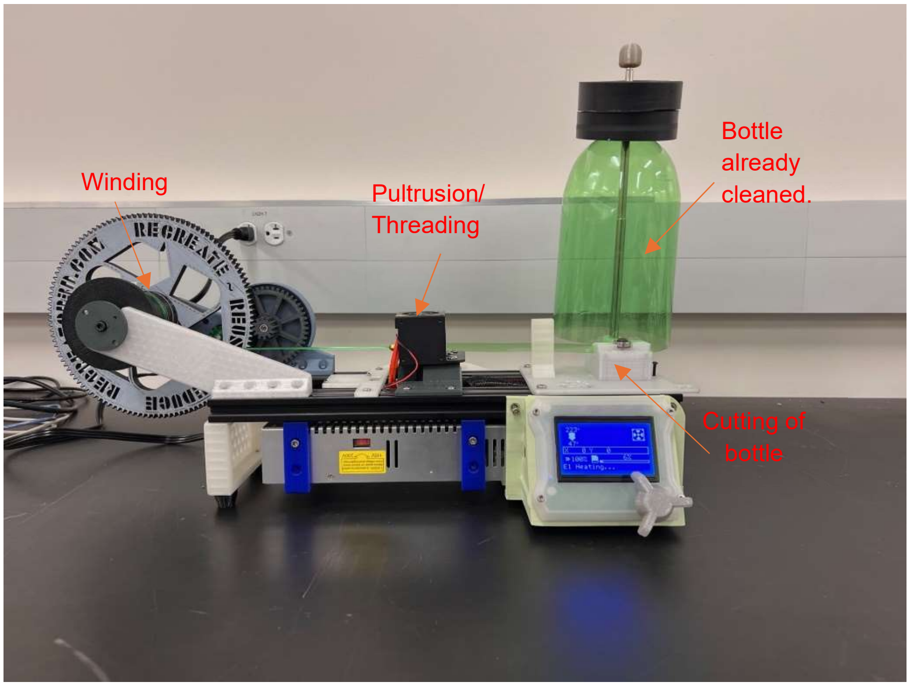

Figure 1: Full machine setup.

Green Ellipsis focuses on utilizing bottles made from polyethylene terephthalate, commonly referred to as PET. PET is a thermoplastic polymer, one of the most common plastics found in various everyday products, from bottles to clothing fibers, and is extensively employed in manufacturing processes. Due to its widespread use, PET production has surpassed a staggering 75 million tons annually [3]. PET two-liter bottles are the primary source of material that Green Ellipsis uses due to their relatively large size and ideal thickness for reforming into filament. Pepsi brand bottles are preferred due to their uniform cylindrical shape compared to other brands. This uniform shape allows for a more consistent filament to be created. These bottles are made from amorphous PET which allows them to be strong and durable yet still pliable. These same properties are desired in a 3D printer filament to provide the highest quality prints. PET plastic does provide some difficulties that make it hard to work with. PET has a glass transition temperature of 70° C and a melting point of 245° C [4]. The glass transition temperature represents the point above which the material can be easily reformed but it not a liquid like if melted. If during the process the material is not thermally quenched quickly enough, about two seconds, the amorphous material will begin to crystallize [4]. The semi-crystalline

PET is much less pliable than the original amorphous form. If the plastic is allowed to crystalize too much, it will be brittle and not survive the spooling and printing process.

Using the recycled PET filament is quite straightforward and may be used on most home 3D printers. The quality of the printed object is directly related to the quality of the filament produced. According to Green Ellipsis, filament that was made from a very uniformly stripped bottle with a consistent pull speed produces a very high-quality product similar to commercially available PET filament. As the quality of the upcycling procedure falls, so does the quality of the produced filament. Although generally easy to use, the upcycled filament does have some requirements for printing that must be followed. The first requirement is that the print must be executed at relatively high extrusion temperature, ideally at 265° C. This temperature often requires an all-metal hot end for the printer which is not included for every model. According to Green Ellipsis, a lower temperature may be used but the printing quality is generally worse. Additionally, an enclosure is preferred so that the material does not cool too quickly during the printing process.

3D printer filament is generally sold in 1kg spools, and this is typically more than enough for a single print. If a switch must be made mid print, however, either because the end of a spool was used or color needs to be swapped out, it can damage or cause inconsistencies in the print. Additionally, if filament swaps occur multiple times during a print, the user must be much more involved with the process which is often inconvenient. In cases where filament swaps would otherwise be needed, one potential solution is filament splicing. Splicing is the joining of two ends of different continuous pieces of filament, commonly through heat-based methods. Most splicing methods that have been developed are for the more common types of printer filament, mainly PLA. There are numerous methods that have been experimented with and used by different hobbyists [5]. Due to the nature of PETs chemical structure these methods aren't as consistently viable as they are with PLA mainly due to the risk of recrystallization.

Project Problem Statement and Description

Polyethylene terephthalate (PET) plastic waste is a major contributor to pollution of the environment [6]. Because of this, many people and companies have been working to create ways to manage this waste by reusing and recycling. Green Ellipsis, the sponsor of this project, processes two-liter PET plastic bottles and upcycles them into usable filament for 3D printing. The company currently has a manual process that creates a viable end product but is not economically feasible due to the labor-intensive nature of the operation and the minimal amount of filament that is produced from each bottle. The goal that Green Ellipsis has for the future of this endeavor is to reduce the cost of producing the filament (primarily labor) so that the filament can be sold for a profit or at least cover the cost of producing it as much as possible. After optimizing the process, Green Ellipsis plans to either sell kits with the required components for individuals to replicate it or offer free plans to achieve the same goal. The hope is that the process developed will be used by community level groups that have interest in environmental work, 3D printing, or both. Because the raw material (two-liter bottles) will generally be acquired at no cost through donation and recycling collection, the only cost to these groups would be buying/building the process and whatever running costs it takes to make the filament.

The problem faced by Green Ellipsis is that the current cost of producing the filament compared to what it can sell for is too high. It is expected of this group to find solutions to improve that cost/revenue ratio to make the process economically feasible. Currently, the filament is produced one bottle at a time which produces discrete, 10m long, 20g strands of filament as seen in Figure 2. Generally, it is desirable to have a single longer strand of filament for ease of use while 3D printing. Due to the short length of the filament currently produced, the sale value of the product is low. Green Ellipsis has indicated that one of the best ways to increase the value is by splicing multiple strands of filament together into 1kg or half kg spools.

Figure 2: Filament production workflow from bottle to strips to filament.

There is currently no known process for reliably splicing strands of PET filament in a way that maintains the desired mechanical properties for 3D printing. Creating such a process would increase the value of the filament and increase the viability of selling the product. The main hurdle that must be overcome when splicing PET filament is avoiding the brittleness that comes from recrystallization. If the material is brought above the glass transition temperature, as is common in many traditional splicing methods, it must be quickly cooled in order to maintain its amorphous form. The filament also needs to stay a consistent diameter of 1.75 mm so as not to cause any inconsistencies when running through the 3D printer. Attempts by others to find methods to splice this filament have had mixed results. Some solutions have been found but have been unreliable and difficult to repeat with any level of accuracy. The objective of splicing would be to explore and identify a simple, repeatable method for connecting plastic from one bottle to the next, aiming to create a continuous spool of filament that can be effectively utilized by a 3D printer. This would involve chemical, thermal, and mechanical experimentation as part of the efforts to seek a solution to the problem.

Requirements and constraints:

Each of the following design requirements and constraints were imposed by Green Ellipsis and are needed for the final process to be viable. The constraints are strict limitations to be followed to create a final product. The goal of this project is to produce an open-source solution and implement it into community-based buildings. Because of this, it needs to be safe and usable by an average person with minimal or no training. Safety is the number one constraint; whatever process is created should not pose any harm to the user. Because the goal is to make a widely appealing product, the filament produced must work in an average 3D printer. The standard filament size of 1.75 mm is most used and is the target size for production by this process. The filament must consistently hold up against the stress of being wrapped around a spool and being used in a 3D printer. The filament needs to survive a bend of 45 degrees about a radius of 5mm and a tensile force of 30N. A break or jam of the filament will prevent the printer from functioning correctly and consistent problems like these are a sign of a poor product. Finally, any power requirements the design needs must come from a standard U.S. outlet, being 120V AC.

Design Requirements:

- Process should use all portions of the plastic bottle with minimal waste or byproducts.
- The filament should be continuous up to 1kg spools.
- The raw materials should be sourced from used plastic bottles.
- All design components should use the metric system of measurements.
- Any changes to the process should be low cost to build so the average consumer can afford to repeat it, ideally less than $100.
- Any changes to the process should improve the cost/revenue ratio of the filament.
- The process should be environmentally friendly with a net positive impact.
- The project budget should stay under $1000.

Design Constraints:

- The process must be safe and usable by an average person.
- The filament must be of desirable properties to use on any standard 3D printer: 1.75mm diameter +/- 0.1mm.
- The filament must withstand the stress of spooling and 3D printing. Bending stress is the greatest risk. Must withstand 45° bend with radius of 5mm.
- The filament must withstand 30N of tensile force.
- The ribbon must not break or become jammed during the pultrusion process 90% of the time.
- The filament should not consistently clog or outgas the 3D printer. Should at least get through five prints without clogging or outgassing.
- Any power requirements must be available from a standard outlet: 120V.

To meet these requirements and constraints multiple experimental designs were thought up and created. Each method went through many iterative designs and experimentation to give it the best shot at being successful. The finalized versions of the methods were then conducted, and initial testing was done to see if a successful standard joint could be made and hold itself up. After this the methods were further narrowed down by eliminating those that could not pass the first round of testing. More rigorous testing was then conducted for the remaining methods to see if all requirements and constraints were met. The methods that could accurately and consistently make a joint that met all criteria were then further improved through the creation of prototypes that aimed to correct any remaining potential issues of the initial methods, including environmental impact. It is recommended that these prototypes continue to be fleshed out and used by the sponsor in the future.

Division of Labor

Figure 3 breaks down the division of responsibilities within the Green Ellipsis team. Brian Alano and Jane Kang acted as primary industry points of contact for all project-related needs. Brian orchestrated progress update meetings and steered the team towards accomplishing the laid-out objectives. Meanwhile, Jane played a pivotal role in procurement, sourcing parts and tools, while also facilitating the transformation of ideas into tangible designs.

During the first semester Ryan Hunter served as the team lead, orchestrating meetings within the senior design group and organizing weekly work agendas. Jacob Davis utilized Autodesk Inventor and Siemens' NX to craft high-quality CAD drawings. Allison Wolfson conducted thorough research and translated conceptual ideas into practical implementations. Christopher Zervos took the helm in overseeing test builds, spearheading the testing protocols across various scenarios. These roles collectively contributed to the team's cohesive functioning.

During the second semester solution methods were split up between each person. Ryan focused on the perforation and zip tie methods, Jacob focused on the ultrasonic and friction welding methods, Allison focused on the simple soldering and silicone methods, and Christopher focused on the nichrome method. Each person iteratively worked on and finalized their methods for testing, reaching out to each other if help was needed. Allison and Christopher then focused on conducting the various tests on each method while Jacob and Ryan worked to further design prototypes for the methods that were found to be successful. Ryan also spearheaded much of the 3D modeling that was needed for multiple designs.

Table 1, presented below, outlines the billable hours logged by each team member over the course of the first semester, reflecting their individual contributions and engagement. Table 2 follows with the relevant information for the second semester. These hours represent only time spent working on the project and do not reflect class sessions nor instructor meetings.

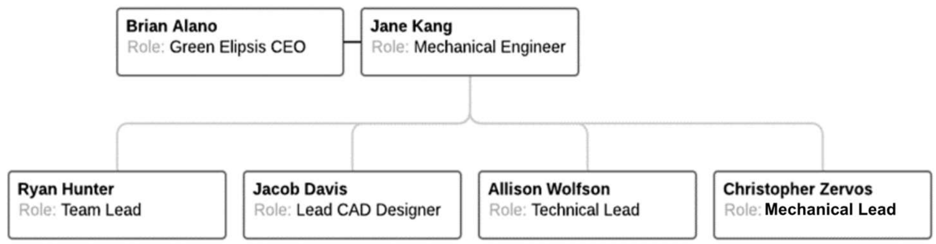

Figure 3: Company Tree.

Table 1: Billable hours by person for first semester.

Week/Person	1	2	3	4	5	6	7	8	9	10	11	12	Total
Ryan Hunter	0	2	4	5	6	3	7	6	26	3	2	10	74
Jacob Davis	0	2	3	5	5	2	3	3	17	3	2	7	52
Allison Wolfson	0	2	4	5	5	3	7	8	23	3	2	9	71
Christopher Zervos	0	2	3	4	5	1	5	5	17	3	2	5	52
Total Hours	0	8	14	19	21	9	22	22	83	12	8	31	249

Table 2: Billable hours by person for second semester.

Week/Person	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Ryan Hunter	2	5	7	10	20	10	13	22	22	15	13	16	18	15	17	205
Jacob Davis	2	4	4	5	8	7	6	10	10	8	7	7	9	8	12	107
Allison Wolfson	2	5	5	7	6	6	8	8	10	10	11	10	15	14	22	139
Christopher Zervos	2	4	4	7	7	6	6	9	10	8	9	11	10	10	14	117
Total Hours	8	18	20	29	41	29	33	49	52	41	40	44	51	47	65	567

Design

Project Problem Statement and Description

Polyethylene terephthalate (PET) plastic waste is a major contributor to pollution of the environment [6]. Because of this, many people and companies have been working to create ways to manage this waste by reusing and recycling. Green Ellipsis, the sponsor of this project, processes two-liter PET plastic bottles and upcycles them into usable filament for 3D printing. The company currently has a manual process that creates a viable end product but is not economically feasible due to the labor-intensive nature of the operation and the minimal amount of filament that is produced from each bottle. The goal that Green Ellipsis has for the future of this endeavor is to reduce the cost of producing the filament (primarily labor) so that the filament can be sold for a profit or at least cover the cost of producing it as much as possible. After optimizing the process, Green Ellipsis plans to either sell kits with the required components for individuals to replicate it or offer free plans to achieve the same goal. The hope is that the process developed will be used by community level groups that have interest in environmental work, 3D printing, or both. Because the raw material (two-liter bottles) will generally be acquired at no cost through donation and recycling collection, the only cost to these groups would be buying/building the process and whatever running costs it takes to make the filament.

The problem faced by Green Ellipsis is that the current cost of producing the filament compared to what it can sell for is too high. It is expected of this group to find solutions to improve that cost/revenue ratio to make the process economically feasible. Currently, the filament is produced one bottle at a time which produces discrete, 10m long, 20g strands of filament as seen in Figure 4. Generally, it is desirable to have a single longer strand of filament for ease of use while 3D printing. Due to the short length of the filament currently produced, the sale value of the product is low. Green Ellipsis has indicated that one of the best ways to increase the value is by splicing multiple strands of filament together into 1kg or half kg spools.

Figure 4: Current produced end product, from bottle to strips to filament.

There is currently no known process for reliably splicing strands of PET filament in a way that maintains the desired mechanical properties for 3D printing. Creating such a process would increase the value of the filament and increase the viability of selling the product. The main hurdle that must be overcome when splicing PET filament is avoiding the brittleness that comes from recrystallization. If the material is brought above the glass transition temperature, as is common in many traditional splicing methods, it must be quickly cooled in order to maintain its amorphous form. The filament also needs to stay a consistent diameter of 1.75 mm so as not to cause any inconsistencies when running through the 3D printer. Attempts by others to find methods to splice this filament have had mixed results. Some solutions have been found but have been unreliable and difficult to repeat with any level of accuracy. The objective of splicing would be to explore and identify a simple, repeatable method for connecting plastic from one bottle to the next, aiming to create a continuous spool of filament that can be effectively utilized by a 3D printer. This would involve chemical, thermal, and mechanical experimentation as part of the efforts to seek a solution to the problem.

Requirements and constraints:

Each of the following design requirements and constraints were imposed by Green Ellipsis and are needed for the final process to be viable. The constraints are strict limitations to be followed to create a final product. The goal of this project is to produce an open-source solution and implement it into community-based buildings. Because of this, it needs to be safe and usable by an average person with minimal or no training. Safety is the number one constraint; whatever process is created should not pose any harm to the user. Because the goal is to make a widely appealing product, the filament produced must work in an average 3D printer. The standard filament size of 1.75 mm is most used and is the target size for production by this process. The filament must consistently hold up against the stress of being wrapped around a spool and being used in a 3D printer. The filament needs to survive a bend of 45 degrees about a radius of 5mm and a tensile force of 30N. A break or jam of the filament will prevent the printer from functioning correctly and consistent problems like these are a sign of a poor product. Finally, any power requirements the design needs must come from a standard U.S. outlet, being 120V AC.

Design Requirements:

- Process should use all portions of the plastic bottle with minimal waste or byproducts.
- The filament should be cheaper to produce than the cost it can sell for, the current cost to produce is $109 including labor.
- The filament should be continuous up to 1kg spools.
- The raw materials should be sourced from used plastic bottles.
- All design components should use the metric system of measurements.
- Any changes to the process should be low cost to build so the average consumer can afford to repeat it, ideally less than $100.
- Any changes to the process should improve the cost/revenue ratio of the filament.
- The process should be environmentally friendly with a net positive impact.
- The project budget should stay under $1000.

Design Constraints:

- The process must be safe and usable by an average person.
- The filament must be of desirable properties to use on any standard 3D printer: 1.75mm diameter +/- 0.1mm.
- The filament must withstand the stress of spooling and 3D printing. Bending stress is the greatest risk. Must withstand 45° bend with radius of 5mm.
- The filament must withstand 30N of tensile force.
- The ribbon must not break or become jammed during the pultrusion process 90% of the time.
- The filament should not consistently clog or outgas the 3D printer. Should at least get through five prints without clogging or outgassing.
- Any power requirements must be available from a standard outlet: 120V.

Design Alternatives and Decision-Making Process:

The final concepts considered to increase the cost/revenue ratio were as followed:

- Automation of the cleaning process
- Automation of the pultrusion process
- Automation of the winding and packaging process
- Creation and automation of a coloring method
- Creation of a reliable splicing method

Each of these concepts were discussed and brainstormed. Potential ideas and solutions were created for each. A down selection process in the form of a Pugh chart was used to determine which process was best suited for the goals of this project. The following section provides detailed descriptions of process improvement ideas and their components.

Automation of the Cleaning Process

The concept that received the most consideration from the sponsor, Green Ellipsis, was the automation of the cleaning process due to its significant time consumption and operational challenges. The heat shrunk labels of the bottles must be removed, then the leftover glue and remaining pieces of the label must be gently scraped or scrubbed off. This is currently done by a dull blade and an abrasive sponge dipped in D-limonene. D-limonene is a natural cleaner derived from citrus fruits and acts as a solvent for the glue. The inside of the bottles must also be cleaned to ensure there are no contaminants in the filament once formed.

Illustrated below in Figure 5 is a potential design for automating the cleaning process. This proposed design drew inspiration from the principles of a car wash. In this envisioned setup, warm water was introduced into a lower reservoir located beneath a spinning contraption upon which the bottle was secured. The table the bottle sat on was spun by a slowly revolving motor. D-limonene was added and mixed into the warm water. This mixture was delivered through a nozzle equipped with an abrasive cloth that moved vertically, meticulously cleaning the spinning bottle.

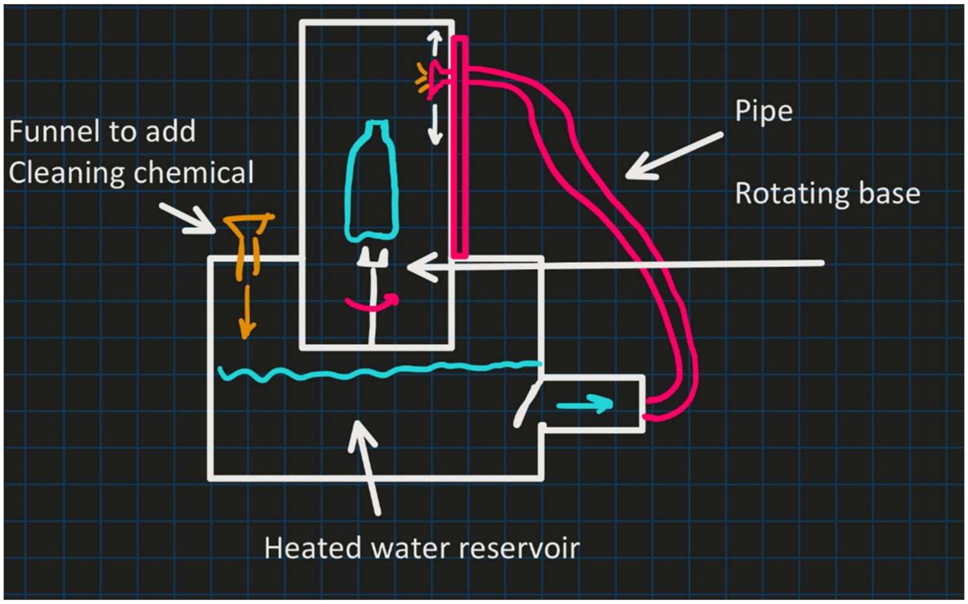

Figure 5: Potential design sketch for automation of the cleaning process.

Automation of the Pultrusion Process:

The pultrusion process can be difficult to get started. The user must fish a thin piece of the ribbon into the hot nozzle using pliers before pultrusion can begin. The current process, which is done by hand, is prone to unreliability and often requires multiple attempts to achieve proper alignment. A proposed concept that the sponsor presented was to cut the hot end nozzle in half and have it close around the initial strip cut from the bottle. Once the hot end was closed around the strip, an automatic locking mechanism would activate and the pultrusion process would begin. There is already a program implemented in the machine to track the temperature, so once the temperature reached steady state, rollers would be used to propel the strip forward through the nozzle. A sketch of this proposed process can be seen below in Figure 6.

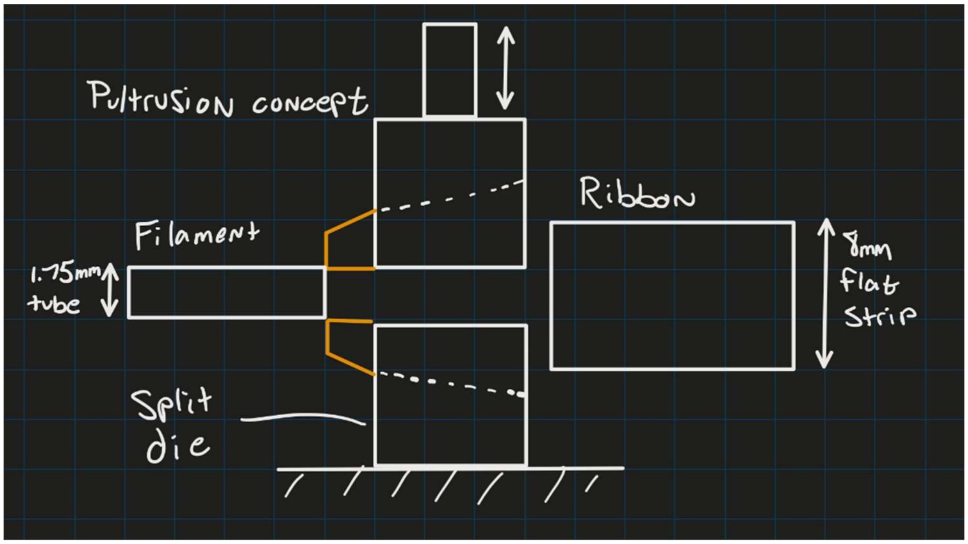

Figure 6: Potential design sketch for automation of the pultrusion process.

Automation of the Winding and Packaging Process:

In the current process, the filament is wound onto a spool at the end of the upcycle machine. This spool is powered by a stepper motor controlled by the same interface as the pultrusion hot end. The filament is tightly wound during the process of its creation but must be undone and cleared off by hand after each bottle is processed. Automating this procedure would save time and allow more bottles to be processed consecutively with less down time. Figure 7 below shows a sketch of a proposed concept for the automation of this process. This concept involves double-sided spools that automatically flip using a sensor-controlled motor once a bottle has been fully processed into filament, enabling a seamless transition to the next round of filament production.

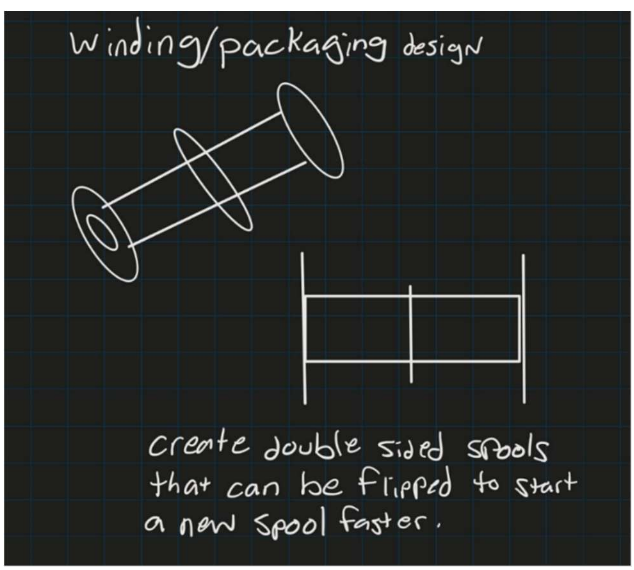

Figure 7: Potential design sketch for automation of the winding/packaging process.

Creation and Automation of a Coloring Method:

Single use PET bottles are typically clear; this means any filament made from the upcycling of the bottles will also be clear. Clear filament means a semitransparent, colorless result out of the 3D printer which is not always desired. One way to increase the sale price of the produced filament would be to diversify the product by adding color to it. This proposal would be an additional process that could be implemented and automated with the existing machine. The initial design concept was to implement a device consisting of two piston-like ink reservoirs immediately after the pultrusion hot end. These pistons would continuously stamp down on both sides of the filament, dyeing it with a selected color just as it is created. A sketch of this proposed idea can be seen below in Figure 8.

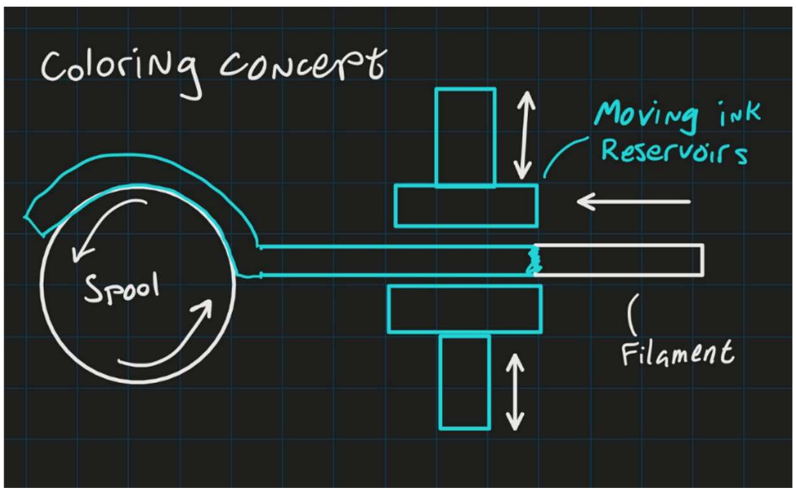

Figure 8: Potential design sketch for automation of the coloring process.

Creation of a Reliable Splicing Method:

Each standard two-liter PET bottle creates approximately 20 grams of usable filament. Typically, 3D printer filament is sold in either 1kg or half kg spools. It is difficult to sell or use such a small amount of product because a single print may require multiple 20g strands. The sponsor suggested that a great way to improve the marketability of the filament would be finding a way to splice multiple strands of filament into a single continuous 1kg spool. PET filament is notoriously difficult to splice together. Currently, the only agreed upon method by hobbyists is to use a $700 machine known as the Palette 2 Pro [7] which can be seen below in Figure 9. Even this professional method of filament splicing can be unreliable for PET due to the plastics tendency to crystalize. If splicing was to be the selected method for improving the overall process, multiple methods would need to be explored and tested experimentally to find a viable solution. If a reliable method of splicing was found, optimizing it, and ideally automating it would be the stretch goal.

Figure 9: Palette 2 Pro [7].

Down Selection of Process Alternatives:

A Pugh chart was created to determine which design alternative would yield the greatest benefit for the main process. Eight criteria were selected and weighted on a scale from one to five, with one indicating the least importance and five indicating the most importance. This Pugh chart can be seen below in Table 3.

Table 3: Pugh Matrix and results for process down selection.

Pugh Matrix							
Critical Quality	*Weight 1-5*	Cleaning/ Prep	Pultrusion	Winding/ Packaging	Coloring	Splicing	
Difficulty	1	1	-1	0	1	-1	
Team Knowledge	2	0	1	1	-1	-1	
Time Saved	3	1	0	1	0	0	
Sponsor Preference	4	1	0	-1	-1	1	
Benefit	5	0	-1	0	0	1	
Maintenance	2	-1	1	0	-1	1	
Cost to Reproduce	2	0	-1	0	1	0	
Safety	3	0	1	1	1	0	

Summary Table						
Total "1s"	3	3	3	3	3	
Total "0s"	4	2	4	2	3	
Total "-1s"	1	3	1	3	2	
Total Weighted Score	6	-1	4	-2	8	

The difficulty criterion was based on how difficult the team perceived it would be to move forward with a given concept. This matched with the next criterion of the team's prior knowledge on the individual topic. These were both given lower rankings since the team could conduct research and learn about each topic, minimizing the impact these criteria have on the final product. The time saved criteria are a measure for how much time the proposed idea would reduce the filament creation process by. This criterion was given a moderate weight since the main goal of the project is to lower cost/revenue ratio and time saved is labor saved. The sponsor's preference received a high ranking because the group aimed to enhance what the sponsor had identified as the most important. The benefit criterion was given the highest weight. This criterion measures the positive impact a given concept would provide the process based on the group's experience and research. Both maintenance and cost to reproduce were given equal weight, as it's moderately important for the chosen process to be replicable by hobbyists and communities. Finally, safety was included as a measure of how safe it would be both for the team to expand upon and for someone else to be able to use.

Final Concept Selection

The down selection process yielded that the creation of a reliable splicing method for the filament would be the most beneficial concept to move forward on. For this process, a single concept could not be picked since it would be based on experimentation and the testing of different methods to find something consistent and viable. The following pages of this review will discuss the different methods the team will attempt and how these methods will be tested.

Design Calculations and Testing Criteria

Multiple of the splicing methods described below, in the proposed solutions portion of the report, use heat as a method of splicing the two ends together. Because it is common to many of the methods, it is useful to calculate the energy required for the splice to occur. For this calculation, it was assumed that the PET was a cylinder 10mm long and 1.75mm of constant density. The total heat energy transfer required was calculated using equation 1 below.

$$\text{Total Energy Transfer} = m*c*\Delta T \tag{1}$$

Where:

m is mass

c is the specific heat of the material

ΔT is the temperature differential.

The temperature change used for this equation was the glass transition temperature of PET. This varied between different samples of PET, so two calculations were performed to get the most conservative and least conservative heat transfer values [8][9]. Running through these calculations yielded a maximum value of 16.524J and a minimum value of 6.14J. The hand calculations made supporting this value can be seen in Appendix A.

Before presenting the proposed splicing methods to examine, it is important to discuss how the various solutions will be evaluated against each other. Each proposed method will be experimented with and finalized. After being finalized, each method will aim to create 10 splice points that can hold their own weight in the filament stage. If success in joining the filament is achieved, then each of the 30 joints will be made and evaluated for strength, flexibility, shape, and printability where each test will require 10 joints for testing. According to the sponsor, a 99% success rate is required for commercial success. However, since time is a major limiting factor, and this is a project exploring experimental designs to further be improved before becoming a commercial product, the sponsor has requested aiming for a 70-80% success rate with a 70-80% confidence. This will mitigate both type I and II errors, considering the potential for human error [10]. Since the production material, PET bottles, are so cheap to acquire, the only constraint for testing the methods is time.

Tensile Testing

The first criteria that will be evaluated is the tensile strength of the filament joint. Whether it was joined before or after reforming, the joint must withstand the tension requirements of 30N, according to internal testing done by the sponsor. A testing apparatus has been designed and can be seen below in Figure 10, with the full dimensioned drawing placed in Appendix C. This apparatus holds one side of the filament joint fixed while the other is connected to a mass of 3 kilograms. Once the mass is lifted to where it will not add tension to the joint, the filament is then placed into the grips. Screws are then placed into the screw holes shown in Figure 10 to add pressure so that the filament does not move.

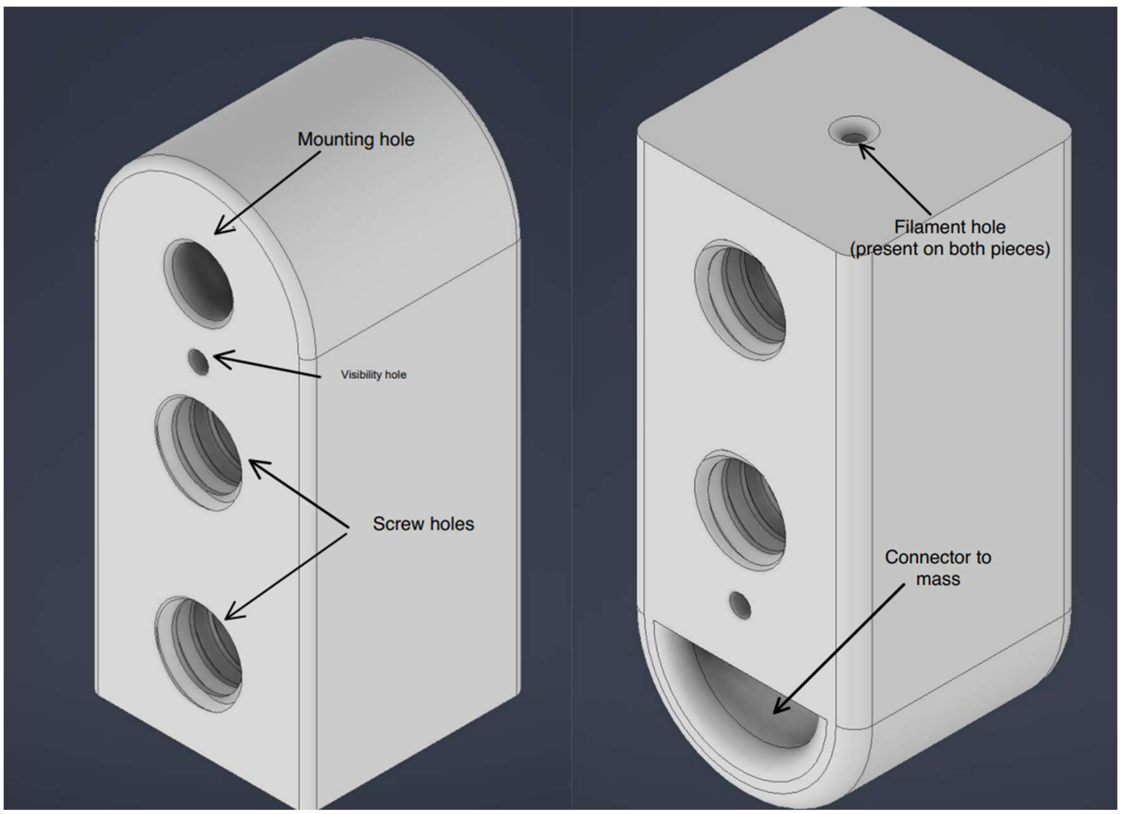

Figure 10: Filament tensile test parts.

Angle Testing

The second criterion that the filament will be graded on is the flexibility of the joint. Because the methods that heat the plastic could turn the joint brittle, it is important to test the joint's bending strength so that it does not snap while spooled or while going through the 3D printer. The proposed design for a bend testing jig can be seen below in Figure 11. This test is designed to bend the filament to a 45º angle at a radius of three times its diameter. The diameter of the filament is

1.75 mm, so the radius of the bend is 5.25 mm. This angle and radius combination is a common requirement for filament to withstand the spooling and 3D printing process according to the project sponsor. The filament joint will be graded by the number of these bends it can withstand before failing. For full dimensions of this part, refer to Appendix C where an engineering drawing is provided.

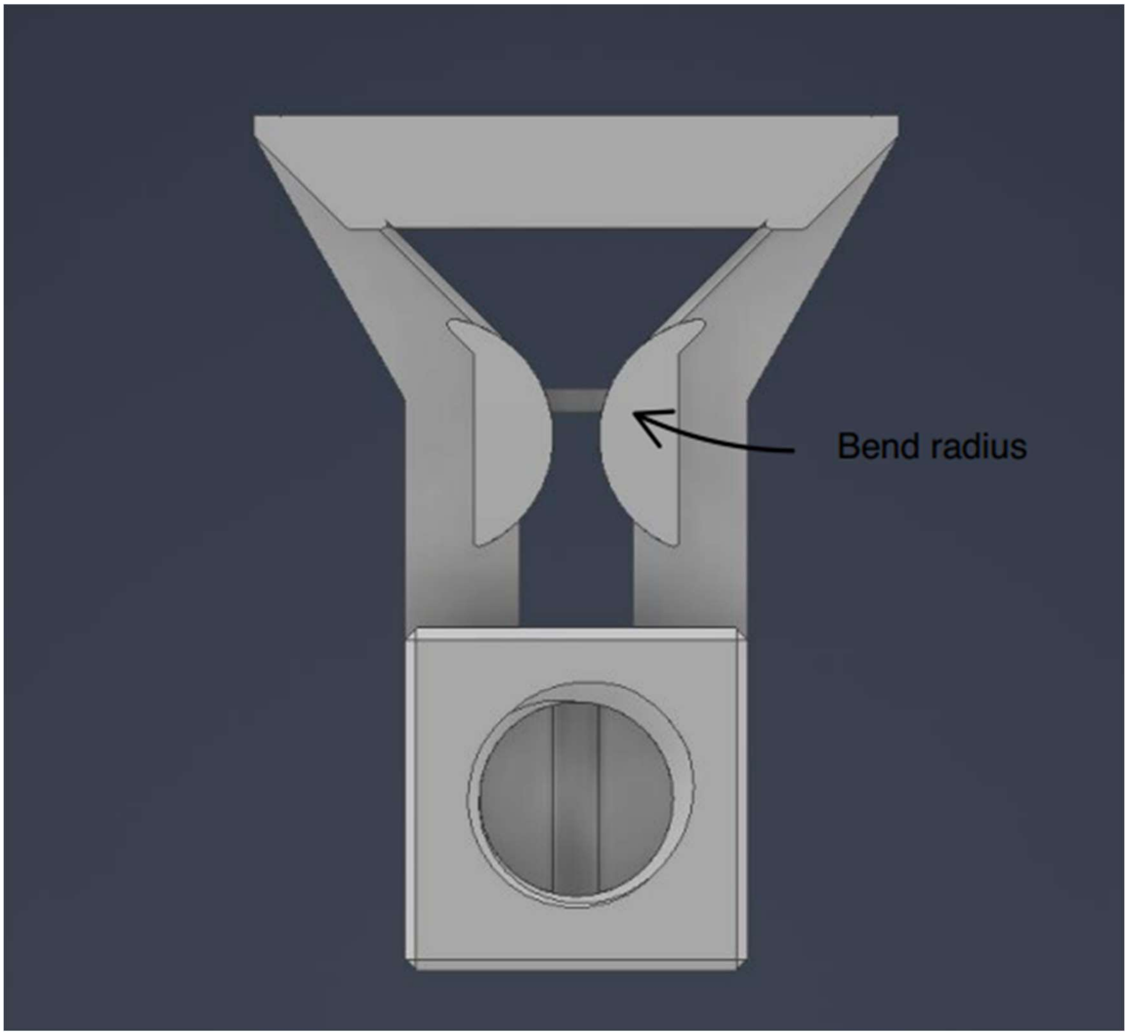

Figure 11: Filament bending test jig.

The filament joint must be of a constant diameter identical to the rest of the filament. An increase or decrease in diameter can cause the 3D print to be inconsistent or worse, the printer could clog. The diameter of the filament joint will be measured with calipers and error will be calculated from the actual diameter and the ideal diameter as seen in Equation 2. The lower this error value, the better the joint will be graded on its shape.

$$\text{Percent Diametral Error} = \frac{|D_{actual} - D_{ideal}|}{D_{ideal}} = \frac{|D_{actual} - 1.75mm|}{1.75mm} \tag{2}$$

Another shape factor that needs to be addressed is the angle of the joint. A perfect joint will have 180º between the two sides. If a joint is spliced at an angle, it is more likely to break and could fail to fit through the extruder or bowden tube on a 3D printer. The angle for each joint will be measured and the error percentage will be calculated using Equation 3 below.

$$\text{Percent Angle Error} = \frac{|\theta_{actual} - \theta_{ideal}|}{\theta_{ideal}} = \frac{|\theta_{actual} - 180^{\circ}|}{180^{\circ}} \tag{3}$$

The two error values described above will be combined to grade the overall shape of the splice joint. This overall shape grade will be used to compare the shapes of each produced joint to that of the ideal seamless joint.

Printing/Clog Testing

The final test of the filament joints is to evaluate the quality of the 3D prints of those connections. It needs to be verified that the splice will run through the printer without breaking or clogging the hot end. To test this ability, a sample print guide was created and can be viewed below in Figure 12. The sample print consumes 20cm of filament which is equivalent to 1g. To test specifically how the joints print, the 20cm of filament consumed will have multiple splices along it, much more than the standard joint every 10 meters. A higher frequency of splice joints facilitates quicker testing of the joints and simplifies the detection of any printing flaws. The test print will be completed multiple times for each splicing method to ensure the splice does not break or clog while printing.

The sample print design is a hollow cylinder 30mm in diameter and 60mm tall with a thickness of .6 mm to match the output of the 3D printer nozzle to reduce the chance of clogging when printing. After completion the cylinder will be inspected for defects such as poor bed adherence, over/under extrusion, or other visual imperfections that could result from a poorly spliced section of filament.

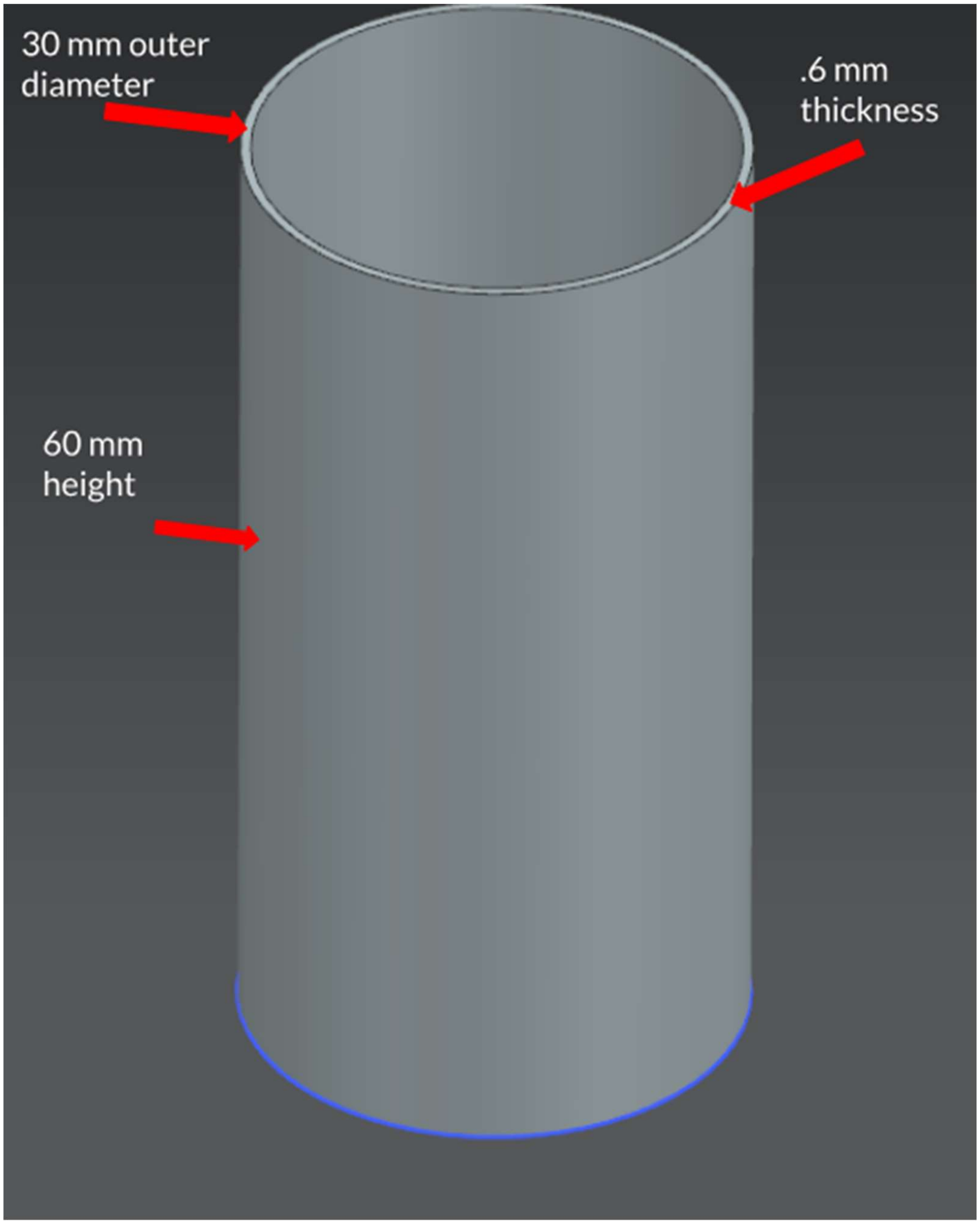

Figure 12: Test print model for 30mm diameter hollow cylinder.

Statistical Analysis

These testing methods will be evaluated with a binomial nomograph as provided by the sponsor and as shown in Figure 13. They will also be evaluated with a confidence interval of 70%, the lowest value given by the sponsor, to find the true probability of success. The equations for these probability calculations are shown below as equations 4 through 7. The z value for a confidence interval of 70% is 1.036.

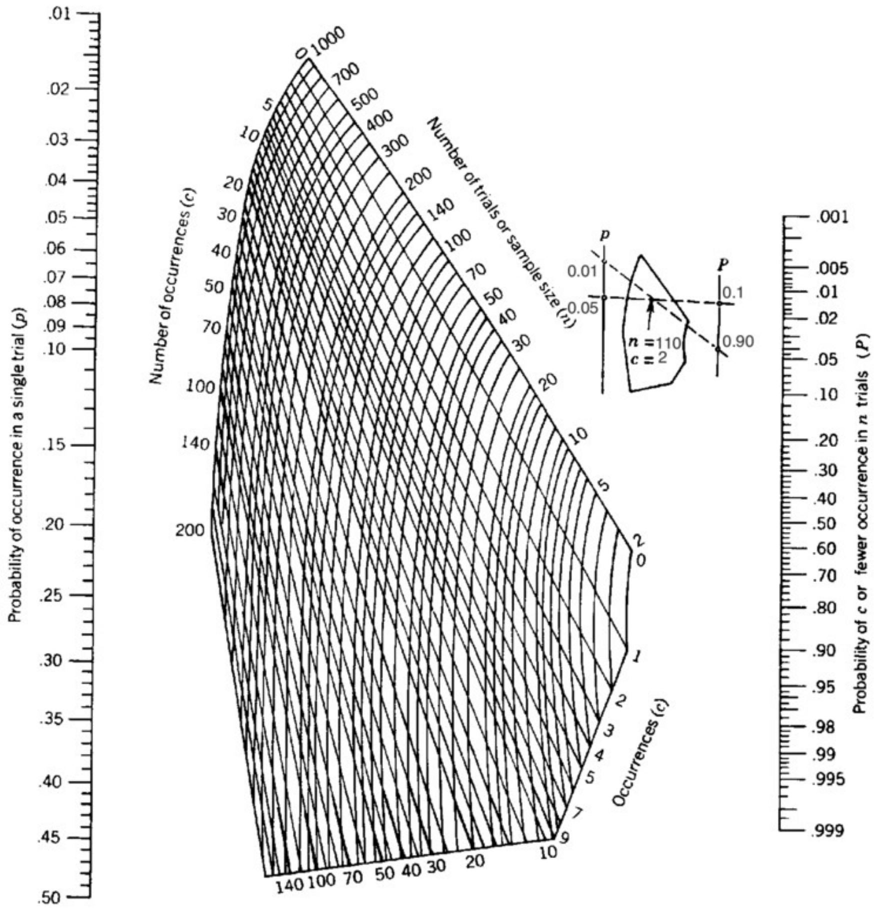

Figure 13: Binomial nomograph.

$$P(success) = number\ of\ successful\ trials/total\ number\ of\ trials\ (n) \tag{4}$$

$$standard\ error\ =\ sqrt((P\ *\ (1-P))\ /\ n) \tag{5}$$

$$Margin\ of\ error\ =\ z\ *\ standard\ error \tag{6}$$

$$Lower\ confidence\ interval = (P - margin\ of\ error) \tag{7}$$

After all proposed solutions have been completed and assessed, the experimental data found during these evaluations will guide the project towards the most viable solution which will then be optimized. Once this solution path is apparent, the method will be refined and ideally an automated or semi-automated process based on this solution will be created.

Proposed Solutions

Multiple attempts by others have been made to solve this splicing problem with no reliable answer found [11]. The aim of this project is to first find a reliable method to splice the PET filament together then to optimize that process either through partial or complete automation. As many possible solutions may exist, the decision was made to design and complete a series of experiments to test the effectiveness of many methods. The attempted solutions can be broadly categorized into two groups: ribbon methods and filament methods. The primary distinction between these categories is that the former aims to join the strands before reforming them into filament, whereas the latter does the joining after the reforming process.

Ribbon Connection Methods

The first group of solutions is a series of attempts to connect the ends of two PET ribbons together. A simple diagram of this can be seen below in Figure 14. In the current process, these ribbons are created during the middle stages of production. The bottles would still need to be prepped and cut into ribbon before this connection could occur. The connection could take many forms, but they would all be connected before going through the hot end to be reformed into filament. These methods rely on the fact that before reforming, there will be very little stress on the joint, so only a minimal connection is required to keep them together. The ribbon itself is never under much tension during the process. After going through the hot end, the filament must continue to pull the ribbon through the hot end which can require upwards of 30 Newtons of force according to Green Ellipsis. The idea is that after going through the hot end, whichever joint method that held the ribbons together will be strengthened and will withstand the stresses of spooling and printing that are required. If a method of joining ribbons together proves successful, large spools of connected ribbon could be set up and turned into a continuous filament all in one go with limited human interaction.

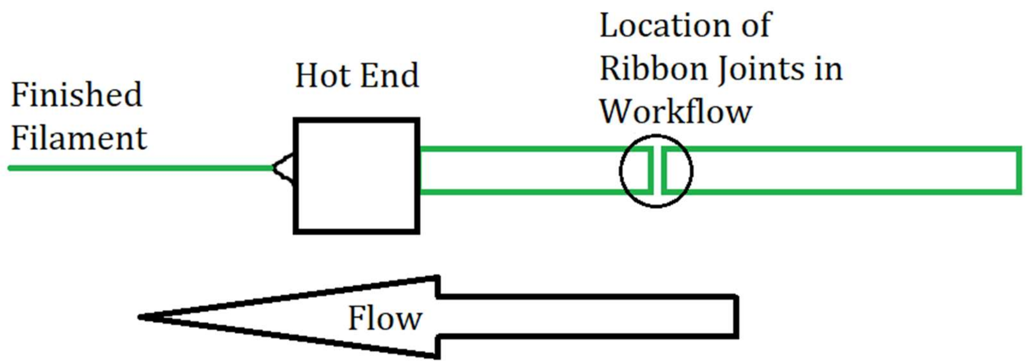

Figure 14: Diagram of a generic ribbon joint before going through the hot end

Zip Tie Method

One proposed ribbon connection has been nicknamed the 'zip tie' approach. This method cuts a specific geometry into the end of one ribbon and the start of the next so that they fit together. This mechanical connection can take many shapes, but the leading design can be seen below in Figure 15. This design weaves the arrow portion of the second ribbon through the slits cut into the first. The tip of the arrow will rest in the foremost slit and provide mechanical strength so that the two pieces do not slip apart. The “tail” of the first ribbon is also tapered to tuck into the slits cut in the second ribbon.

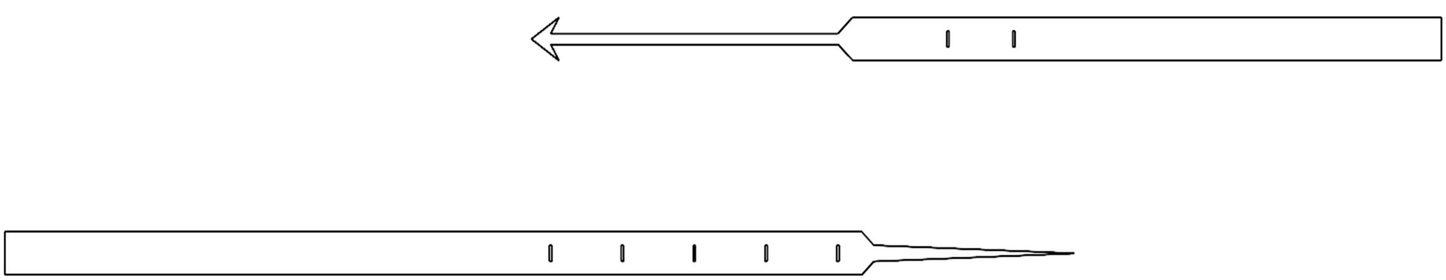

Figure 15: Zip tie method cut example.

This method of joinery between the two ribbons holds a lot of promise. The long, thin portion of the second ribbon should provide a large amount of contact area on the first once sent through the hot end. This contact area, once formed, should hold the two newly formed pieces of filament together.

The zip tie method does have several drawbacks. Both pieces of ribbon have several important, precise cuts required to work together to form the connection. Cutting these shapes by hand would be tedious at best and possibly dangerous. The goal with this joinery method would be to test its effectiveness and if it works, create a device to make these cuts automatically.

Perforation Method

A second proposed method of connecting two ribbons together is to perforate them into each other. This method overlaps two ends of ribbon and punctures uniform holes through both ribbons. The punches through the plastic ribbons will temporarily hold them together until it can be sent through the hot end. Different shapes of perforations will be tested but a device like that seen in Figure 16 below is to be used to create the perforations. A schematic of this type of device can be seen in use in Figure 17. The tool shown in this Figure is not equipped for it, but a heated version of the perforation method is also to be tested using a metal wheel that has been heated up above PET’s glass transition temperature.

Figure 16: Example of perforation tool.

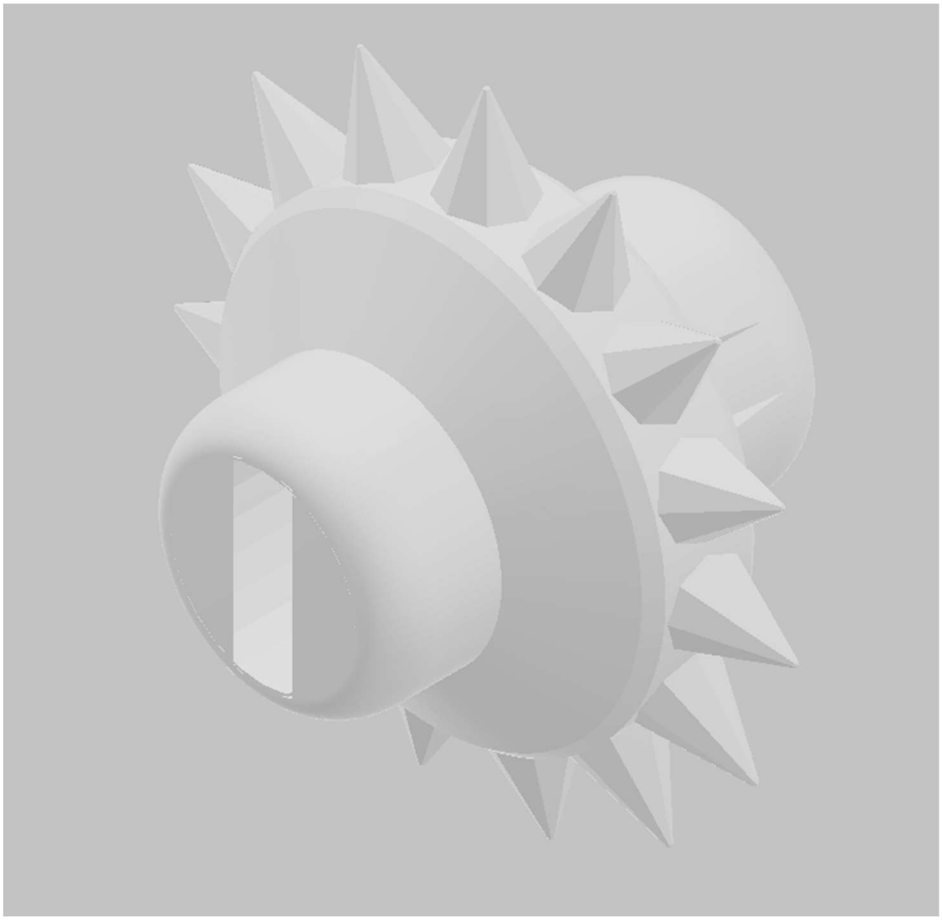

Figure 17: Spiked Wheel of the Perforation Tool zoomed in [12].

The advantage of this connection type is that it is very easy to create and requires a minimal amount of time to use. This type of tool can be very versatile because the perforating wheel is easy to replace with either a new sharper wheel or one of a different shape. Different shaped wheels create different shaped perforations, and each can be tested for strength and effectiveness.

The disadvantage to this type of connection is that it may be weak or fragile. Preliminary tests have proven that the connection is possible but does not hold up to very much stress on the joint. Luckily, as previously stated, the ribbon methods of connection are never under much tension during the reforming process. Once the two overlapping ribbons go through the hot end and are turned into filament, the strength of the joint should increase.

Filament Connection Methods

The second group of possible solutions attempts to join two ends of already formed filaments together. This could happen in a multitude of ways, but all would follow the same workflow in terms of the filament creation process. The bottles would be processed into filament exactly as the process currently does but would be attached end to end after reforming. Many other types of 3D printer filament such as PLA or ABS are spliced this way but as discussed above, the high melting point and risk of crystallization prevents these methods from working well on PET. Some preliminary success has been seen by others attempting these types of connections with PET, but none so far have proved to be a repeatable or reliable method.

Nichrome Filament Welder

The first filament connection method to be tested uses nichrome wire to weld the filament. The proposed welder will be created using a 3D printed outer shell, a battery box, nichrome wire, a limit switch, a clothespin, and aluminum foil. The 3D printed outer shell is designed to facilitate sliding, allowing the current to flow through the nichrome wire when in position. The nichrome wire conducts electricity, heating the material to a stable high temperature. The activation of the nichrome wire is controlled by the limit switch, which detects the connection of the screw to the nichrome for current conduction. Moving the block outward disengages the heating element, and a clothespin with a 1.75 mm hole, wrapped in aluminum foil, is used to rapidly cool the filaments.

As illustrated in Figure 18, the filament welding test involves two different filament color combinations: one with clear and green filaments, and another with clear filaments. These color differences will help determine what the splice looks like after joining. Once the filament is joined, it will go through the process again to assure the splice was created. Once this is complete, the material will be cut to have a smooth outer surface and a diameter of 1.75 mm. The joined filament that was created from the process being the green-to-clear mixture and the clear-to-clear mixture will be tested to see if the different colored materials influence the strength or brittleness of the joint.

This method has several advantages, including the ability to quickly splice the materials together and have them ready to use for printing. This method also uses relatively inexpensive materials that are readily available to order and use, which is one of Green Ellipsis' goals of open sourcing its products. This method does have some disadvantages, the battery box is separate from the main unit so it could easily become detached, and the wires would have to be attached again. Additionally, nichrome wire can become rapidly hot and burn someone who is not paying close enough attention.

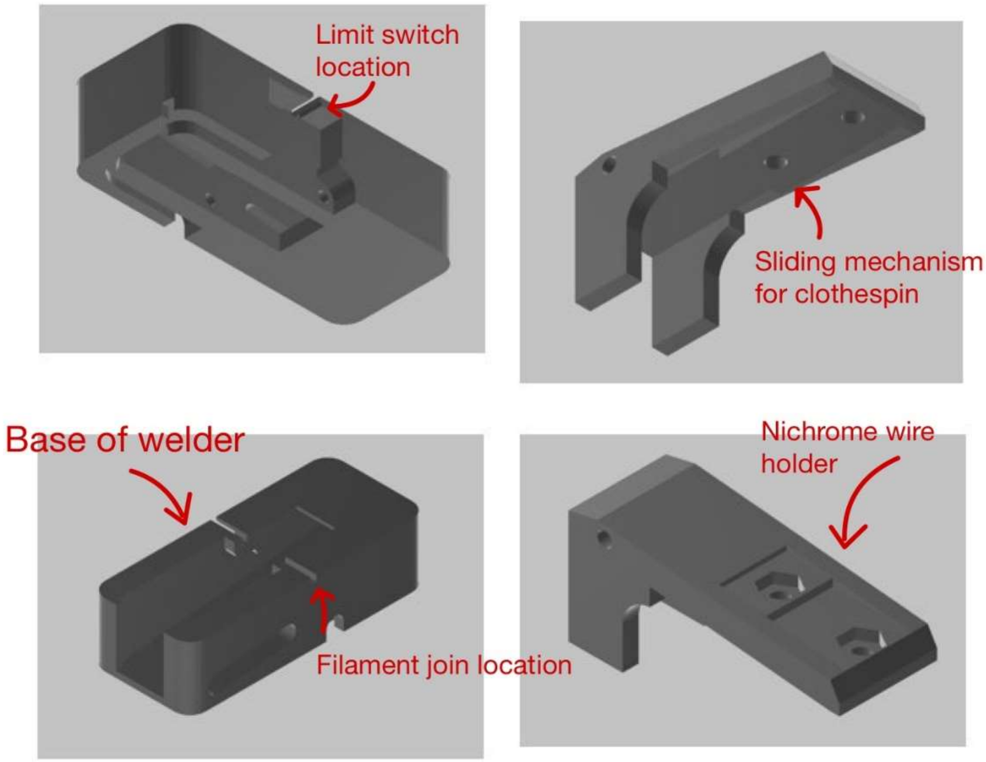

Figure 18: Nichrome Filament Welder [13].

Soldering Iron

The Soldering Iron test will include two main parts, the soldering iron and the 3D printed block in Figure 19. The 3D printed block allows for the 1.75 mm filament to smoothly enter and exit the block. The block contains a notch to allow for the soldering iron to be placed in between to allow for the two to be melted together. Once the two filaments are together, they are pushed to the left side of the block and pushed back and forth to smooth and join the two together. The material is then removed from the 3D block and smoothed using cutting tools to have a smooth finish.

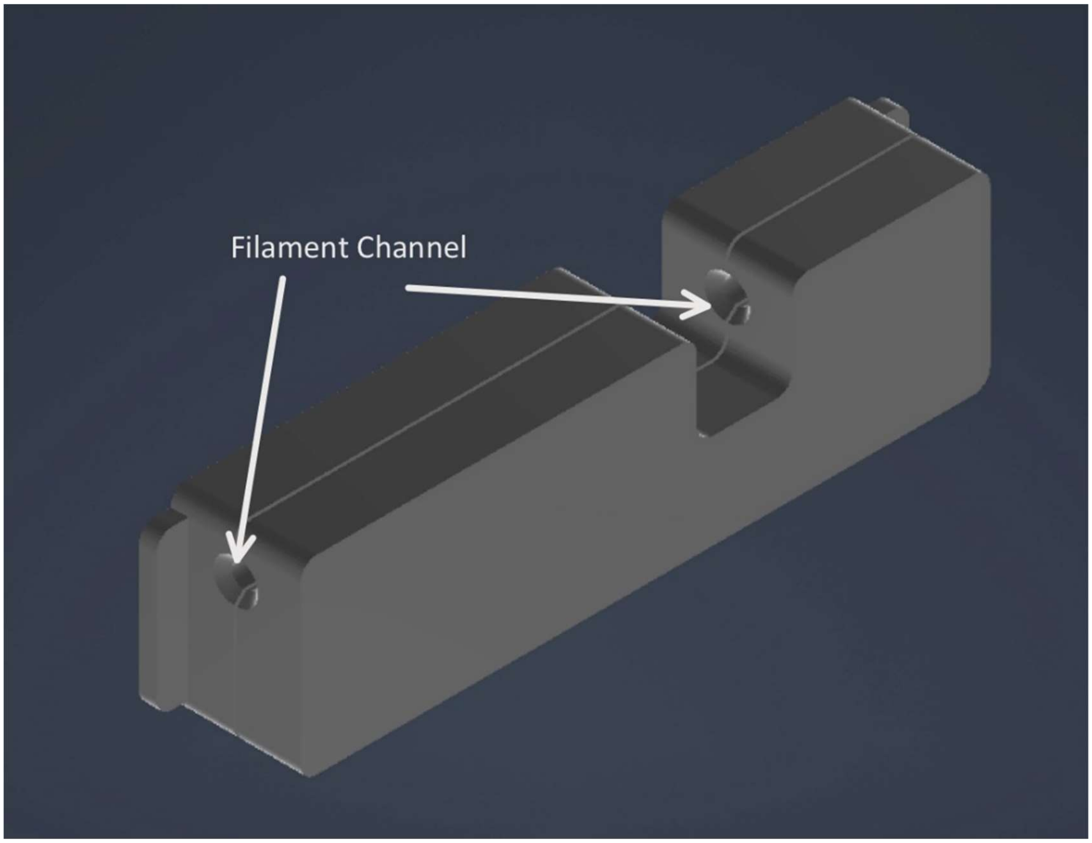

Figure 19: Soldering jig to hold filament in place.

To better improve the described soldering method, some hobbyist forums suggest using food grade silicone tubing as a heat sink and guide for the filament to heat up in [14]. As seen in Figure 20 the two pieces of filament slide snuggly into the tubing and are further held by a small aluminum band to better distribute heat. Silicone can withstand higher temperatures than PET and, even when reaching an elevated temperature, only degrades instead of melting, this makes it an excellent joiner for the filament. As the soldering iron is pushed against the aluminum piece its heat is distributed through the silicone tubing, which then evenly distributes the heat across the filaments' points of contact. This melts the filament together just enough without causing burning. After removing the soldering iron, the splice point will be quickly cooled by either a rag wetted with cool water or a high-powered fan. The silicone tubing can then be cut off or slid off and the filament should be joined together. Silicone tubing is very easy and cheap to acquire. Since the material is food grade, there should be no safety concerns in exposing it to heat. Due to the even distribution of heat and the rapid cooling, the PET should remain relatively strong and not recrystallize.

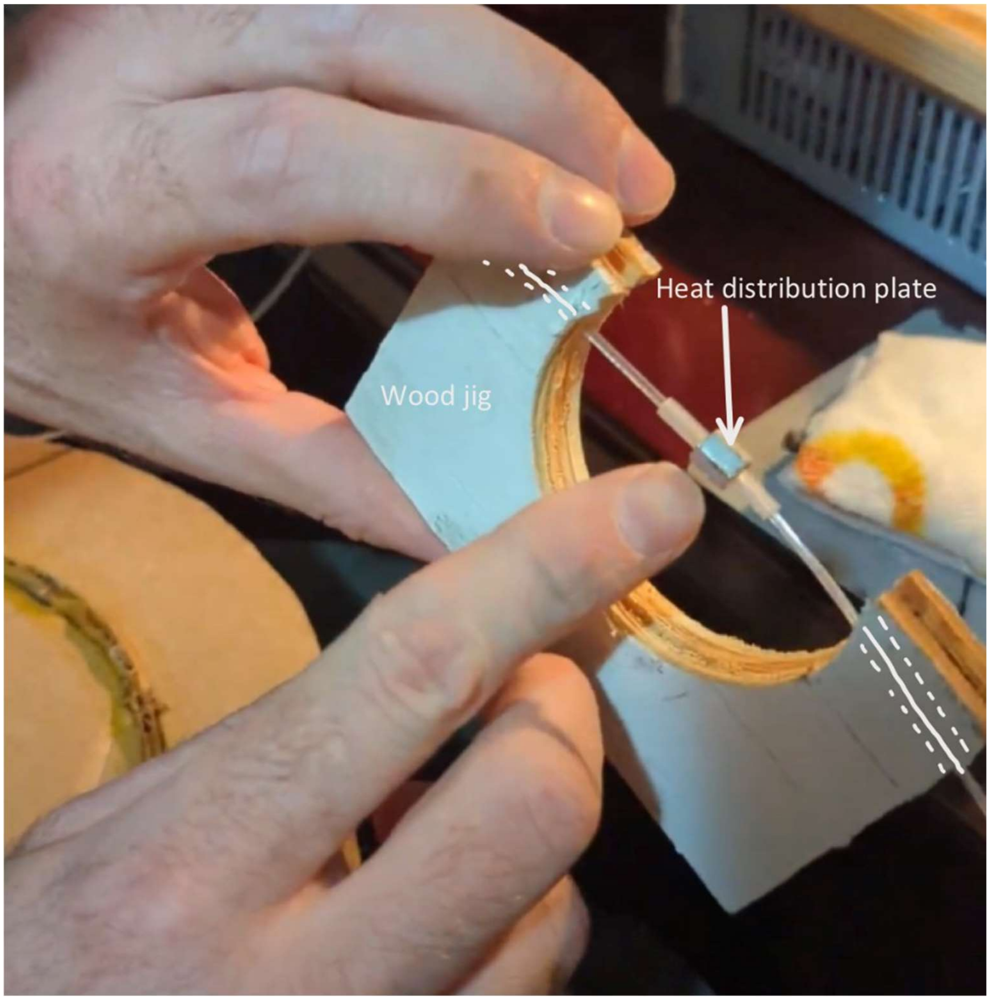

Figure 20: Set up for silicone soldering.

Friction Welding 1

A different filament joining method under examination involves friction welding. In this approach, one end of a small piece of filament is rapidly spun against the stationary ends of two strands held end to end by a jig. As illustrated in Figure 21, a rotary tool will have a small segment of pre-made filament placed inside the chuck which will then be spun at a high speed, upward of 5000 rpm. The two ends of filament will then be clamped into place within a jig to keep them square to one another. The spinning filament will then be pushed into the seam of the two filaments to be joined and the friction will generate heat and mechanically mix the material together. This process must be done multiple times as the filament needs to be rotated and clamped back in to reach other areas.

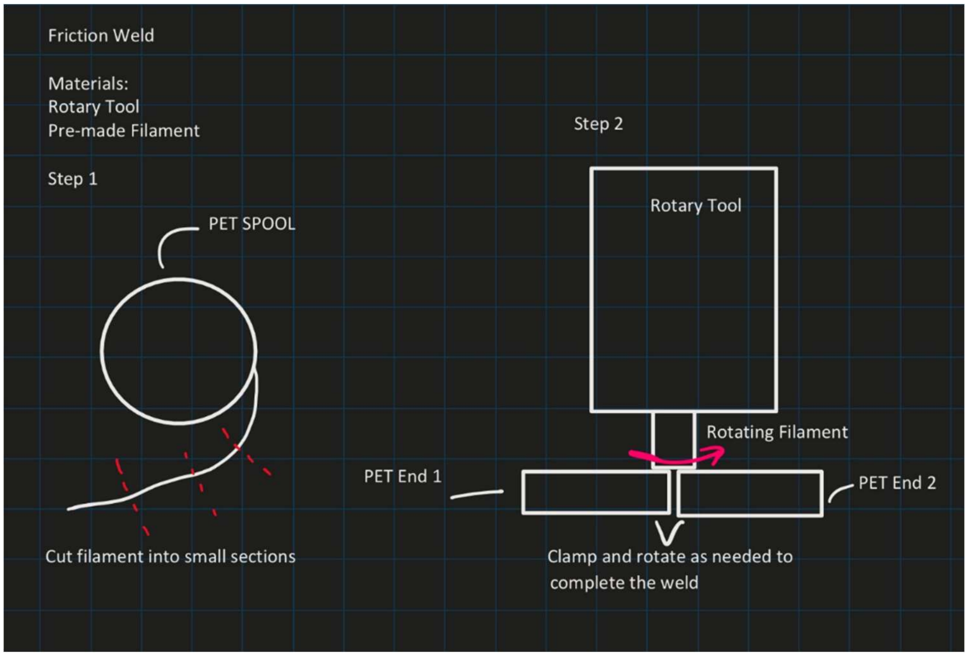

Figure 21: Friction Weld Clamp Method.

This method for joining the filament could be advantageous because it has no need for external heating sources. Additionally, the only material needed besides the jig is a rotary tool which is very common and relatively inexpensive.

The main disadvantage of this method is needing to cut small, straight pieces of filament to fit into the chuck and getting consistent diameter. This can be cut or sanded down to mitigate the inconsistent diameter and the strength of the joint may make up for this downfall.

Friction Welding 2

In addition to the friction welding method described above, a second type of friction welding will be used to fuse two ends of filament together. This method of friction welding will also spin one side of a filament strand very quickly (around 5000rpm) while in the chuck of a rotary tool. The other end of that piece of filament will be inserted into a bowden tube. This tube is made of heat resistant thermoplastic called PTFE that has very low friction. The tip of the rotating filament will be pressed against the stationary end of a second filament piece that is also clamped inside the bowden tube. The friction of the two pieces of filament as they rub together generates heat and promotes the joining of the two ends. The primary distinction between the two friction welding methods lies in their approach. In method one, two strands of filament remain stationary while a small third piece is used to weld them together. In method two, one side of the splice joint rotates rapidly in relation to the other, and it's this relative motion that generates the friction, facilitating the joint. The bowden tube has very tight tolerances and should prevent the joint from bulging or bending out of shape. If necessary, the joint can be cleaned up with a razor blade to the desired diameter.

This method has recently shown a lot of promise and has reportedly produced good results by both hobbyists and members of Green Ellipsis. An image of this method in use can be seen below in Figure 22. In this image, the white bowden tube can be seen sticking out of the piece of wood. The rotating filament is sticking out the top of the bowden tube and into the rotary tool. The second piece of filament is fixed out of view at the bottom of the bowden tube inside the piece of wood.

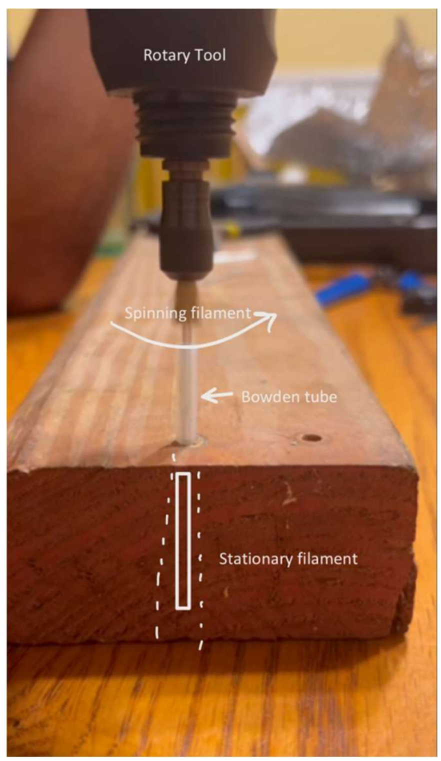

Figure 22: Stationary Friction Weld 2 Method.

The advantages of this method of joinery are that it is a quick and relatively safe method of splicing. There has been a recent surge of promising results that have shown successful splices with nice size and shape tolerance due to the bowden tube. This method is also relatively easy to recreate as the only required materials are a rotary tool, piece of bowden tube, and something to hold the parts in place.

The disadvantages of this method are that the current setup can only weld together short pieces of filament. The goal is to join 10m strands end to end which would not be compatible with sticking a piece in the chuck of the rotary tool. A separate method or device would need to be created to adapt it to working with full length strands.

Ultrasonic Welding

Another method of welding the filament is to use an ultrasonic welder. Ultrasonic welders use high-frequency acoustic vibrations ranging from 30kHz to 75 kHz to produce low amplitude mechanical vibrations that generate heat at the splice points of the parts being welded [15]. This method will require the welding tool itself, a metal plate to conduct the welding on top of, and the 3D printed block from the soldering iron test. As shown in Figure 23, the filament ends will be clasped in the case and placed on top of the metal plate. The ultrasonic welder will then be placed on the metal plate to conduct a safe weld of the PET plastic.

The greatest advantage of this method is that it is the fastest known welding technique. This method also allows for the PET to cool much more quickly than the previously mentioned tests. The finished welded material should be the most consistent when evaluated in the durability section due to the process it undergoes. The material is not affected as much as the others and should have few errors when it is printed. The main disadvantage of this method is how expensive the welding tool is and that ultrasonic welders are not commonly owned by hobby level enthusiasts.

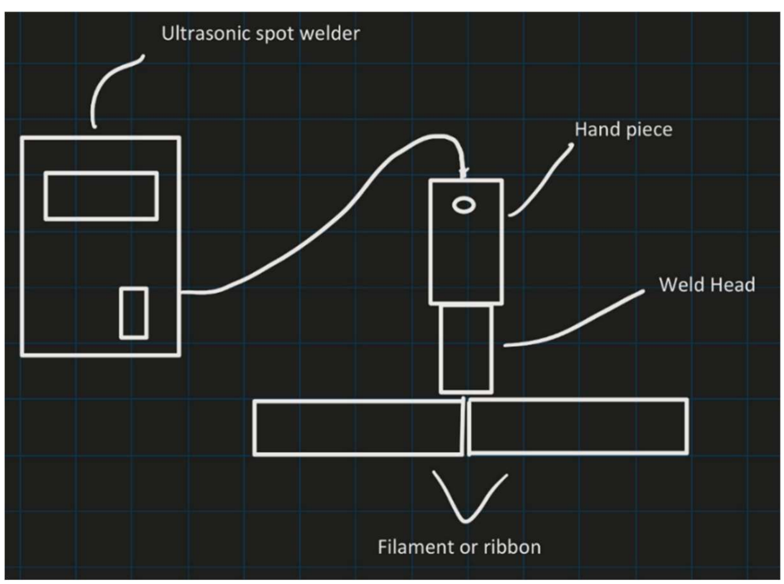

Figure 23: Ultrasonic Spot Welder Diagram

Design Changes

Perforation

The perforation method changed significantly from the early design phase to the final design. Originally, a 3D printed perforation tool seen below in Figure 24 was planned to be used. It was quickly determined that the printed spikes of the tool were too soft to effectively pierce the PET ribbon, so a similar tool made from metal was tested. The metal version of the tool can be seen below in Figure 25.

Figure 24: 3D printed perforation tool.

Figure 25: Metal perforation tool.

The metal tool was able to pierce through the double layer of PET ribbon more effectively, but the pieces were not adhering together well. Eventually, it was discovered that heating the metal spikes of the tool before perforation helped create a bond between the two pieces of ribbon. The rolling spike tool was inconsistent to use so to improve this method further, a 3D printed punch-press was designed for the final design iteration. This press device can be seen below in Figure 26.

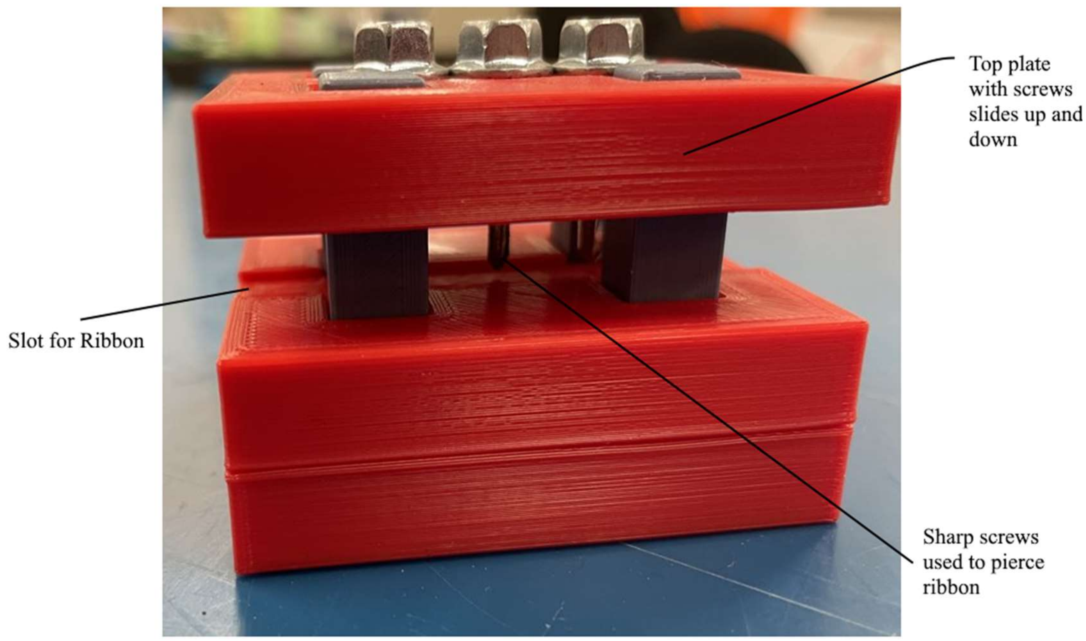

Figure 26: Punch-Press for ribbon perforation.

Zip Tie Method

The zip tie method had no meaningful changes from the initial to the final design and stayed constant throughout the testing process.

Ultrasonic Welding

Ultrasonic welding underwent many changes regarding how the filament was secured and cut. The first change was to cut some spare wood into a clamp to avoid any of the hot plastic touching the operator. This worked but was slow to set up. Painter's tape became the method to keep the ribbons in place for the welding, this can be seen in Figure 27. This tape can be reused for multiple welds but is not ideal due to it eventually needing to be thrown away or recycled.

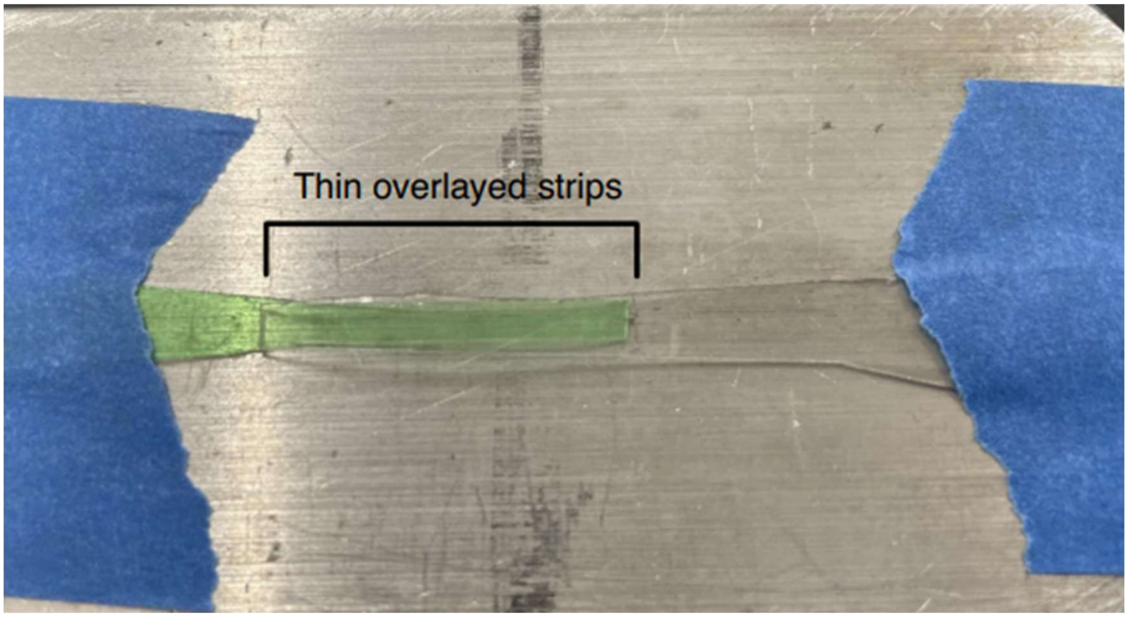

Figure 27: Overlayed strips of filament for ultrasonic welding.

After getting the joints consistent and sent through the pultruder, the strips would fail due to mass overflow. The decision to cut the ribbon to make the section where the welds take place was made, going from two 8 mm strips to 4 mm strips being welded in the cross section. This would keep the mass flow consistent if the strips were consistent throughout. This led to weaker connections in the welded areas due to less surface area for the welds, but the first successful filament was pulled through the pultruder using this method. This was unable to be reliably repeated, with the strongest joints having too much material causing the machine to stall. The smaller strips also took longer overlapping pieces to get welds of the same strength, causing excess ribbon to be wasted for a single connection that would be pulled through the pultruder.

Friction Welding

The friction welding methods proved to be very difficult for the user to complete reliably. The original plan of using the filament as a tool head became a challenge as the filament was smaller than the chuck on the rotary tool so could not be used as is.

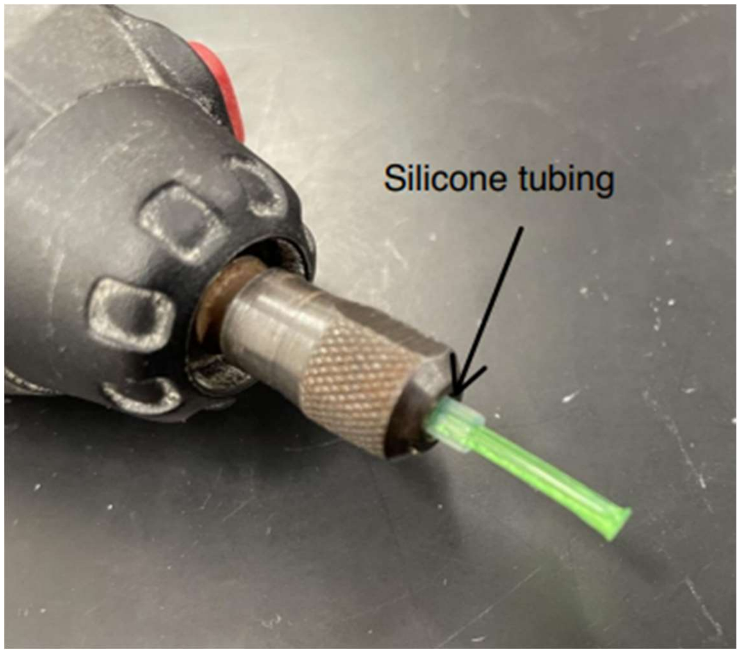

Figure 28: Rotary tool chuck with silicone for fitting.

Silicone tubing was inserted onto the filament to allow it to fit into the available chucks that the rotary tool used as shown above in Figure 28. After this change, testing of joints was able to go underway for the ribbon method of friction welding. The first joints proved to be extremely weak, being unable to bend and did not resist tension to the degree needed while undergoing pultrusion. Testing with higher pressures yielded stronger welds, but also increased the errors made during the process. The small filament diameter undergoing higher forces would cause holes to easily be drilled through the filament making it unusable for further processing. For the successful joints on the ribbon, it would be sent through the pultruder. This yielded the error of mass overflow, so solutions to the cuts of ribbon were made to have a smaller width along the joint area. This made the joints even more brittle and unable to go through any pultrusion, so this method was ultimately deemed a failure.

The second friction welding method that focused on filament joining faced similar issues with the material being eaten away. This was unable to be solved through any alterations made and was deemed a failure.

Nichrome Welding

When looking at the initial design of this method not much was changed from the original. During testing, the filament was burning from exposure to the nichrome wire. To help alleviate this small issue a silicone tube was slid onto where the two joints would meet to help evenly spread the temperature out and prevent the PET from burning instead allowing it to slowly heat above glass transition temperature. Once the PET reached this form, the joined filament was quenched in a wet towel or sprayed directly with water to cool down the filament rapidly. These new additions to the method allowed for better testing joints. Below in Figure 29 is the updated method with design changes. As mentioned earlier, the cooling method for the PET changed to a water spray or wet towel. This made the clothesline pin wrapped in aluminum obsolete in the model and became an added support to keep the coil in line with the filament. The change in quenching method also had to do with the fact that the clothesline would smash the filament and create a bulge and uneven radius around the joint.

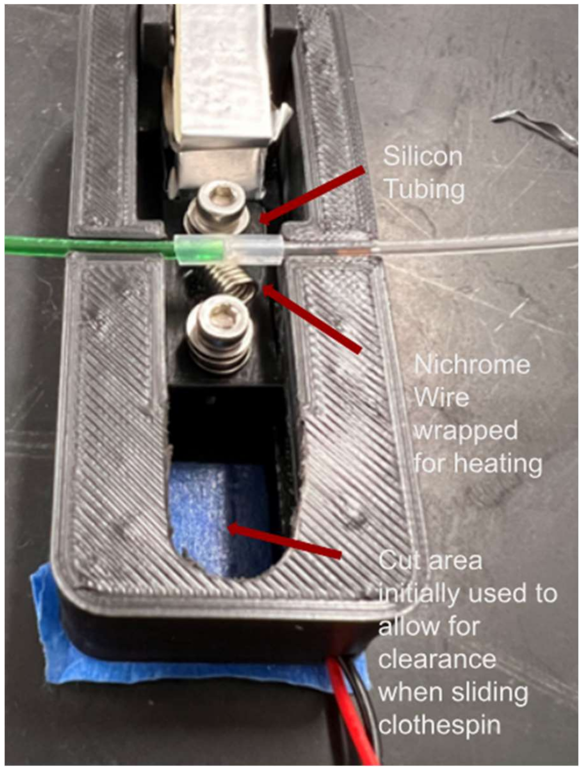

Figure 29:Nichrome Welder Updated.

Soldering Iron

The soldering iron method became two methods, a simple soldering method using the same jig as described in the proposed solutions and shown in Figure 18, and a soldering method that involved a silicone sleeve. This silicone sleeve method was also mentioned in the proposed designs but was further iterated and improved.

Simple Soldering

As described in the proposed designs a block jig was 3D printed using PLA, the actual printed jig can be seen in Figure 30 within the full set up. This jig had two holes on either end sized just slightly bigger than the diameter of the filament at 1.75mm so the filament could slide in. A soldering iron was equipped with a flat head known as a knife tip and the temperature was set to 255 degrees Celsius. The flat head made it so both pieces of filament could be held against each side of the soldering iron. Once melting of the filament began to occur, the soldering iron was quickly removed and the pieces were pushed into each other. The splice point was quickly cooled by wrapping a damp washcloth around the joint. There was a struggle to consistently keep the filament straight so an even weld could be made, especially when the pieces needed to be compressed into one and other. This struggle was limited by the help of another person, but to eliminate the need for a second person and thus more labor costs, clamps were added to the design to hold down the filament.

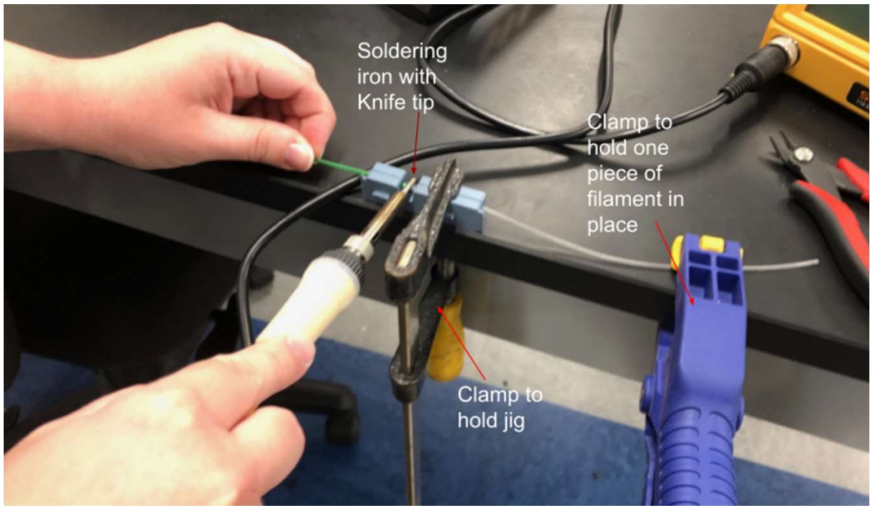

Figure 30: simple soldering method in use.

Silicone Sleeve

Initially for the silicone sleeve method a jig like that shown in Figure 19 of the proposed solutions was used. This jig was 3D printed using PLA. This jig had a 75mm gap in the center for the soldering iron and a 25mm long, 25mm deep, hole cut on each side with a diameter slightly bigger than the filament at 1.8mm to hold the filament in place. This set up can be seen in Figure 31. This jig did not work well in holding the filament straight for creating a proper and even splice, this is why another jig design was created.

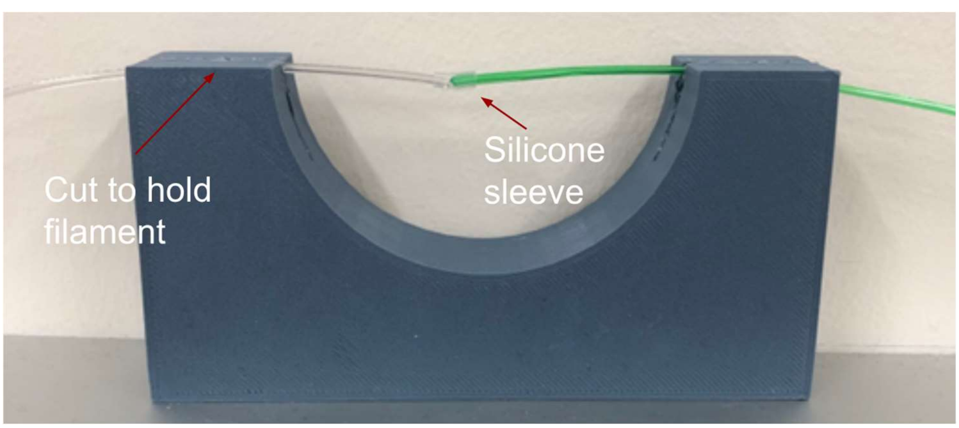

Figure 31: initial jig design for silicone soldering.

The iterated design can be seen in Figure 32. This jig is a plier type design made from 3D printed PLA. The pieces of filament to be welded together are first lined up and then connected by a piece of silicone sleeve which is then wrapped with a small piece of aluminum foil, another change from the proposed designs. A cut piece of rounded aluminum was planned to be used to distribute the heat since it could be easily removed and reused but was found to not distribute heat as well as hoped. The thin aluminum foil worked better to create an even weld at the cost of needing to be rewrapped often and thus taking more time. The aluminum foil wrapped around the silicone sleeve can be seen in Figure 33. After the pieces of filament are centered under the sleeve and foil, they are placed within the jig at the openings shown in the side view of Figure 32. One set screw is tightened on one side and then the bottom of the jig is compressed to create tension in the spring, this is held as the second set screw is tightened on top of the other piece of filament. This leaves the spring in tension as the soldering iron with a hoof tip is placed directly against the aluminum foil. As the two pieces of filament melt and weld together the spring compresses until the two back points hit to indicate a return of the spring to its initial state and a joining of the filament. The soldering iron is held in place for 10 more seconds after this moment and then the splice point is quickly cooled with a damp washcloth. The full set up of this method can be seen in Figure 34.

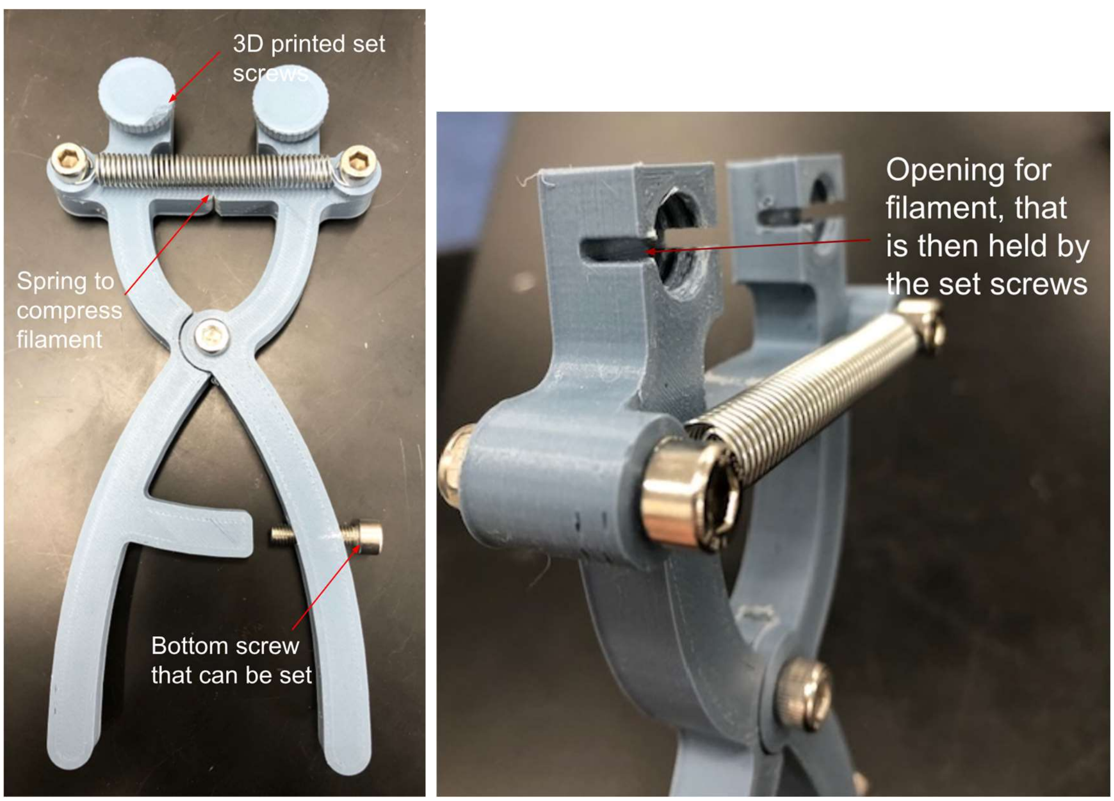

Figure 32: full and close up side view of redesigned jig.

Figure 33: Aluminum foil before and after being wrapped around the silicone.

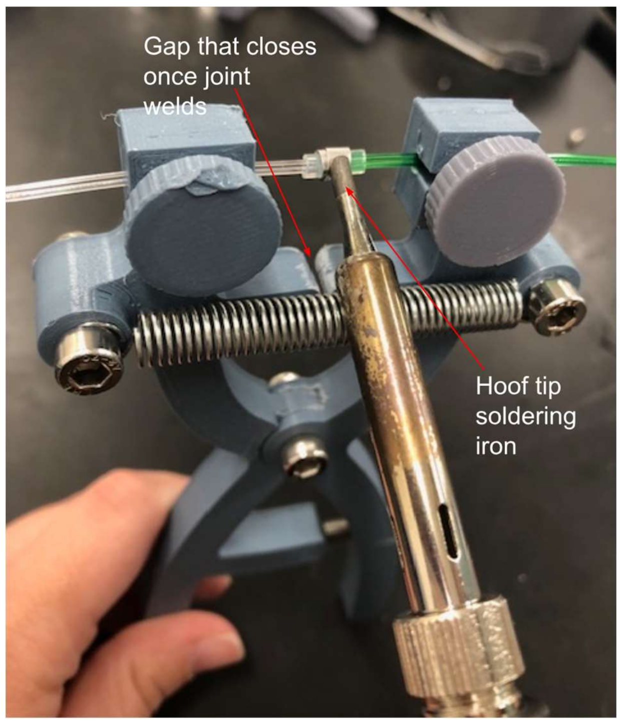

Figure 34: Silicone method in use.

Testing

Overall

As mentioned in the calculations section, all methods of filament splicing would be tested three ways: with a bend, print, and tensile test. Each testing method needed 10 spliced filaments each. First, however, an initial round of testing was done by attempting to create 10 solid splice points with each method. This initial test would allow for any joining methods to be ruled out and narrow down the methods to only those that work. With this initial test all the ribbon proposed methods: zip tie, ultrasonic, friction welding and perforation failed and did not move on to the main three tests. These methods were statistically analyzed using a binomial nomograph seen in Figure 35.

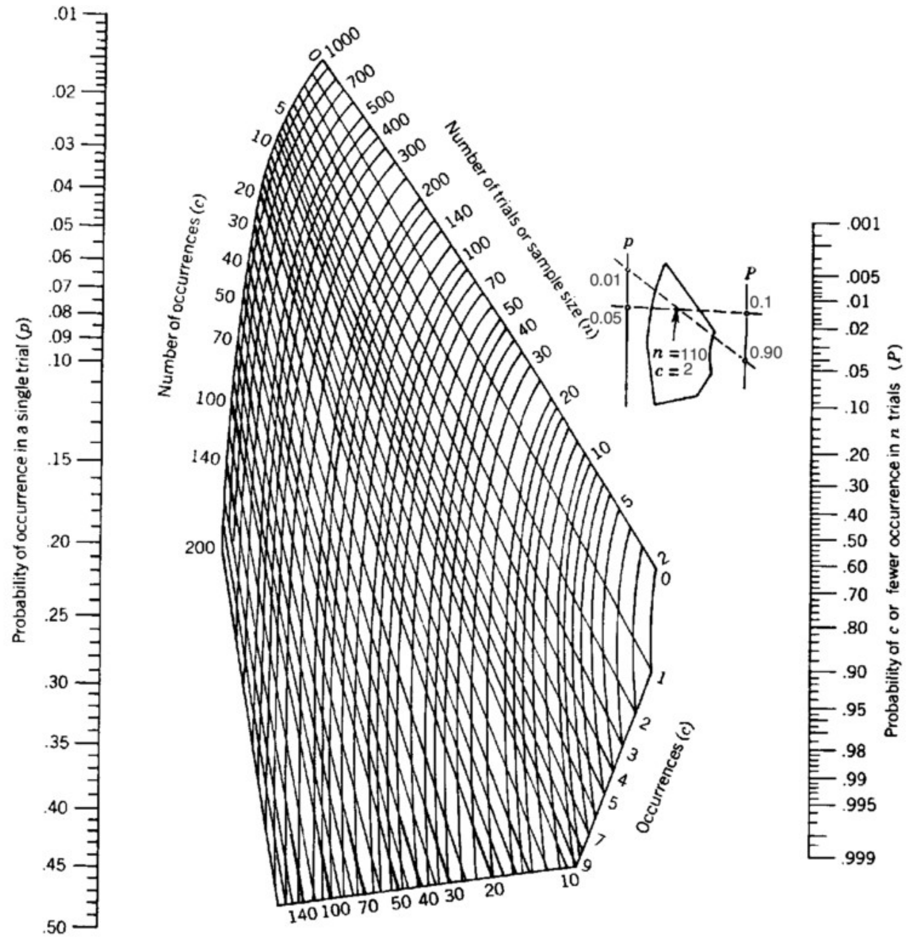

Figure 35: Binomial Nomograph

The binomial nomograph allows for 10 tests to be ran and for every pass or fail changing the chance for a failure rate. For example, if 10 tests are run with zero failing there is an 80% probability that the failure rate is 15% or less for failure. If 10 tests are run with 2 failings, then there is an 80% probability that failure rate is 41% or less. Appendix A shows how these exact numbers were found using the nomograph. This method of measurement was used to evaluate the first evaluation of joints with each method. Figure 36 shows how each method did on a pass or fail criteria for joint creation.

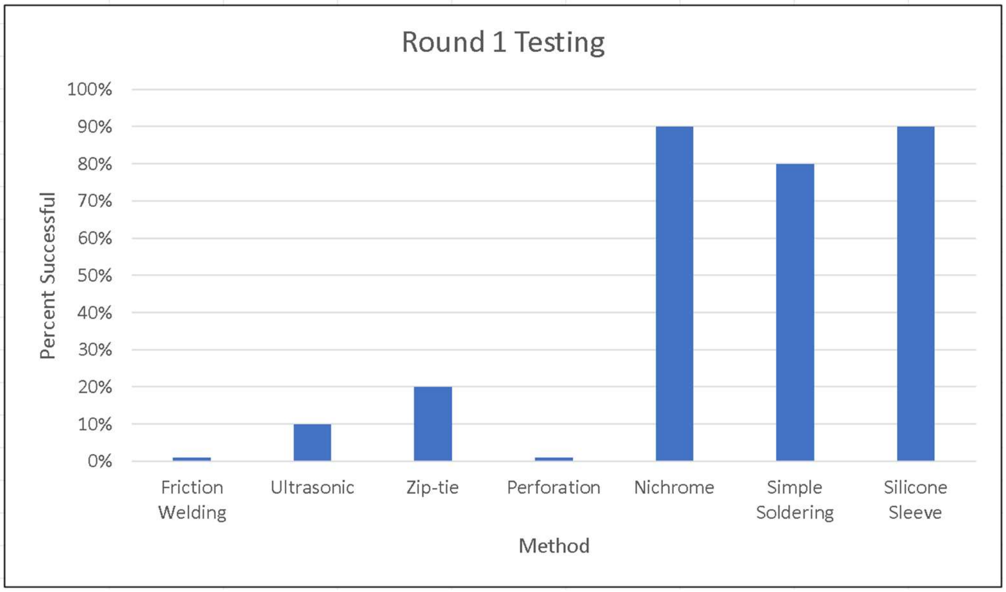

Figure 36: Testing of Joint Splice

Based on this testing it was found that friction welding, ultrasonic, zip-tie, and perforation were not viable methods to create spliced filament. These methods had less than 40% successful joints and therefore did not meet the requirement to conduct further experimentation. The nichrome, simple soldering, and silicone sleeve moved further with testing due to having an 80% success rate or higher which led to an 80% probability that the methods have a 15% chance of failure based on the binomial nomograph. It should be noted that for each test a piece of clear filament was welded to a piece of green filament to show the exact point of the splice better visually.

Bend Test

Each passing method underwent the bend test as its initial assessment, utilizing 10 strands of spliced filament. The filament was placed into a specially designed bend tool, as depicted in Figures 37 and 38, providing a clear visual of the bending process during the test. This tool securely held the filament in place, preventing any slipping during the test. Passing this test was crucial for all methods due to the potential movements the filament experiences during printing. As the filament flows freely into the nozzle during printing, it experiences less stress. However, when passed through alignment tubes, bends can occur, placing stress on the joints.

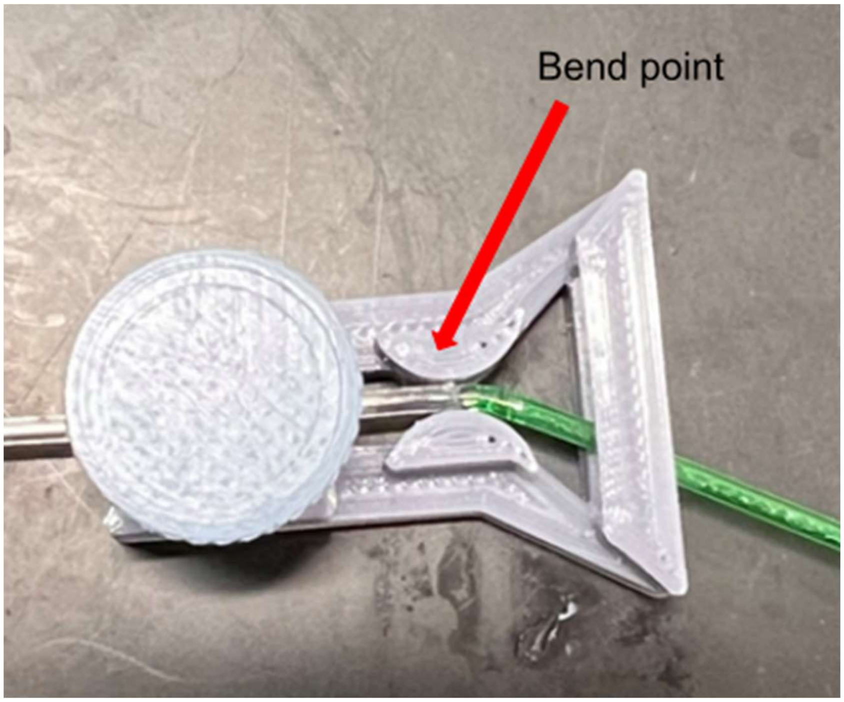

Figure 37: Bend test.

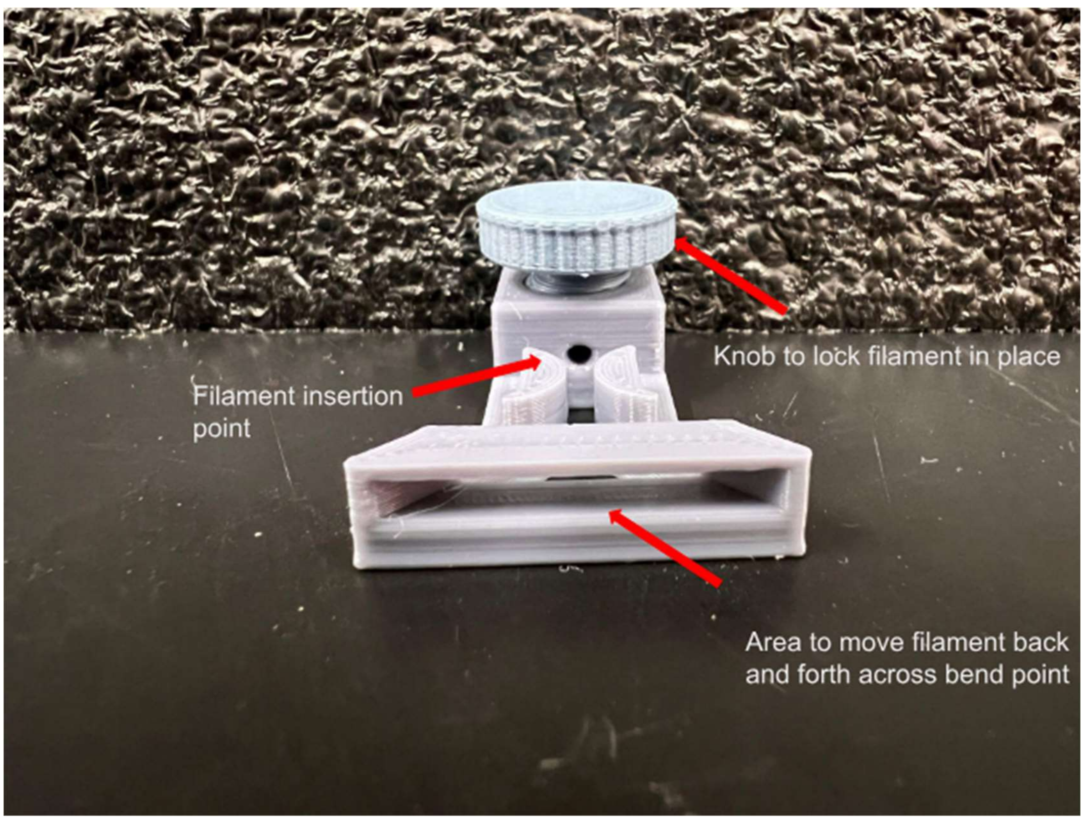

Figure 38: Bend test tool.

The filament that was tested in the bend test was graded on a pass or fail criteria with a pass being an intact piece undergoing 5 bends with no breakage. A failure would be given if the filament was broken completely or more than 50% of the joint was separated from the other. Below in Figure 39 are the results of the three methods and how many successful bends the joints passed.

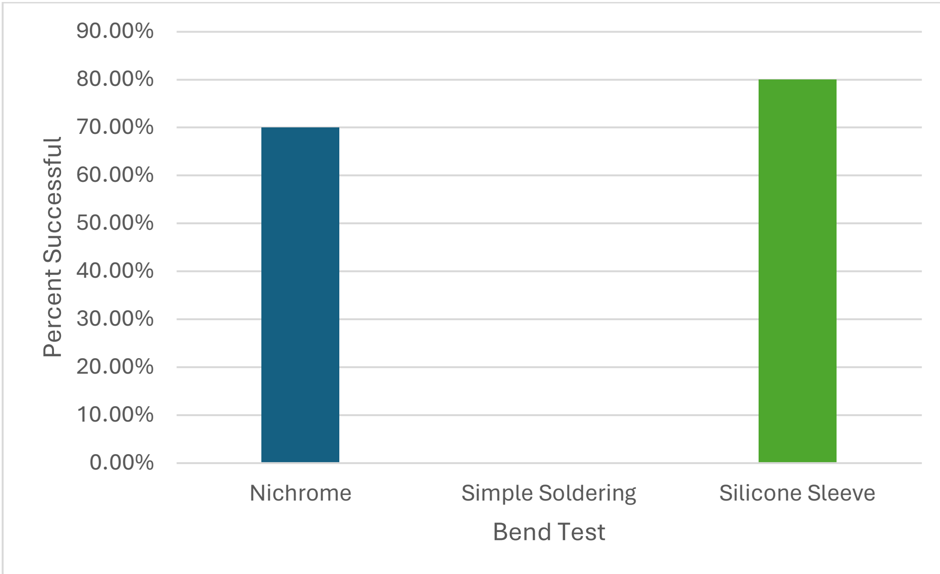

Figure 39: Bend test results.

After the bend test was completed, 70% of the nichrome joints successfully passed the bend test, and 80% of the silicone joints had success. The simple soldering method however had 0 of the joints pass due to how brittle the joint was. Below in Figures 40 through 43 are examples of the filaments before and after being bent in the tool. As shown there is a slight noticeable decrease in the diameter of the joint at the point of bending, but not enough to indicate a failure.

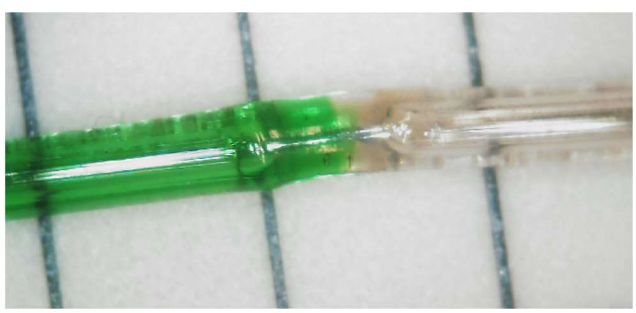

Figure 40: Silicone Before

Figure 41: Silicone After

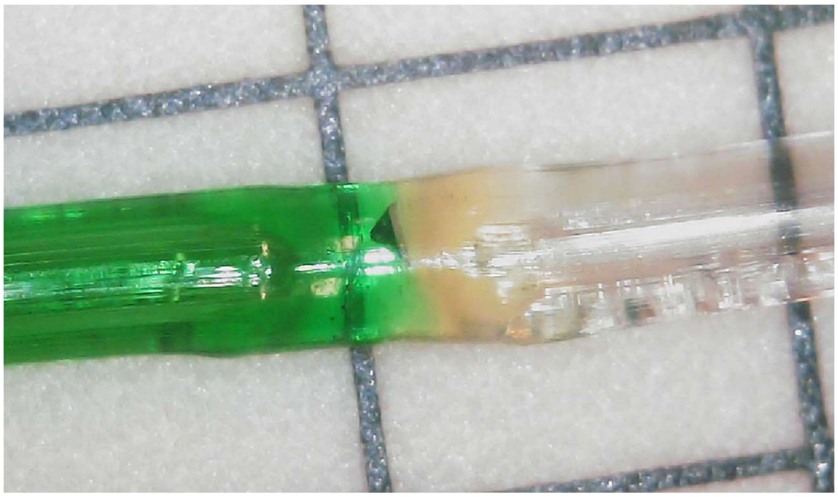

Figure 42: Nichrome Before

Figure 43: Nichrome After

Tensile test

Following the bend test was the tensile test. For this test the filament had to support 3kg of mass in a vertical orientation. The method consisted of two 3D printed parts that secured the PET. One side had an access point for hardware to be bolted down. The other side consisted of a piece of rope that held 3 water bottles that in total weighed 3kg to match the needed requirements for the test. Figure 44 shows the set up for the 3D tool and Figure 45 demonstrates the full assembly. This method was also a pass-fail test, where a failure was a complete snap of segments in tension and a pass was the filaments staying together under the tension for more than 5 seconds of force being applied.

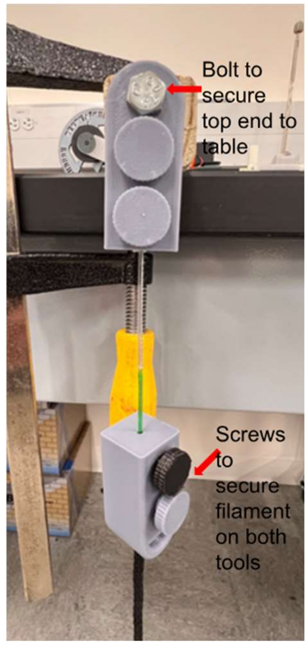

Figure 44: Upper and Lower Portion of Tensile Tool

Figure 45: Full Assembly of Tensile Test.

In contrast to the previous test, all three methods yielded results in this section, as illustrated in Figure 46. Simple soldering passed the tests in this portion; however, due to its low success rate, it was deemed unreliable and not suitable for continuation into the final print test. Nichrome also had a low success rate at 60%; nonetheless, it still proceeded to the print test phase as it demonstrated success in other testing benchmarks. Lastly, the silicone sleeve soldering method achieved a 90% success rate with only one failure.

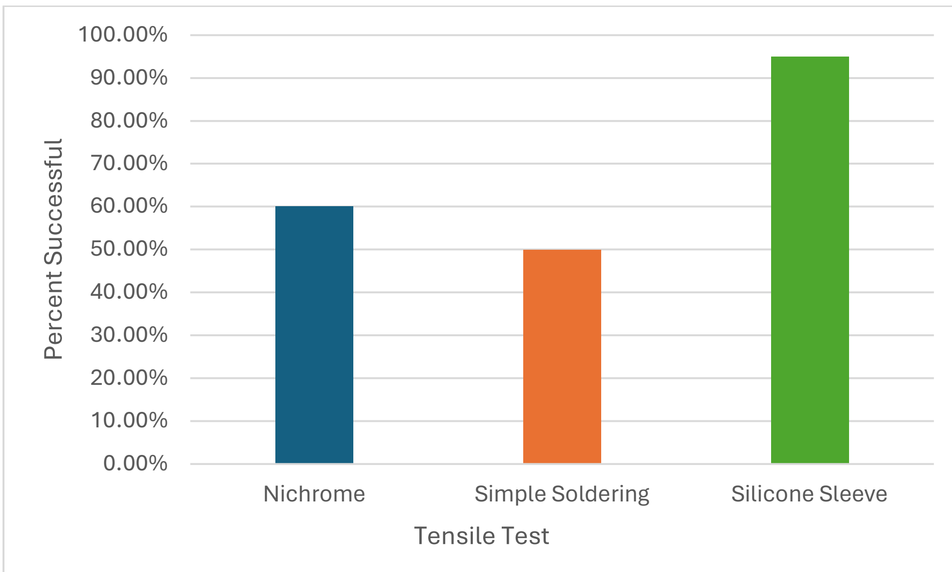

Figure 46: Tensile Test Results.

Print Test

The final test the methods went through was the print test. This consisted of connecting strands of filament together with changing colors from clear to green nine to ten times. This allowed for the cylindrical print to have multiple print lines to be viewed after printing. Once the longer strands of filament were created it was ready to undergo the printing process. However, due to the nature of the PET, changes to the print settings and the nozzle had to be made.

Experimentation with virgin PET filament was conducted to determine the optimal settings. The best results were achieved with the cooling fan set to 30%, a line width and thickness of 0.6mm each, and an infill density of 15%. Some of the required print settings are displayed in Figure 47. The QIDI X-Maker printer, as depicted in Figure 48, was used for the tests. Typically, 3D printers like this one come equipped with a 0.4mm nozzle, which was replaced with a 0.6mm nozzle to reduce the occurrence of clogging. Although the larger nozzle sacrifices some detail in the print, it was unnecessary for the prints in these tests. Additionally, the 0.6mm nozzle must be a high-temperature variant to withstand the printer's operating temperature of 265°C.

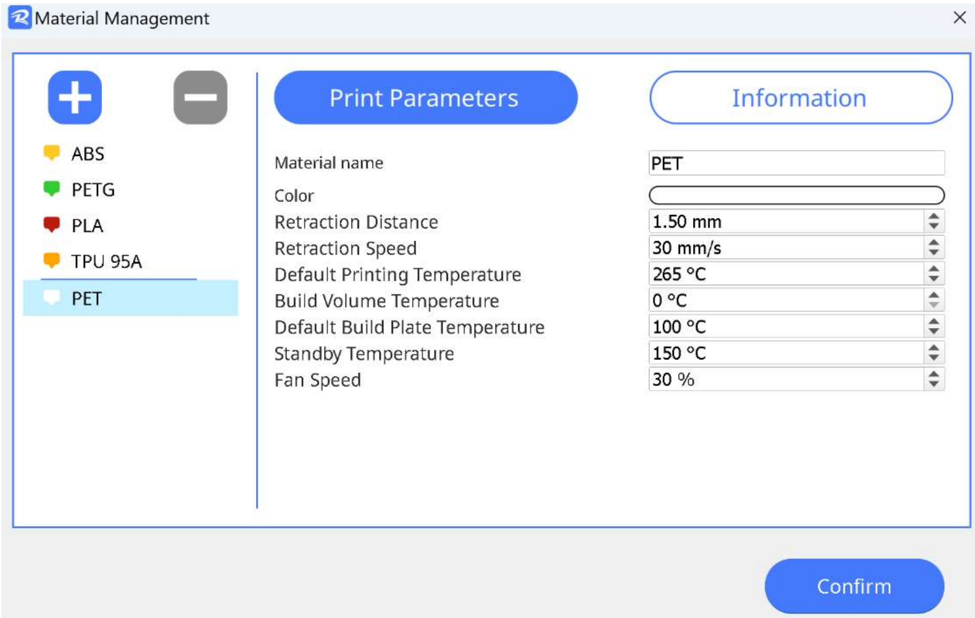

Figure 47: X-Maker Printer Settings

Figure 48: QIDI X-Maker

The results of the print testing can be seen in Figure 49. The nichrome had a 95% success rate with one print having to be done again due to stoppage during the print however, this did not affect the joint. The silicone sleeve method had failed its first test in initial testing due to clogging in the bowden tube of the printer. The joint itself was more than 1.75 mm and unable to clear into the tube. The simple soldering method was unable to have any prints come out due to the uneven geometry of its joint and brittleness.

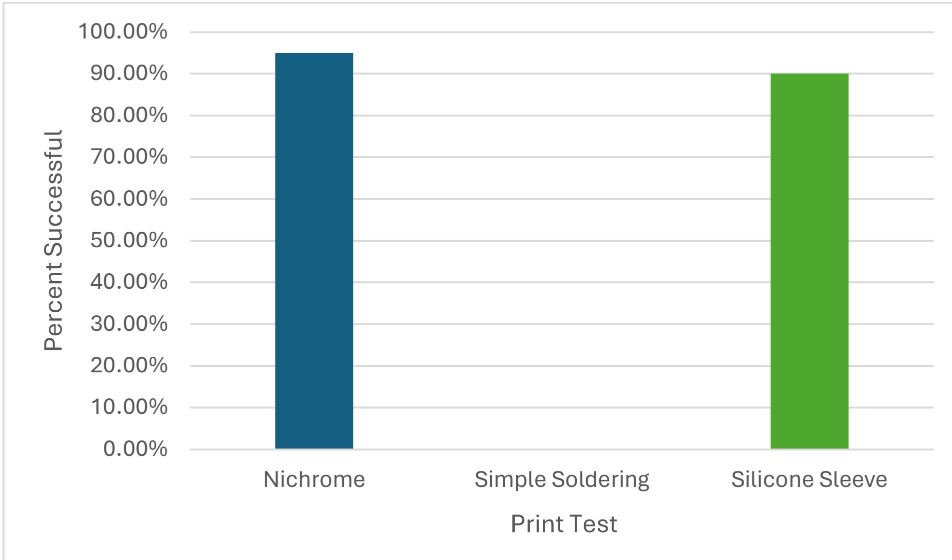

Figure 49: Print test results.

The physical outcome of the print test for the nichrome and silicone methods can be seen in Figure 50. These prints had no noticeable indication of joint failure in the print at the points where the colors changed. Proving success in that PET can be spliced with these two methods.

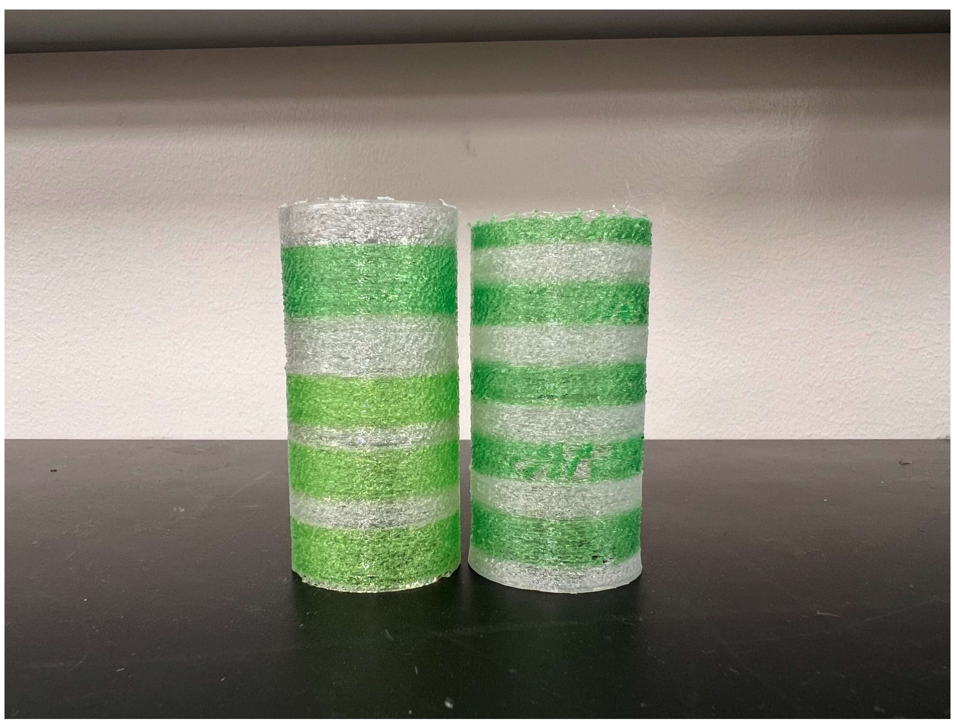

Figure 50: Print of silicone method(left) and nichrome method(right)

Further testing was conducted outside the scope to create other items and see how well the filament would do on more common types of prints. These prints can be seen in Figure 51 and Figure 52. As shown, no major defects can be seen along the color transition in any of these prints, meaning the joints successfully went through the 3D printer.

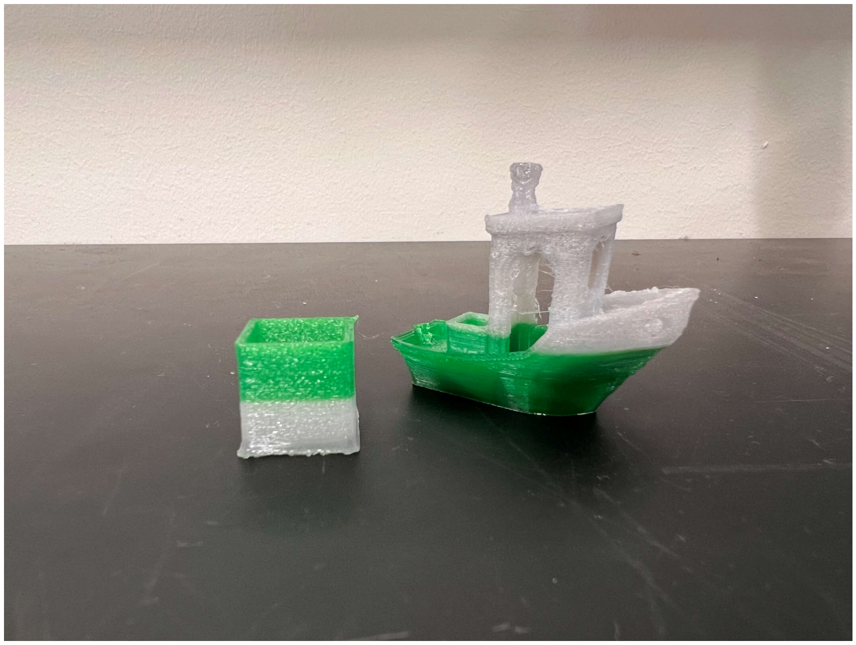

Figure 51: Small Cube and Tugboat.

Figure 52: Printed Small Bottles.

Final Design

The final design for this project included seven methods for creating splices in PET filament. These methods were tested against each other to determine which ones were most likely to produce strong, reliable splices that can withstand the stresses of spooling and printing without failing. The initial ideas and iterations of each method were described above in the proposed design and design changes section. Here, the finalized designs of each method used for the analysis are described in detail.

Each method was used to create 40 splices which were tested for bending strength, tensile strength, and printability as described above. The methods were then compared against one another to determine which were most reliable. The methods with the highest scoring splices were identified and recommendations were made for further development and optimization.

Manufacturing Scope of Work

Each method had its own manufacturing that needed to be done as seen in Table 4. Most of the methods did not have a lot of machining or processing, instead simply needed to be 3D printed and assembled. This was true for the silicone, simple soldering, perforation, nichrome, and zip tie methods. The friction welding and ultrasonic welding methods needed some extra modifications to supply that was already made and provided. At the bottom of the table three extra major components that were needed by all methods were completed, the first being a new spool holder for the pultrusion machine. The major components of bottle prep through cleaning and filament producing with the pultrusion machine were periodically done numerous times over the semester.

Table 4: Manufacturing Scope of Work

Task Number	Major Component	Minor Component	Task Type	Estimated Time	Start Date	Actual Time	Actual Completion Date	Owner	Tools	Tool on Hand	Stock/MAT'L
1 (Silicone method)											
1.1	Holding Jig		Assembly	1 hour	1/20/2024	2 hours	1/20/2024	Ryan	Screwdrivers		
1.2		3D Print	Printing	5 hours	1/19/2024	5 hours	1/20/2024	Ryan	Ender 3 printer		
2 (Soldering method)											
2.1	Holding Jig		Assembly	6 hours	1/18/2024	16 hours	2/1/2024	Allison			
2.2		3D Print	Printing	5 hours	1/18/2024	12 hours	2/1/2024	Allison	QIDI 3D X-MAX Printer	Y	
2.3		Drill holes	Machining	1 hour	1/19/2024	1 hour	2/1/2024	Ryan		Y	
3 (Perforation method)											
3.1	Perforation Jig		Assembly	1 hour	1/25/2024	2 hours	1/25/2024	Ryan	CA glue and blades		
3.2		3D Print	Printing	4 hours	1/25/2024	4 hours	1/25/2024	Ryan	Ender 3 printer		
4 (Friction Welding)											
4.1	Holding/Cooling Base		Machining	1 hour	2/4/2024	2 hours	2/21/2024	Jacob	Mill, Band Saw, Sander	Y	4x Screws
5 (Ultrasonic Welding)											
5.1	Tool Modification		Machining	2 hours	2/4/2024	3 hours	2/21/2024	Jacob	Mill, 1.8mm Drill Bit	Y	Welder Head
6 (Nichrome wire)											
6.1	holding Jig		Assembly	14 hours	1/19/2024	10 hours	2/13/2024	Chris		Y	
6.2		3D Print	Printing	5 hours	1/19/2024	5 hours	1/19/2024	Chris	QIDI 3D X-MAX Printer	Y	PLA
6.3											
7 (Zip tie Method)	Zip tie cutting jig		Assembly	1 hour	1/25/2024	2 hours	1/25/2024	Ryan	CA glue and blades		
		3D Print	Printing	4 hours	1/25/2024	5 hours	1/25/2024	Ryan	Ender 3 printer		
8	Bottle prep		Cleaning	30 mins	2/1/2024	5 hours	4/18/2024	Allison	Sponge, Goo gone, Sink	Y	15x Bottles
9	Spool Holder		Printing	9 hours	1/18/2024	9 hours	1/19/2024		QIDI 3D X-MAX Printer	Y	
10	Filament		Machining	1 hour	2/1/2024	15 hour	4/18/2024	Allison	Autotruder	Y	

Zip Tie Method

The zip tie method involved cutting two ends of ribbon in a way that one could be woven through the other then sent through the pultrusion machine together and form a joint. Many methods of cutting the ribbon were used in testing but the final form was to cut the ends to shape using scissors. The method was relatively easy to perform although there was a learning curve to making the cuts precisely. A jig was created to assist with making the required cuts, but it was found to be easier to cut freehand with a pair of sharp scissors. The final shape of the mating ends of the ribbon can be seen below in Figure 53. Images of this method before being sent through the pultrusion machine can be seen below in Figures 54 and 55.

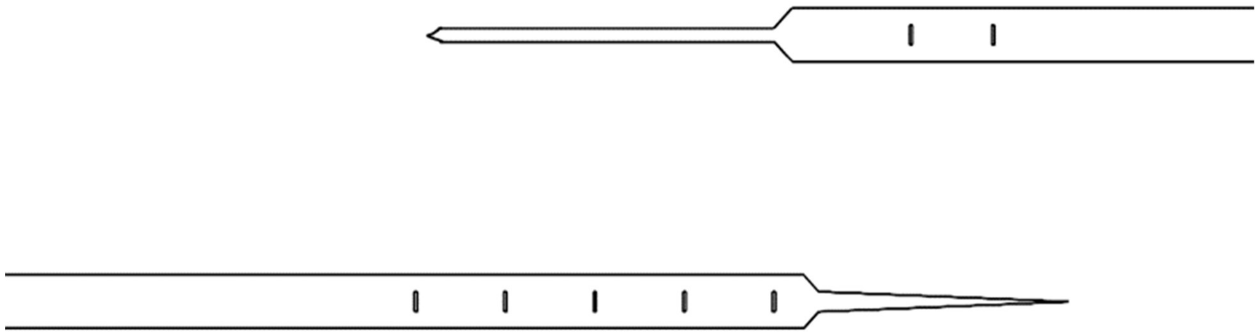

Figure 53: Zip Tie Method diagram of cuts.

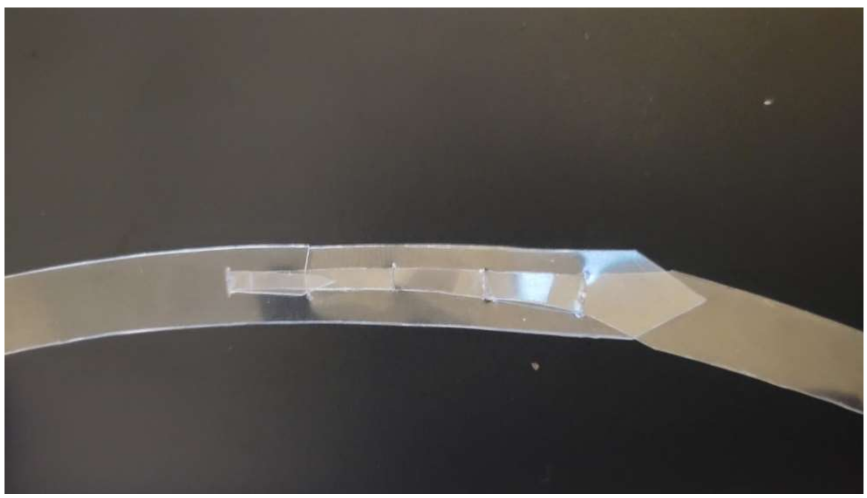

Figure 54: Zip Tie method top view (pre pultrusion)

Figure 55: Zip Tie method side view (pre pultrusion)

Unfortunately, this method had severe problems from the start. The hope for this method was that as the joint was heated and reformed into the filament shape, the woven nature of the ribbon would prompt the two ends to “grab” each other and keep the two strands of filament together long enough to be spooled and printed. After many attempts and iterations, it was found that this “grabbing” does not occur. Furthermore, the splice attempt often clogged the pultrusion machine causing the filament to break. As no reliable splice was able to be made, this method was abandoned and deemed unsuitable for continuing research. An image of a zip tie method joint after clogging the pultrusion machine can be seen below in Figure 56.

Figure 56: Failure mode for zip tie method joint after clogging pultrusion machine.

Perforation Method

The perforation method was another ribbon-based method that aimed to join the pieces of cut bottle together before being turned into filament. The final form of this method involved a press-punch device that aimed to pierce two pieces of overlapping ribbon in a way that joined them together. The aim with this method was to perforate the plastic ribbons so that they could be held firmly together until the pultrusion process bonded them further. The press-punch device designed for this process can be seen below in Figure 57.

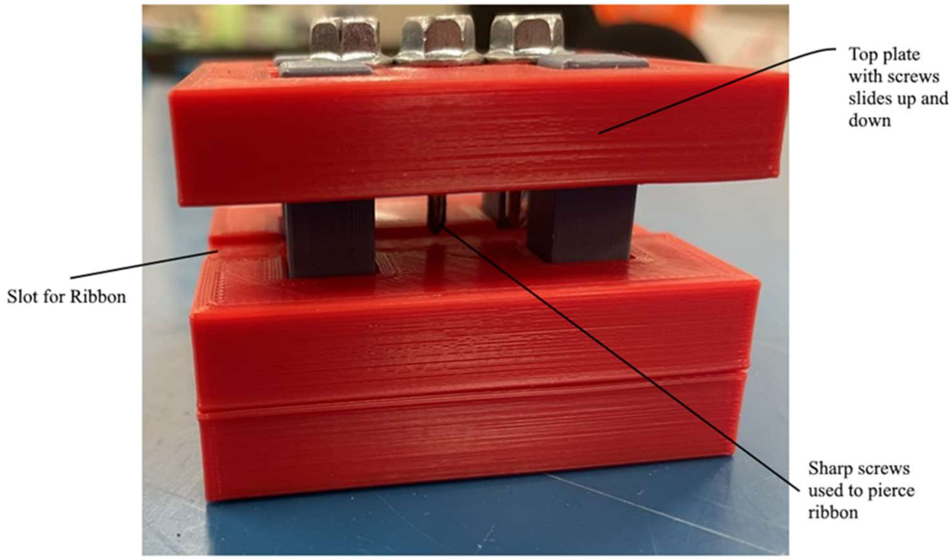

Figure 57: Press-punch device for perforation method.

This device was 3D printed from ABS plastic and was designed to be able to have a changeable tool holder that performed the punches. Various metal tips were used in attempting to make the perforated joints, but it was found that m3, stainless steel, self-tapping screws worked best. It was also found that heating the screws before pressing the ribbon ends created a stronger bond between them. An example of a ribbon joint made with this method can be seen below in Figure 58.

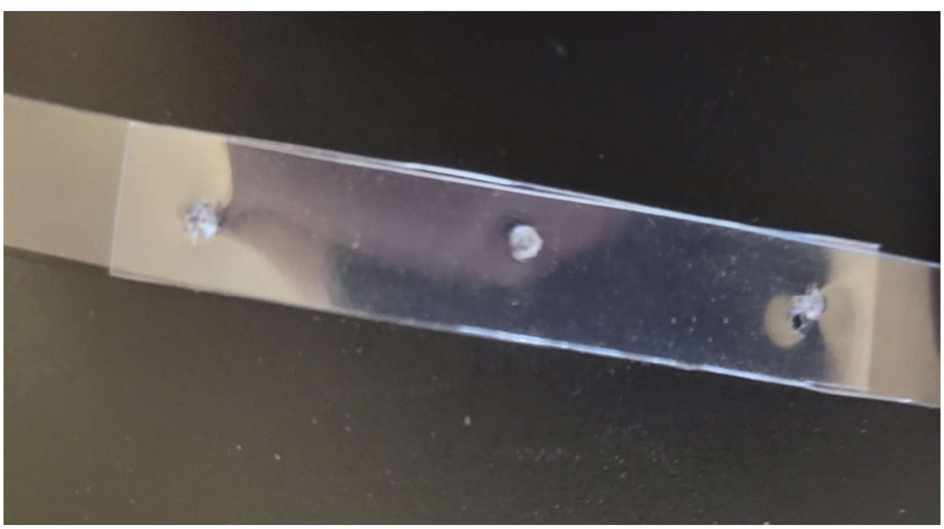

Figure 58: Example of perforation method ribbon joint before pultrusion.

Although the method showed initial promise, the ribbon connections were not very strong and often came apart before they were able to be reformed into filament. The few attempts that did get to the pultrusion process jammed the machine and none were able to produce a joined length of usable filament. For this reason, this method was deemed unsuitable for further exploration. An image of a failed perforation connection can be seen below in Figure 55.

Figure 59: Failure mode of perforation method ribbon connection.

Friction Welding

The friction welding method was a ribbon based joining method using a rotary tool to "weld" two lengths of ribbon together before pultrusion. A small length (one inch) of already created PET filament was inserted into the tool chuck of the rotary tool. The tool was turned on high and the small piece of filament was held against two overlapping pieces of bottle ribbon. The high speed of the spinning filament created enough friction to quickly melt and "weld" the two ribbon ends together. This operation was performed on an aluminum block to provide cooling to the connection quickly after forming. This method can be seen below in Figure 60.

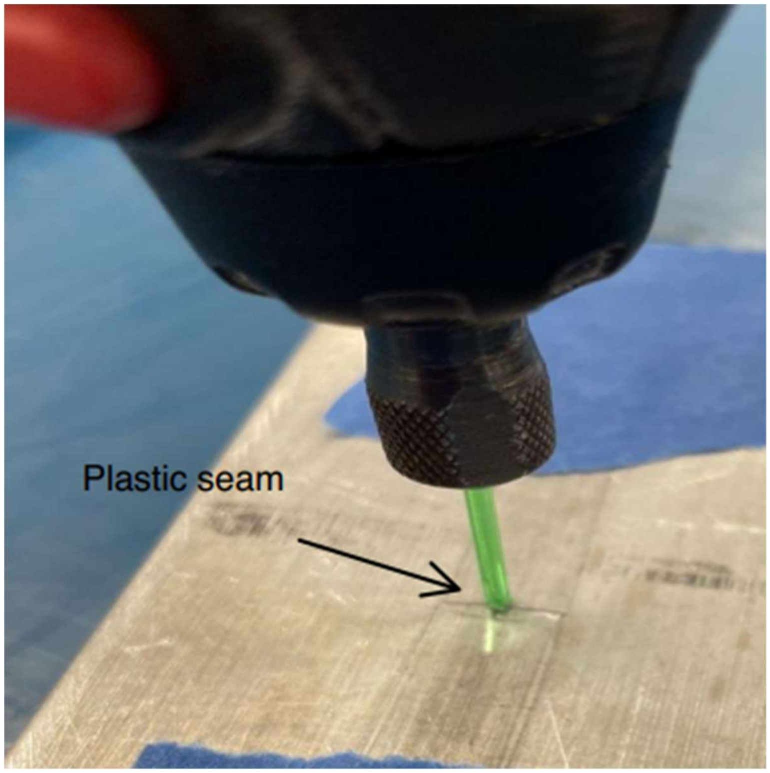

Figure 60: Friction welding method in use.

After the connection was made, it was sent through the pultrusion machine to be turned into filament. This method created strong joints but suffered from inconsistency. Performing this method required a high level of precision in terms of location of the spinning filament and timing. If either parameter was off even slightly, the quality of the connection was much worse, often resulting in burning a hole through the ribbon or making the connection too fragile. An example of a failed connection can be seen below in Figure 61.

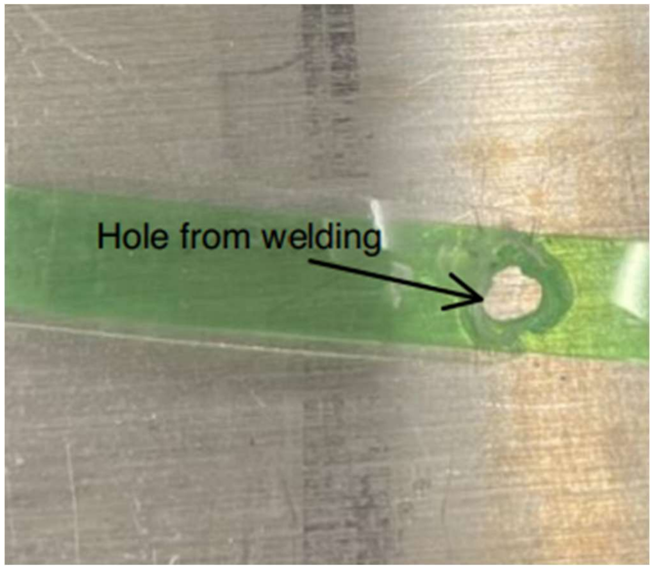

Figure 61: Example of failed friction welding connection.

Unfortunately, even the best of connections made with this method failed to produce continuous filament and broke during pultrusion. Because of its inability to produce continuous filament, this method was determined to be unreliable, and efforts were discontinued on it.

Ultrasonic Welding

The ultrasonic welding method was another ribbon connection method. Two pieces of ribbon were to be welded together by high frequency sound waves using an ultrasonic welding device borrowed from UNF. The ultrasonic device releases low amplitude waves at 28 kHz causing the material to rapidly reshape. For this method to work, a strong connection needed to be formed between the two ribbon ends. The joining process was performed on a block of aluminum to facilitate rapid cooling of the joint immediately after creation. The block and welder can be seen below in Figure 62. A waffle shaped tip, Figure 63, was used on the ultrasonic device after finding it more effective than the other shape options.

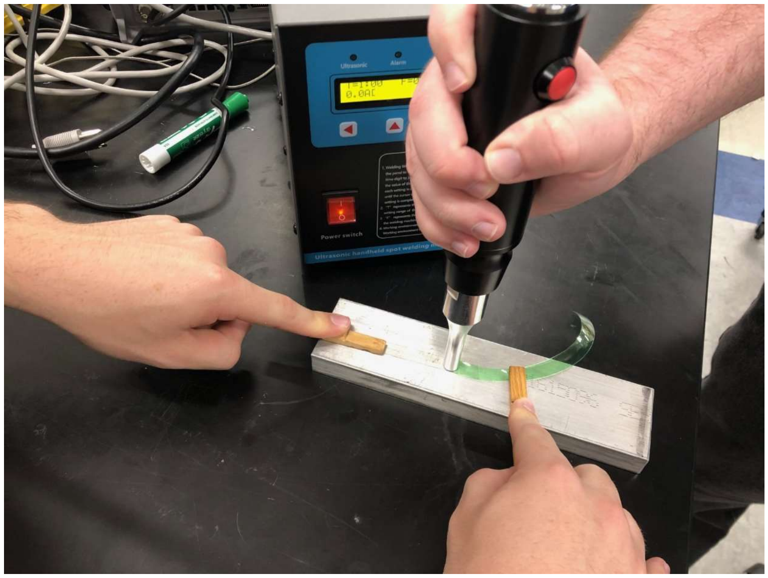

Figure 62: Ultrasonic welder connection method on aluminum cooling block.

Figure 63: Waffle tip for ultrasonic welder.

The ribbon connections formed with the ultrasonic welder were very strong while still being relatively pliable. An example of a ribbon connection made using the ultrasonic welder can be seen below in Figure 64. Although the overlapping surface area was small, the connection strength was by far the highest of all ribbon connecting methods.

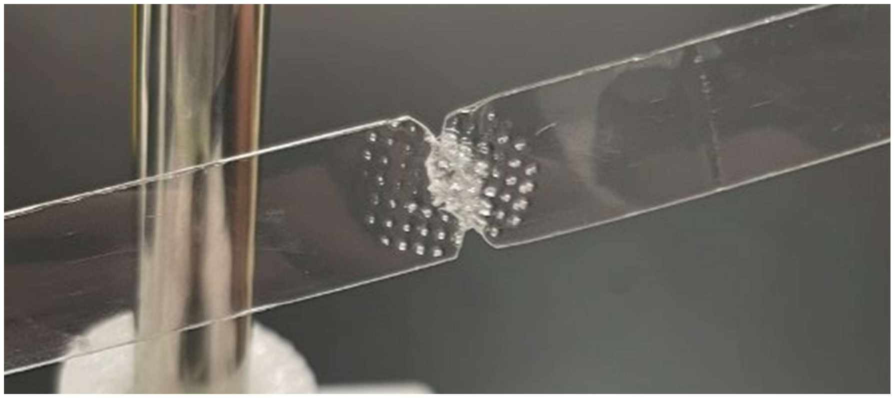
Figure 64: Ultrasonic welding method ribbon connection before pultrusion.

Unfortunately, even the high strength of this ribbon method was unable to reliably withstand the pultrusion process into becoming filament. Approximately 90% of ultrasonic based connections failed during pultrusion. Although the joint was strong, the heat and force of the pultrusion machine was too great for it to handle. As soon as the connection reached the hot nozzle, the machine would stall until the joint was either forced through or broken. Because of this high level of unreliability, this method was additionally selected as unfit for further testing. The failure of such a strong connection relative to the other ribbon based joining methods further confirms the decision to abandon the ribbon based splicing methods. An ultrasonic ribbon connection that failed in the pultrusion process can be seen below in Figure 65.

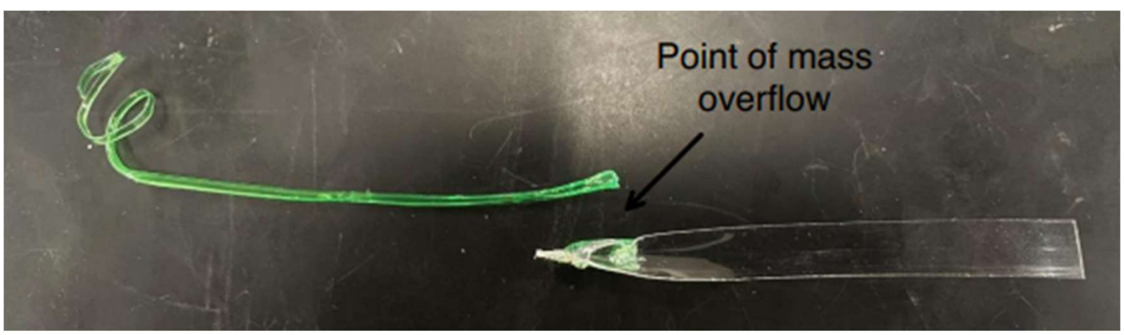

Figure 65: Failure mode of ultrasonic welder method after jamming pultrusion machine.

Simple Soldering

The simple soldering method was based around a method that is typically used to splice PLA filament together. This method revolves around the use of a soldering iron to melt the two ends of filament to be joined. A two-part simple jig that could hold two pieces of filament together was found online and 3D printed using PLA as shown in Figure 66. Each piece of filament was slid into either end of the holder. There was an opening in the jig for the soldering iron to fit. It was found that a solder with a knife tip was best for attempting to fuse the filament. There was difficulty found in keeping the two pieces of filament straight and lined up for the connection, it was also hard to hold the solder and then quickly put it down to press the two pieces of filament together. Both these issues were remedied through the editions of clamps as shown in Figure 67 which can also be seen in the design changes

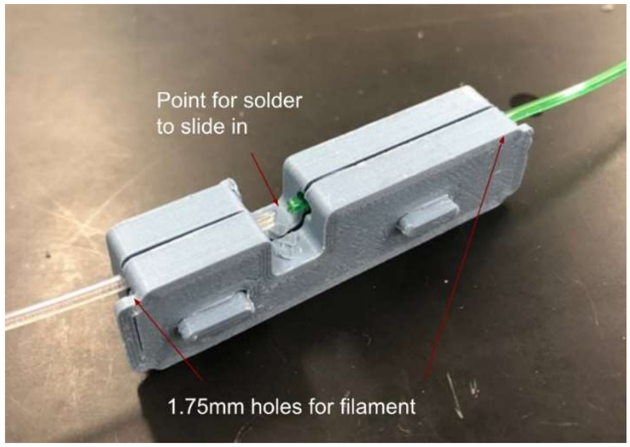

Figure 66: Jig for simple soldering.

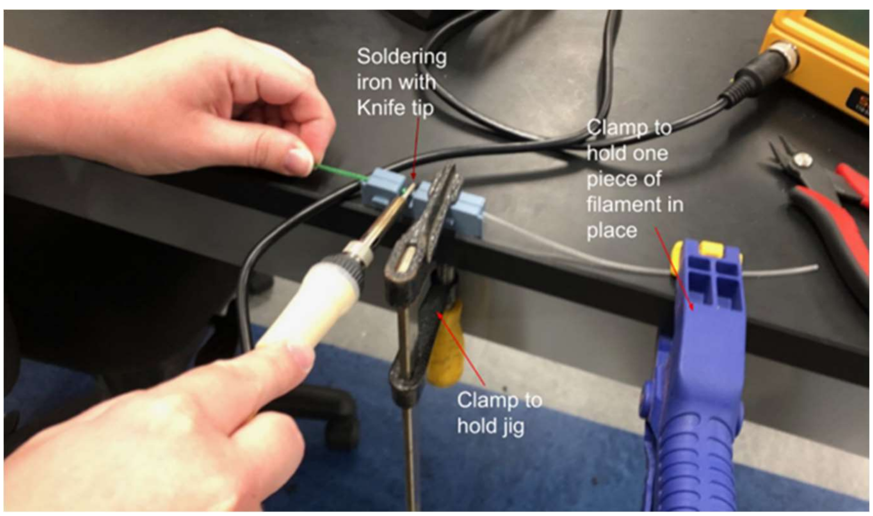

Figure 67: Full set up for the simple soldering method.

After testing with different temperatures, the solder was set to 255 degrees Celsius, the minimum temperature needed to reform the PET. Joints could successfully be made but they were often uneven and resulted in large bulges exceeding the constraint that the filament needed to be 1.75mm +/- .1mm as seen in Figure 68. These joints were also very fragile, as the connection was only a few layers deep. This method often led to burning the filament even though the soldering iron was set to the minimum temperature needed. An example of this burning could be seen in Figure 69 along with showing how the method pushed the material of the filament outward.

Figure 68: Splice made with simple soldering method.

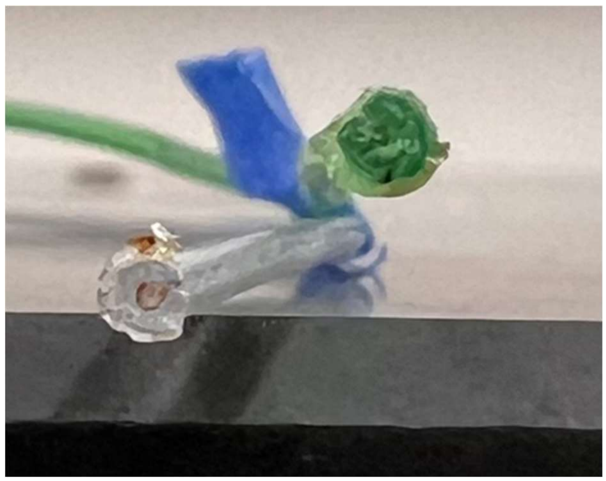

Figure 69: close up of each piece of filament after it's been heated by the soldering iron.

Although this method wasn't pretty and didn't show promise in meeting all the requirements and constraints of the project, it was still further tested to prove that while this method does work for other 3D printer filament types, it doesn't work for PET. Joints could still be made but not successfully enough to be used in a 3D printer. This method was fully scrapped after complete testing, and it is not recommended that the sponsor moves forward with it.

Silicone Soldering

The silicone soldering method was an upgraded version of the simple soldering method. The main improvement over simple soldering was the inclusion of a tight-fitting silicone sleeve over the ends of filaments. The silicone sleeve works to shield the filament from burning while holding both ends tight together for splicing. Additionally, a small length of aluminum foil was tightly wrapped around the silicone to help heat the joint from all sides.

The final design for the silicone soldering method included a 3D printed jig that helped hold the two filament strands so the other hand could hold a soldering iron to the silicone wrapped joint. In addition to holding the filament secure, this jig was spring loaded to provide force directly onto the joint during splicing. This extra force provided by the spring promoted strong joints and reliable splicing. The distance the jig compresses can be adjusted via a screw in the handle to allow for fine tuning of the joint. The jig used in the final design can be seen below in Figure 70.

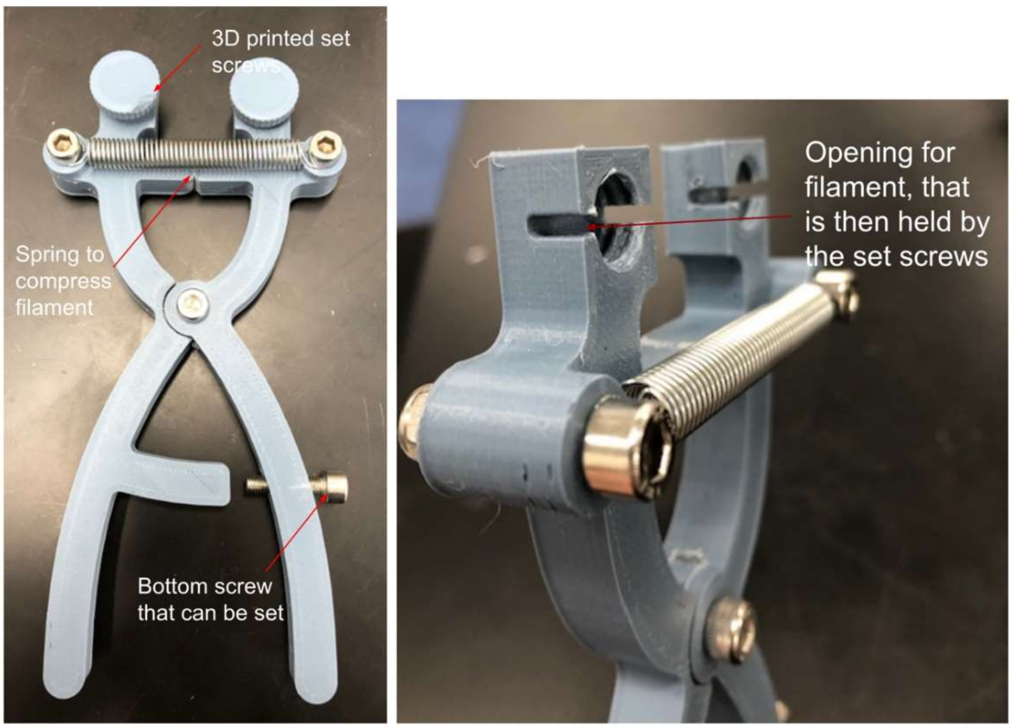

Figure 70: Silicone soldering jig in use.

The silicone soldering method was able to produce consistently reliable splices. The even heating and consistent force of this method made it more repeatable than other methods. Silicone soldering had the highest rating for both the bend test and the tension test. The print quality test showed very high results as well, coming in second place only to the nichrome method. An example of a splice made with the silicone soldering method can be found below in Figure 71.

Figure 71: Example splice made with silicone soldering method.

The silicone soldering method was found to be a strong method of splicing with promising results. It is recommended that Green Ellipsis select this method to continue further research.

Nichrome Heater

The nichrome heater method was a method that attempted to easily join two pieces of already created filament together. This method used three AA batteries in series with a coil of nichrome wire to produce heat connecting the filament ends. A tight-fitting sleeve of silicone was placed on the joint to prevent the filament from burning and to hold the ends in place for splicing. In the final design, a limit switch is depressed when the filament is in place, completing the circuit. As the nichrome heated, the two filaments were pressed together to strengthen the joint. The joining device can be seen below in Figure 72.

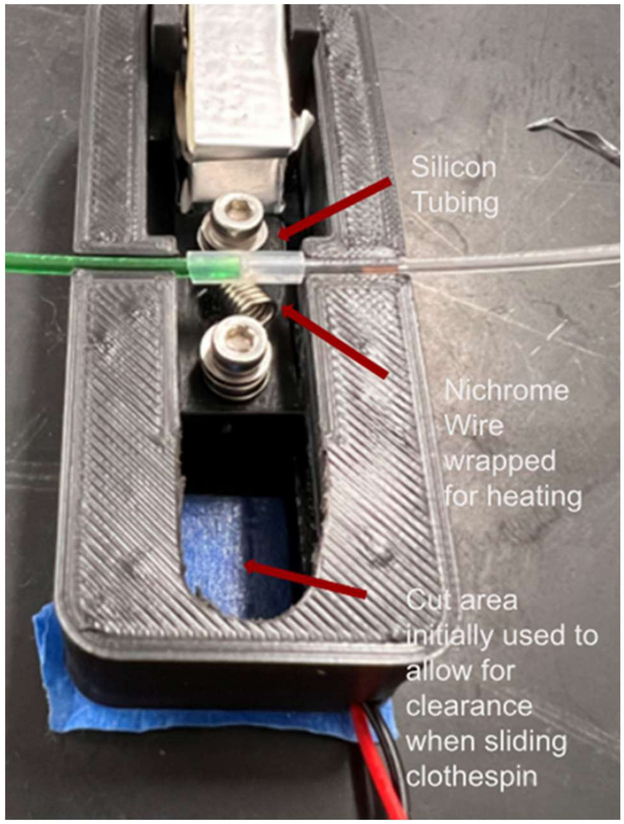

Figure 72: Nichrome heating method device.

The advantage of this method is the speed and convenience of creating a splice. The user only needs to insert each end of filament into the silicone sleeve and place them into the device. The limit switch is depressed, and the circuit is completed, heating the nichrome. Once the coil is hot, the pieces of filament are pushed into each other to complete the splice and rapidly cooled with water. An example of a splice made with this method can be found below in Figure 73.

Figure 7373: Splice made with nichrome heating method.

Joints made with the nichrome heating method are strong, pliable, and consistently pass the print test. This method's splices did not perform as well as those from the silicone soldering method in bending and tension. It is believed that the heat distribution of the silicone soldering method provides the joint with more even heating than the single nichrome coil of this method.

Final Design Optimization

After using and testing each of the described methods extensively, it was determined that both the nichrome heating method and the silicone soldering method are promising techniques that can produce reliable PET filament splices. While the goal of this project was simply to compare many methods and identify one that works, it was deemed beneficial to begin the process of further optimizing the methods with the most potential. To that end, two further optimized methods have been proposed for Green Ellipsis to promote. The silicone soldering jig has been optimized and is being recommended as a budget friendly option for hobbyist users. The nichrome method has also been upgraded and could be recommended as a more industrial option for higher level users.

Improvements were needed for the original silicone soldering jig to enhance the reliability and success of the method. This was addressed by iterating on the previous model of the jig, primarily by increasing the distance between the spring mounts by 2 cm. Further iterations adjusted this tension as required. The upcoming iteration will focus on ergonomic enhancements and a mountable base, aiming to streamline the silicone soldering process. These additions are expected to make silicone soldering easier and more reliable for hobbyists. Figure 74 below illustrates the initial iterative change without additional hardware. Additionally, the screws have been updated, as shown in the CAD drawings section of Appendix C.

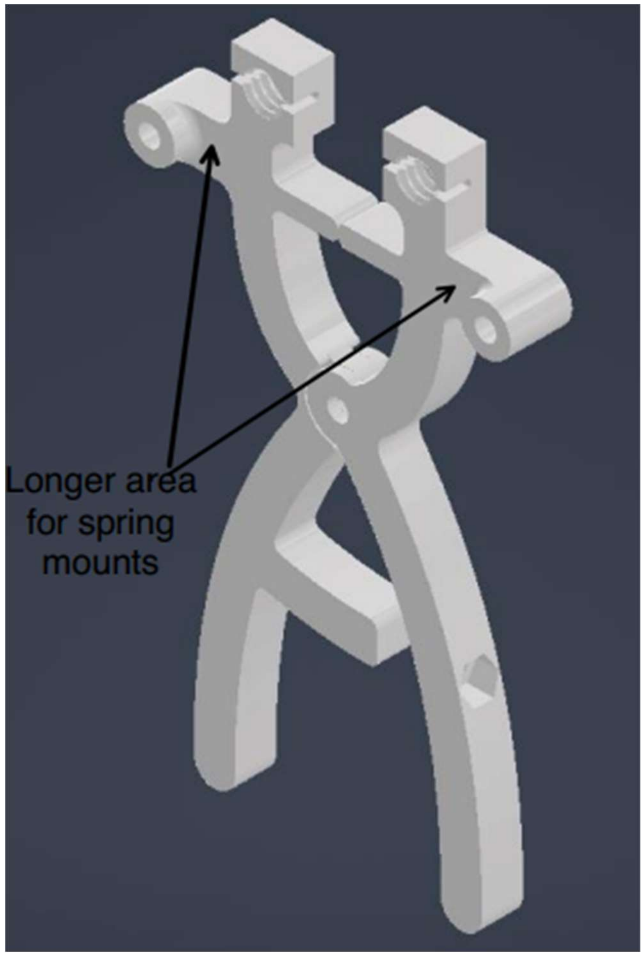

Figure 7474: Updated silicone soldering tensioner.

The silicone soldering method has two advantages over the original nichrome method. The first is a spring powered clamp that provides consistent pressure on the joint during heating. This force promotes the two ends of filament to join once above the glass transition temperature. The nichrome heater relied on the user pushing the ends together which, while effective, was inconsistent from user to user. Taking this clamp from the silicone soldering and adding it to the nichrome should provide more consistent force and consistent results. The second advantage the silicone soldering method had over nichrome was the ability to draw its power from an AC power source compared to disposable batteries. A wall outlet is a more reliable power source and has the added benefit of producing less waste material.

The upgraded design uses a 12V power supply to an adjustable buck boost converter. This converter allows the user to dial the power supplied to the nichrome coil up or down to achieve optimal splices. Additionally, this new design uses two nichrome coils (one above and one below the joint) to provide more uniform heating across the joint. A proposed prototype design upgrading the nichrome method can be seen below in Figure 75. This device provides variable power to the nichrome to allow fine tuning of the temperature.

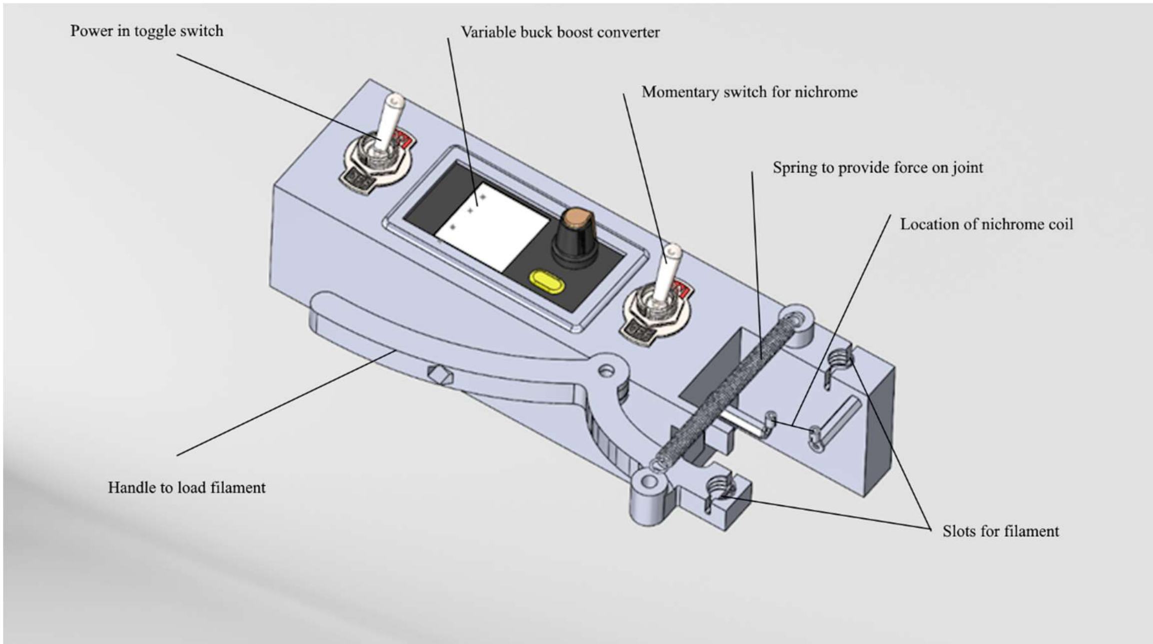

Figure 75: Prototype design for further optimizing nichrome method.

Failure Modes and Effect Analysis

The failure modes and effect analysis, or FMEA, was used to identify any or all potential failures for designs, processes, and assemblies. This can be used for all phases of the design process. An RPN or risk priority number is calculated for each failure mode that could occur within a design to see how safe and successful it is. The RPN is found by multiplying the severity, occurrence, and detection of a given possible failure mode.

For this project, FMEA was conducted on design changes done to methods that passed initial testing. In Table 5 the nichrome wire was analyzed for two different failures. The filament burnt from overheating and quenching too fast. The effects of the failure modes were that too much current flows though the nichrome wire; this is caused by an unstable amount of voltage being applied to the design. This was a mildly severe occurrence and the only way to avoid this was by visually inspecting it. A solution and action that was taken was to update and be able to control the voltage and current output into the model. This was updated in the new prototype design and lowers the occurrence rate. When looking at the process of quenching, an effect of failure came from too much exposure to heat overall. This was caused by the filament coming into direct contact with the wire. A solution to this was adding a silicone sleeve to protect the filament and create a more even heated area.

Table 5: FMEA for the nichrome wire method.

				FAILURE MODE AND EFFECTS ANALYSIS										
Method:	Nichrome Wire			Responsibility	C.Zervos									
Model:	Current			Prepared by:	C.Zervos			Date (orig)		Rev:1				
								1/20/2024						
Team: Green Ellipsis														
Process Function	Potential Failure Mode	Potential Effects of Failure	Sev	Potential Cause(s)/Mechanism(s) of failure	Occur	Current Process Controls	Detect	RPN	Recommended Action(s)	Action Results				
										Actions Taken	Sev	Occur	Det	RPN
Joint Weld	Filament exposed to too much heating	Too much current traveling	6	Voltage travelling through wire is unstable and prodcuing to much heat	6	Visual inspection	3	108	Improve voltage output via control	Updated in new design	6	4	3	72
	Quenches too fast	Too much exposure to heat	8	Direct contact with filament	10	Keeping a timer for weld amount	2	160	silicone sleeve	Updated in new design	8	1	2	16

The silicone sleeve method was then analyzed as found in Table 6. An initial problem was the joint was unable to remain straight during connection. This was a major problem that occurred every time a connection was attempted due to the way the initial jig was structured. To combat this issue a completely new design was created from scratch and implemented, greatly lowering the RPN. Another issue that was not occurring as often but still had mild effects was incomplete welds. This failure occurred because of the new design not holding a strong compressive force. This was easily fixed with a new spring that had a higher spring constant, thus lowering the occurrence rate. The other issue for incomplete welds came from being exposed to too much heat. These occurrences were very rare since a timer was used to have consistent welds. A cooling towel was also implemented after the weld was created to rapidly decrease the temperature after heating. The last control for this method was adding an aluminum wrap to evenly distribute the heat from the soldering iron. Since these potential failure modes already all had a substantially low RPN no recommended actions were needed.

Table 6: FMEA for the silicone sleeve method.

				FAILURE MODE AND EFFECTS ANALYSIS										
Method:	Silicone Sleeve			Responsibility	Allison W.									
Model:	Initial			Prepared by:	Allison W.			Date (orig)	1/20/2024	Rev:				
Team:	Green Ellipsis													
										Action Results				
Process Function	Potential Failure Mode	Potential Effects of Failure	Sev	Potential Cause(s)/Mechanism(s) of failure	Occur	Current Process Controls	Detect	RPN	Recommended Action(s)	Actions Taken	Sev	Occur	Det	RPN
Hold Filament	Filiment does not remain straight at connection	uneven weld	7	Structure of Jig	10	Visual inspection of filament	3	210	Redesign of jig	Jig redesigned	7	2	3	42
Joint Weld	compressive force not strong enough	Incomplete weld	6	Spring tension not strong enough	3	Visual inspection of joint and spring	4	72	Replace with stronger spring increase spring distance/tension	increased spring distance	6	2	2	24
	Filament exposed to uneven or too much heating		7	Soldering iron held on filament for too long	2	Keeping a timer for weld amount	2	28	none needed					
				Joint not cooled quick enough	2	rewetting cooling towel before each	2	28	none needed					
				Soldering head distrubuting uneven heat	2	aluminum foil wrapped around silicone	1	14	none needed					

The last FMEA was for the simple soldering method as shown in Table 7. This method was also failing from uneven welds due to the filament not remaining straight. Visual inspection was used to detect when this was happening, and manual adjust was done, but was unable to fully prevent the problem. This was a severe issue that needed action to resolve. Clamps were added to keep the filament straight, lowering the occurrence rate. This method was also suffering from burnt welds, this was being caused by uneven heat across the filament and was a critical issue creating an incomplete weld that easily broke. This was attempted to be prevented through keeping a timer for how long the heat was applied. There was no recommended action for this issue since none could be decided. Another way the filament burned was from the joint not being cooled enough, this was currently prevented through pre-wetting the cooling towel before each weld, but with a high occurrence rate still happening it is recommended a better more reliable cooling method is found. The filament also burned from uneven heat distribution. This burning was caught by visual inspection but was not prevented so a recommended action of making sure flux was added to the soldering tip before each attempted weld was given. This lowered the occurrence rate by cleaning the oxidation off the soldering tip, leading to more even welds more often. Even after recommended actions the RPNs of the major process functions remained high, indicating that this method was not as successful as hoped and should not be continued.

Table 7: FMEA for the simple soldering method.

				FAILURE MODE AND EFFECTS ANALYSIS										
Method: Simple Soldering				Responsibility	Allison W.									
Model: Initial				Prepared by:	Allison W.			Date (orig)	1/20/2024	Rev: 1				
Team: Green Ellipsis														
Process Function	Potential Failure Mode	Potential Effects of Failure	Sev	Potential Cause(s)/Mechanism(s) of failure	Occur	Current Process Controls	Detect	RPN	Recommended Action(s)	Action Results: Actions Taken	Sev	Occur	Det	RPN
Hold Filament Jig	Filiment does not remain straight at connection	Uneven weld	7	Jig printed or assembled inaccuratly	6	Visual inspection of filament, realigning of jig of filament	3	126	addition of clamps to better secure filament and keep straight	Clamps added	7	4	3	84
Joint Weld	Filament exposed to uneven or too much heating	Burnt weld	9	Soldering iron held on filament for too long	4	Keeping a timer for weld amount	3	108						
				Joint not cooled quick enough	4	rewetting cooling towel before each weld	5	180	improving cooling method					
				Soldering head distrubuting uneven heat	7	Visual inspection of filament	4	252	Apply flux before soldering	Applying flux before	7	4	4	112

Project Budget

For this project, the budget was $1000. This included any parts we needed to buy, any spare parts for redundancy, shipping, and any other expense incurred through the development of these methods. Table 8 below contains the list of parts used in the final designs being recommended. All these items include tax.

Table 8: Bill of Materials for working methods.

	Item	**Vendor**	**Quantity**	**Price**	**Total Cost**
1	Nichrome wire	Amazon	1	$8.49	$9.09
2	Clothespin (pack of 50)	Amazon	1	$5.99	$6.41
3	Aluminum foil	Amazon	1	$2.99	$3.20
4	Battery box (pack of 3)	Amazon	1	$5.99	$6.41
5	Omron SW (pack of 4)	Amazon	1	$6.91	$7.40
6	3D Printer Filament	Provided From Sponsor	1	$0.00	$0.00
7	Soldering Iron	Amazon	1	$35.99	$38.51
9	Silicone Tubing	Amazon	2	$12.99	$27.80
10	Pepsi Brand Bottles	Donations	25	$0.00	$0.00
11	M3 X10 mm screws	Accu	6	$0.21	$1.35
12	15 mm screws	Screwerk	4	$1.30	$5.57
13	Washers	Donated	10	$0.00	$0.00
14	Rocker Toggle Switch (5 Pack)	Amazon	1	$9.99	$10.69
15	DC Buck Boost Voltage Regulator	Amazon	1	$15.98	$17.10
16	6mm Hex Standoff	McMaster-Carr	6	$1.60	$10.27
17	316 Stainless Steel Hex Drive Screws (100 Pack)	McMaster-Carr	1	$7.20	$7.70
18	Ring Connector	DigiKey	4	$0.17	$0.73
Total				$115.80	$152.23

This table is a combination of all methods that have passed testing and that are being recommended to the sponsor for consideration. Parts of this could be bought in bulk for further reducing of the price per joining unit. The remainder of the parts are listed below in table 9 with the additional cost totaled there.

Table 9: Other items purchased throughout the project's lifespan.

	Item	**Vendor**	**Quantity**	**Price**	**Total Cost**
1	Painter's Tape	Amazon	1	$4.88	$5.22
2	Ultrasonic Welder	Borrowed- UNF	1	$0.00	$0.00
3	Rotary Tool	Donated	1	$0.00	$0.00
4	Aluminum Block	Amazon	1	$14.99	$16.04
5	SUNLU 3D Printer Filament Dehydrator	Donated	1	$0.00	$0.00
Total				$19.87	$21.26

With both sets of items, the total amount spent for this project was $173.49. This was only possible due to all the donations made from both Green Ellipsis, UNF, and some items donated from the group. UNF purchased the ultrasonic welder for this project's research, and it will return to the institution after this project is over, this saved an estimated $450 after tax. The rotary tool and filament were provided from Green Ellipsis, saving a further $55 of development costs, along with other tools which did not make it into use during testing or final designs. Donations from the group members of the dehydrator saved another $55 of development costs. Should the group had needed to purchase everything it would have cost an estimated $733.49, which while under the total budget, was higher than the sponsor wished to spend.

Environmental Impact Analysis

This project along with the sponsor Green Ellipses aims to have a net positive environmental impact. PepsiCo is one of the world's leading plastic polluters creating over 2.6 million metric tons of plastic packaging per year (as most recently reported in 2022) [16] PET, Polyethylene terephthalate, the material soda bottles are made from and that this project uses as filament, majorly contributes to pollution. In 2021 PET contributed to 12% of global solid waste [17]. The creation of one ounce of PET causes the emission of approximately one ounce of carbon dioxide according to the U.S. Environmental Protection Agency [18]. The EPA also determined that recycling PET leads to 1.13 Metric tons of carbon dioxide equivalent per short ton. This is why Green Ellipsis promotes recycling using 3D printing with plastic soda bottles instead of just throwing them out.

3D printing itself is also better for the environment as a manufacturing type. Since it is additive manufacturing, it produces less waste than subtractive manufacturing. 3D printers are also small, and thus take up less land and use less energy than other manufacturing processes [19]. The filament produced by the PET soda bottles is excellent at making support structures that could be used in an engineering design, the machine used to create the filament is itself made up of PET printed parts. The ability to create one's own parts instead of sourcing them from multiple places especially limits the carbon footprint of making a design.

Life Cycle Analysis of Designs and Energy Consumption

The initial main two successful designs of the silicone sleeve method and nichrome wire method will be discussed here along with the final prototype designs for each.

Silicone Sleeve Method

The initial jig created for the silicone method is a 3D printed design. It is mainly made up of 3D printed PLA, about 32g. There are also 4 stainless steel hex socket screws, one steel nut, and a tension spring made of tempered steel with nickel plating. The method also uses about 1cm of silicone tubing and a piece of aluminum foil .25cm wide and 5cm long. The only hardware used with this method is a soldering iron set to 255 degrees Celsius.

For this design, the greatest energy consumption will come from the PLA used to print the main component of the jig. Then through the sourcing of the metal and aluminum components. Lastly through the sourcing of the silicone material for the sleeve.

PLA, or polylactic acid, is a bioplastic which is produced from biodegradable materials with lower greenhouse gas emissions than fossil-based plastics [20]. PLA is fabricated out of lactic acid from the fermentation of starch in sugarcane and corn. The life cycle of PLA can be seen in Figure 76. For the PLA to be created it must first be sourced from sugarcane and corn and collected from a farm and then be transported to a plant, like a sugar mill. The corn or sugarcane is then converted into lactic acid through fermentation taking an energy input of electricity and natural gases. This conversion of feedstock into PLA resin requires 32.91 mm Btu of fossil fuel per ton PLA produced and produces 2.74 tons of carbon dioxide emission per ton of PLA produced [21]. After this the PLA resin produced must be reformed into filament to be used in the 3D Printer. The 3D printer uses .03 to .17 kWh on standby and anywhere from 0.06 to 3.08 kWh of energy while in use [22]. The higher the temperature the printer needs to get, the more energy it consumes. Carbon dioxide is also emitted during the printing process, about 11.60 and 112.16 g per print depending on the size of the print and again how high of a printing temperature is needed. Once a print no longer has use, it will likely be thrown out. PLA can be recycled mechanically through a process of separation, grinding, washing, drying, extrusion, cooling, granulation, and sieving [23]. However, recycling is not practical as it must be fully separated from other plastics, or it will contaminate them. Recycling of PLA currently takes more energy than it saves, that is why most PLA products end up landfilling. PLA is biodegradable but has a slow degradation rate and only one percent biodegrades in 100 years [20]. The landfilling of PLA produces 0.1% of methane and an insignificant amount of carbon dioxide emissions. Figure 77 shows the greenhouse gas emissions (GHE) for PLA compared with other plastic grades, where EOL stands for end of life.

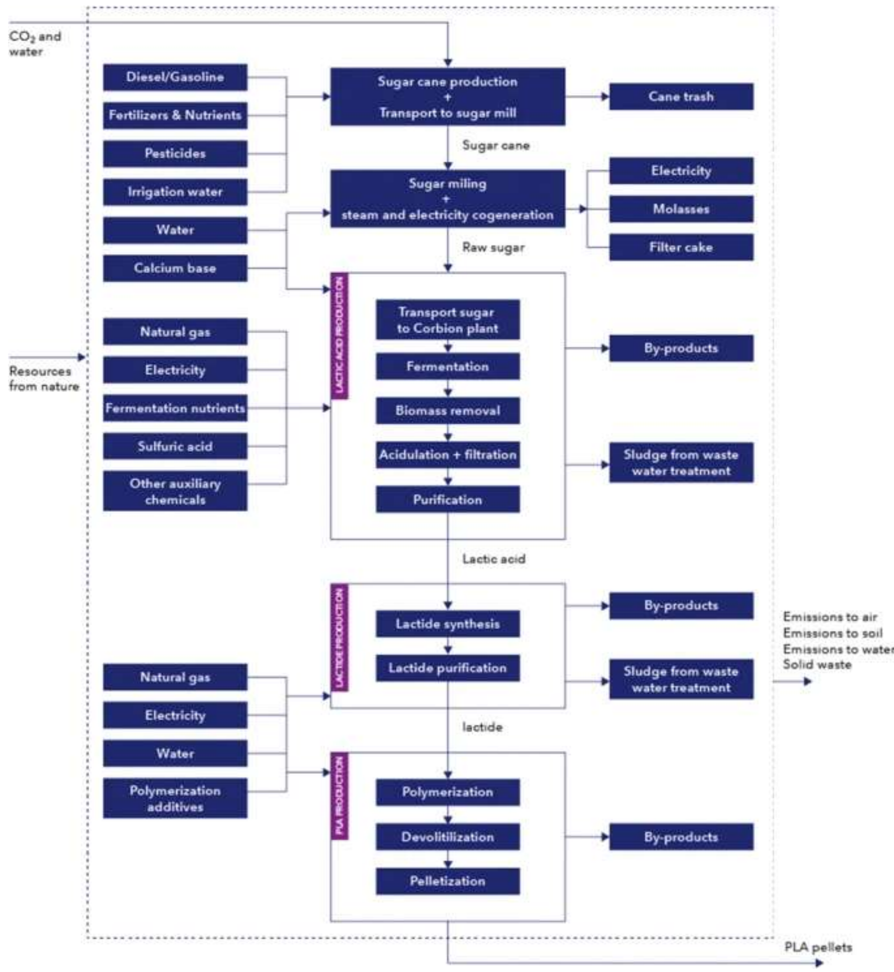

Figure 76: PLA life cycle [24].

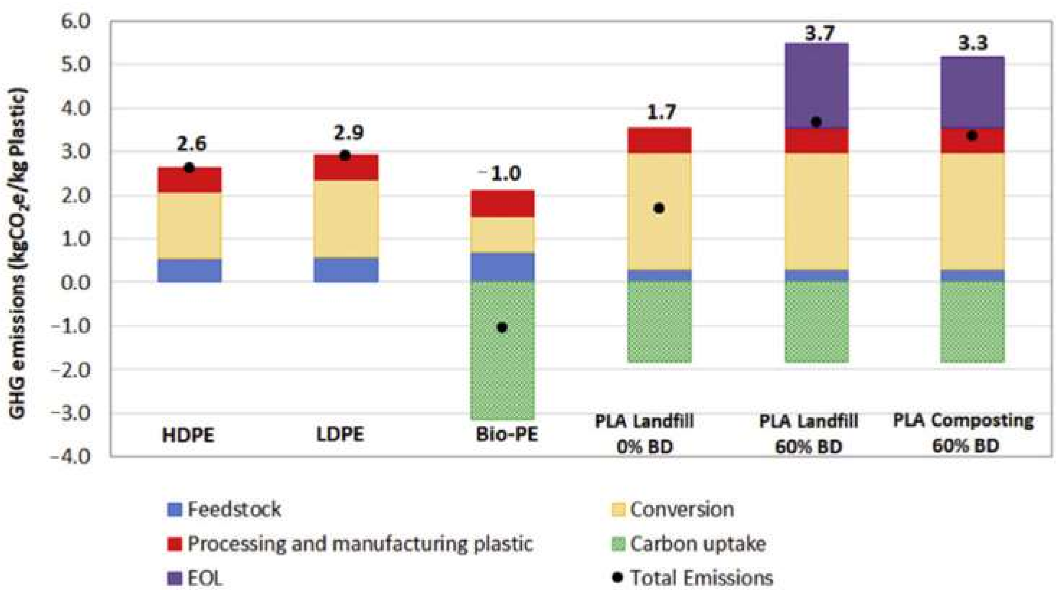

Figure 7777: Greenhouse gas emissions during the lifecycle of PLA [20]

The other components of the jig are all made from steel. Stainless steel screws are created first by sourcing raw materials through the mining of iron [25] This mining takes lots of energy using fossil fuel dependent machinery and releases carbon dioxide into the air. It also disturbs the land through soil erosion and deforestation. The mined iron is then transported to a manufacture where it is placed in a furnace to become steel by removing the carbon. 6.5% of carbon dioxide emissions are derived from iron and steel production [26]. The produced steel is then manufactured into different mechanisms, in the case of this design: hex socket screws and a spring. Screws are made from either cold forming or machining [27]. While the springs are made through spring winding. heat treating, grinding, and coating and finishing [28]. All these processes take energy consumption. After they are made, they are then shipped to different sellers. This transportation again takes energy. Some energy was saved with this design since the components sourced, the screws and spring, were not bought specifically for this design but were instead reused from previous projects, instead of being thrown away. When a steel mechanism does reach the end of its life it can be repurposed and applied in new applications, just as it was in this project thus lowering the energy consumption and release of harmful gases of a design [29]. Steel can also be recycled by melting and being reformed into new pieces, consuming less energy and resources than it takes to create virgin steel.

For this method, the silicone sleeve is wrapped in thin aluminum foil to distribute heat. Aluminum foil is first sourced through the mining of bauxite ore which is processed. The production of 1 ton of aluminum ingot creates 12 tons of carbon dioxide and requires 170 million Btus of energy [30]. Further energy is consumed as this ingot is melted, mixed with iron and silicone, and rolled extremely thinly. The foil is then packaged and shipped to different sellers again consuming energy. For this design only a very thin piece of aluminum is used to create a weld, this piece of aluminum can be reused repeatedly until it rips, and a new piece is needed. Aluminum can be infinitely recycled and if the foil used is recycled it can be melted and reformed [31]. If the old piece is thrown away, it will end up in a landfill. Aluminum foil adds no poisonous compounds to the soil or ground water while it is decomposing, it gradually oxidizes and becomes aluminum oxide, this does take many years, however.

This design relies on the use of a silicone sleeve. Silicone is a synthetic material consisting of silicon, hydrogen, oxygen, and carbon. The production of silicone has a much lower carbon footprint than that of plastic [32]. Silicone is produced in China the process of creating it does rely heavily on the use of non-renewable resources and leads to carbon emissions. Coal based thermal power is the main way silicone is made, and this process produces 4 kg CO2e/kg Si [33]. The silicone also must be transported, again consuming energy and releasing greenhouse gases. At the end of its life silicone cannot be recycled and will therefore be landfilled. However, silicone is an exceptionally durable material and can last for a long time, for this design only a small amount is used and can be continuously reused multiple times as it does not melt or deform from the heat of the soldering iron. The silicone can simply be slid off one welded joint and used again to create another.

The final component of the silicone method is the soldering iron used to reform the filament. The specific soldering iron bought for this project uses a maximum of 60 watts of electricity while plugged into a 120V wall plug. The soldering iron only needs to be used for about 2 minutes per weld, including heat up time, and thus can be turned off in between welds to save power and limit energy consumption. Assuming the soldering iron is using the maximum voltage for the full time, .0072 MJ of energy are used per weld.

The only difference between the initial silicone sleeve design and the final prototype design is the need for slightly more PLA to be used in 3D printing the part, about 4g. This will increase the energy consumption needed to create the main component of the jig, but not by much. Once the initial jig has reached its end of life, the PET filament created and spliced by the very jig could be used to print a new one, thus being self-sustaining.

Nichrome Wire Method

The nichrome wire method consists of a PLA 3D printed base (about 27g), a battery box which takes three AA alkaline batteries, nichrome wire, a clothespin, aluminum foil and a 1cm piece of silicone sleeve.

As previously explained in the silicone sleeve method the greatest energy consumption comes from the use of the PLA in 3D printing the main jig component, after which the battery pack is a close second. The main detriment to the environment this method provides is that it uses up batteries very quickly, creating waste as they are thrown out.

Between this method and the silicone sleeve method, the major change is the use of a nichrome wire and a battery pack to heat the filament and create an even weld. The biggest contributor to energy consumption is thus the battery pack. This method goes through batteries quickly, after about 20 welds the batteries must be switched out. AA alkaline batteries consume a high amount of energy in their production through the synthesizing and mining of the raw materials. Alkaline batteries are made up of multiple chemicals such as lead, zinc, manganese dioxide, carbon, potassium hydroxide, nickel, brass, and plastic [34]. These batteries are better for the environment when compared to lithium-ion and Ni cadmium batteries as seen in Table 10, consuming the least amount of energy and carbon dioxide. Energy is also consumed in the transporting and manufacturing of batteries. After they are used the batteries are most likely landfilled, Table 11 shows the energy spent for a single AA battery in its whole life, including its disposal in a landfill.

Table 10: Energy and carbon consumed are compared for AA batteries: alkaline (23 g), Lithium ion (15 g), and Ni Cadmium (31 g) [34]

AA Battery	Alkaline	Lithium ion	Ni Cadmium
Energy (MJ)	.965	3	4.43
CO_2 (Kg)	0.0724	0.225	.332
End of life potential Energy (MJ)	Option not available	Option not available	Option not available
End of life potential CO_2 Footprint (Kg)	Option not available	Option not available	Option not available

Table 11: Energy spent for each AA battery as listed by material, manufacture, and transport, and disposal. Landfill option [34]

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 foot print (%)
Material	1.65	94.8	0.1	93.6
Manufacture	0.0635	3.7	0.00495	4.6
Transport	0.0226	1.3	0.00162	1.5
Use	0	0.0	0	0.0
Disposal	0.00355	0.2	0.000249	0.2
Total (for first life)	**1.73**	**100**	**0.107**	**100**
End of life potential	0		0	

Nichrome wire is a heating element made of nickel, iron, and chromium alloy [35]. To create the wire these raw materials must first be mined for or synthesized resulting in chemical release, land use, and energy consumption. Of all stages of life this has the highest impact on the environment. It then must be drawn and extracted into wire and then transported to sellers, again consuming energy. This alloy can then be recycled or landfilled.

For this method 22-gauge nichrome wire is used which takes the 4.5 voltage, and 7,500mAh of the three batteries in the pack and allows for current to flow through the wires heating them [36]. It takes 1.5Wh or .0054 MJ per weld since 20 welds can be done per battery set. It takes 50 welds to create a 1kg spool. This method if used for high production would lead to an exuberant amount of waste in the form of dead batteries, this is why a prototype method that used power from the wall was created and is recommended to move forward with.

The prototype version of the nichrome method adds more nichrome wire, a couple switches hooked to a small adjustable variable voltage regulator power supply and uses more PLA, about 120g, to create the support components and main jig. This prototype takes more components and thus has a higher consumption of energy in its manufacturing of each part but has a longer total lifespan than the initial method in that it takes wall power instead of batteries.

Using all the information found above Table 12 gives the estimated total environmental impact of each method including the amount of energy consumed to produce a single mechanism, the energy lost in use during a single weld, and the amount of carbon dioxide released. This was estimated mainly with the information of how much PLA went into each method, since a 3D printed design was the major component of all methods. To produce one ton of PLA it takes 27,309 MJ of energy. The use of AA batteries was also considered for the initial nichrome method. The energy lost is based on how much power it takes for each method to heat up and create a single joint.

Table 12: Total environmental impact for each method

Method Type	Energy Consumption In Production (MJ)	Energy Lost (MJ)	Carbon Dioxide Released During Life (Ton CO_2e)
Initial Silicone	0.963	0.0072	2.638
Silicone Prototype	1.083	0.0072	2.967
Initial Nichrome	6.003	0.0054	2.227
Nichrome Prototype	3.604	0.0054	9.875

Conclusions and Recommendations

PET plastic soda bottles are a major contributor to global pollution, filling landfills all around the world. Green Ellipsis has been working to help regulate this environmental problem through the promotion of recycling soda bottles into filament. However, Green Ellipses faced an issue in trying to incentivize community organizations to take on and further promote this recycling due to the uneven ratio of cost to produce to cost of product. The current process has a high cost of labor, while the filament produced is too minimal to create worthwhile prints.

Over the past year this group aimed to decrease this production and sell cost ratio through the improvement of the final product. A single soda bottle can only create about 15 to 20 grams of usable filament, while typically commercial filament is sold in 1kg spools, this 1kg spool can be created for the PET filament through the method of splicing. Splicing of PET filament is a complicated endeavor, though, since the polyethylene terephthalate can recrystallize easily when exposed to heat, becoming brittle and breaking before it can successfully be extruded through a 3D printer. To splice PET filament a successful method needed to be discovered and thoroughly tested. Multiple methods were brainstormed, created, iteratively finalized, and the results of each were tested against the requirements and constraints needed to move through a 3D printer and create a 3D print without any defects.

Through testing and research, it was discovered that the creation of a successful splice could only be achieved through the connection of the filament after it had already been pultruded through the machine. No mechanical or thermal ribbon method created a full joint consistently, instead all lead to a mass overflow failure when being put through the pultrusion machine. The three filament methods, simple soldering, silicone sleeve, and nichrome wire all made joints that could hold the weight of themselves. These three methods were then further specifically tested against the decided requirements and constraints. It was found that the simple soldering method could not meet the constraints and is recommended to be scrapped.

All the requirements were met by the final two methods. The process used all portions of the plastic bottle with minimal waste. The silicone sleeve and nichrome method did introduce the need for both silicone and aluminum foil that can’t be infinitely reused but can be used multiple times before needing to be replaced. The initial nichrome method does produce waste in the form of needing to change batteries often, but this will be remedied through a recommendation of using power from an electrical outlet instead. Using both methods, a 1kg continuous spool could be achieved by connecting 50 or more bottles together. The raw materials of the filament are still only sourced from used plastic bottles. All design components used the metric system of measurements as requested by the sponsor. Each method has a low cost to build, mostly made up of 3D printed parts and cheap materials that can be sourced from amazon. The two processes thus improve the cost/revenue ratio by being cheap to build but making more final products to sell. The total project cost stayed below the given budget of $1000.

Both final methods also met most of the constraints needed to be successful filament, as shown in the testing section. The sponsor requested 70-80% success at a confidence of 70-80%. Following the binomial nomograph provided by the sponsor and true probability of success calculations, the nichrome wire method was 70% successful in withstanding the needed bend out of 10 trials, and thus had a true success rate of 55% at a 70% confidence. For the bend test the silicone method had an 80% success rate in withstanding the bend during 10 trials, or a true success rate of 68% with 70% confidence. The true success of both is lower than what the sponsor hoped for, but still show a promise in the methods to be further explored. The same can be said for the constraint of holding a tensile stress of 30 Newtons. The Nichrome method had a success rate of 60% with a true success rate of 45% at a confidence of 70% while the silicone method had a success rate of 90% with a true success rate of 80% at a 70% confidence. The nichrome and silicone method did fully meet the constraint of staying within 1.75mm +/- .1mm and not clogging the 3D printer by successfully creating a solid print 95% and 90% of the time respectively, with a true success of 88% and 80% at a 70% confidence value respectively. The silicone method which required outlet power got it from a standard 120V outlet as requested in the constraints. Finally, both methods met the constraint of being safe a usable by the average person.

The final designs of the testing methods mostly met the constraints and requirements but could be further improved and optimized as discussed in the final design section with the introduction of final prototypes. It is recommended that the sponsor continues with these prototypes in order to achieve 100% consistent joints. The silicone method should remain a quick and simpler handheld method for hobbyists and the nichrome method should be further pushed into an automated design that could attach to the main pultrusion machine. Most iterations regarding silicone soldering will be about ergonomics and ease of use. The changes needed for success are minimal but should be noted for a final product if this were to be made and shipped out. The proposed changes to upgrade the nichrome method would very likely increase the quality of the splices made and the ease of making them. Using power from a standard outlet rather than batteries is essential for any long-term solution. It is the belief of this group that both methods hold high potential as solutions to the problem of PET filament joining and with the suggested further optimization could become reliable enough to consistently make perfect splices.

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Appendices

Appendix A: Calculations

Heat transfer calculation:

Maximum energy transfer allowed:

All references from Matweb Source

Most conservative case:

$T_{glass} = 70°C \quad T_i = T_\infty = 23°$

$C_{cons} = 1 \, J/g\,K$

$\rho_{avg} = 1.36 \, g/mL$

length $\approx$ 1cm - Assumed

radius : 1.75mm = 0.175 cm

$A_{circle} = 0.096 \, cm^2$

$\forall = 0.096 \, cm^3$

$m = \rho_{AVG} \forall = 0.13056 \, g$

$Q = mc\Delta T = 0.13056 \cancel{g} \cdot 1 \frac{J}{\cancel{g} \cdot \cancel{K}} (70° \cancel{C} - 23° \cancel{C}) = 6.13632 \, J$

Least conservative case

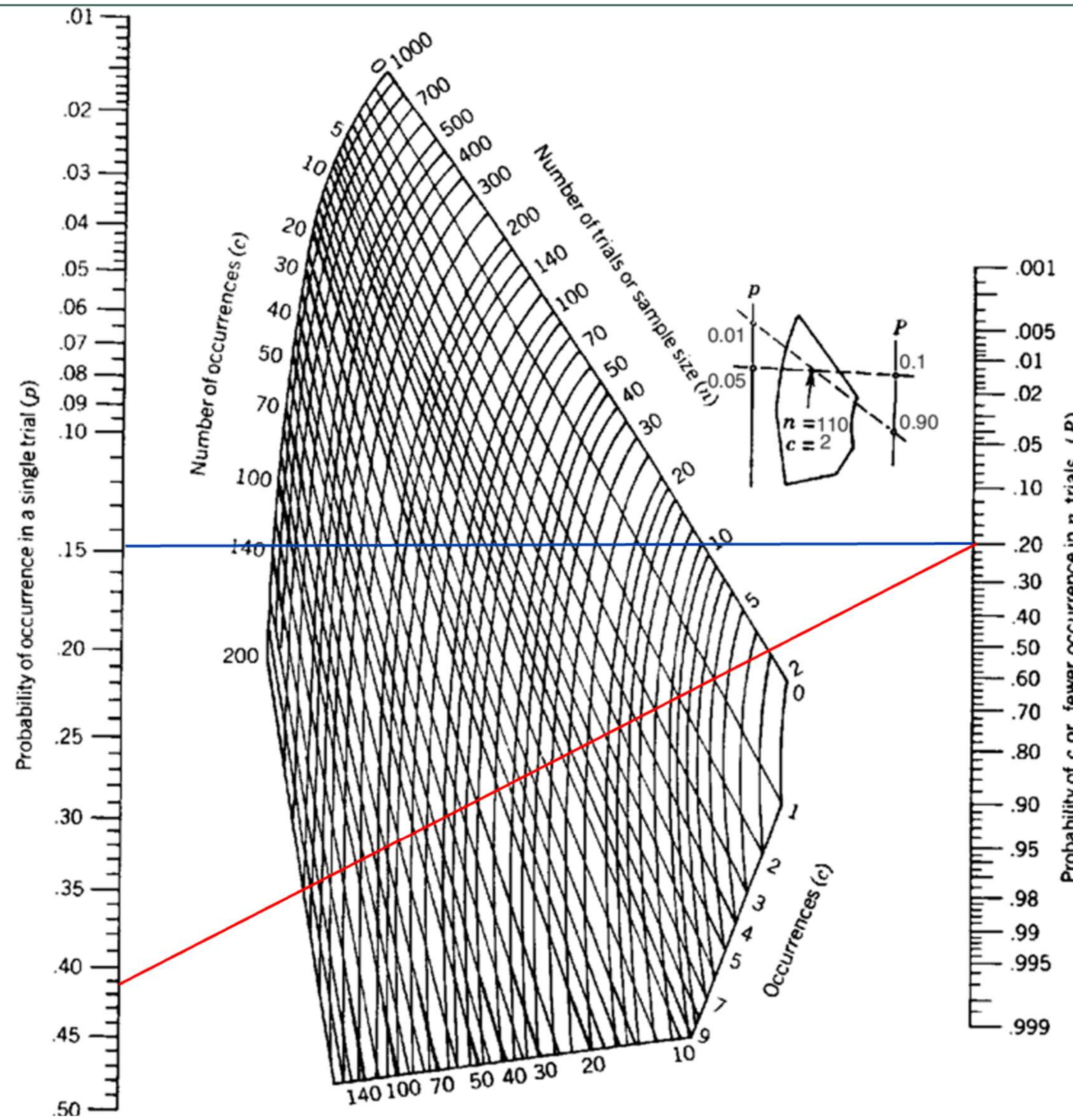
$T_{glass} = 78°C \quad T_i = 23°C$

$m = 0.13056$

$c = 2.30$

$Q = mc\Delta T = 0.13056 \cancel{g} \cdot 2.30 \frac{J}{\cancel{g} \cdot \cancel{K}} \cdot (78 - 23)° \cancel{C} = 16.51584$

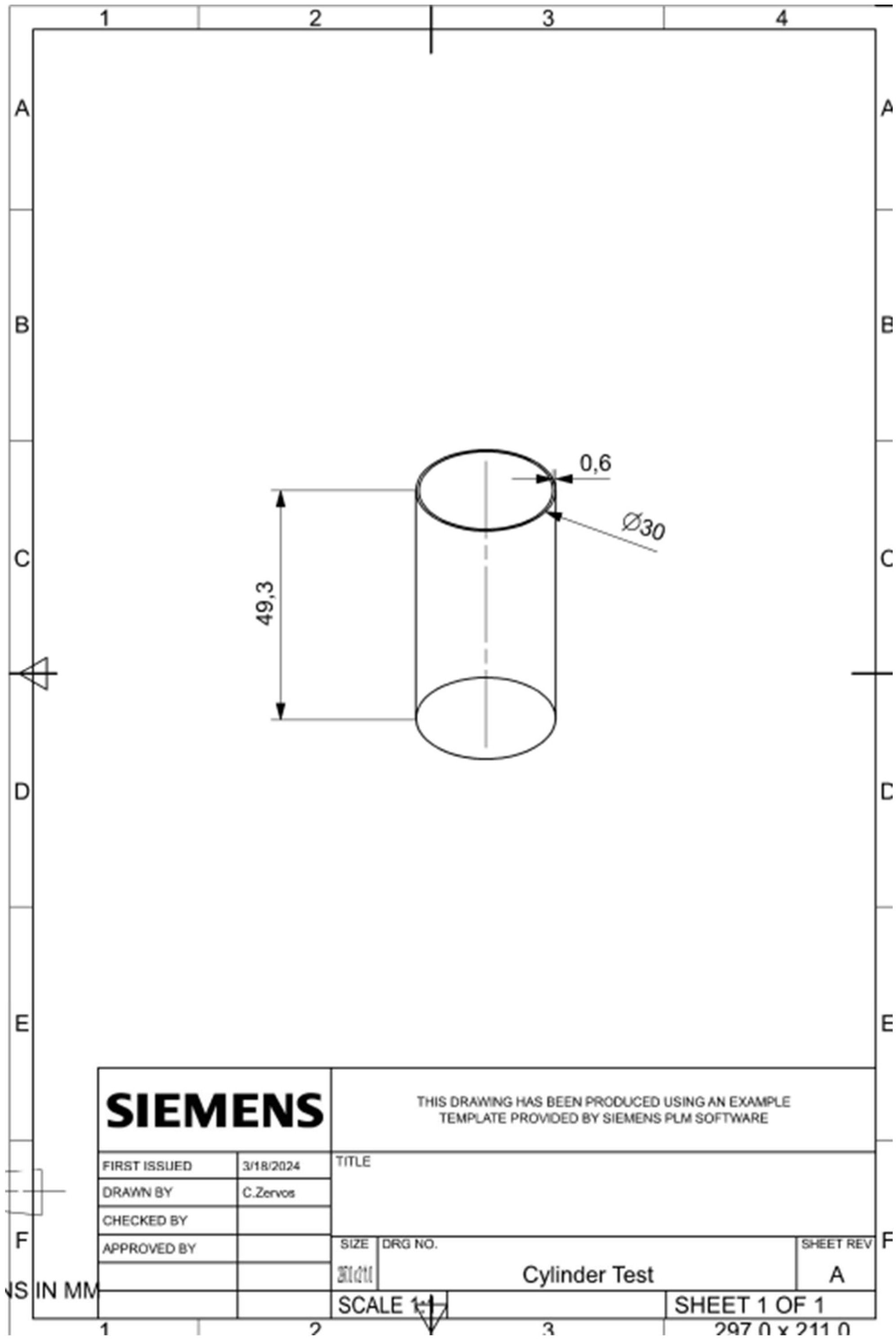
Binomial nomograph in use:

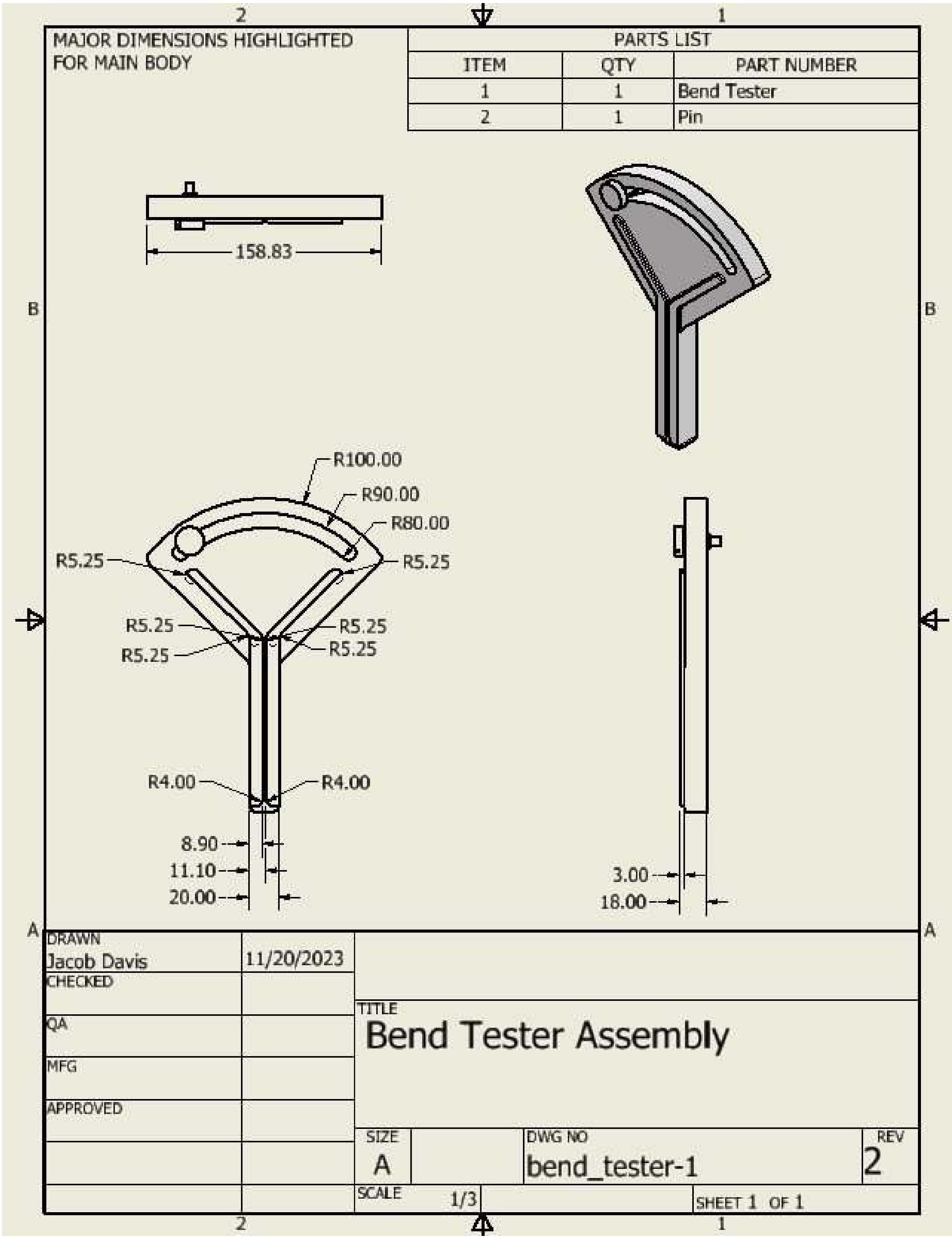


Appendix B: Bill Of Material Links:

Nichrome Wire	www.amazon.com/dp/B01FHX7R3M
Clothespin	www.amazon.com/dp/B092LBVPPP
Aluminum Foil	www.amazon.com/dp/B005GPJCHQ
Battery Holder	www.amazon.com/dp/B07TB4HDYH
Omron Switches	www.amazon.com/dp/B01K0ZLMYM
Soldering Iron	www.amazon.com/dp/B0C36VB783
Thermoplastic Welder	www.grainger.com/product/4UZR6
Silicone Tubing	www.amazon.com/dp/B093F6F2L4
Thermocouple	www.amazon.com/dp/B08ZYHFBYW
10mm Screws	www.accu-components.com/us/cap-head-screws/3819-SSCF-M3-10-A2
15 mm Screws	www.us.screwerk.com/en/shop/detail/stp/STP420300150S.html
Toggle Switches	https://www.amazon.com/d/B078KBC5VH
Voltage Regulator	https://www.amazon.com/d/B0978T3JKH
6mm Hex Standoff	https://www.mcmaster.com/product/95947A525
316 Stainless Steel Hex Drive Screws	https://www.mcmaster.com/product/94500A221
Ring Connector	https://www.digikey.com/en/products/detail/molex/0192030485/3185529

Appendix C: CAD Drawings




MAJOR DIMENSIONS HIGHLIGHTED FOR MAIN BODY
PARTS LIST
ITEM QTY PART NUMBER
1 1 Bend Tester
2 1 Pin
158.83
R100.00
R90.00
R80.00
R5.25
R5.25
R5.25
R5.25
R5.25
R5.25
R4.00
R4.00
8.90
11.10
20.00
3.00
18.00
DRAWN
Jacob Davis
11/20/2023
CHECKED
QA
MFG
APPROVED
TITLE
Bend Tester Assembly
SIZE
A
DWG NO
bend_tester-1
REV
2
SCALE
1/3
SHEET 1 OF 1

PARTS LIST		
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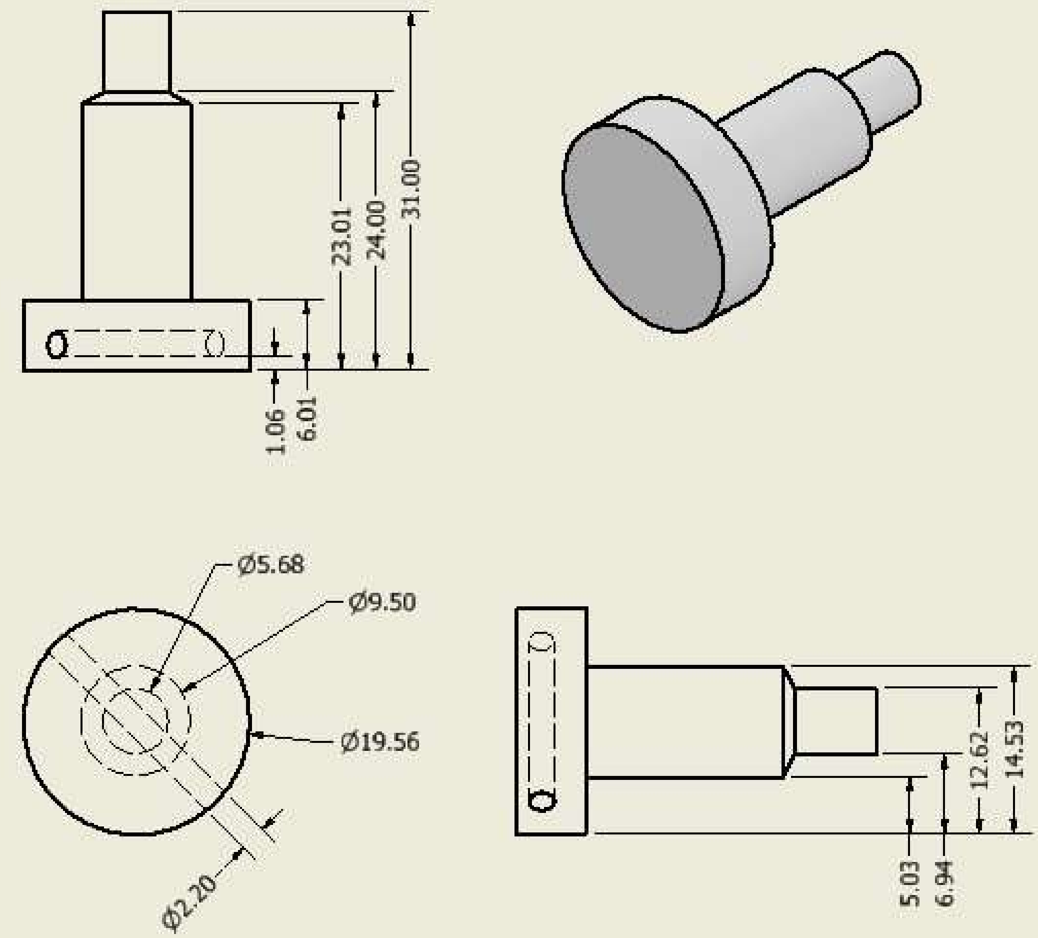

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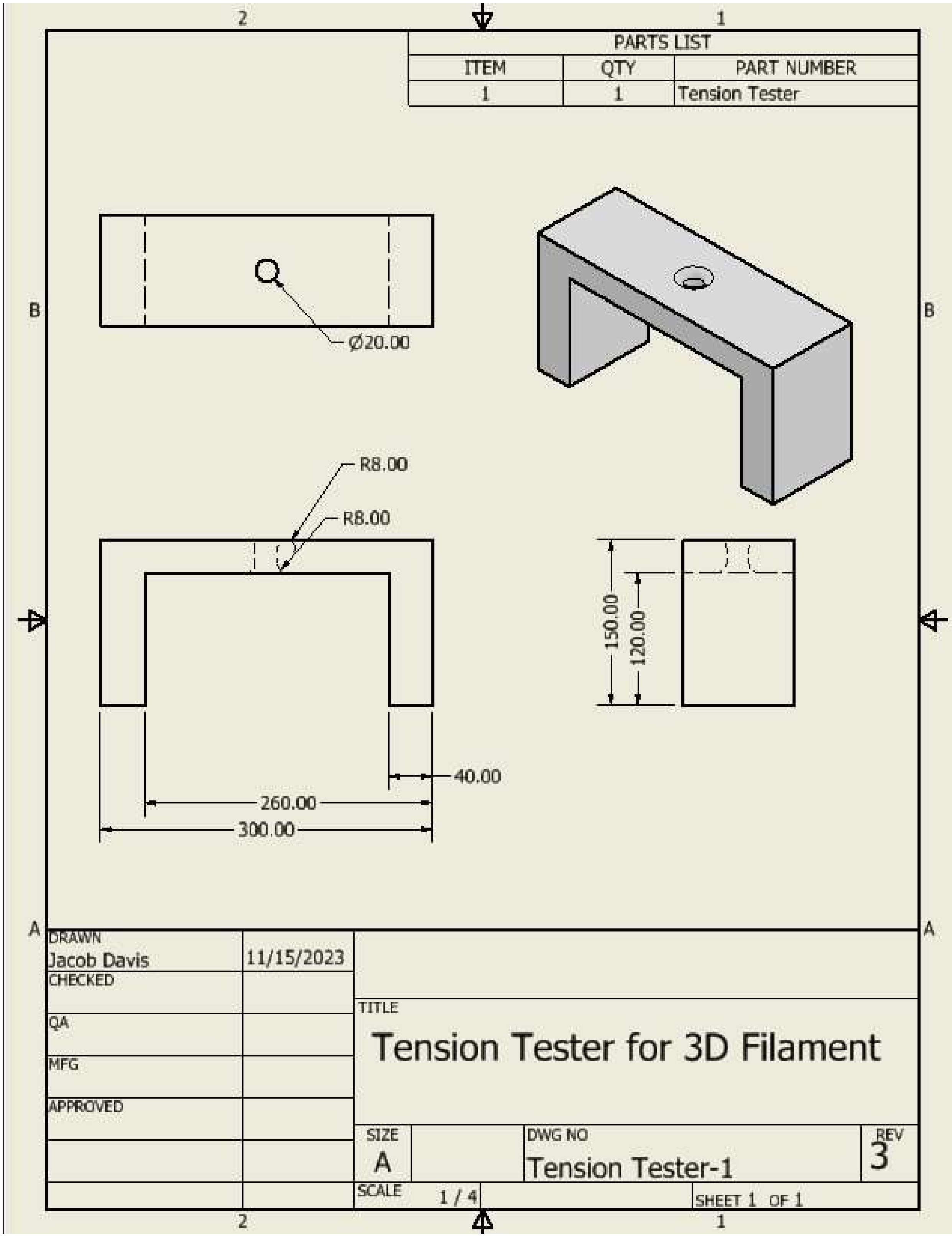
CHECKED		TITLE Bend Tester Pin
QA		
MFG		
APPROVED		

SIZE	DWG NO	REV
A	Bend Tester Pin	2

SCALE 2 : 1 | SHEET 1 OF 1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QTY
PART NUMBER
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1
Tension Tester
Ø20.00
R8.00
R8.00
150.00
120.00
40.00
260.00
300.00
DRAWN
Jacob Davis
11/15/2023
CHECKED
QA
MFG
APPROVED
TITLE
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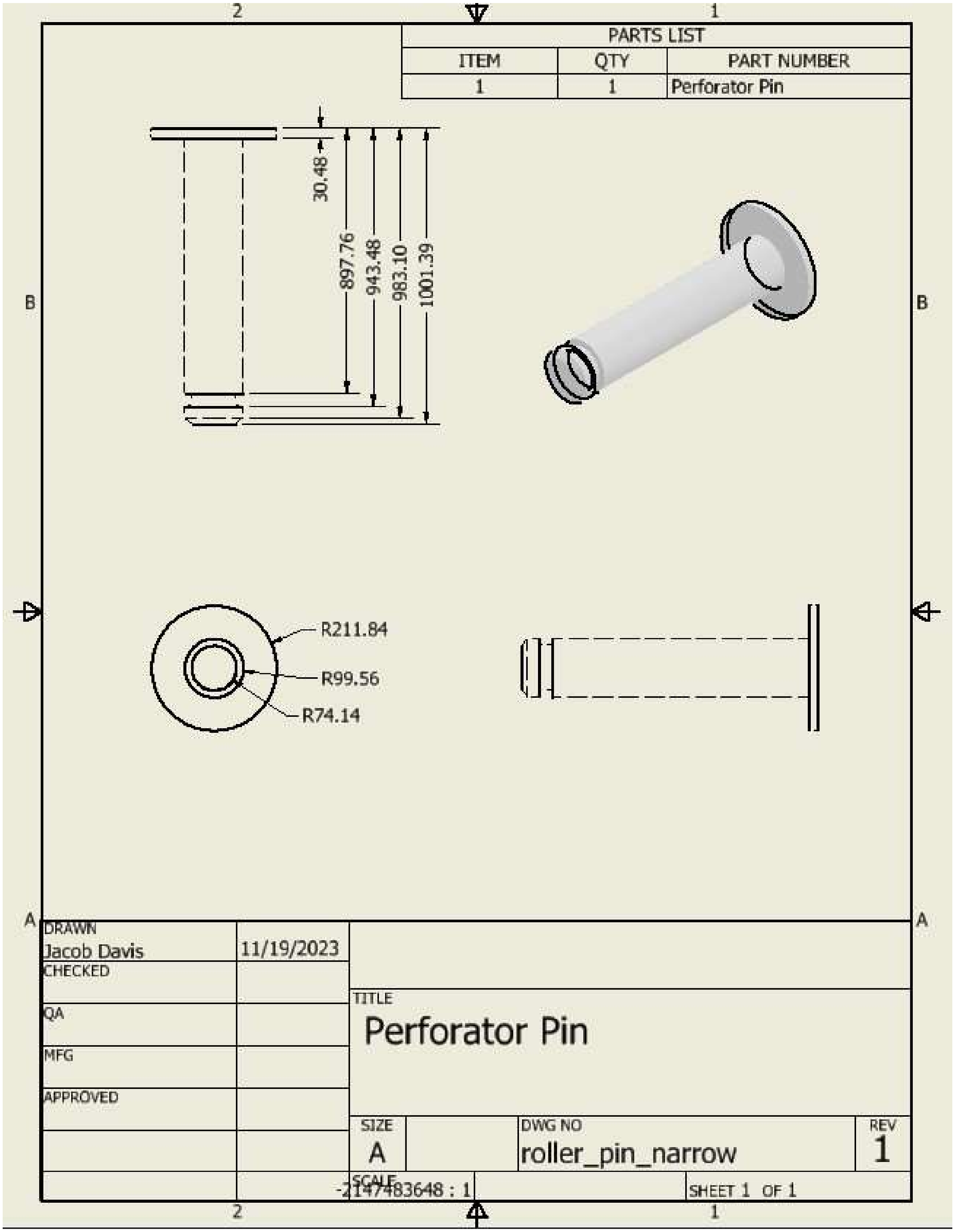
SIZE
A
DWG NO
Tension Tester-1
REV
3
SCALE
1 / 4
SHEET 1 OF 1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ITEM
QTY
PART NUMBER
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1
Perforator Pin
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897.76
943.48
983.10
1001.39
R211.84
R99.56
R74.14
DRAWN
Jacob Davis
11/19/2023
CHECKED
QA
MFG
APPROVED
TITLE
Perforator Pin
SIZE
A
DWG NO
roller_pin_narrow
REV
1
SCALE
-2147483648 : 1
SHEET 1 OF 1

PARTS LIST		
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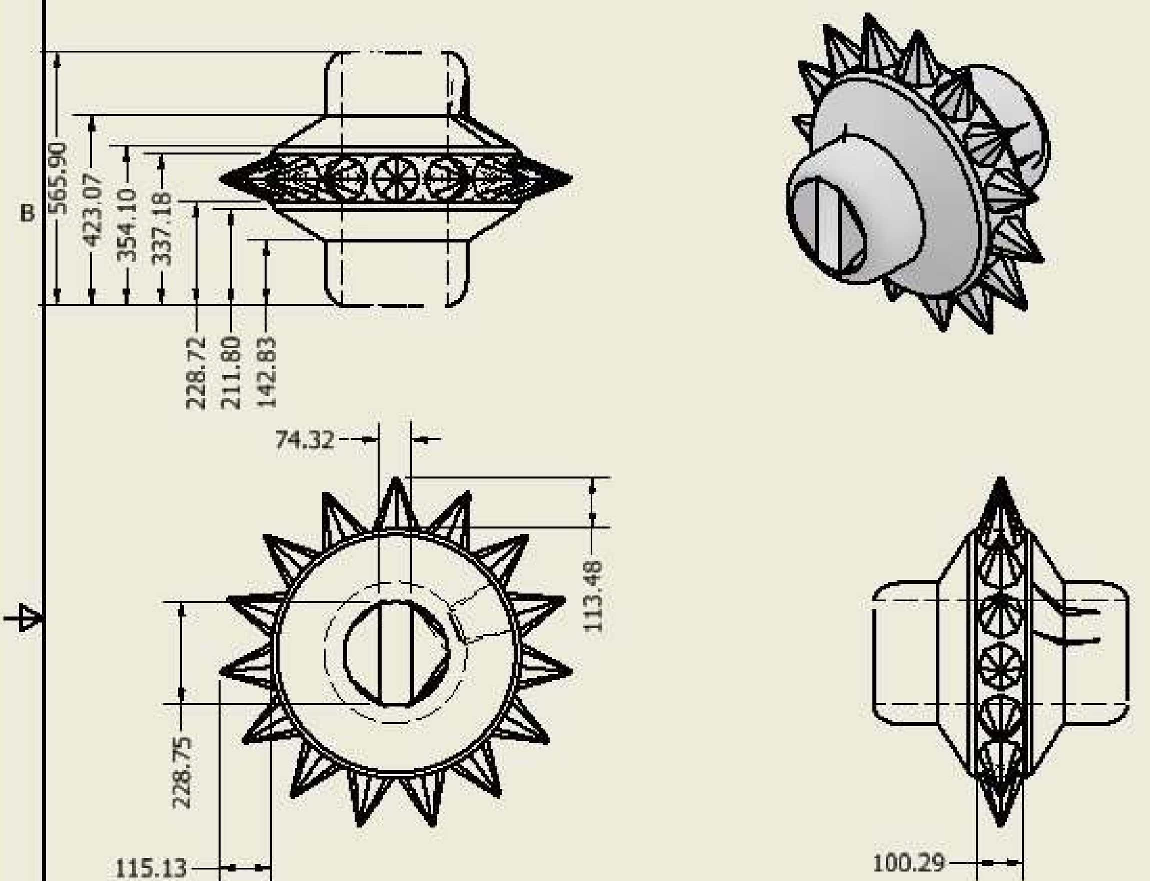

DRAWN		
Jacob Davis	11/18/2023	
CHECKED		TITLE
QA		Perforator Wheel
MFG		
APPROVED		
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		SCALE -2147483648 : 1 · SHEET 1 OF 1

PARTS LIST		
ITEM	QTY	PART NUMBER
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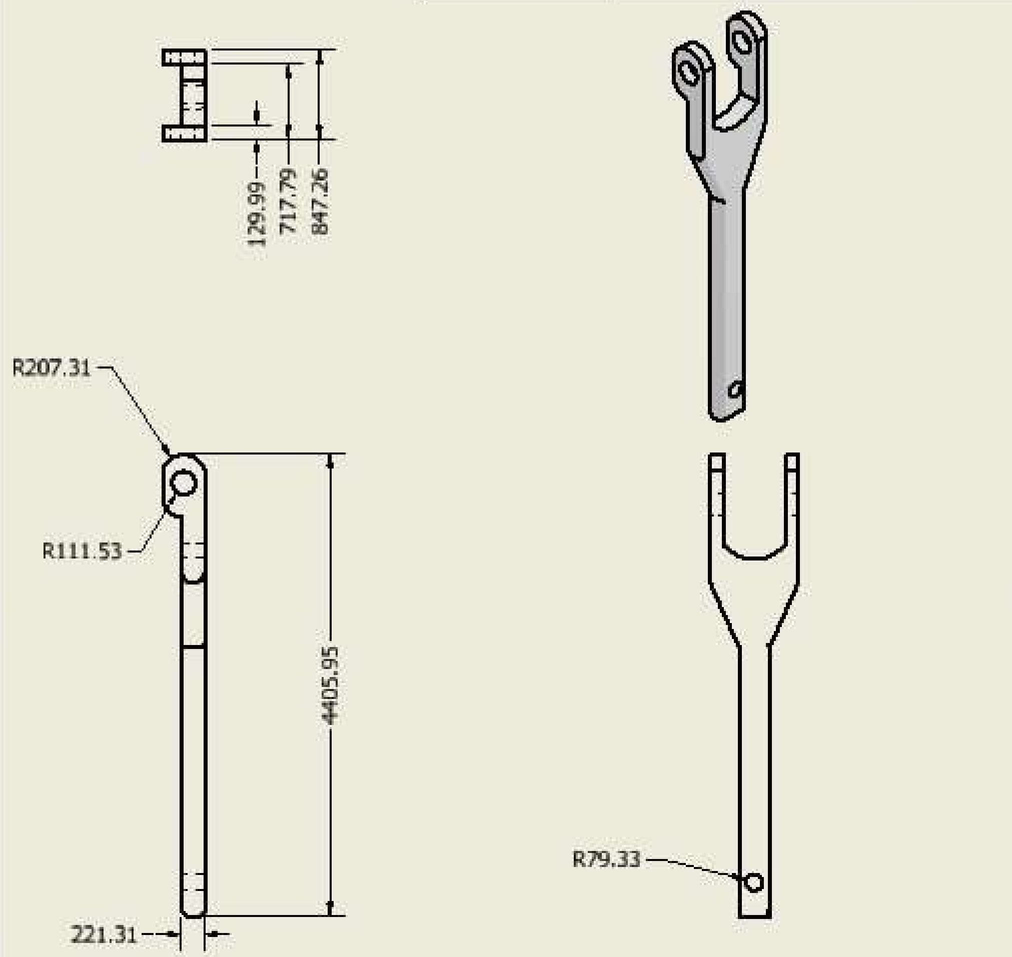

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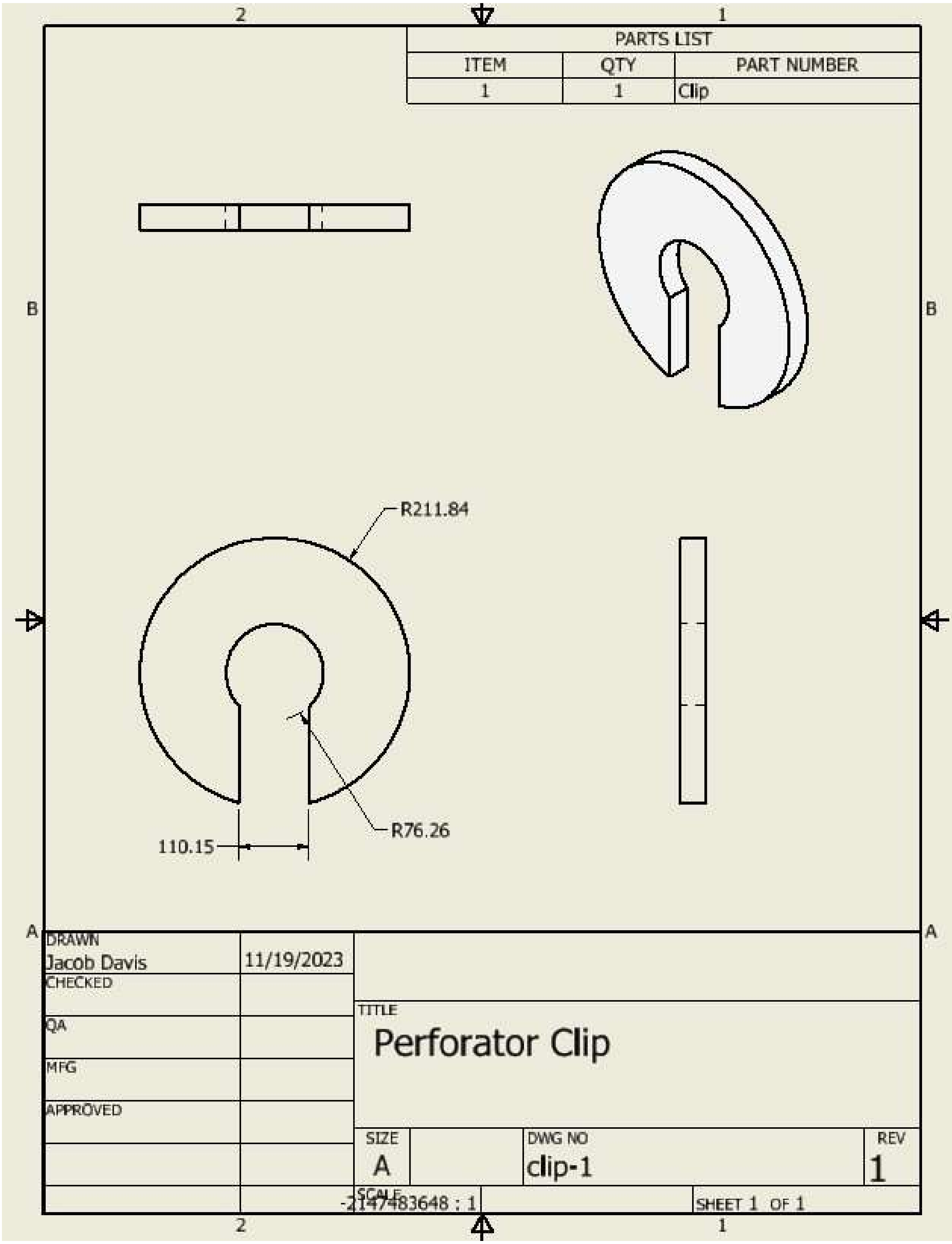
CHECKED		TITLE Perforator Handle		
QA				
MFG				
APPROVED				
		SIZE A	DWG NO Handle	REV 1
		SCALE -2147483648 : 1	SHEET 1 OF 1	



PARTS LIST
ITEM
QTY
PART NUMBER
1
1
Clip
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R76.26
110.15
DRAWN
Jacob Davis
11/19/2023
CHECKED
QA
MFG
APPROVED
TITLE
Perforator Clip
SIZE
A
DWG NO
clip-1
REV
1
SCALE
-2147483648 : 1
SHEET 1 OF 1

*NOT FINAL VERSION
*DIMENSIONS SUBJECT TO CHANGE

PARTS LIST		
ITEM	QTY	PART NUMBER
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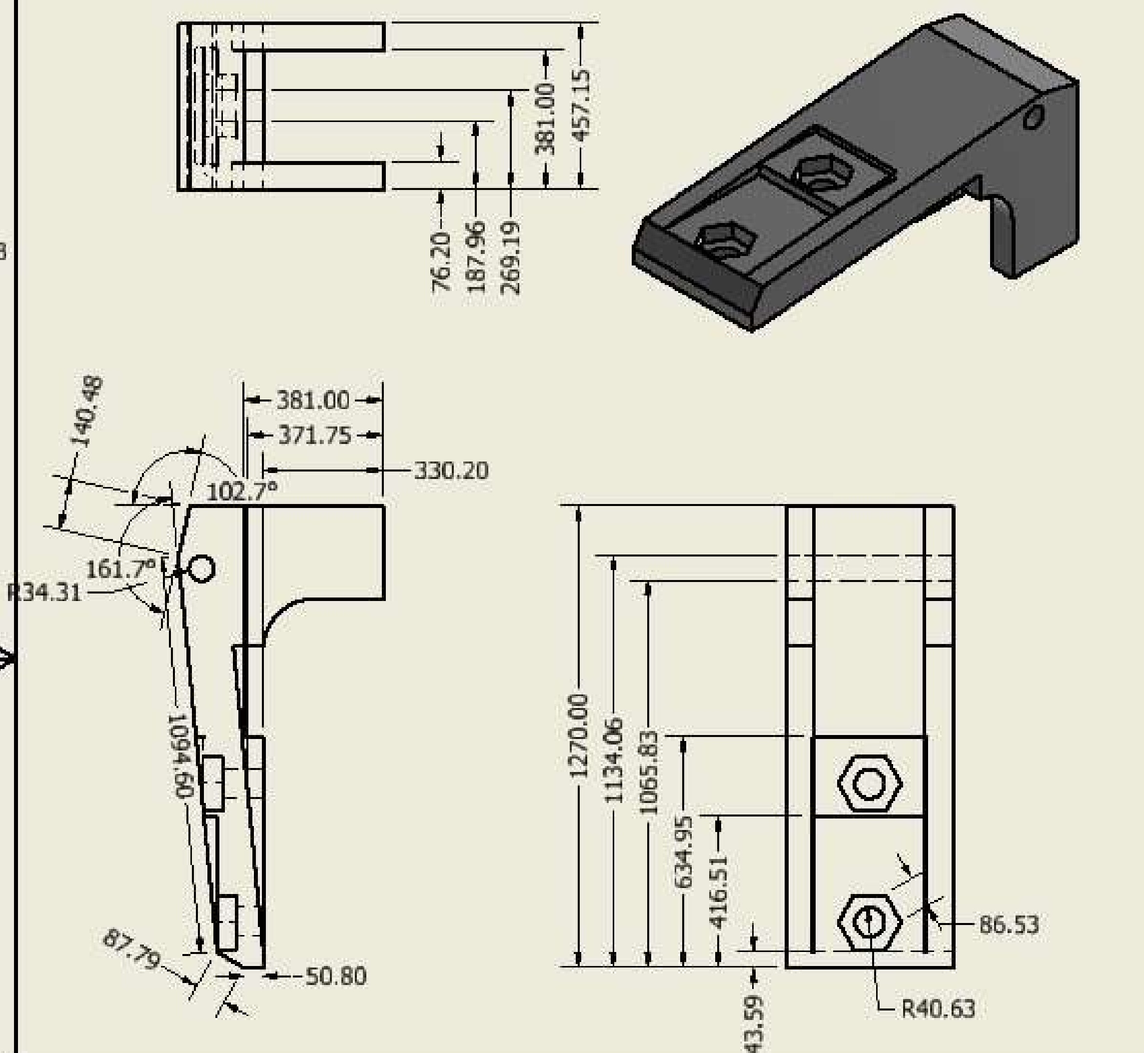

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CHECKED		TITLE Filament Joiner Piece 2		
QA				
MFG				
APPROVED				
		SIZE A	DWG NO Joiner-p2.stl	REV 2
		SCALE -2147483648 : 1	SHEET 1 OF 1	

*THREADS ARE M22 ON 10MM SHAFT
ON TOP HOLE

PARTS LIST		
ITEM	QTY	PART NUMBER
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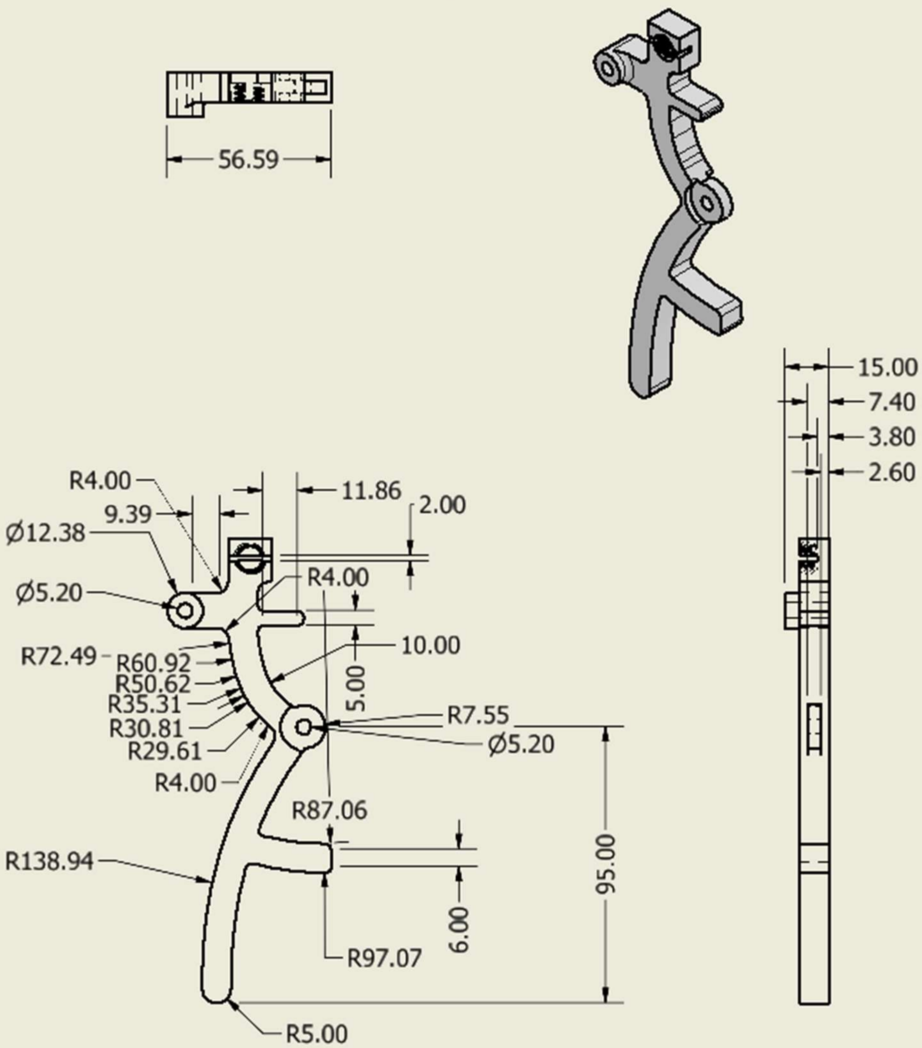
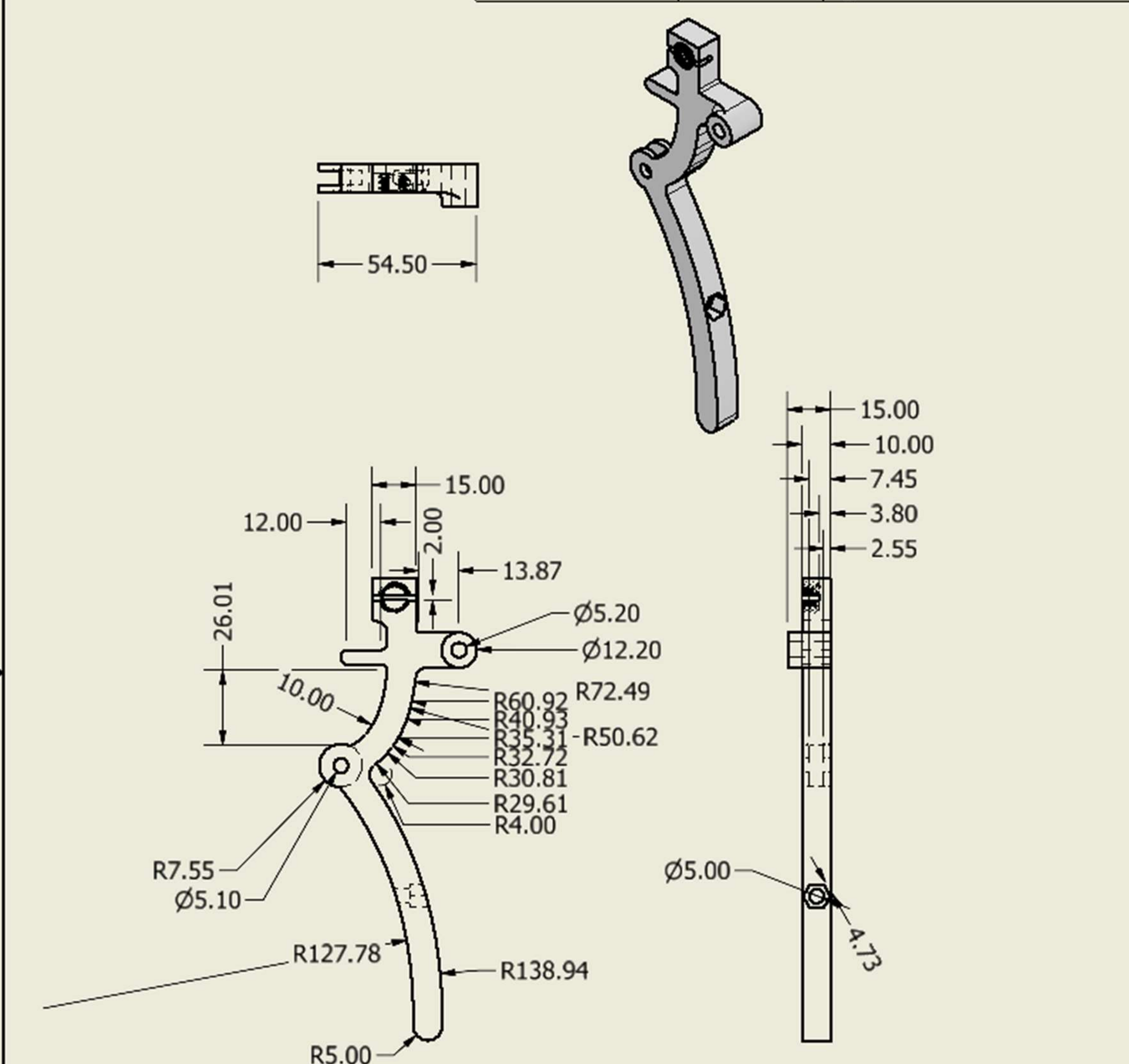


DRAWN		
Jacob Davis	4/17/2024	
CHECKED		
QA		TITLE Tensioner Left Handle
MFG		
APPROVED		
		SIZE A · DWG NO left handle · REV 3
		SCALE 1 / 2 · SHEET 1 OF 1

*THREADS ARE M22 ON 10MM SHAFT ON TOP HOLE

PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	right handle v2



DRAWN Jacob Davis	4/17/2024	
CHECKED		TITLE Tensioner Right Handle
QA		
MFG		
APPROVED		SIZE A · DWG NO right handle · REV 3
		SCALE 1 / 2 · SHEET 1 OF 1

*THREADS ARE M22 ON 10MM SHAFT

PARTS LIST		
ITEM	QTY	PART NUMBER
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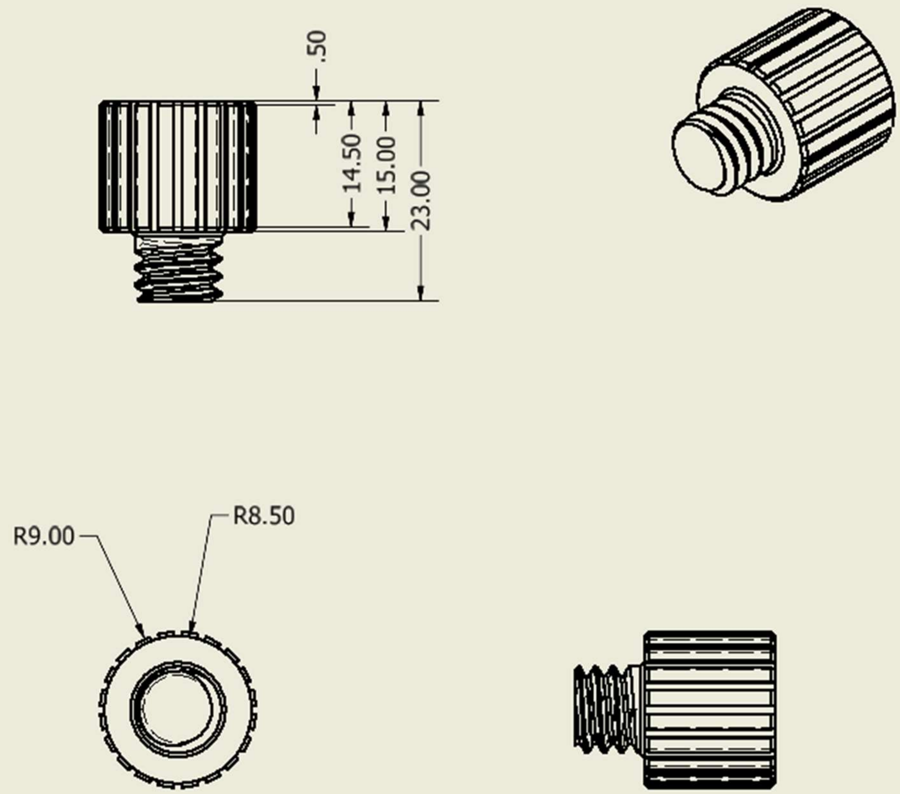

DRAWN Jacob Davis	4/15/2024			
CHECKED		TITLE Thumb Screw		
QA				
MFG				
APPROVED				
		SIZE A	DWG NO Thread test screw	REV 2
		SCALE 1.5	SHEET 1 OF 1	

*THREADS ARE M22 ON 10MM SHAFT

PARTS LIST

ITEM	QTY	PART NUMBER
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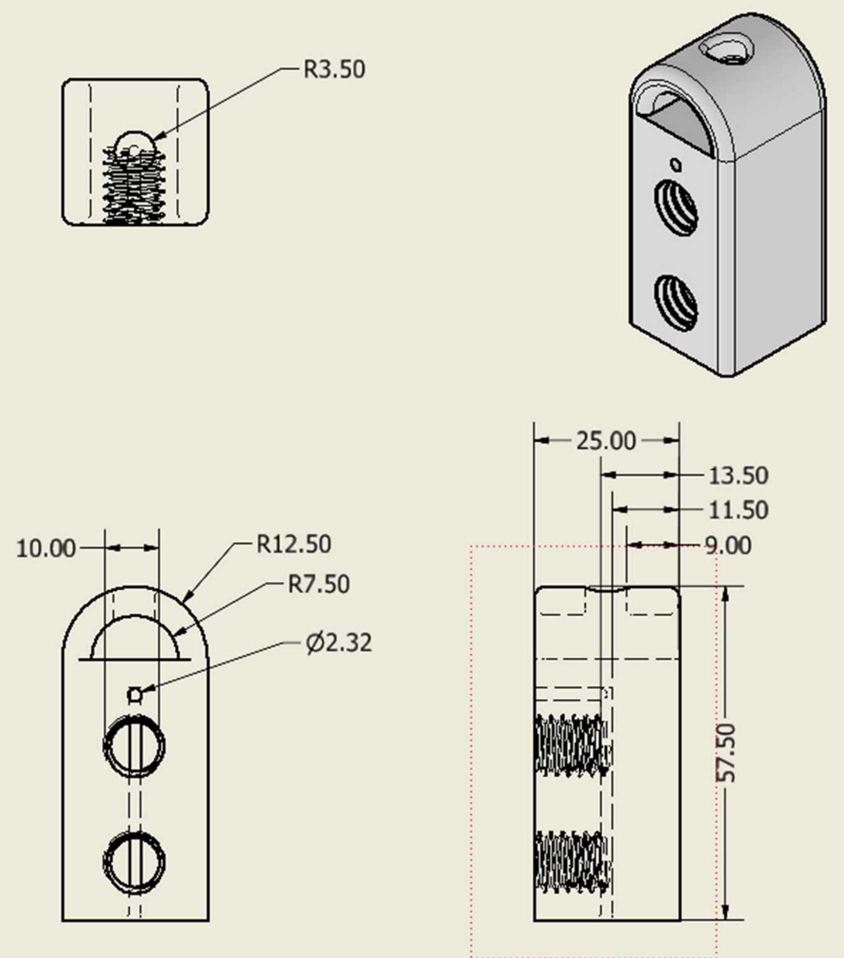


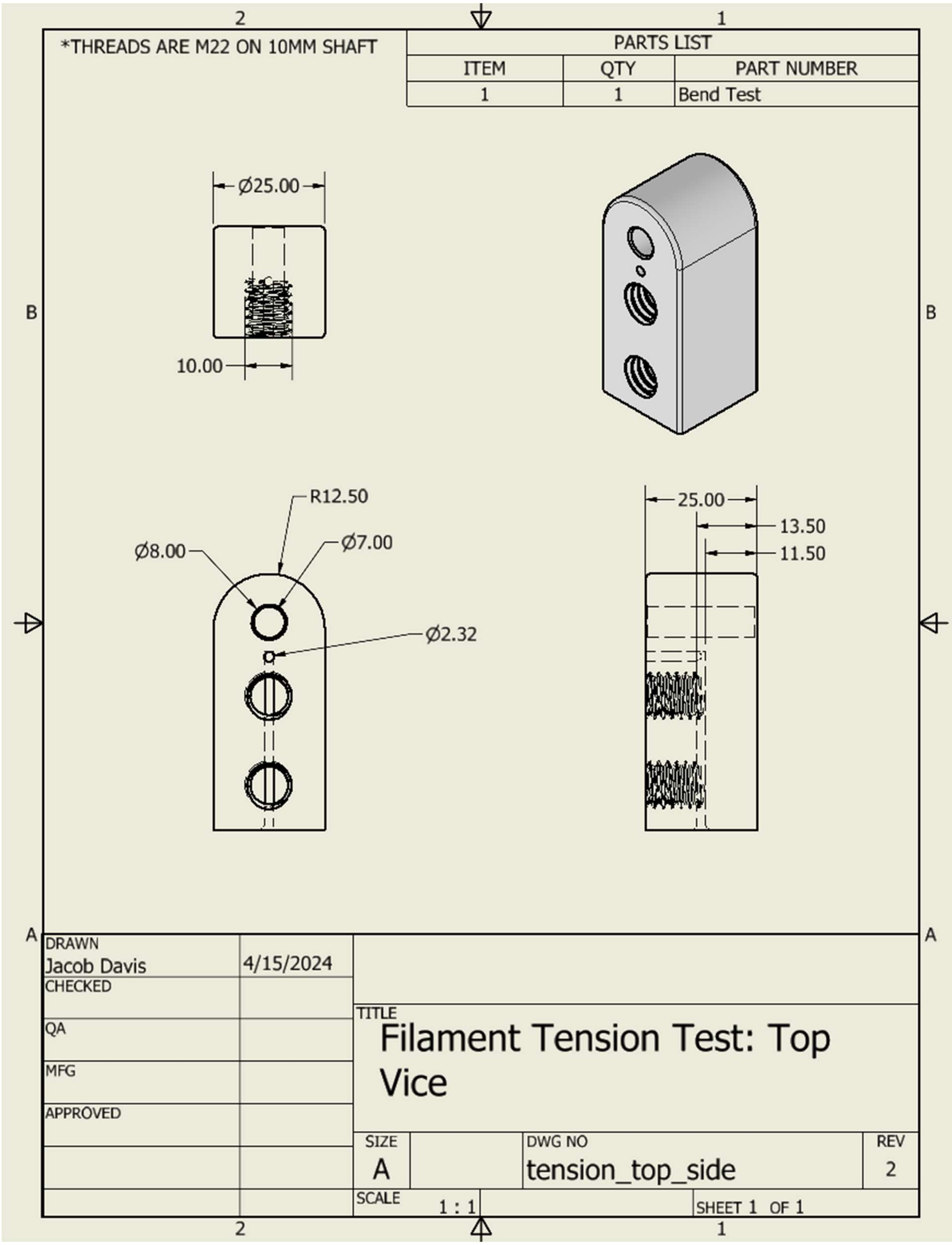
DRAWN Jacob Davis	4/15/2024
CHECKED	
QA	
MFG	
APPROVED	

TITLE

Filament Tension Tester: Bottom Vice

SIZE	DWG NO	REV
A	tension_bot_side	2

SCALE 1 : 1 SHEET 1 OF 1



PARTS LIST		
ITEM	QTY	PART NUMBER
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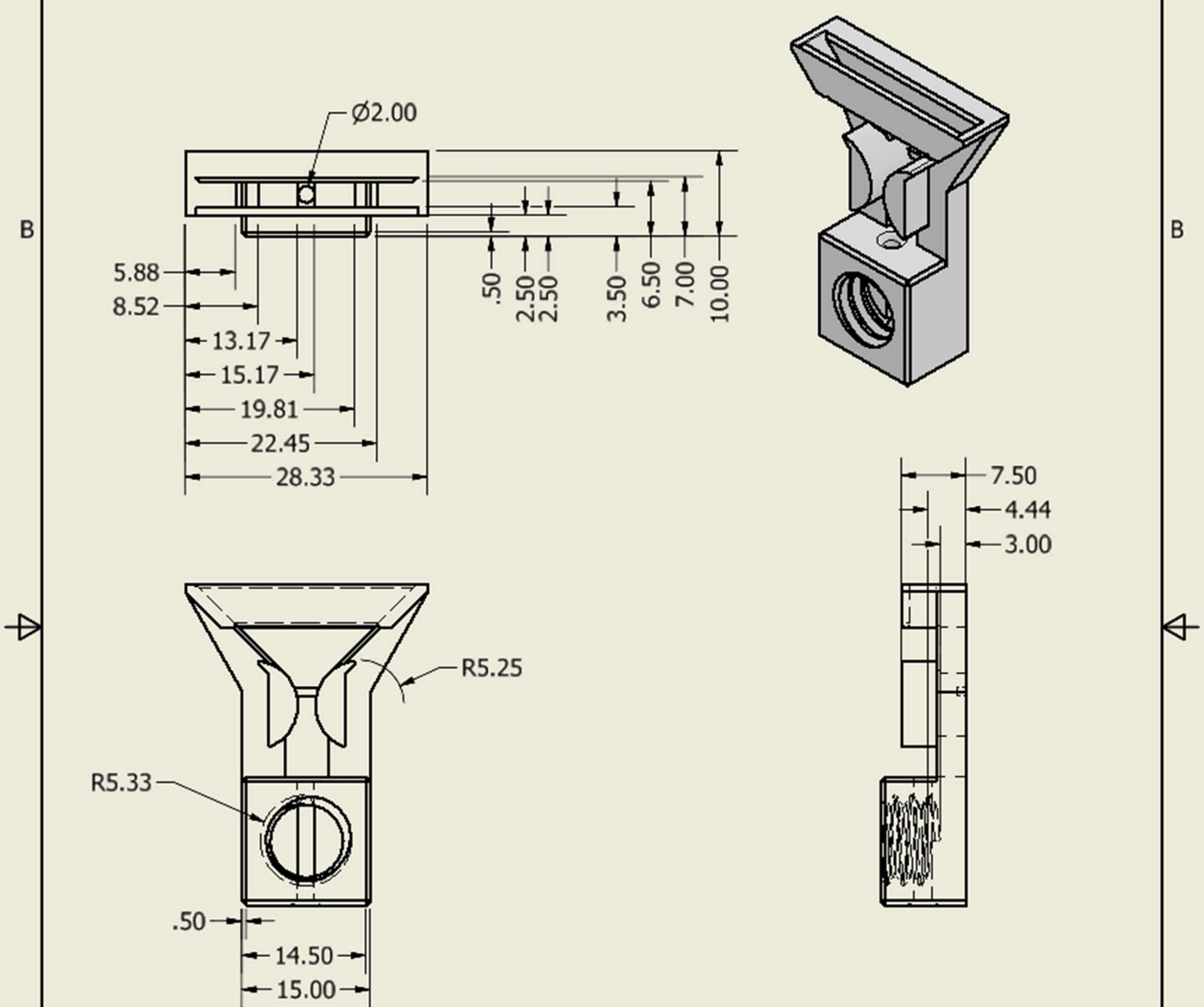
CHECKED		TITLE Filament Tension Test: Top Vice	
QA			
MFG			
APPROVED			
		SIZE A	DWG NO tension_top_side · REV 2
		SCALE 1 : 1	SHEET 1 OF 1

*THREADS ARE M22 ON 10MM SHAFT
*45 DEGREE ANGLE ON INSIDE
SECTION EITHER DIRECTION

PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Bend Test



DRAWN Jacob Davis	4/15/2024		
CHECKED		TITLE	Filament Bend Tester
QA			
MFG			
APPROVED			
		SIZE A	DWG NO Bend_Test-1 · REV 2
		SCALE 1.5	SHEET 1 OF 1