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Poly Pelletizer: Recycled Pet Pellets From Water Bottles

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SANTA CLARA UNIVERSITY

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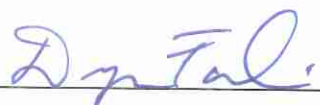
**POLY PELLETIZER: RECYCLED PET PELLETS FROM
WATER BOTTLES**

**BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF**

**BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING**



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POLY PELLETER: RECYCLED PET PELLETS FROM WATER BOTTLES

By

Logan Costa-Smith, Ian Maltzer, and James Martino

SENIOR DESIGN PROJECT REPORT

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the Department of Mechanical Engineering
of

SANTA CLARA UNIVERSITY

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for the degree of
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Abstract

Plastic water bottles comprise a large amount of waste worldwide. The goal of the Poly Pelletizer project is to create a system that will turn water bottles into polyethylene terephthalate (PET) pellets compatible with extruders to produce 3-D printer filament, along with other recycling applications. The system promotes a sustainable solution to plastic pollution by giving manufactures, particularly in developing nations, the means to produce their own bulk materials using waste plastic. Shrinking industrial recycling processes to a workbench scale gives individuals the ability to convert excess bottles into seemingly limitless products. The system works by using a dual heating and pressure system to both evenly mix and melt the plastic before pushing the resin through a die. The Poly Pelletizer successfully created pellets using various mixtures of virgin PET and shredded water bottles.

Contents

1	Introduction	1
1.1	Background Information	1
1.2	Literature Review	2
1.2.1	Previous Projects	2
1.2.2	Industry Research	2
1.2.3	Material Properties	3
1.2.4	Products on Market	3
1.3	Problem Definition	5
1.4	Team Objectives	5
2	Systems-Level	6
2.1	Customer Needs	6
2.1.1	Data Acquisition	6
2.1.2	Data Interpretation	6
2.1.3	Hierarchy of Needs	7
2.1.4	Relative Importance	7
2.1.5	Reflection and Summary	8
2.2	Benchmarking Results	8
2.3	Design Process	8
2.3.1	Brainstorming	8
2.3.2	Prototyping	9
2.4	Key System Level Issues	9
2.5	Hardware Limitations/Lead Time	9
2.6	Team and Project Management	10
2.6.1	Project Challenges and Constraints	10
2.6.2	Budget	11
2.6.3	Timeline	11
2.6.4	Risks and Mitigations	11
3	Subsystems	12
3.1	Preliminary Processes	12
3.1.1	Role of Preliminary Processes	12
3.1.2	Options and Trades for Preliminary Processes	13
3.1.3	Design Description of Preliminary Processes	13
3.2	Temperature Control	14
3.2.1	Role of Temperature Control Subsystem	14
3.2.2	Temperature Control Options and Trades	14
3.2.3	Temperature Control Design Description	14
3.2.4	Temperature Control Test	15
3.3	Melting	15
3.3.1	Role of Melting Subsystem	15
3.3.2	Melting Options and Trades	15
3.3.3	Melting Detailed Design Description	16
3.3.4	Melting Subsystem Test	17
3.4	Pressure	17
3.4.1	Role of Pressure Subsystem	17
3.4.2	Options and Trades for Pressure Subsystem	17
3.4.3	Detailed Design Description of Pressure Subsystem	18
3.4.4	Pressure Subsystem Supporting Analyses	19
3.4.5	Pressure Subsystem test	19

4	Finite Element Analysis	19
4.1	Modeling Approach	19
4.2	Model Expectations	21
4.3	Hand Calculations	21
4.4	Assumptions Made	22
4.5	Results and Interpretations	22
4.6	Simulation Conclusions	25
4.7	Tuning	26
5	System Integration	27
5.1	Assembly and Systems Testing	27
5.2	Experimental Process	27
5.3	Testing and Results	29
6	Costing analysis	32
6.1	System Cost	32
6.2	Economic Analysis	32
7	Business Plan	34
7.1	Executive Summary	34
7.2	Introduction	34
7.3	Objectives	34
7.4	Product Description	34
7.5	Potential Markets Competition	34
7.6	Sales and Marketing Strategies	36
7.7	Manufacturing Plans	36
7.8	Services and Warranty Plan	37
7.9	Product Economics	37
	7.9.1 Production Costs	37
	7.9.2 Investment and Sales Plan	38
8	Engineering Standards and Realistic Constraints	39
8.1	Economic	39
8.2	Environmental	39
8.3	Sustainability	41
8.4	Social	41
8.5	Health & Safety	42
8.6	Santa Clara University Arts Requirement	43
9	Summary and Conclusion	44
9.1	Problems occurred	44
9.2	Further Work	44
9.3	Lessons Learned	44
	References	46
	Appendix A: Customer Needs Survey	47
	Appendix B: Decision Matrix	48
	Appendix C: Timeline	49
	Appendix D: Budget	51
	Appendix E: Design Drawings	53

List of Figures

1	Plastic pollution in Long Beach, California [1] Photo Credit: Bill McDonald, Algalita Marine Research Foundation(Public Domain).	1
2	Akabot 1 Senior Design Project [2]. Image reproduced from Akabot 1 report with permission from Dr. Panthea Sepehrband.	2
3	Akabot 2 Senior Design Project [3]. Image reproduced from Akabot 2 report with permission from Dr, Panthea Sepehrband.	2
4	B-PET recycled plastic 3-D printer filament [10]. Image reproduced with permission from David Perez at B-PET.	4
5	Protocycler system [11]. Photo credit: Jill Shomer.Reproduced without permission.	4
6	Ekocycle 3-D printer [12]. Reproduced without permission from Bob Yirka, Tech Explore. . .	5
7	System level sketch including respective component placement for each subsystem.	12
8	Plastic shreds shown with a quarter for scale.	13
9	Ink bird dual digital PID Controllers and switches used for the temperature control system. .	14
10	Temperature Control system configuration [2]. Image reproduced from Akabot 1 report with permission from Dr. Panthea Sepehrband.	15
11	The melting pot which was the initial idea for melting the PET [8]. Used without permission from Barlow's Tackle.	16
12	Sheet metal hopper that helped load the PET into the melting subsystem.	16
13	The final pressure subsystem.	18
14	SolidWorks model of the brass die.	18
15	SolidWorks model of the plunger mechanism.	19
16	Results from an extrusion test with Akabot 2 at 260 °C and 265 °C.	20
17	10.16 cm brass tube with single 5.08 cm band heater with temperature range from 260°C to 260°C indicating negligible gradient.	22
18	15.24 cm brass tube with single 5.08 cm band heater with temperature range from 248°C in blue to 260°C in red.	23
19	15.24 cm brass tube with 2, 5.08 cm band heaters with temperature range from 260°C in blue to 260°C in red indicating negligible gradient.	23
20	30.48 cm brass tube with 2, 5.08 cm band heaters with temperature range from 218°C in blue to 260°C in red.	24
21	30.48 cm brass tube with 3, 5.08 cm band heaters with temperature range from 259°C in blue to 260°C in red.	24
22	Assembly with 30.48 cm brass tube with 3 band heaters, brass tee joint, and 15.24 cm brass tube with 2 band heaters with temperature range from 192°C in blue to 260°C in red.	25
23	Same as simulation 6 with the addition of a 5.08 cm brass tube and band heater at the tee joint connection with temperature range from 192°C in blue to 260°C in red.	26
24	Rewired power source used to split up the controllers.	27
25	The fume hood that all tests were conducted under.	28
26	Copper foil used to maximize heat transfer between heating band and brass pipe.	29
27	2.22 cm Auger with plastic solidified onto it.	29
28	Burnt plastic results from testing.	30
29	Final results of testing.	31
30	Graph of the return on investment of the Poly Pelletizer.	33
31	The number of months needed to begin generating revenue off Poly Pelletizer sales.	38
32	Carbon Emissions for producing PET plastic water bottles in one year in the U.S. categorized by type of disposal.	39
33	Carbon emissions of producing the Poly Pelletizer compared with the emission needed to create one cubic meter of PET.	40
34	Scoring matrix for melting subsystem.	48

List of Tables

1	Questionnaire results	6
2	Table of Hierarchy of Needs test	7
3	Table of system requirements	9
4	Risks and Mitigations	11
5	Hand calculation results	21
6	Breakdown of cost by subassembly for the Poly Pelletizer	32
7	Comparison of similar products on the market	35
8	Drawings for the our Santa Clara University Arts Requirements which can be found in the appendix	43

1 Introduction

1.1 Background Information

Plastic pollution is a serious problem that extends to all corners of the globe. The problem stems from plastic pollution and the unsustainable manner in which plastic bottles are produced. Figure 1 shows an abundance of plastic bottle pollution in California. These scenes are all too common in our world today. Although polyethylene terephthalate(PET), which is commonly used to make plastic water bottles, has many ideal qualities for products such as its light weight and high ductility, it also presents many more problems during its production process. Millions of barrels of petroleum are extracted from the ground every year for the purpose of creating plastic bottles.



Figure 1: Plastic pollution in Long Beach, California [1] Photo Credit: Bill McDonald, Algalita Marine Research Foundation(Public Domain).

One of the main reasons that plastic products are so widely used is the inexpensive price. In many developing communities around the world, people have no choice but to use disposable plastic bottles for clean water. Unfortunately, in most of these areas, there are not convenient ways for these people to recycle their plastic waste. Because of this, the majority of their plastic waste either becomes pollution or sits in landfills for hundreds of years before decomposing.

The best way to deal with this issue is to not only give people more convenient ways to recycle their plastic, but also to incentivize them to. Utilizing 3-D printing technology is an exciting new way to incentivize recycling. Giving manufacturers a product to handle all of this plastic pollution would be fixing two problems at the same time. First, it helps reduce the amount of plastic pollution that may already be prevalent around ones home, helping them clean up the area and reduce pollution related problems, such as disease. Secondly, greater recycling of plastics would lead to a reduction in the production of new plastic products. This would be beneficial for the planet as a whole by diminishing the annual carbon emissions from PET bottle production.

1.2 Literature Review

1.2.1 Previous Projects

The first project, Akabot, partnered with Village Energy, a social enterprise in Uganda. Village Energy began implementing 3-D printing as a means of manufacturing, but were unable to continue because of the high cost of importing filament. The Akabot project, sought to provide a low cost alternative to importing 3-D printer filament by melting plastic water bottles and extruding 3-D printer filament. Akabot produced PET filament, but their material properties were too inconsistent to make a usable filament [2]. The horizontal orientation of the system, as seen in Figure 2, made generating enough pressure to extrude a filament of consistent diameter difficult. As a result, the plastic extruding from the system was too inconsistent in geometry for use as 3-D printer filament. Additionally, the plastic extruded from the system was too brittle, as a result of a slow cooling rate. Filament must be ductile enough not to snap as it is rolled into a spool.

The second project, Akabot 2.0 again sought to utilize waste plastic water bottles to produce 3-D printer filament. They modified the extruder from a horizontal orientation to vertical one in an attempt to produce a more consistent filament, but again it was not successful when using shredded water bottles as an input [3]. Akabot 2.0, shown in Figure 3, produced a filament of consistent diameter and improved ductility and when using virgin PET pellets. However, when using shredded plastic water bottles, Akabot 2.0 performed similarly to its predecessor. Akabot 2.0 produced a more consistent filament in terms of geometry, but still lacked the ductility necessary for spooling.

The Poly Pelletizer project will Create pellets instead of filament. Pellets are utilized in a broad range of recycling applications including injection molding, blow molding, and extrusion into 3-D printer filament. Constraints on the quality of material properties for pellets are not as strict. Pellets require further processing to reach a final product, so issues like the Akabot project's lack of filament ductility will be avoided.

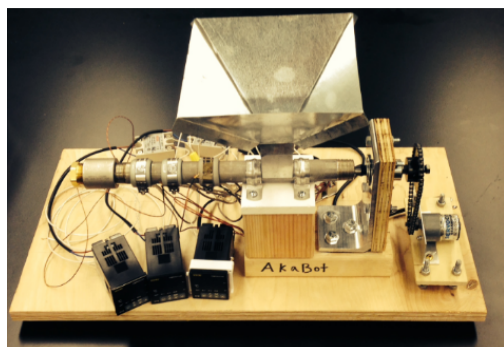


Figure 2: Akabot 1 Senior Design Project [2]. Image reproduced from Akabot 1 report with permission from Dr. Panthea Sepehrband.

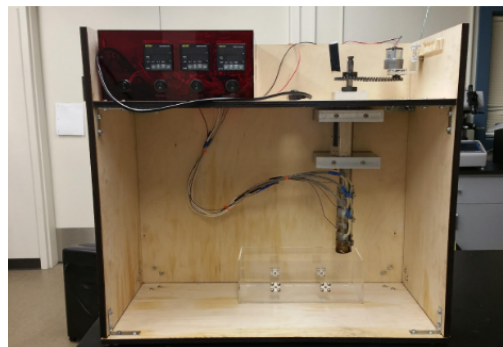


Figure 3: Akabot 2 Senior Design Project [3]. Image reproduced from Akabot 2 report with permission from Dr. Panthea Sepehrband.

1.2.2 Industry Research

The creation of PET pellets is currently widely practiced, but only on an industrial scale. The pellets created get processed by dehumidifying them at 120°C for 5 hours and then sent into an extrusion barrel at 260°C, resulting in pellets with diameters between 2 mm and 3 mm [4]. Dehumidifying the plastic serves to remove moisture from the plastic. Moisture in the resin creates pellets of inconsistent quality. The process takes place at 120°C as to not break the polymer chains inside the material. Dehumidifying at a higher temperature would take less time but degrade material properties. The extrusion barrel operates at the melting point of PET to increase formability. While the Poly Pelletizer does not utilize a dehumidifying stage, the

shreds are stored in a dry environment for at least a week before utilization for testing. The system operated as close to the temperature of the extrusion barrels used in industry to most closely emulate the process.

During conventional ways of extrusion such injection-molding or pelletizing of recycled PET plastics, there is a significant degradation of the material properties. The more times that a plastic is melted down, the more that the polymer chains it consists of will break down. If this is done at too high a temperature, or done too many times, the material properties will become unusable [5]. The Poly Pelletizer sought to minimize this issue by operating as close to the melting point of PET as possible to prevent further breaking of polymer chains.

Throughout the world, we find high amounts of plastic pollution in our environment which requires an efficient and practical way to recycle it. It is extremely important to separate the different types of plastics before proceeding with any recycling processes because having the wrong types of plastics mixed together in certain processes can ruin the resulting product. Another important process is cleaning the plastics before trying to recycle them. If there are other substances such as glues or oils, they will degrade the material properties of the plastic once recycled and reprocessed [6]. These practices are all being implemented in the Poly Pelletizer project. PET will be the only plastics that are used in order to be able to fully control the material properties of the product. This project will also implement similar techniques to clean labels and glue off the bottles before being shredded and melted down, in order to keep the resulting plastic pellets as pure as possible.

1.2.3 Material Properties

It is very important to optimize the material qualities of any plastic products that go into a system, because they ultimately dictate how good the material qualities of the final product can be. Tests have been run using plastics embedded in cement mix which have been shown to change the compressive stress and strain that the material can handle [7]. While these tests were done for a different application, it still gives valuable insight on how the plastic changes the material properties of the plastic pellets that will be produced by the Poly Pelletizer. This research exhibits the importance of analyzing the change of material properties, and how small changes in the initial inputs can have major effects on the final product.

1.2.4 Products on Market

B-pet is a company that utilizes PET plastic to create 3-D printing filament in different colors. Their product, shown below in Figure 4, has no roundness deviation, 100% recyclable, and has the same properties as virgin PET but costs 70% less. The price is about 35 dollars for a spool 1.75 mm diameter filament [10]. The filament comes in multiple different colors, as can be seen in Figure 4 below.

While B-pet creates filament with 100% recycled material, it does not fully solve the problem statement because it is not dealing directly with the fact that many of these developing countries have an issue with too much PET plastic waste. Improvements could be made to the work that B-pet does by focusing solely on PET plastic waste, which would make it very applicable and useful to areas with excess waste. While the filament that B-pet produces works well with 3-D printers, its application outside of the 3-D printing field is limited. This brings up another potential improvement that can be made on B-pet's product. The pellets that the Poly Pelletizer will produce will not only be able to be made into 3-D printer filament, but will also have other potential applications in various recycling processes.

ProtoCycler is a 3-D printing device that was created by three students at the University of British Columbia. The device, shown below in Figure 5, works similarly to a juicer. It can take recycled plastic pellets and utilize it for 3-D printing. The team claims that the mechanism is great for the environment and offers substantial savings on 3-D printing filament costs. The device goes for \$699 but they make the argument that it makes up for its cost in savings on filament costs [11].



Figure 4: B-PET recycled plastic 3-D printer filament [10]. Image reproduced with permission from David Perez at B-PET.

The ProtoCycler is a very good product that makes access to 3-D printing much easier for everyday consumers. However, the main improvement that can be made on this device is that it does not use plastic water bottles directly. The ProtoCycler, like many other devices utilizes PET plastic pellets to create its filament. Thus, the Poly Pelletizer would be the optimal product to improve upon these previous devices because it creates the plastic pellets that are compatible with many different devices.

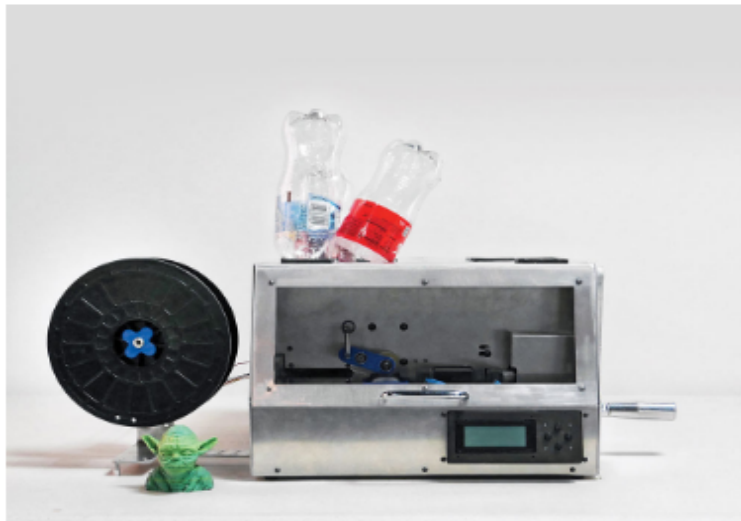


Figure 5: Protocycler system [11]. Photo credit: Jill Shomer.Reproduced without permission.

The Ekocycle cube 3-D printer, as shown in Figure 6 below, uses a filament that is made in part from recycled plastic bottles. The company cubify sells the Ekocycle printer for \$1200 and uses filament cartridges that contain at least three recycled 20 oz PET plastic bottles. The filament used in this machine is 25% of post-consumer recycled materials [12].

The Ecocycle Cube makes 3-D printing using PET plastic much easier with its cartridge design. However



Figure 6: Ekocycle 3-D printer [12]. Reproduced without permission from Bob Yirka, Tech Explore.

one of its bigger flaws is that it only uses 25% recycled materials for its filament. While this is a step in the right direction, there is much room for improvement in terms of creating a product that is more efficient in terms of sustainability and recycling. The Poly Pelletizer improves upon the Ecocycle Cube because it will use 100% recycled plastic, and will be much more applicable to communities in developing countries where plastic bottle waste is extremely prevalent.

1.3 Problem Definition

Plastic water bottles comprise a large amount of waste worldwide. The goal of the Poly Pelletizer project is to create a system that will turn water bottles into polyethylene terephthalate (PET) pellets compatible with both extruders to produce 3-D printer filament, and additional recycling processes. Poly Pelletizer will employ both a heating and pressure system to melt PET shreds into a pellet with the material properties necessary for effective filament. If successful, Poly Pelletizer will turn plastic water bottle waste into usable PET plastic pellets.

1.4 Team Objectives

Our team hopes to build a product that will help manufacturers around the world by giving them safe and sustainable ways to create their products. With the Poly Pelletizer, we hope that people will not only have a much more convenient way to recycle their plastic waste, but will also have a much greater incentive to as well. If they can use the plastic pollution around them in a profitable way, there would be a much higher rate of recycling. We also hope to inspire others to work towards innovation in environmentally friendly ways. We face tremendous problems with the health of our world today, and it is imperative that we start taking these issues more seriously. The more work and research we invest in this field today, the better off we will be in the future. Lastly, we hope to successfully create PET pellets that can be used for creating 3-D printer filament and other applications. The beauty of the PET pellets is that they have such a wide array of applications making their potential uses practically endless.

2 Systems-Level

2.1 Customer Needs

When it comes to recycling plastic PET water bottles, developing nations face a multifaceted problem. The previous iterations of this project worked alongside manufacturers in Uganda and India. Each sought to take the abundant plastic water bottle waste around them, and utilize it as a means of production. For example, the company in Uganda, Village Energy, sought to create 3-D printed solar panel casings, but found the cost of importing printer filament prohibitive to expanding production. The needs of Village Energy highlight the inadequacies of the recycling industry, and point to the possible solutions.

A major issue with the recycling industry stems from the lack of on-site capabilities. Developing nations suffer from a lack of recycling infrastructure in general. A different problem exists for developed nations. Citywide collection services take recyclables from each building and bring them to a centralized plant for processing. While this is convenient for the average citizen, manufacturers miss out on the ability to utilize plastic waste around them. Additionally, industrial scale recycling equipment is cumbersome or impossible to transport from one location to another. Where it exists, recycling processes are centralized and rigid in their utilization. Where nations lack these processes altogether, plastic bottles are disposed of in dangerous and wasteful manners. The need for change is evident.

Ideally, Village Energy would be the subject of an interview to net the most relevant information. Unfortunately, Village Energy no longer operates. Instead, 20 people were asked about recycling, 3-D printing, and system ownership. A sample survey is provided in the appendix.

2.1.1 Data Acquisition

The group surveyed was comprised of Santa Clara Students that live off campus. This group was chosen because they represent more closely the recycling habits of the general public. On campus students have easy access to recycling receptacles in their rooms. This likely leads to a higher rate of recycling than the average consumer. All the students surveyed were juniors and seniors.

2.1.2 Data Interpretation

From the data acquired from the questionnaire, shown in Table 1, the majority of the the people interviewed answered that they recycle a majority of plastic water bottles they use. This shows that there are raw recycled materials that can potentially be utilized. According to the survey, most people averaged using between 2-3 water bottles a week. The Poly Pelletizer also focuses on working in communities of developing countries where there is a much greater abundance of plastic waste materials, paired with an inadequate access to usable materials for manufacturing. However, every single person surveyed answered that they

Table 1: Questionnaire results

Question Number	Answer	Answer	Answer	Answer
1	All the Time (4)	A Lot (10)	Sometimes (7)	Not a Lot (0)
2	7 or More (0)	5 or 6	3 or 4	Less than 2 (10)
3	Yes (20)	No (0)		
4	Yes (15)	No (5)		
5	Yes (1)	No (9)		
6	Lack of Need (6)	Cost (4)	Access to Filament (0)	Other (10)
7	Yes (3)	No (1)	Not Sure (16)	
8	Yes (20)	No (0)	Not Sure (0)	
9	Yes (20)	No (0)		
10	Yes (12)	No (8)		

believe that recycling is worth the time and money. Every person that answered the survey also agreed that recycling plastics plays a crucial role in global sustainability. This shows that there is already a real desire to recycle materials and thus, an interest in creating more beneficial uses for recycling. 75% of the people surveyed answered that they do have at least some interest in the 3-D printing industry. When this question is paired with the previous question about interest in recycling, it can be deduced that there is a significant interest in creating a product that uses recycled materials for the purpose of 3-D printing. When asked if they would consider owning a 3-D printer in their own home, the people surveyed were almost completely split between yes and no. For people who did not want a personal 3-D printer, their main reasons were either a lack of need or that it would cost too much. However, if access to filament for a 3-D printer was improved, the data shows that the interest in having a 3-D printer increased. Every person surveyed answered that they would be interested in purchasing 3-D printed products that were created using recycled materials. This shows that there is a significant market for products made from recycled materials. The last question, shows another split between people who would rather manufacture their own products and save money and those who would prefer the convenience of simply buying a product. From the last two questions, it can be deduced that while not everyone is interested in printing their own products, there is still a market for 3-D printed products. Since everyone answered that they would purchase 3-D printed products from recycled materials, the data shows that all people surveyed would be willing to either create their own, or buy 3-D printed products. This shows the market area that the Poly Pelletizer design could capitalize on.

2.1.3 Hierarchy of Needs

Table 2 below shows the hierarchy of needs that our team deduced from the survey results we received.

Table 2: Table of Hierarchy of Needs test

Need	Evidence
Most important: Able to recycle effectively	All those surveyed indicated recycling is important.
Cost	A few cited cost as an inhibitor to owning a system.
3-D printing capabilities	Disinterest in owning a system came mostly for Lack of Need.
Least important: Access to filament	No one surveyed indicated easier access to filament would increase their chances of owning a system.

2.1.4 Relative Importance

The Poly Pelletizer appeals to the survey group because of the potential to repurpose common PET water bottles into useful goods. Societal emphasis on recycling has grown in recent years, as evident in the 100% affirmative response rate to the question of whether recycling is important. Additionally, the 3-D printing industry is constantly growing in size and people are becoming more interested in it as seen from the surveys. If the Poly Pelletizer project is a success, the pellets created by the mechanism will be compatible with any filament extruder that is used to create 3-D printer filament. Giving consumers the ability to recycle in their own homes is the most important aspect of the project in terms of surveyed responses.

2.1.5 Reflection and Summary

After establishing the characteristics of other similar devices, interviewing potential users on their hierarchy of needs revealed the most and least important consumer concerns. The survey shown previously in this report was distributed to 20 potential users. The contact in Uganda for previous iterations of the project is no longer available, and as such our survey population was changed. A good handle of the needs required in the project existed from those previous projects, so the survey was targeted to an audience that may someday use a 3-D printer in their home. This is not out of the realm of possibility, as technology often gets cheaper as advancements are made. These devices could one day be found in many homes, so the Poly Pelletizer team attempted to see if the project could make this demographic more likely to consider owning a 3-D printer. There was a fair amount of interest in owning a 3-D printer someday, as 11 of the 20 participants indicated they would consider owning a compact 3-D printer. One participant even explained that his father was currently in the market for a home 3-D printer. This backs up the assertion that 3-D printing technology is expanding to the point that people consider it a possible future purchase. This demographic is different than the main target audience, manufacturers in developing countries, but the strong interest in 3-D printers makes their implementation with the target audience seem more plausible.

The major difference between the survey participants and the target audience was the hierarchy of needs. From previous projects, the list of needs has been fairly well established. Developing countries need systems capable of cheaply and effectively utilizing waste products to aid in manufacturing processes. The need for on site filament creation was a necessity, but in the sample survey it played no role in determining the likelihood of 3-D printer ownership. Zero people sampled cited lack of access to filament as a reason they would not own a system. Our sample demographic showed that the interest for on site 3-D printers exists, but their needs differ from the needs of those in developing countries.

2.2 Benchmarking Results

In order to deliver a product that meets all the stated criteria, it is necessary to quantify the system and its products. Starting with the system, certain performance aspects must be reached. The final product, PET pellets, must be as close to virgin pellets as possible to broaden the range of usable applications. All requirements were organized into Table 3, shown below.

2.3 Design Process

The process of coming up with the Poly Pelletizer system involved numerous iterations. Initial ideas formed during brainstorming sessions. Each session moved the team closer to the final design. After numerous meetings with the team advisor, the first prototype began to take shape. As problems arose, additional parts were ordered and design changes were implemented. Finally, the Poly Pelletizer took on its final shape and only small tune ups were made.

2.3.1 Brainstorming

The initial ideas for the Poly Pelletizer system revolved around research conducted about the previous designs, Akabot and Akabot 2. Both systems sought to melt PET shreds directly into 3-D printer filament, but had difficulty evenly melting the plastic. The team hypothesized this was due to the difficulty in densely packing the shreds into the system. The team thought the air between the shreds was the issue, as air doesn't conduct heat efficiently. The idea of using a vacuum pump was floated, but due to cost and difficulty of implementation the team moved on. The next idea was a melting pot system. This suggestion boasted large batch sizes and simplicity of design, but was lackluster in its ability to generate the necessary temperature gradient. The initiation of the two chamber system was inspired by attempting to overcome the main problem of the Akabot projects. Both had major problems generating the pressure necessary to push the plastic resin through the extrusion die. The team thought that separating the melting and pressure application processes would alleviate this issue. With a design in mind the team moved into prototyping.

Table 3: Table of system requirements

	Requirements	units	Datum	Target
System Performance Specifications	Heating Temperature	$^{\circ}C$	250	260 - 270
	Electrical Power Consumption	KWh/kg	.4	.4
System Size Specifications	Main Body Height	cm	30.48	60 - 70
	Body Diameter	cm	2.54	10 - 12
	Die Hole Diameter	mm	2	2
Pellet Specifications	Pellet Diameter	mm	$2.2 \pm .2$	$2.1 \pm .1$
	Plastic Density	g/cm ³	1.3 - 1.4	1.4
Misc. Specifications	Cost	\$	500 - 750	450 - 650
	Auger Speed	RPM	10	10
	Input Shred size	mm	3	3 ± 1
	Extrusion Speed	cm/s	.2-.7	.7-1

2.3.2 Prototyping

Once the two chamber system idea was conceived it was necessary to acquire parts and begin assembly. Essentially, the team attempted to take the positive aspects of the previous designs and avoid the drawbacks. The original prototype was comprised of six band heaters with three around the heating chamber and three on the pressure system. Initial tests resulted in an failure to push plastic from the system. Cold spots existed throughout the system, resulting in solidification of the resin. These solidified pieces of PET acted as plugs, effectively rendering the system incapable of extruding plastic. The Poly Pelletizer team went back to the drawing board, using the Solidworks simulation tool, and optimized the location of the heating bands.

2.4 Key System Level Issues

Cold zones are the major issue in the system. The controllers do not perfectly maintain the temperature of the system. Using an external K-type thermocouple the accuracy of each band heater is determined. With this accuracy test each band heater can be customized to bring the entire system closer to the desired gradient. However, adjusting one band heater has repercussions on the gradient at the adjacent band heaters. Achieving an efficient temperature gradient is the most pressing issue to the system as a whole.

2.5 Hardware Limitations/Lead Time

The hardware on the Poly Pelletizer is limited by the specifications of the electronics that run the band heaters and the band heaters themselves. The controllers do not operate perfectly. This generates errors of approximately plus or minus 10 $^{\circ}C$. Additional errors in the thermocouples attached to the band heaters

result in the steady state relay sending power to the system at incorrect times. These factors all contribute to limit the maximum effectiveness of the system.

The band heaters have a maximum temperature of 900°C. Luckily this is well above the melting point of PET. Because of this the working temperature of the band heaters does not limit the performance of the system.

The lead time for all aspects of the project proved to be nearly inconsequential. The longest shipping time for any order only amounted to a week or so. This allowed project iterations to happen quickly. The design team utilized this to overcome problems quickly and effectively.

2.6 Team and Project Management

2.6.1 Project Challenges and Constraints

Challenges and Constraints are inevitable parts of any project. Working as part of a team introduces its own set of obstacles. Overcoming these obstacles in a construct way is the key to the smooth operation of any group of people working toward a common goal. Logistical constraints, differing opinions, and a lack of expertise in certain areas all contributed to the numerous challenges the Poly Pelletizer team faced. The most important attributes of the team included the ability to work through such problems in a manner that brought all team members along together.

The Poly Pelletizer team involved contributions from three mechanical engineering students. Logistical considerations arose most consistently. Two members of the team held jobs at various times throughout the year, while the third member rows for the Division I Mens Crew. The uniqueness of each schedule at times created a scenario in which meeting to work on the project proved difficult. The main remedy for this issue was a clear and constant line of communication between group members. Coupled with the understanding that certain scheduling conflicts would be unavoidable, the group successfully avoided the feeling that any one member contributed much more or less than any other member. Communication was crucial in the Poly Pelletizer teams ability to overcoming logistical issues.

Whenever multiple group members brainstorm design ideas multiple conflicting visions of the final design will surface. It is perilous to fall into the habit of tearing down the ideas of others in attempt to push ones own idea to prominence. It is a fine line to toe when trying to display conviction for an idea while carefully considering the ideas of others. An open mind and a willingness to listen to constructive criticism allow a team to meld multiple ideas together and create the best possible solution. Each group member of the Poly Pelletizer team showed respect when considering new ideas. Each member had times when they took the lead in deciding the next course of action, as well as a willingness to allow others to do the same. When a confronting constructive criticism, team member acted with maturity and dignity. The team fostered an environment conducive to creativity and teamwork.

From a technical standpoint, the biggest challenge was simply a lack of expertise about the project. This is an obvious issue that all senior design teams face. No team goes into the project with comprehensive knowledge of the task at hand. The major areas the Poly Pelletizer team had to brush up on were the chemical and material properties of PET and control system implementation. The team brought itself up to speed with research, help from our advisor, and long hours in the lab. All in all, the Poly Pelletizer team excelled in matters of team and project management.

2.6.2 Budget

The original budget called for \$1,990. In October the team submitted a grant proposal to the Miller Center for Social Entrepreneurship asking for funding in the form of the Roelandts Grant. In the first week of November, the Miller Center generously approved our proposal. Additionally, the Santa Clara School of Engineering awarded the team an additional \$100 as a contingency. This funding covered the proposed budget broken down in appendix E.

2.6.3 Timeline

The first steps of the project was forming the team, finding a project and advisor, and submitting a grant worthy of funding. These steps were completed by the middle of October. From there, the team conducted research and ran test using the Akabot projects to get a feel for issues at hand. This learning process lasted until the end of fall quarter. Beginning in winter quarter, the team began drawing up preliminary designs. By the end of the quarter, the team had a prototype design, began ordering parts, and partially assembled the system. Spring quarter saw the completion of the prototype, finite element analysis, system tuning, testing, results evaluation, and showcasing. A monthly time line is shown in appendix D for further details.

2.6.4 Risks and Mitigations

An important step in team management is analyzing potential risks and problems before they may occur. Envisioning as many problems as possible and devising avoidance tactics keeps a team on track. For the Poly Pelletizer team, deadlines were the most prominent way to avoid pitfalls. Table 4 below lists the most critical risks to project completion and the solution to minimize each.

Table 4: Risks and Mitigations

Risk	Mitigation
Failure to receive adequate funding	Multiple meetings with advisor to ensure rigorous proposal
Non operational design by Senior Design Conference	Strict self-imposed hardware deadlines
Falling behind schedule	Weekly meetings with advisor and professor to assess progress

3 Subsystems

The Poly Pelletizer system was made up of three subsections as seen in Figure 7. These subsections include the controllers, melting system, and pressure system. The three main controller components are the power source, power transfer, and PID interface that the operator uses to designate the desired temperature. The melting subsystem consisted of a hopper, an auger attached to a gear motor, and three heating bands. The pressure subsystem was a basic plunger mechanism used to push the PET out a die at the end once it had been melted down by the melting subsystem.

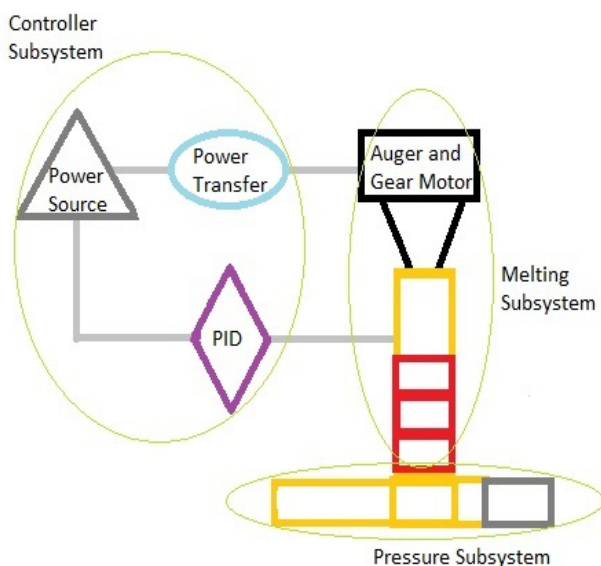


Figure 7: System level sketch including respective component placement for each subsystem.

3.1 Preliminary Processes

3.1.1 Role of Preliminary Processes

Before any water bottles could be put into the Poly Pelletizer, they were first subjected to preliminary processing. The bottles had to be cleaned of all labels and glue. Then, the clean bottles were shredded in a multi step process to produce the smallest shreds possible. The preliminary processes were extremely important for maintaining usable material properties in the plastic after it had gone through the system. Label or glue materials in the resin could degrade the final pellets, rendering them useless. Shredding the bottles was crucial to minimizing air pockets in the melting system as burning could occur. The ideal size of a water bottle shred can be seen in Figure 8.

One of the biggest issues that the previous senior design projects ran into was melting down the plastic shreds evenly. Prior to this year, the Akabot design teams had been using a paper shredder, making long ribbons of plastic. These plastic ribbons did not compress well, causing a lot of air to get trapped in the system. If air gets trapped during the heating process, the heat cannot transfer directly to the plastic ribbons, causing uneven heating. Improper heat transfer can result in burning the material beyond usability. With an improved shredding system, the plastic were reduced to flake-like sizes, which lead to both improved melting and increased plastic volume per batch.



Figure 8: Plastic shreds shown with a quarter for scale.

3.1.2 Options and Trades for Preliminary Processes

Initially, the team used a hand grinding mechanism to cut down the plastic into small flakes. Although this process was relatively proficient in achieving small enough flakes, it was an extremely slow and inefficient procedure. Our team ultimately decided to start using a coffee grinder which proved to expedite the process.

3.1.3 Design Description of Preliminary Processes

To make the proper plastic flakes for our project, our team implemented a two-step system. Once the bottles were cleaned they were put through a shredding system that created plastic ribbons. This was the same preliminary step that previous senior design projects used. However, our team decided to introduce another step to reduce the plastic shreds even more. Utilizing a coffee grinder's rapidly spinning blades, we were able to easily create the necessary size PET flake. With this dual-step system, we had plenty of plastic to conduct all the tests needed to optimize our system.

3.2 Temperature Control

3.2.1 Role of Temperature Control Subsystem

The temperature control subsystem in Figure 9 was designed so that it would maximize the amount of control the user had over the temperature of the melting subsystem. These PID controllers gave the system a way to turn on and off power to the heating bands. There were also master power switches that could completely cut off power to the controllers, heating bands, and gear motor. There had to be an AC to DC converter added for the gear motor to run properly. The PID controllers ideally would be accurate within $\pm 3^{\circ}\text{C}$ but the main goal was to have a way to regulate power to the heating bands so they would not overheat and burn the shreds.



Figure 9: Ink bird dual digital PID Controllers and switches used for the temperature control system.

3.2.2 Temperature Control Options and Trades

The controllers originally considered were from McMaster-Carr. They were precision programmable temperature controllers at \$199 per controller. If this option was pursued approximately 75% of the budget would be depleted by just the controllers and each of those controllers would still need a k-type thermal couple purchased along with a solid state relay. This was not going to be possible with the given budget. Some significantly less expensive controllers (Ink Bird dual digital PID controllers) were found on Amazon.com for \$37.99 which included the solid state relay and a k type thermal couple. These controllers proved to have a limited life span and were a challenge to get operational with the heating bands.

3.2.3 Temperature Control Design Description

The controllers and steady state relays used were ink bird dual digital PID temperature controllers paired with a k type thermal couples. The k type thermal couple was used because it had the capability of reading a wide range of temperatures between -50°C and 1300°C , and they were also conveniently included with the ink bird controllers that were purchased. The solid state relay is what enabled and disabled power to the heating bands as they reached the designated temperature by the PID controller using a single pole single throw (SPST) configuration. A layout of how the PID controller, solid state relay, thermocouple, and band heater was wired can be seen in Figure 10. There were master switches wired into each controller system to allow the user to be able to cut off the power to the controller and heating band.

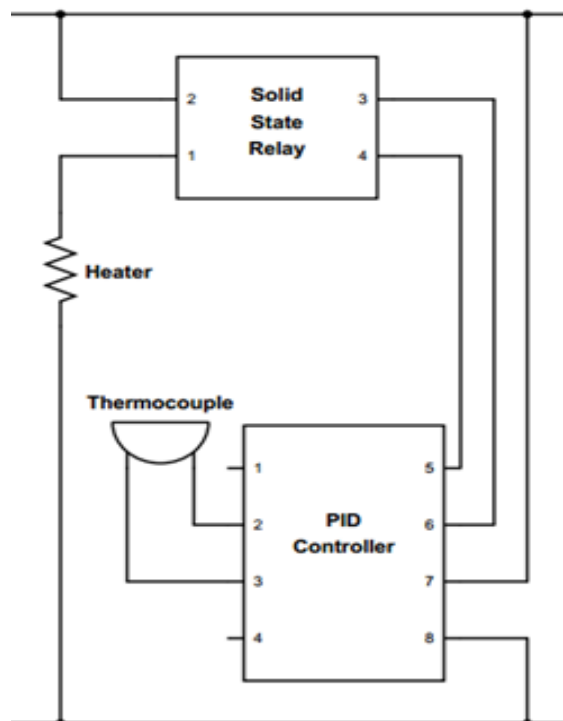


Figure 10: Temperature Control system configuration [2]. Image reproduced from Akabot 1 report with permission from Dr. Panthea Sepehrband.

3.2.4 Temperature Control Test

Wiring the controllers to the melting subsystem and power source proved to be one of the greatest time consumptions of the project. Every controller was wired to a thermal couple as feedback for the heating band temperature. The reading on the controllers were checked for accuracy by using a k type thermocouple made by AMPROBE. The thermal couple on the measurement tool was assured to be accurate by boiling water and seeing that it read 100°C before it was used to test the readouts of the controllers. The controllers read about 5 to 10°C below what the actual heating bands were at.

3.3 Melting

3.3.1 Role of Melting Subsystem

The melting subsystem was where the PET entered the Poly Pelletizer system and began the process of becoming pellets. The subsystem was kept around 260°C (the melting point of PET) with the implementation of an auger to add constant mixing for an even and consistent melt. The PET had to become completely liquefied before exiting the melting subsystem.

3.3.2 Melting Options and Trades

The initial idea for the melting subsystem was to utilize a melting pot as seen in Figure 11. This would give a simple, inexpensive solution to melting down the PET flakes. The melting pot was deemed not viable as the lack of precision temperature controlled proved too big a problem to overcome. The melting pot when turned on its lowest setting would reach temperatures of about 450°C, far past the melting point of PET, which would result in burning of the plastic. The second design that was proposed was utilizing heating bands. This was a much more expensive option but with the trial of the melting pot, the need to optimize control

over the amount of heat being given off was prioritized. The materials for this melting system were much harder to acquire than the simple melting pot and would require time to wire and optimize the placement of the heating bands along the system.



Figure 11: The melting pot which was the initial idea for melting the PET [8]. Used without permission from Barlow's Tackle.

3.3.3 Melting Detailed Design Description

To load the plastic flakes into the heating system, a hopper was used as seen in Figure 12. The hopper consisted of some sheet metal that was bent into a funnel shape. The hopper offered an efficient way of feeding into the auger. The combination of the heating bands, auger, and PID controllers proved to be the better option although it was more expensive. It was necessary to maximize the amount of control there was over the heating bands to create the best possible heat gradient. The melting subsystem consisted of three 300 Watt high temperature nozzle band heaters from McMaster-Carr. They were each 3.81 cm in diameter and 5.8 cm in width. A 2.54 cm brass tube was used to mount the heating bands with copper foil added for a snug fit onto the brass tube. They could reach around 650°C, which proved to be more than enough heat for reaching the melting point of the PET.

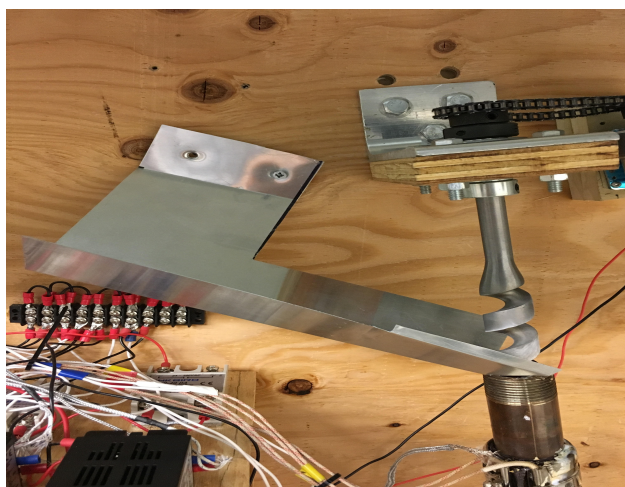


Figure 12: Sheet metal hopper that helped load the PET into the melting subsystem.

The auger that was used had a 2.54 cm outer diameter so that there was a snug fit inside the 2.54 cm inner diameter tube. This kept any PET flakes from falling directly through the melting subsystem and remaining in the solid state. The auger was ran at 10 rpm with a gear motor that had a stall torque of 3.30 m s²/kg². The combination of the auger and gear motor proved to be sufficient for mixing of the PET while the melting

occurred.

The initial placement of the heating bands was found using the finite element analysis software on Solidworks which is elaborated on in chapter 4. It showed that the optimal placement to create a consistent heat gradient throughout the melting subsystem was to have them evenly spaced along the 30.48 cm tube with 5.08 cm gaps between them. When the heating bands were placed like this it resulted in an inconsistent melt. The gaps between the heating bands proved to be too large and created cold spots, which resulted in the re-solidification of the PET in the system and eventually stalling the auger. The heating bands were then moved to be in contact with one another so that there was a consistent heat throughout the melting subsystem. An additional preliminary heat up time was also implemented to assure that the auger would reach at least the 260°C melting point of PET. The preliminary heat up time proved to be crucial to assure that the PET would not solidify onto the auger. The first successfully melted PET exited the melting subsystem when the heating bands were ran around 275°C, were given a minimal amount of space between each band, a preliminary heat up time was allowed, and insulation was added to help minimize heat loss to the environment.

3.3.4 Melting Subsystem Test

All testing that involved melting the PET was done in a vacuum hood to assure that the users were not breathing in any fumes (although all fumes emitted by melting PET are non-toxic). There were 4 iterations of the melting subsystem before it reached a sufficient heat gradient to allow the PET to enter in the solid state and easily exit the system in the liquid state. The initial set up had all the power for the heating bands, auger, and control system being drawn from one outlet. When the system was first plugged in to run there was too much power being drawn from one outlet and resulted in the rewiring of the gear motor power source to its own power outlet. The first set up of the melting system utilized a 2.22 cm diameter auger and 30.48 cm brass tube. It resulted in too many cold spots and PET was able to get past the auger because of the .3175 cm gap between the outer diameter of the auger and the inner diameter of the tube. If solid PET was able to exit the melting subsystem it resulted in a jam in the following subsystem (the pressure subsystem). A new auger was used with a 2.54 cm outer diameter, which gave a much tighter fit and prevented the PET from falling through the melting subsystem. The subsystem originally had a valve that was there to prevent the PET from exiting the melting subsystem and entering the pressure subsystem. The valve caused an issue because of its small lip, which created a spot in the melting process for PET to solidify and create a seal. Even when the valve was in the open position the PET would not exit the melting subsystem because of the solidification on the valve lip. This resulted in removing the valve all together. This was allowed because the valve was originally there to prevent PET from entering the pressure subsystem in the solid state but with the larger auger, this was no longer an issue. The PET was now able to flow freely into the pressure subsystem in the liquid state.

3.4 Pressure

3.4.1 Role of Pressure Subsystem

The pressure subsystem was designed to allow for the extrusion of the PET out of the brass die. The system was a plunger mechanism as seen in Figure 13. The PET enters the system in the liquid states and begins to enter the semi solid state before being pushed out of the die to create a pellet that is ductile and has the desired material properties needed to be re-used. There has to be a sufficient amount of force on the material for it to exit out of the die. When the material exited it had to be ductile enough to cut into the pellets.

3.4.2 Options and Trades for Pressure Subsystem

The pressure subsystem was initially going to involve a vacuum to assure during the solidification of the PET there would be no water vapor trapped in the final product. The implementation of a vacuum system in our pressure subsystem turned out to be not within the given budget. The device that was going to initially help the user apply pressure was a lever system using metal rods to give the operator a mechanical



Figure 13: The final pressure subsystem.

advantage. Figure 13 shows the pressure subsystem. The addition of a rubber o-ring to help add a tighter seal during the extrusion was initially used. The o-ring was expensive and failed during the first test so it was not replaced. A machined dowel was made to create a tolerance fit which resulted in enough pressure to push the semi solid PET out of the brass dye. The brass dye that was machined had an exit hole where the PET had to fit through to begin cooling and create the final product.

3.4.3 Detailed Design Description of Pressure Subsystem

The pressure subsystem was manually controlled. Meaning the lever component must be pushed on by the operator for extrusion to occur. The Brass die where the PET comes out of and solidifies into pellets has a hole .2 cm in diameter, a CAD drawing of this component can be seen in Figure 14. The die was ordered as a solid pipe cap and then was machined using a mill.

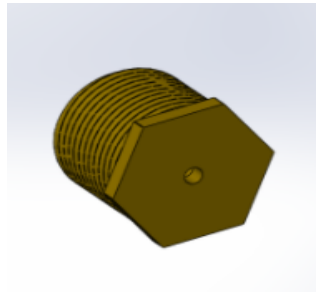


Figure 14: SolidWorks model of the brass die.

The brass tube was 2.54 cm in diameter and 15.24 cm in length. There were 2 heating bands added to the outside part of the brass tube to assure that the PET did not solidify while in the pressure subsystem. These heating bands were ran around 240°C, slightly below the melting point of PET. The heating bands on the pressure subsystem were the same as the heating bands in the melting subsystem. They were set up with a PID controller, solid state relay, and k-type thermal couple. The metal rod that was used was threaded on one end where the machined dowel was attached. The machined dowel was around 2.54 cm in diameter and made to have a tolerance fit inside of the tube. There was a notch made at the front to allow a spot for an o-ring to be added if needed. The CAD depiction of this plunger can be seen in Figure 15. The initial design of the lever arm to add mechanical advantage proved not to be necessary when testing began so a simple handle the operator could use was added to the end of the threaded rod. When operating the pressure subsystem the user wore heat resistant gloves to assure they would not burn themselves while operating the system.

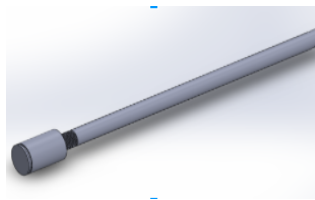


Figure 15: SolidWorks model of the plunger mechanism.

There is a t-joint that connected the melting subsystem to the pressure subsystem. As stated in the melting subsystem chapter there was a valve initially to prevent solid PET from entering the pressure subsystem but it was later removed. The pressure subsystem was secured to the wooden frame using large bolts, nuts, and machined washers to keep it secure and easily adjustable if needed.

3.4.4 Pressure Subsystem Supporting Analyses

The pressure subsystem was initially overly complicated. The lever arm that was made on paper seemed much more appealing than when it was actually implemented. It was supposed to give the user a mechanical advantage by adding torque, but only diminished the amount of control the user had over the pressure subsystem. The lever arm was removed and a simple handle was implemented which allowed the operator to have more control of the extrusion dowel and more easily push the melted PET out of the die.

3.4.5 Pressure Subsystem test

The initial tests of the pressure subsystem showed that the PET was sitting too long in the subsystem and was beginning to burn in the dye before being extruded. This was because the controller that was used to operate the heating bands attached to the brass dye was not working properly. The heating band on the dye was then left off because of the lack of control there was over the temperature. The first time the PET exited the dye it came out burnt and very brittle. It was only after the dye heating band was turned off and the valve was removed that the resulting extruded PET was ductile enough to be turned into pellets.

4 Finite Element Analysis

4.1 Modeling Approach

Determining the necessary temperature range resulted from numerous laboratory tests. The Pelletizer team discovered that 260 °C was the lowest temperature in which purely plastic water bottle shreds would be extruded from the system. Figure 16 shows results from different temperature tests conducted.

The experiment showed that no material would extrude from the system under 260°C. Polyethylene Terephthalate has a melting point of 260°C, but the previous project, Akabot 2, extruded a blend of shreds and pellets at temperatures as low as 250°C. At this temperature, the extruded filament was in a semi-solid state. This is ideal for the Poly Pelletizer as completely liquefying the plastic reduces its ductility. Extruding in a semi-solid state preserves this ductility by keeping the long molecular chains of the polymer intact. Therefore, our system will be required to reach at least 260°C consistently, but the Akabot 2 system had major issues generating enough pressure to extrude the plastic. The Poly Pelletizer took this into account when designing by adding a larger opening between the heating and extrusion chambers. Pressure will not be as big an issue for the Poly Pelletizer, so the system consistently reaching 260°C is the upper limit of what must be capable.

With the knowledge that the system requires the capability of staying at a consistent 260°C, SOLIDWORKS modeling proceeded. The melting and mixing chamber was the first subsystem analyzed. The chamber itself



Figure 16: Results from an extrusion test with Akabot 2 at 260 °C and 265 °C.

was modeled as a 30.48 cm long brass tube with an inner diameter of 2.54 cm and an outer diameter of 3.34 cm. Combinations of one, two, and three heating bands were tested. Each temperature gradient was labeled in °C and an image was captured for comparison against the others. Next, combinations of one and two heating bands were simulated on both the 10.16 cm and 15.24 cm brass tubes. Finally, assemblies of the heating/mixing chamber and extruding chamber were tested with various configurations of heating bands until the optimal setup was determined. All simulations were conducted under the same assumptions.

In order for each simulation to be comparable to the next, the same set of assumptions were used for each. Brass has a high thermal conductivity. As such, the internal resistance of the brass tubing was considered negligible. Similarly, because the heating bands have temperature control, it is safe to assume they will be capable of fully reaching 260°C. Therefore, the internal resistance in the heating band because the bands could be turned up to an experimentally determined temperature to ensure a steady state temperature of 260°C. Next, the resistance between the heating bands and brass tubing was neglected due to the high thermal conductivity of brass. The next assumption may carry the largest implication on the simulation. It was assumed that there was no heat lost to the ambient environment. In actuality there will be some heat lost, but the design team plans on employing insulation on as much of the system as possible. While this will not completely negate heat loss, the temperature gradient is more important than the actual temperature reaching in the simulation. Having the ability to turn up the heating bands alleviates the fear of not reaching a high enough temperature. Another assumption was each heating band will supply 100 watts of power. This is the max wattage output of the heating bands, and since they are capable of reaching temperatures of 650°C it is unlikely there max wattage will be utilized. Again, this is a safe assumption to use because it only affects the time the system will take to heat up, not the characteristics of the temperature gradient at steady state. These assumptions allowed for a simplified simulation that was easily repeatable and consistent in demonstrating the nature of the temperature gradient.

The final part of the simulation before running the results involved determining the transient conditions of the system. To start, each part of the system was assumed to be at a typical room temperature of 23°C. The transient state was mapped over the course of 120 seconds. This time was chosen so the temperature gradient would be apparent. The idealistic assumptions in our simulation would lead to the entire system being 260°C because no heat loss was considered. The purpose of the simulation was to determine which part of the system had cooler temperatures than the other. For the purposes of our simulation 120 seconds was enough to determine where the cooler parts of the system exist. This guided the design of subsystems for subsequent simulations until the point in which the entire system was within a the allowable limit designated by experimentation. No point in the system should fall below 250°C to avoid premature solidification and

subsequent jamming of the system.

4.2 Model Expectations

The objective of using solidworks was to find the most efficient number and placing of the heating bands on the brass tube. The most efficient placing of the heating bands will result in a consistent temperature of 260°C throughout the system. The more heating bands that are used the more consistent the temperature is but it will also cost more to acquire the extra heating bands. The model shows the best way to achieve a consistent temperature throughout the system while utilizing the minimum amount of heating bands resulting in a more efficient use of money.

The largest factor is how much thermal conductivity will occur in the brass pipe. The longer the pipe that is used the more power that must be used to achieve the 260°C melting point of PET. Ideally the system will be able to reach the desired temperature within five minutes, so the model is expected to heat up the system to 260°C within that amount of time.

4.3 Hand Calculations

The initial calculations found the conduction rate of heat transfer for the 30.48 cm, 15.24 cm, and 10.16 cm brass pipe at 260 °C for the temperature of the heating band and room temperature for the brass tube. This gives the rate at which heat will flow between the heating band and the length of the rod. In equation 1 the surface area A that was used was of the entire outer surface of the brass tube. The entire outer surface area of the tube was used because the entire tube needs to reach 260 °C. The thermal conductivity k of brass at room temperature is 110 Wm K. The thickness L was the difference between the outer and inner diameter of the tube being .58 cm. The two temperatures used were room temperature (23°C) and the desired temperature of 260°C. The results of the calculations are shown in Table 5. From the handed calculations, using equation 1, it is concluded that the longer the brass pipe the higher the conduction heat transfer rate which means there will be a need for more heating bands and wattage on the larger 30.48 cm pipe for it to reach 260°C. This was more accurately represented in the simulations and tests that were run on Solidworks. The hand calculations only give how much wattage the pipes need while the Solidworks simulations show the ideal number of heating bands and the best locations for them.

$$q = \frac{kA(T_2 - T_1)}{L} \quad (1)$$

Table 5: Hand calculation results

Length of Brass Pipe (m)	Surface Area Needed to be heated (m ²)	Conduction heat transfer rate (Watts)
.3048(12 inch)	.0299	133500
.1524(6inch)	.0150	66750
.1016(4inch)	.00997	7676

4.4 Assumptions Made

The modeling that was done in SolidWorks helped with finding the ideal position and number of heating bands in an ideal condition. The modeling does not take into account the potential for outside influences such as a colder environment or if the material has any flaws. Also the analysis that was done does not give the time it will take for the system to reach the desired temperature of 260°C. This problem was resolved by working with the Akabot, a past senior design project that utilized the same heating bands that are being used on the Poly Pelletizer.

4.5 Results and Interpretations

Taking into account the problems and assumptions used in the simulation, it is possible to compare the temperature distribution in the brass tubing to determine the optimal placement of heating bands. Each simulation is depicted below.

Simulation 1:

The first simulation sought to determine if a single heating band would be capable of heating the entire

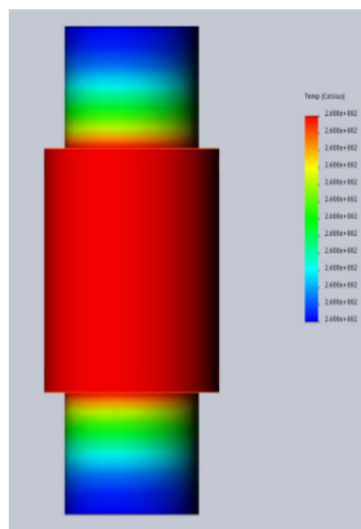


Figure 17: 10.16 cm brass tube with single 5.08 cm band heater with temperature range from 260°C to 260°C indicating negligible gradient.

10.16 cm brass tube under consideration for the extrusion chamber. A gradient is visible, the temperature differences are negligible as the entire temperature scale is 260°C. This would be a viable option for the extrusion chamber. It is not vital for this part of the system to be quite as hot as the melting portion, but it is important to verify this part of the system is capable of reaching this temperature consistently.

Simulation 2:

The second simulation was conducted on the 15.24 cm brass tube which led the temperature to fall to 249.7°C, at the bottom end of our desired range. Considering heat losses, it appears from the simulation that two heating bands would be needed to create a more even and controllable temperature distribution.

Simulation 3:

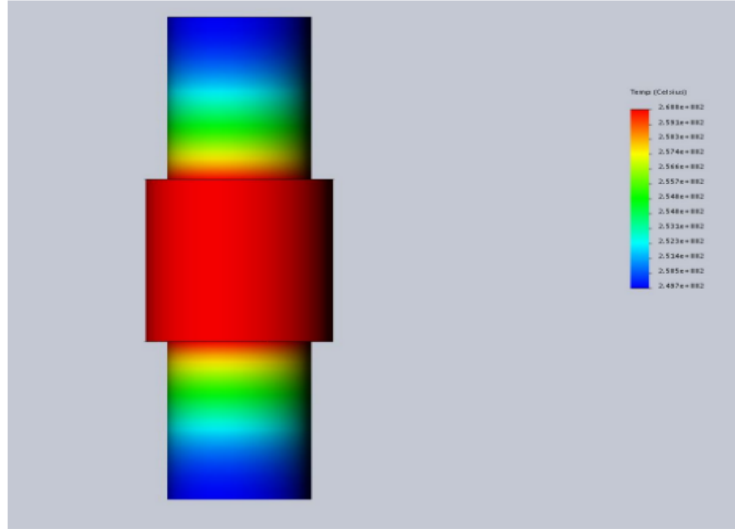


Figure 18: 15.24 cm brass tube with single 5.08 cm band heater with temperature range from 248°C in blue to 260°C in red.

The third simulation that we ran produced a very even temperature distribution across the entire pipe. A

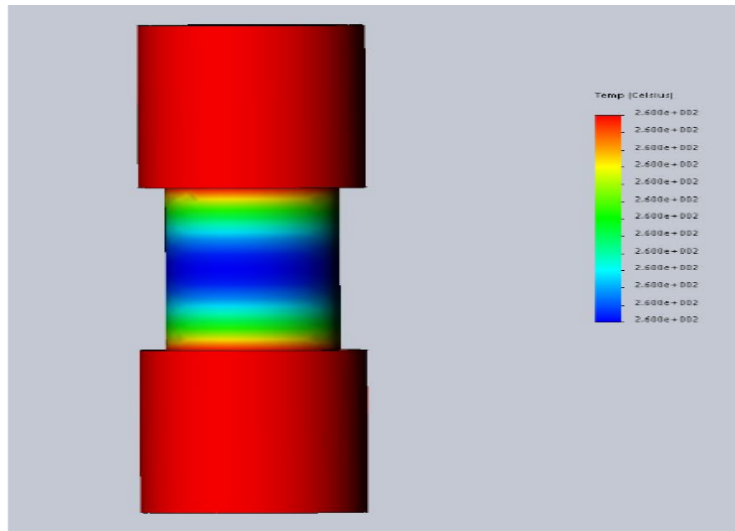


Figure 19: 15.24 cm brass tube with 2, 5.08 cm band heaters with temperature range from 260°C in blue to 260°C in red indicating negligible gradient.

temperature of 260.0°C was reached across the entire brass pipe. While there will be some heat loss to the surrounding air, this section of the system is only used to maintain the plastic in a semi-solid state, and thus does not need to reach as high a temperature as other sections. The most important takeaway from this simulation is the even heat distribution across the entire pipe achieved with only two heating bands at each end. The 10.16 cm pipe is ideal because it allows us to place a heating band directly over the die, which will ensure that the plastic does not solidify in the die, and back up the entire system.

Simulation 4:

In this simulation the 30.48 cm brass tube was analyzed with two heating bands. The results of this

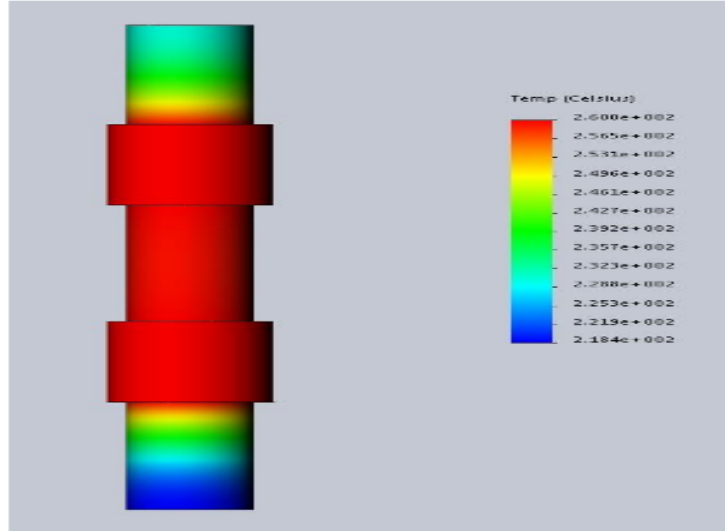


Figure 20: 30.48 cm brass tube with 2, 5.08 cm band heaters with temperature range from 218°C in blue to 260°C in red.

simulation shows that the temperature towards the bottom becomes significantly too cool, being around 218°C. The result of this simulation shows that it is necessary to place another heating band on the 30.48 cm brass tube to allow for a more uniform heating throughout the tube. The simulation also rules out the possibility of using one heating band, as the results have a temperature gradient even further from the desired case.

Simulation 5:

In this simulation the 30.48 cm brass tube reached a much more uniform temperature with its coolest

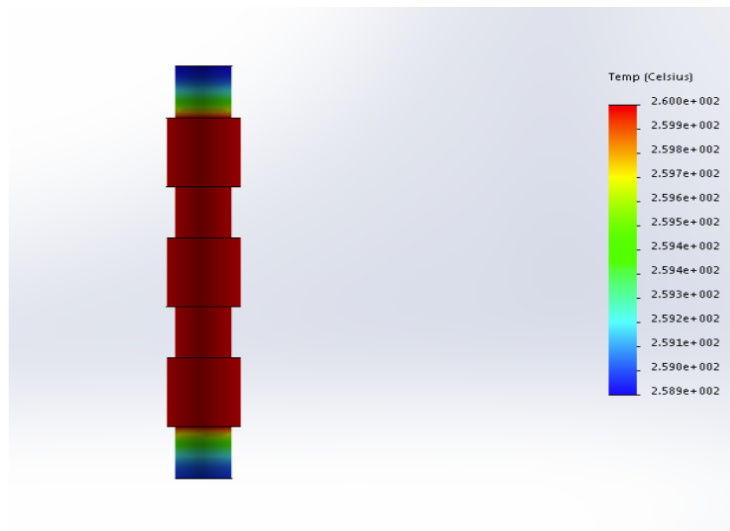


Figure 21: 30.48 cm brass tube with 3, 5.08 cm band heaters with temperature range from 259°C in blue to 260°C in red.

parts being at 258.9°C. This is the design that will be used for the 30.48 cm brass tube section. The placing of the first heating band is 2.54 cm from the top, with two inch gaps between the lower heating bands,

and the bottom heating band sitting 2.54 cm from the bottom. This spacing showed the most even heating distribution throughout the 30.48 cm tube.

Simulation 6:

The first assembly simulation showed that the unheated side of the tee joint falls to 192.8°C. This is

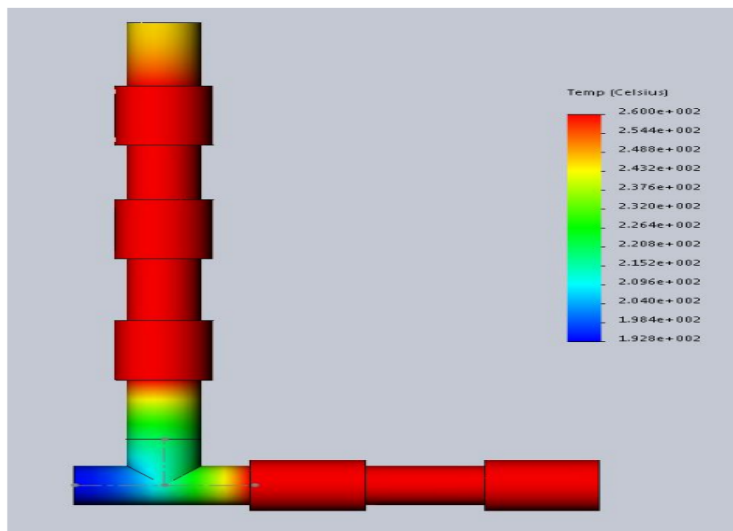


Figure 22: Assembly with 30.48 cm brass tube with 3 band heaters, brass tee joint, and 15.24 cm brass tube with 2 band heaters with temperature range from 192°C in blue to 260°C in red.

far below the desired operating range. The system will be mounted at an angle so the plastic is unlikely to come into contact with that portion of the tee joint. However, the portions of the tee joint that will be in contact with the plastic are also too low. In the interest of creating a more even temperature distribution, a new design was formed.

Simulation 7:

The final simulation verified that the updated design more sufficiently maintains even temperature distribution throughout the system. The coolest part of the system falls to about 249°C. This is slightly out of the desired operating range, but that portion of the design represents the value between the heating and extruding chambers. Therefore, the plastic will spend time in the upper section which lies within the desired range. Additionally, once the valve is opened the plastic resin will flow through the valve and spend little time in this slightly cooler section. Ideally, the system will extrude a semi-solid filament that will be cut into pellets, so this minimal amount of cooling should not be an issue. The addition of the extra heating band keeps both ends of the tee joint heated, keeping the resin at the desired temperature will the extruding process takes place.

4.6 Simulation Conclusions

Using the heat transfer simulations on SolidWorks was extremely helpful for the optimization of our final design for the Poly Pelletizer. For our project, creating an even heat distribution along the brass pipes was essential to being able to melt the plastic evenly without burning any of it. These simulations not only help our team determine the number of heating bands we need for our design, but also the best locations to place them in order to minimize local hot or cold spots. Beyond the actual results of the finite element analysis done, this exercise also helped us to better understand the problems we may face with heating our system

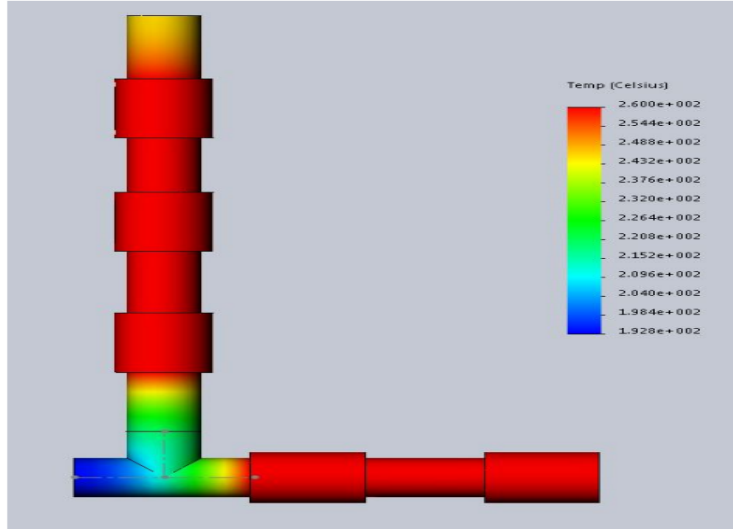


Figure 23: Same as simulation 6 with the addition of a 5.08 cm brass tube and band heater at the tee joint connection with temperature range from 192°C in blue to 260°C in red.

as well as to understand the assumptions we have been making for our project.

Although these simulations were very successful in determining the amount of hardware needed for our heating system, there is still more work to be done. Once we order the heating bands and controllers for our heating system, we will need to assemble them and test our system to confirm that our simulations were correct and our assumptions were reasonable. Although all of the simulations had the temperatures of our heating bands at 260°C, when implementing these heating bands into our actual system, different temperatures will be tested to create temperature gradients conducive to retaining optimal material properties of the plastic. Additionally, after further research and testing our team may also be able to re-run some of these same simulations with more rigorous boundary conditions and underlying assumptions in order to improve the accuracy of the simulations themselves.

4.7 Tuning

After analyzing the Solidworks models the system was changed to match the model as close as possible. Numerous tests were run with varying degrees of success. Each failed test lead to an adjustment of the temperature gradient of the system in an attempt to minimize cold zones.

5 System Integration

5.1 Assembly and Systems Testing

After the final round of purchasing, the team mounted each subsystem to the frame, and integrated all components of the project. We first tested the electric power components of the system to make sure that it did not draw too much power from a single outlet. The first round of testing revealed the system drew too much power to be accommodated by a single power cord. We then had to rewire our system in order to split up some of the controllers and motors onto different power sources, shown in Figure 24.

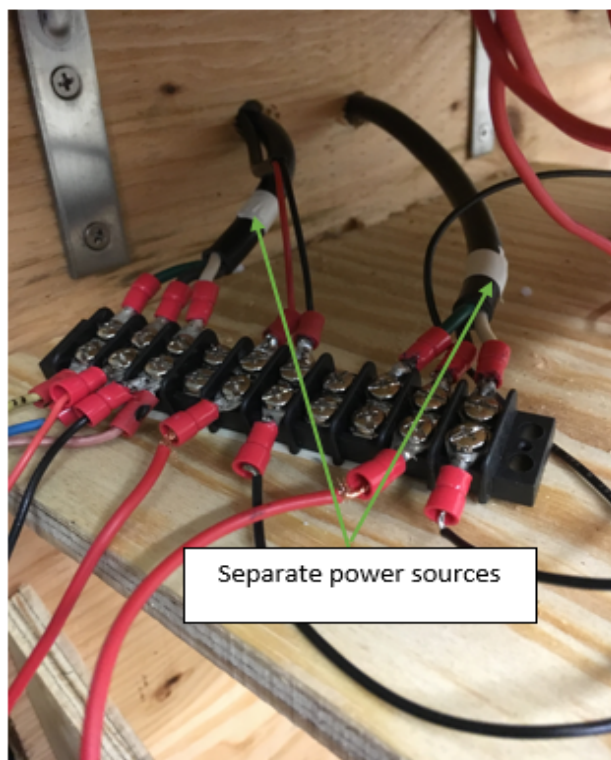


Figure 24: Rewired power source used to split up the controllers.

Once the electrical systems were operational, accuracy and precision tests indicated the expected performance of the controllers. To do this, we ordered a thermocouple to measure the heating bands and made sure that they could not only reach the desired temperatures for our testing purposes, but also that they could remain at the proper temperatures for extended periods of time. The controllers that we used for our project displayed a high degree of variability. At times, it was necessary to test the band heaters with an external K type thermocouple, and manually power individual band heaters to prevent overheating.

5.2 Experimental Process

Although PET plastic is an inert substance, our team decided to do all our testing underneath a fume hood, shown in Figure 25. While the fumes from melting plastic are generally nontoxic, in the case that the PET ignited, we wanted to limit smoke inhalation.



Figure 25: The fume hood that all tests were conducted under.

Prior to the design of our project, our team did extensive research on other similar products and technologies that are already present today in the 3-D printing field. This included research into the the two previous senior design projects, Akabot 1 and 2, which the Poly Pelletizer built off. One of the main problems that these two projects both faced was extruding the plastic out of their systems in a consistent way. Both projects used an auger to push the plastic out of the die, but ran into problems when the extrusion rate would change uncontrollably creating unusable filament. The root cause of this problem was that the auger, and in the case of the Akabot 1 the orientation of the system, the projects could not generate enough force to consistently create 3-D printer filament.

The Poly Pelletizer addressed this issue by changing the entire extrusion subsystem of the project. By replacing the inconsistent pushing force of an auger with a manual plunger system, a consistent and controllable extrusion rate could be achieved. Although this process was able to get our team our first successfully extruded plastic, our team eventually ran into other problems. During the testing, our team found there were cold spots in the system which created blockages and ultimately hindered the extrusion process.

In order to address these issues, our team used finite element analysis as well as testing to determine the optimal locations for the heating bands. In order to maximize the contact area between the heating bands and the brass pipe, our team used a copper foil wrap, shown in Figure 26. With the heating bands in the ideal locations along with the copper foil, we were able to minimize cold spots in the system where plastic could prematurely solidify.

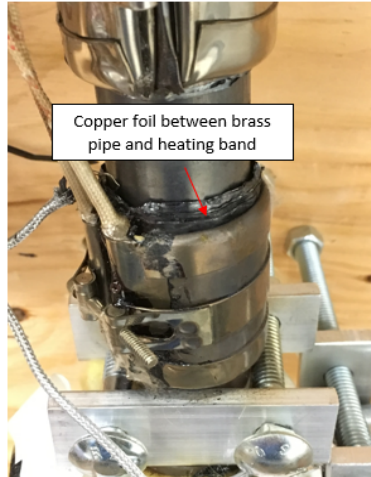


Figure 26: Copper foil used to maximize heat transfer between heating band and brass pipe.

5.3 Testing and Results

After a few initial tests to confirm that the system was operational, we began the testing with actual melted plastic. The inner diameter of the pipe used was 1 inch, so our team decided to test two different sized augers, in order to get the best and most consistent melt. The first auger tested was a 2.22 cm diameter, which allowed for an easier rotation, but allowed too much of the unmelted plastic to fall to the bottom of the system before being properly heated. This led to the plastic blocking up the system and eventually forcing the plastic back out of the top of the system. Another issue that arose during these tests was that the plastic itself would start to solidify on the auger, which would lead to plastic ultimately backing up out of the system. This can be shown in Figure 27 below. After multiple tests and attempted troubleshooting, our team decided it was best to use a different auger.



Figure 27: 2.22 cm Auger with plastic solidified onto it.

The second auger used was just under 2.54 cm giving it a much tighter fit to the pipe. Due to the tight tolerance of the second auger and the pipe, the feed rate had to be reduced in order to avoid burning out the motor that drove the auger. The initial tests with this auger also had issues with plastic backing out of the system, but for different reasons. Although our team waited for all of the band heaters to reach the desired temperature of 260C before loading in the plastic, we did not allow enough time for the inner wall of the auger to reach the necessary temperature. This led to cold spots on the auger itself, which led to solidification, which in turn caused the plastic to back out of the top of our system. Due to these solidification backups, much of the plastic in the system began to burn, shown in Figure 28. This led to our team getting a charcoal like substance for a result.



Figure 28: Burnt plastic results from testing.

To remedy this issue, we gave the system a preliminary heat-up time of 10 minutes. This meant waiting for all of the heating bands to reach 260C, then waiting an additional 10 minutes before putting any plastic into the system. However, even with this additional testing step, our team was still unable to get any of the melted plastic to flow down into the secondary pressure system. While the preliminary heat-up time did remedy the problem of the plastic re-solidifying on the auger itself, our team still ran into issues of cold spots in our system. After running multiple tests, it became apparent that the cold spot location that was causing our project to continually back up was in the valve itself. Once we identified this problem, our team decided the best course of action was to remove the valve entirely.

With the valve removed and the preliminary heat up time, our team was able to run its first successful test. Without the valve, our team was able to eliminate all cold spots which allowed the plastic to flow into the pressure system before ultimately being extruded out of the die. Unfortunately, after some of the plastic was successfully extruded, the lower heat bands malfunctioned and burned the remaining plastic before it could be extruded. Our team was able to successfully collect some of the extruded plastic and cut it down into pellet like pieces, shown in Figure 29. Although the color of the pellets does look different, the important part is testing the material qualities of the plastic we created, in order to compare it to the industry standards of the virgin PET pellet



Figure 29: Final results of testing.

Once our system was able to produce the plastic we wanted, we began running tests with different ratios of plastic flakes to virgin PET pellets. Since there is always some material degradation that occurs when melting plastic, it is necessary to use some virgin PET pellets to ensure that the material qualities remain optimal. The task then became to determine what the best ratio of flakes to virgin pellets our project could operate on without losing material qualities.

We decided to begin testing with different ratios of flakes to virgin pellets by weight. The initial tests run to optimize our system had been done with mostly virgin PET pellets, because we knew that these would yield the most favorable results. Once we got our system operation, we could then try running tests with higher and higher ratios of flakes rather than virgin pellets. Our team decided that the best way to do these tests were to run them with set ratios of all virgin pellets, 75% pellets and 25% flakes, 50% pellets and flakes, 25% pellets and 75% flakes, and finally, 100% plastic flakes.

In future iterations of the project these pellets could undergo Differential Scanning Calorimetry to determine the quality of the material properties produced. These would give evidence for which mixture is optimal.

6 Costing analysis

6.1 System Cost

The total cost of the system is \$1,084.87. The breakdown of this cost is shown in the figure below, highlighted by large cost of the heating subassembly and electronics subassembly.

Table 6: Breakdown of cost by subassembly for the Poly Pelletizer

Subassembly	Cost
Frame	\$86.79
Heating	\$562.06
Control	\$287.18
Mixing	\$93.55
Pressure	\$55.29
Total	\$1084.87

6.2 Economic Analysis

The Poly Pelletizer costs \$2,000 and operation of the system costs \$2.27 per hour assuming a kilowatt hour costs 12 cents. It takes 12 batches of produce 5 kg of pellets (the average weight of a spool of PET filament). This means the operating cost to produce 5 kg of pellets is \$4.54. As shown in the figure below, after 1840 kg of pellets made by the Poly Pelletizer, the manufacturer will see a return on investment in terms of bulk material price. If a given manufacturer creates about 500 kg a year, there would still be over a year left on the warranty of the system by the time the manufacturer began turning a profit.

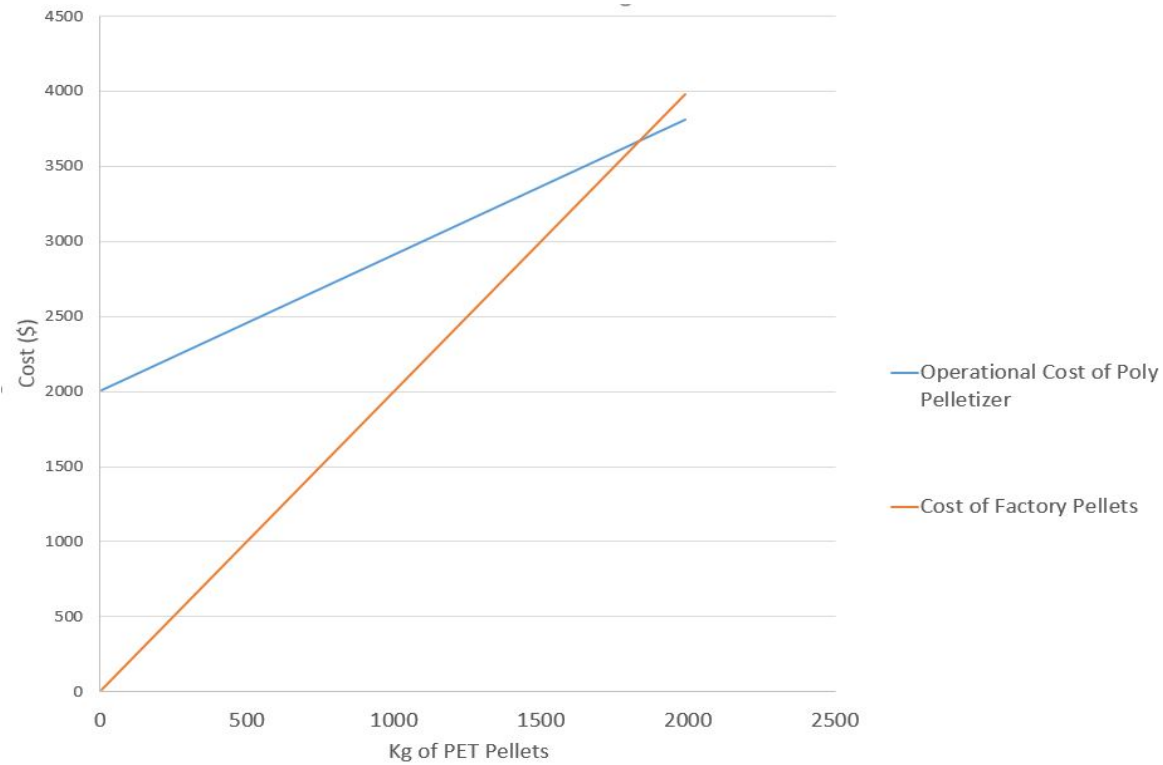


Figure 30: Graph of the return on investment of the Poly Pelletizer.

Ideally, in a mass production setting the Poly Pelletizer will cost less to build, thus decreasing the amount of pellets created before seeing a return on investment. It is reasonable to say that a company could see a return within a few years. This is a necessity in emerging markets, as investment capital is often lacking. One of the big advantages of the Poly Pelletizer is that the only costs that it is associated with after purchasing it are the low electrical costs of running it. There are no additional materials required to run it if the owner uses recycled plastic or plastic pollution that may already be prevalent in their communities.

7 Business Plan

7.1 Executive Summary

The Poly Pelletizer has the potential to capitalize on an exciting and emerging new technology market, as well as play a role in helping people manufacture in a more sustainable and environmentally friendly way. 3-D printing technology is becoming not only a hobby for the few, but an efficient and independent way for people to start building their own products. The Poly Pelletizer can work with both of these types of markets to help people build while reducing the amount of plastic pollution in the world. A big focus of the Poly Pelletizer also revolves around helping manufacturers in developing countries who cannot afford to import manufacturable materials. With this new product, they will not only be able to build sustainable, but independently as well.

7.2 Introduction

The Poly Pelletizer is a new product that takes plastic water bottles and recycles them into PET pellets which have a very wide array of applications. These pellets are used in nearly all large scale plastic recycling processes. Our team hopes to create these pellets and ultimately use them to create 3-D printer filament. The Poly Pelletizer also has a wide variety of potential markets. The original inspiration for this project was to help manufacturers in developing communities around the world who could not afford to import the materials they needed to build their products. However, 3-D printing technology is growing very quickly, and more and more people are using these products at home. The Poly Pelletizer could potentially appeal to many of these hobbyists. There are a couple other competitors in the market however, most of them either fail to give manufacturers the ability to work independently, or are far too expensive.

7.3 Objectives

The goal of the Poly Pelletizer is to create and distribute a device that takes a large scale industrial recycling technique for water bottles and brings them to a table top level. The Poly Pelletizer system will promote sustainability and give 3rd world countries a way to recycle their excess polyethylene terephthalate (PET). Within 5 years the company hopes to have promoted recycling throughout 3rd world countries and given people who have no way of recycling an opportunity to help maintain a healthy planet. The Poly Pelletizer project seeks to provide a means for manufacturers in developing nations to improve their financial standing while improving the environment.

7.4 Product Description


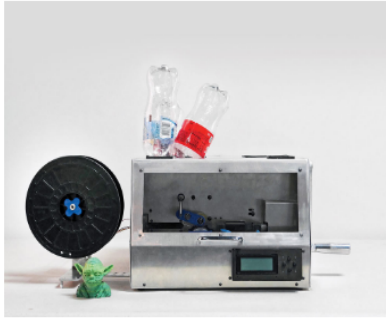

The Poly Pelletizer is a multi part system capable of melting PET plastic shreds and push the resin out a die to form pellets. These pellets are used for a multitude of applications including extrusion into 3-D printer filament, injection molding, and blow molding. The shreds enter the melting system and the auger facilitates an even melt. The pressure system utilizes a manual plunger to push resin from the system to minimize system complexity. The Poly Pelletizer uses six PID controllers for a customizable temperature gradient. Coming in at \$1084.87 the Poly Pelletizer brings industrial recycling capabilities to the workshop scale, making it much more accessible to an entire new market of customers. The Poly Pelletizer presents a new advancement in the exciting and expanding 3-D printing technology market. It allows manufacturers to not only become more independent and sustainable, but it also incentivizes people to recycle more plastic and reducing our carbon footprint.

7.5 Potential Markets Competition

The people who would want something like the Poly Pelletizer have excess water bottles and plastics. There is an excess of plastic waste all around the world. The target market for the system is 3rd world countries with excess polyethylene terephthalate. Currently similar systems to the Poly Pelletizer such as 3-D printers are mostly sold to tech companies but what makes the system appealing to the 3rd world countries is it is not just a fun mechanism like a 3-D printer, but it offers a solution to the problem of excess water bottles.

To start out, an batch of around 50 products should be manufactured because one Poly Pelletizer system will be able to serve a large area. It can be passed from village to village eliminating the excess water bottles and giving the people who reside in it materials that can be used as a source of income. People will find the system appealing as they see the Poly Pelletizer helping relieve the major issue of excess water bottles in 3rd world countries and will want one for their home so they can have an easy localized way to recycle. In Table 7 below, some of the main competing products on the market are shown. These range from recycled filament products to products that create filament from recycled materials.

Table 7: Comparison of similar products on the market

	Image	Price
B-PET		\$35/spool of filament
ProtoCycler		\$699
Ekocycle		\$1200

As shown above, there are a few other competitors for the Poly Pelletizer. These companies products are slightly different than the Poly Pelletizer system as they only make 3-D printer filament rather than pellets that can be used for a multitude of applications. These companies are still comparable to our system because they will be using similar hardware to melt the water bottles down into filament resulting in a similar cost of manufacturing. One company that makes 3-D printer filament out of recycled PET is a company called B-pet. Their product is made from 100% recyclable plastic, although not all from PET, and has the same properties as virgin PET but costs 70% less. The price is about 35 dollars for a spool of material. Although B-pet does make 3-D printer filament, it still fails to help make these manufacturers independent and still forces them to try to import their materials which they often cannot do. Another similar product on the market is the ProtoCycler. The ProtoCycler is a 3-D printing device that was created by three students at the University of British Columbia. The ProtoCycler is a very good product that makes access to 3-D printing much easier for everyday consumers. However, the main improvement that can be made on this device is that it does not use plastic water bottles directly. The ProtoCycler, like many other devices utilizes PET plastic pellets to create its filament. Thus, the Poly Pelletizer would be the optimal product to improve upon these previous devices because it creates the plastic pellets that are compatible with many different devices. The device goes for \$699 but they make the argument for how much it costs it makes up for in saving on filament costs. Lastly, another product on the market is the Ekocycle. The Ekocycle cube 3-D printer uses a filament that is made in part from recycled plastic bottles. The company cubify sells the Ekocycle printer for \$1200 and uses filament cartridges that contain at least three recycled 20 oz PET plastic bottles. The filament used in this machine is 25% of postconsumer recycled materials. Although the cartridge design does make the system easier to use, it leaves much to be desired in performance and level of recycling. Again, the main issue with this product is its high price. The Poly Pelletizer team hopes to improve upon the amount of recycled PET in the filament as well as come in at a significantly reduced price.

7.6 Sales and Marketing Strategies

Marketing to manufacturers in developing nations is not straightforward. Reaching these communities with traditional advertising means is not as productive as in developed nations. The product must be easily accessible via websites like alibaba.com which serves nations all around the world. In order to build a dedicated user base, it may be prudent to distribute discounted systems. Communities that achieve success with their Poly Pelletizer could spread the word about the product and reach potential users that traditional advertising methods would find difficult to reach. The Poly Pelletizer could also potentially link up with humanitarian organizations that work in many of these developing communities. With that partnership, these communities would be able to get access to our product, showing the potential benefits of the Poly Pelletizer to others. In terms of marketing to manufacturers in the United States, the Poly Pelletizer could capitalize on the growing market for 3-D printing technology products. Our product could be marketed to both businesses and hobbyists alike. The Poly Pelletizer could even eventually be used by companies for rebates for using the product and recycling a certain amount of plastic per year.

The initial sales that we intend to have will most likely be with humanitarian organizations who are already interested in trying to invest in new ways to help developing communities. The Poly Pelletizer team could benefit in terms of improved distribution by partnering with an organization. The people working on these sales would be incentivized to work for this product not only for a commission, but also for a humanitarian reason as well. The majority of the marketing for this product would be done online where it is easiest to spread information about the product. Our team would target websites that already sold 3-D printing products.

7.7 Manufacturing Plans

The Poly Pelletizer system is made of mostly common materials and hardware other than its heating and control system. Most of the parts can be acquired in large bulk orders and do not need to be machined specifically for the system. For the initial 100 systems the parts can be assembled by a typical assembly line worker. An entry level machinist could perform the necessary operations to produce the system. It would take an estimate eight hours in an assembly line style setup to create a single system. Depending on the

amount of workers employed, at least one system per day could be created. Plenty to keep up with projected demand.

7.8 Services and Warranty Plan

The warranty for the Poly Pelletizer will last five years. This will cover the replacement of any of the parts of the system that might break from regular use. Since the system is relatively simple, our team would be able to train a user how to fully operate the machine and replace any of the parts that may need to be fixed. This will be especially useful for the products that are used in developing communities that are often much more remote and harder to get a technician out to. However, for the products sold in the United States, our team would be able to provide a more service oriented warranty. Overall, the Poly Pelletizer has few components making the anticipated service rate relatively low. The most common problems are switching out a motor or controller which only requires ordering a new component and connecting the necessary wires the correct ports.

7.9 Product Economics

The Poly Pelletizer seeks to bring developing nations the ability to emulate incredibly expensive recycling processes for a fraction of the cost. Despite the social entrepreneurship roots of the project, it is necessary to turn a profit off the system. The capital generated can fuel the next round of investment, and lead to further integration of the Poly Pelletizer on a global scale. It is necessary to examine the initial cost of investment to begin manufacturing the system on a marketable scale. To calculate the necessary amount of an initial investment production costs must be factored in. Using an estimation of sales volume, a time line to achieving a return on investment can be calculated.

7.9.1 Production Costs

The hardware costs of the Poly Pelletizer ended up at \$1,084.87. Most of the parts that comprise the Poly Pelletizer are standard parts. Only a few part need machining. The average machinist hourly wage in the U.S. is \$19.47 and the average assembly line worker at GM makes \$20.75 per hour [13]. Therefore, it is reasonable to set the rate for labor at \$20.00 per hour. With jigs in place, machining would take about one hour. Assembly of the rest of the system would take approximately 7 hours. Eight hours at \$20.00 per hour is \$160.00. The total cost settles at \$1,244.87 to produce one Poly Pelletizer system.

7.9.2 Investment and Sales Plan

In the first year of operation the Poly Pelletizer team hopes to sell 100 units total. That would be an initial investment of \$119,283. In order to generate capital for a second round of investments, the sale price of the Poly Pelletizer will be set at \$2,000. This price will cover the manufacturing costs and overhead of the company while still generating a profit. At a rate of selling eight systems per month, the investment would pay off in the tenth month of the year. Figure 31 below shows the revenue trajectory of the project.

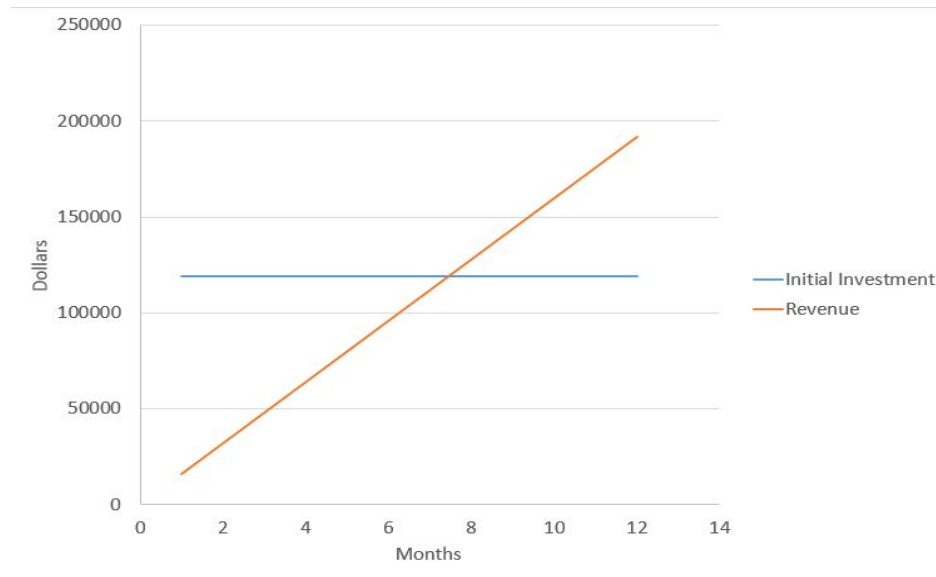


Figure 31: The number of months needed to begin generating revenue off Poly Pelletizer sales.

After about seven, all sales of the Poly Pelletizer would go to generate investment capital for another round of production. Ideally, the next wave of production would be larger, as the name recognition of the Poly Pelletizer grows. The end goal would be creating systems as long as the demand existed in order to deliver on the core goals of the project.

8 Engineering Standards and Realistic Constraints

8.1 Economic

For this project, there are economic constraints because the product we create will be used by manufacturers in developing communities, who are already on tight budgets. The Poly Pelletizer must ultimately be able to create PET pellets from recycled water bottles, but it also must be cheap enough for all manufacturers to afford. In order to keep the design as frugal as possible, our team had to simplify some parts of the system. The extruding mechanism was ultimately changed to a manually pushed plunger and the cutting of the plastic into pellets became a post-production process in order to keep our design affordable.

8.2 Environmental

The Poly Pelletizer was created to help reduce the amount of plastic pollution around the world as well as help reduce the need to create new plastics from petroleum. PET plastic pollution is a huge problem all around the world because it can pollute water supplies as well as harm wildlife. Regarding climate action, the Poly Pelletizer project has the ability to lessen the carbon footprint of plastic manufacturing. Plastic is an organic compound made from petroleum. Extracting petroleum from Earth is environmentally damaging. By utilizing pre-existing plastic, the Poly Pelletizer decreases dependence on petroleum, and enhances the case for divesting from fossil fuels. Looking at the carbon footprint of PET production in the U.S. serves to highlight the benefit of the Poly Pelletizer.

In the U.S. over 91 billion water bottles are used each year with only about 25% being recycled[9]. This leads to an excessive amount of plastic bottles in landfills and the environment. Taking the average weight of a dry water bottle to be about 0.01 kg, only about 229 million kg of PET bottles are recycled compared with 687 million kg that are disposed of improperly. Recycling water bottles does not result in a complete rebate of carbon emissions because the energy necessary to reform the bottle, along with the initial energy input to create the PET is more than the savings generated from using recycled bottles. Figure 32 shows the carbon emissions of plastic bottle creation. However, recycling bottles does result in a process requiring about half of producing a new bottle. If all water bottles produced in the U.S. each year were recycled, over

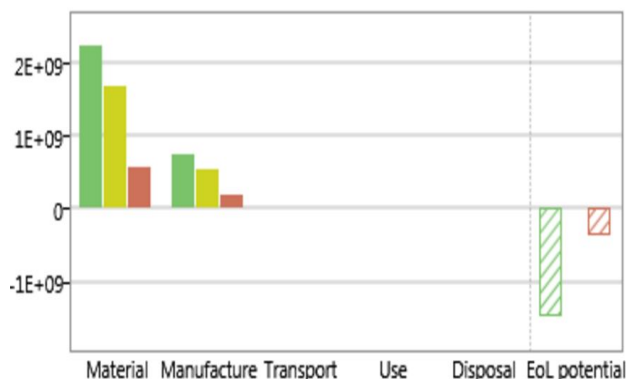


Figure 32: Carbon Emissions for producing PET plastic water bottles in one year in the U.S. categorized by type of disposal.

half the carbon emissions would be rebated (Shown by the green bar with rebated emissions shown with the dashed green bar). However, the yellow bar is the percentage of emission used in bottles that will be recycled. The U.S. currently capitalizes on only about 25% of possible carbon rebates. The Poly Pelletizer looks to help bridge the gap on these lost carbon rebates. To test the validity of the projects potential to reduce carbon emissions, a hypothetical scenario was created. In this scenario, a company wants to use the Poly Pelletizer to produce a cubic meter of 3-D printed PET products throughout the year. Using a density of $1400 \frac{kg}{m^3}$ for PET, the company would need to produce 1400 kg to reach their goal. The average 3-D printer filament spool weights 5 kg, so the company would need to make 280 spools. The average PET

water bottle weights 0.01 kg, so 500 bottles per spool are needed. The Poly Pelletizers maximum capacity is 0.4 kg per batch, equating to 40 bottles per batch, and 12.5 batches per spool. Using an estimation of 10 minutes per batch, one spool would take 2 hours to produce. Over the course of the year it would take 560 hours to create 1400 kg of PET. Using the assumptions above, along with this scenario, it would take 140,000 water bottles to create a cubic meter of 3-D printed material. Figure 33 compares the Poly Pelletizer's emissions to those of plastic production. The carbon emissions involved with creating the ma-

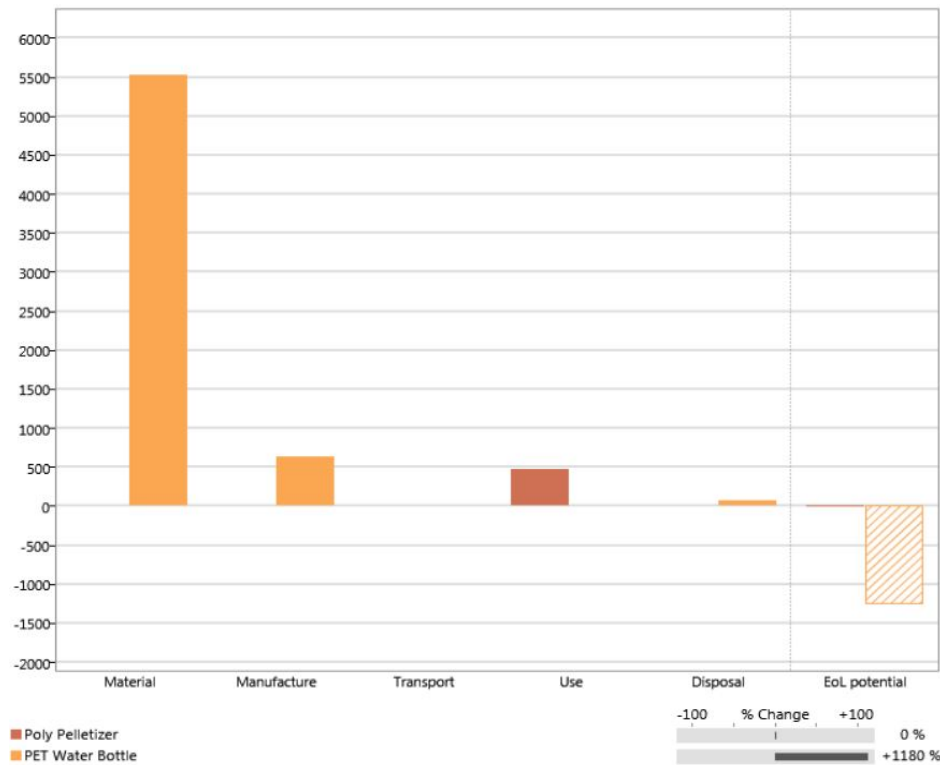


Figure 33: Carbon emissions of producing the Poly Pelletizer compared with the emission needed to create one cubic meter of PET.

terial and manufacturing PET bottles is over 6,000 kg of carbon dioxide. The materials and manufacturing of the Poly Pelletizer amount to 13 kg of Carbon Dioxide, so small in comparison that it cant be seen on Figure 33. The main source of emissions from the Poly Pelletizer is through use. In the course of the hypothetical companys year, they would produce nearly 500 kg of emissions from running the Pelletizer. However, their carbon rebate if using all shredded plastic bottles is about 1250 kg. This means the benefit of repurposing plastic water bottles is more beneficial than the harm it takes to run the system. Even if the system only input 50% shredded bottles, the carbon rebate would still make up for the systems operation.

The Poly Pelletizer seeks to melt shredded plastic water bottles and extrude the resin into PET pellets capable of utilization in multiple recycling applications. The design team sought to positively impact the environment, create more sustainable recycling practices, improve economic conditions in developing nations, create healthier living conditions, and act ethically while doing all of the above. The team made certain assumptions to facilitate a hypothetical scenario to test the validity. After examining data using the Granta software, it could be deduced that the carbon rebate from reusing plastic water bottles is less than the carbon emissions from running the system, even at 50% plastic shreds.

8.3 Sustainability

The system promotes a sustainable solution to recycling PET plastics. The current recycling industry is on a very large scale and requires many man hours to turn PET waste back into reusable material. The Poly Pelletizer will make this process accessible on a much more local scale providing independent businesses with a more efficient method of recycling their PET waste into usable material for manufacturing. Responsible consumption and production is a large part of this project as well. Many manufacturers in developing countries do not have access to materials necessary for their industry. The Poly Pelletizer enables them to produce materials out of fully recycled plastics. The system gives manufacturers more incentive to collect their water bottles for repurposing. This system will allow the manufacturers to have a minimal amount of consumption because they will have the capability to reuse them for uses specific to company needs.

8.4 Social

This project is focused on helping manufacturers in developing countries around the world become more independent as well as environmentally sustainable. Many of these people face very harsh realities when it comes to manufacturing. One of the biggest problems they face is that importing materials can be extremely expensive. Many manufacturers are unable to create and sell products because the raw materials can be costly. Another big issue for them is that they often live in very remote areas where importing materials is extremely impractical if not impossible all together. The Poly Pelletizer takes the large-scale recycling processes previously only available to a limited industrial market, and brings it down to a smaller scale that can be more easily spread around the world.

8.5 Health & Safety

- a. Manufacturing
 - 1. Spinning mechanical parts (coffee grinder, auger, servo motor pellet slicer)
 - i. The project includes multiple devices used to shred water bottles into flakes.
- b. Assembly
 - 2. Power Tools
 - i. Each member must have training with power tools and safety procedures to avoid accidents.
 - 3. Electrical Parts and Assemblies
 - i. The heating system will be controlled by an contained electrical system with no expose wires.
- c. Test/Operation
 - 1. Toxic Chemicals
 - i. PET is inert, but all melting processes will occur under the fume hood as a precaution.
 - 2. High Temperatures
 - i. Heating bands will reach 270° C. Insulation will be used to cover them during operation.
 - ii. Insulated gloves will be used when handling the heating components.
 - 3. Hot Liquids
 - i. The amount of plastic per batch will be fairly small, so overflow will not occur.
 - ii. Insulated gloves will be used when handling the heating components.
- d. Display
 - 1. Presentations
 - i. Any presentations displays will feature the system disconnected from power sources
- e. Storage
 - 1. Advisor's Lab
 - i. When not being operated or worked on, the project will be kept in the project advisors lab.
 - ii. Only students with special access and training can enter the lab.
- f. Disposal
 - 1. After the Design Presentation
 - i. The project may be used for future projects and will be stored in the advisors lab

It will be the advisors discretion as to keeping or disposing of the system.

8.6 Santa Clara University Arts Requirement

Table 8: Drawings for the our Santa Clara University Arts Requirements which can be found in the appendix

Team Member	Drawing Description	Drawing Number
Ian Maltzer	Plunger Mechanism Drawing	E6
James Martino	Brass Die for Plunger	H7
Logan Costa-Smith	Brass T-Joint Drawing	H5

9 Summary and Conclusion

9.1 Problems occurred

The Poly Pelletizer system proved to have many issues along the way before reaching the final product. The biggest problem that occurred during the creation of this system was estimating the amount of time it would take to do any one thing. For example, getting the heating bands to be controlled by the controllers seemed to be as simple as wiring them together and turning on the power. This was not the case at all. There had to be a prong soldered onto each one of the wires so that it was able to attach to the controller and then figuring out the proper way to wire the solid state relays to the PID controllers, thermal couples, and heating bands following the schematics for the solid state relays online and applying what electrical engineering knowledge that was available.

Problem solving was the largest aspect of this project. When the melting subsystem was not allowing the PET to enter the pressure subsystem, a solution of implementing a larger auger and removing the valve was devised. When the pressure subsystem was burning the PET before it could reach the die, the heating band had to be disconnected to assure that it would not burn the material.

Problems are simply part of being an engineer. This project really gave us a good look into what it means to apply the mechanical engineering education to a real world engineering problem that involves potential for loss of money and loss of time if not properly addressed. Every problem our group solved felt like a small victory. Many problems came from over complications in our thought process. The solutions often ended up being more simple than imagined. Removing a valve or adding insulation seemed obvious in hindsight, but often involved trial and error.

9.2 Further Work

There is still some testing left to do for our project. Our team hopes to continue trying different ratios of plastic flakes to virgin PET pellets, in order to see if the Poly Pelletizer can still make usable plastic products. After using multiple different ratios of plastics, our team hopes to see a future iteration of the project perform differential scanning calorimetry analysis on the resultant pellets. The DSC testing will allow us to compare the recycled plastic pellets that we create to virgin PET pellets and be able to determine whether the products the Poly Pelletizer create are usable.

In order to do this testing, we will still need to conduct some more tests in order to get enough material to do that actual testing. For this testing, our team will also have to do some additional work to continually tune the heat bands and their controllers. This is necessary to conduct a successful test and have the plastic melt evenly without solidifying or burning along the way.

9.3 Lessons Learned

Throughout this project, our team has definitely encountered our fair share of problems, but have grown a lot because of them. One of the biggest takeaways from this project for us has been the invaluable experience we have received in problem-solving. For much of this project, as we will likely later encounter in life, unforeseen problems will arise. To a certain extent, these are unavoidable. The important thing then becomes learning how to deal with these problems without becoming overwhelmed. Over the last year, this project has taught us to deal with problems by first taking a step back to understand the root cause of the problem, before breaking it down into more manageable tasks to ultimately find a solution.

Another valuable takeaway from this project is that it helped broaden our knowledge beyond our mechanical backgrounds. All three team members are mechanical engineering students, and thus had to take some extra time to teach ourselves parts of this project such as wiring our controls system. While this was not an easy task, it was extremely beneficial for us as it forced us to work outside our comfort zone and expand upon our engineering skill sets. This project has made all three of us much better and more well-rounded engineers as a result.

Lastly, we learned about the difference between theoretical and physical testing. In the real world, testing hardly ever goes as well as it does when doing it on paper. There are almost always many more variables that are too hard to account for on paper which ultimately make huge impacts when the actual testing begins. These variables can sometimes be the most important aspects, which makes actual testing extremely valuable. Testing, and even failed testing, is an important step in any design process as it can teach you a great deal about your project. This project has helped us learn how to minimize these differences as well as how to manage them when they inevitably occur.

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Appendix A: Customer Needs Survey

1. Do you recycle plastic water bottles?

ALL THE TIME A LOT SOMETIMES NOT AT ALL

2. How much polyethylene terephthalate (PET) plastic, commonly found in water bottles, do you go through on a weekly basis?

7+ bottles 5-6 bottles 3-4 bottles less than 2 bottles

3. Do you think that recycling is worth the time and money?

YES NO

4. Do you have interest in the 3-D printing industry?

YES NO

5. Would you ever consider owning a compact 3-D printer in your home?

YES NO

6. If no, what would hold you back from owning a system?

7. If you circled ACCESS TO FILAMENT, would an in home system capable of producing filament from recycled water bottles increase your likelihood of owning a 3-D printer?

YES NO N/A

8. Do you believe that recycling plastics has a crucial role for sustainability on a global scale?

YES NO NOT SURE

9. Would you buy home products (kitchenware, toys, phone cases, etc.) made from recycled PET plastic filament?

YES NO

10. Would you rather be able to manufacture products for yourself rather than buy them? E.g. Would you rather put extra effort to make your product instead of buying it in order to save money?

YES NO

Appendix B: Decision Matrix

Design Project =	Poly Pelletizer			System=		Heating and Cooling System		
	TARGET							
	or							
CRITERIA	FACTOR	1 = Baseline		Logans 1		james		four
Time – Design	1	1		1		2		
Time – Build	1	1		1		2		
Time – Test	1	1		1		1		
Time Score	10		10		10.00		16.67	
Cost – Prototype	\$ 500.00	\$ 500.00		\$ 500.00		\$ 500.00		
Cost – Production	1900	\$1,900.00		\$ 1,400.00		\$ 1,900.00		
Cost Score	10		10		8.68		10.00	
Heating	5	3	15	3	15	3	15	1
Electric Power	3	3	9	4	12	2	6	1
Cooling	5	3	15	2	10	5	25	1
Main Body Height	2	3	6	3	6	3	6	1
Body Diameter	2	3	6	3	6	3	6	1
Nozzle Diameter	4	3	12	3	12	3	12	1
Filament Size	4	3	12	3	12	3	12	1
Cost	3	3	9	4	12	3	9	1
Extrusion Speed	2	3	6	2	4	4	8	1
0	0	3	0		0		0	1
0	0	3	0		0		0	1
0	0	3	0		0		0	1
	TOTAL		90.0		90.3		92.3	
	RANK							
	% MAX		97.5%		97.8%		100.0%	
	MAX	92.3						

Figure 34: Scoring matrix for melting subsystem.

Appendix C: Timeline

[illegible]

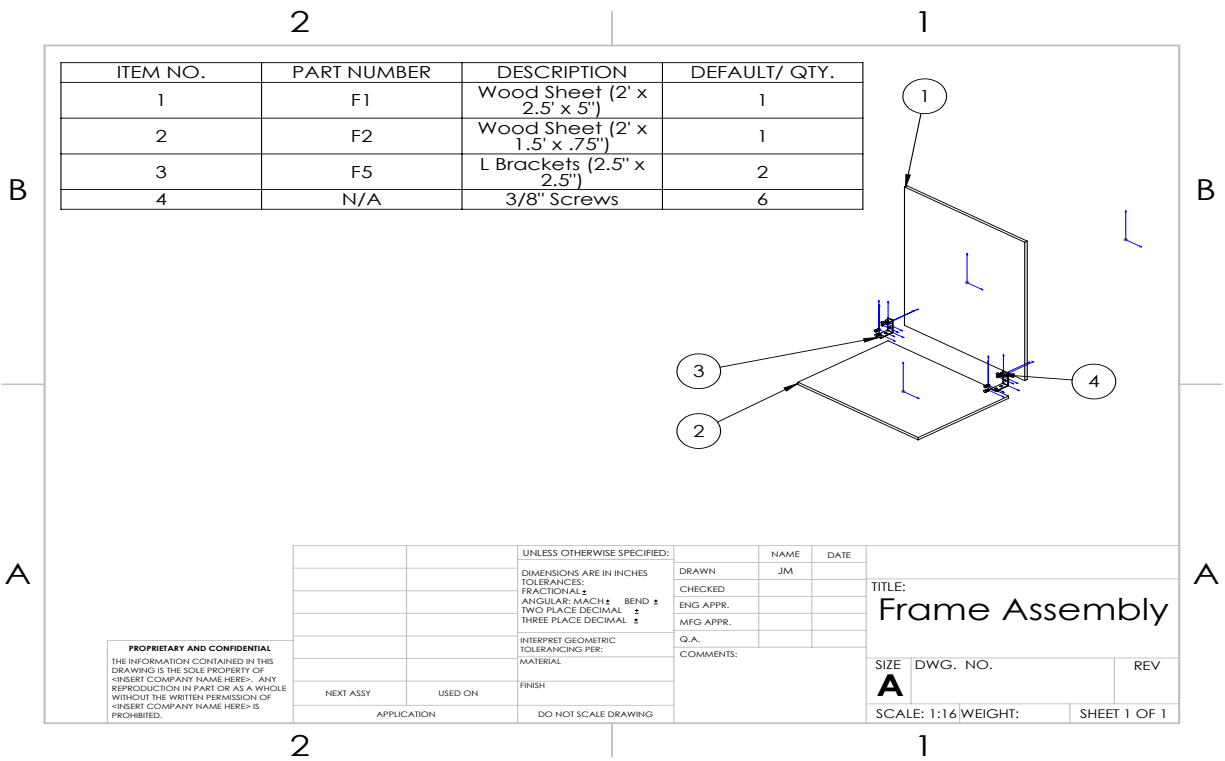
Task	Week of	9-Jan	23-Jan	6-Feb	20-Feb	6-Mar	20-Mar	3-Apr	17-Apr	1-May	8-May	22-May
Begin Winter Quarter												
Updated Plan with Advisor												
Begin Detail Drawings												
Begin Ordering Components												
Design Iterations												
Detail Drawings Due												
Compile Assembly Drawings												
Assembly Drawings and Initial Hardware												
Begin Spring Quarter												
Fabrication												
Assembly												
Testing												
Necessary Iterations												
Finalize Design												
Senior Design Conference												
Senior Thesis												
Open House												

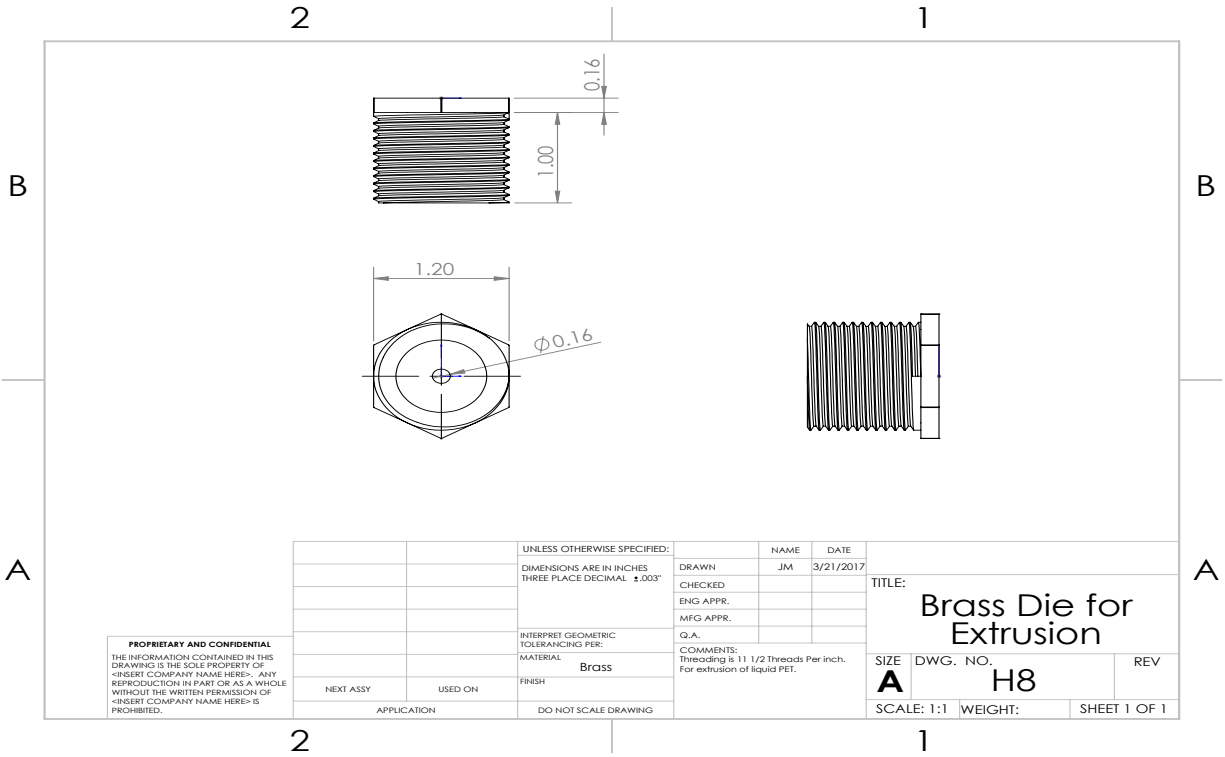
Appendix D: Budget

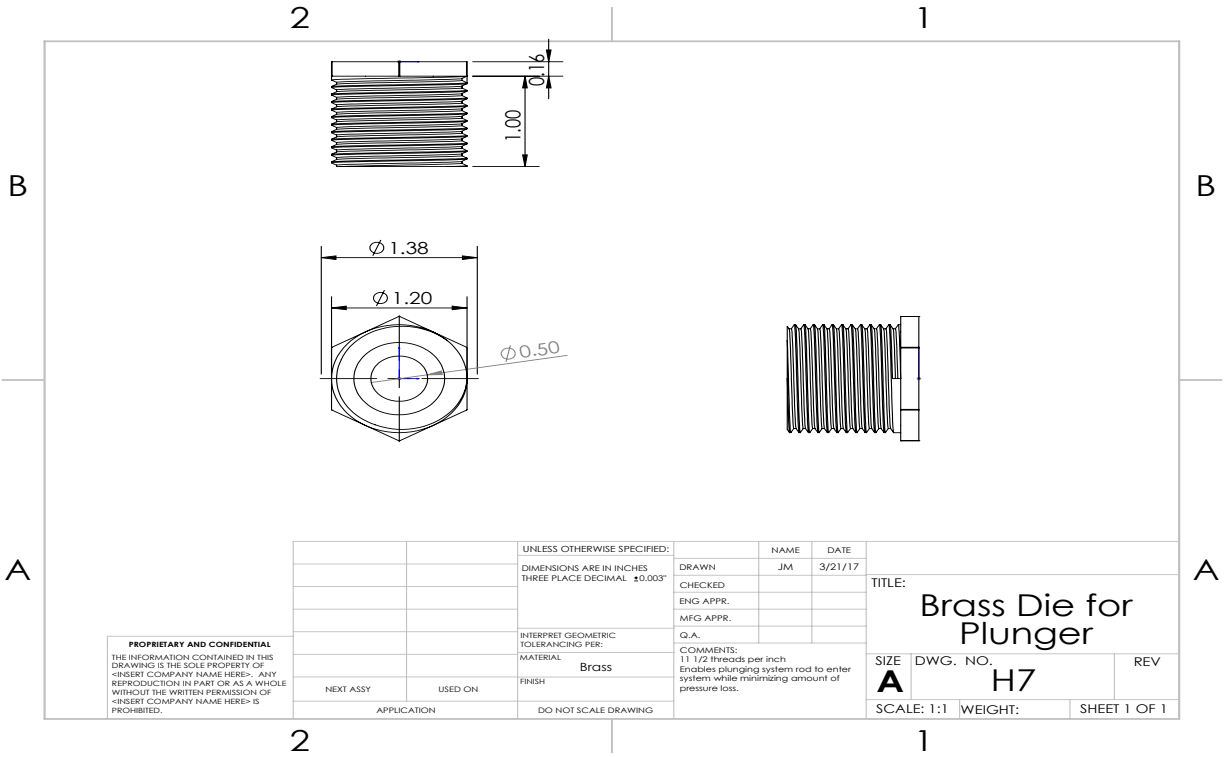
Subsystem	Component Description	Part #	Quantity	# per quantity	Vendor	Cost/Part (\$)
Frame						
	Wood Sheet (2' x 2.5' x .5")	F1	1	1	Lowes	14.98
	Wood Sheet (2' x 1.5' x .5")	F2	1	1	Lowes	
	Wood Board (3.5" x 24" x .75")	F3	1	1	Lowes	
	Bolts (3/8" x 7" - 16)	F4	6	1	Lowes	1.42
	L Brackets (2.5" x 2.5")	F5	2	2	Lowes	2.98
	Nuts (3/8" - 16)	F6	1	50	Lowes	6.58
	Washers (3/8")	F7	2	10	Lowes	2.98
Heating						
	12" Brass Pipe, 1" diameter	H1	1	1	McMaster-Carr	30.48
	4" Brass Pipe, 1" diameter	H2	1	1	McMaster-Carr	10.53
	2" Brass Pipe, 1" diameter	H3	1	1	McMaster-Carr	6.01
	1" Brass Pipe, 1" diameter	H4	1	1	McMaster-Carr	4.89
	Brass T-Joint	H5	1	1	McMaster-Carr	20.5
	Steel Female-Female Collars (1" diameter)	H6	2	1	McMaster-Carr	6.14
	Brass Die	H7	1	1	McMaster-Carr	12.35
	Brass Die	H8	1	1	McMaster-Carr	12.35
	1.5" Diameter Heating Bands, 2" Length	H9	6	1	McMaster-Carr	69.37
	Copper Foil (2" x 0.002" x 50')	H10	1	1	McMaster-Carr	36.45
Control						
	Inkbird Dual Digital PID Temperature Controller	C1	6	1	LERWAY Tech.	37.99
	Inkbird SSR - 40A Solid State Module	C2	6	1	LERWAY Tech.	
	K Type Thermocouple	C3	6	1	LERWAY Tech.	
	Terminal Block	C4	3	1	McMaster-Carr	4.51
	Screw Terminal Switch	C5	7	1	McMaster-Carr	6.53

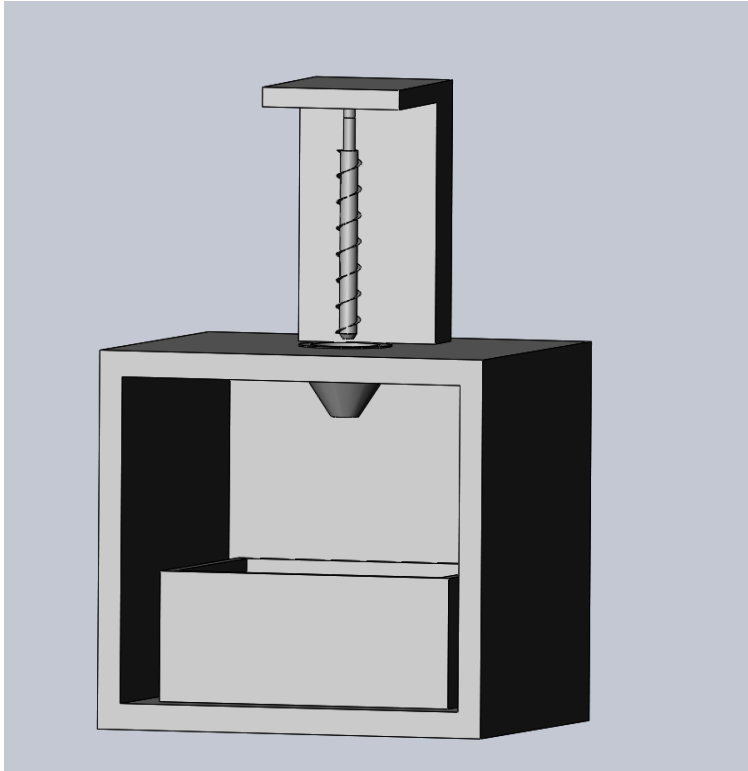
Mixing						
	Auger	M1	1	1	Home Depot	29.97
	Gate Valve	M2	1	1	Home Depot	11.24
	L Bracket	M3	1	1	Akabot 1	NA
	Collars	M4	2	1	Akabot 1	NA
	Sprocket	M5	1	1	McMaster-Carr	10.41
	10 RPM Gear Motor	M6	1	1	SERVOCITY	24.99
	Motor Mount	M7	1	1	RobotShop	7.95
	Chain	M8	1	1	SERVOCITY	8.99
	Nuts	M9	4	1	Akabot 1	NA
	Bolts	M10	4	1	Akabot 1	NA
	Washers	M11	4	1	Akabot 1	NA
Extrusion						
	12"x1/2"x1/4" Aluminum Bar	E1	1	1	McMaster-Carr	12.14
	6"x1/2"x1/4" Aluminum Bar	E2	1	1	McMaster-Carr	
	3"x1/2"x1/4" Aluminum Bar	E3	1	2	McMaster-Carr	
	18" Aluminum Rod Threaded	E4	1	1	McMaster-Carr	17.79
	Clevis Pin	E5	2	1	McMaster-Carr	5.02
	6" Aluminum Rod	E6	1	1	McMaster-Carr	15.32
	Page Totals					\$1,084.87

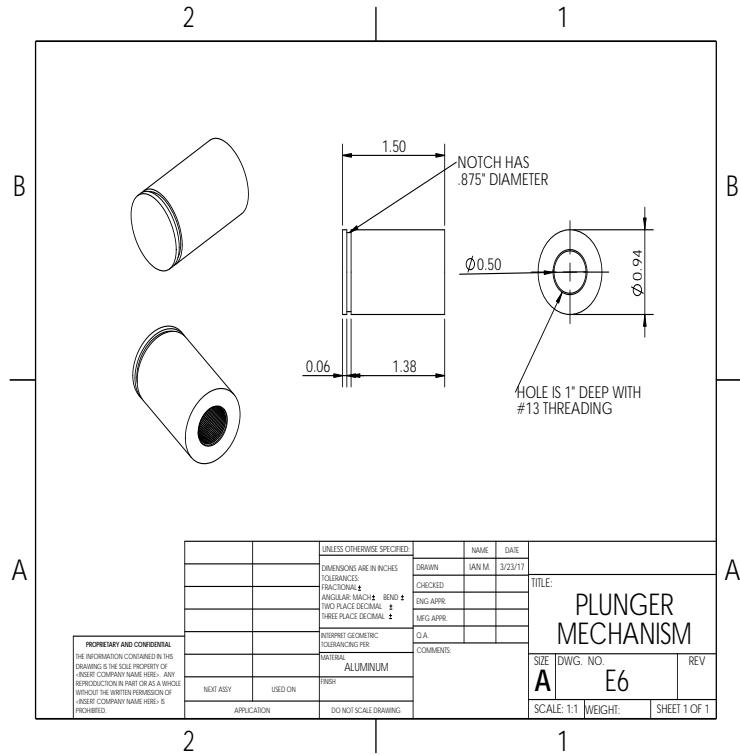
Appendix E: Design Drawings

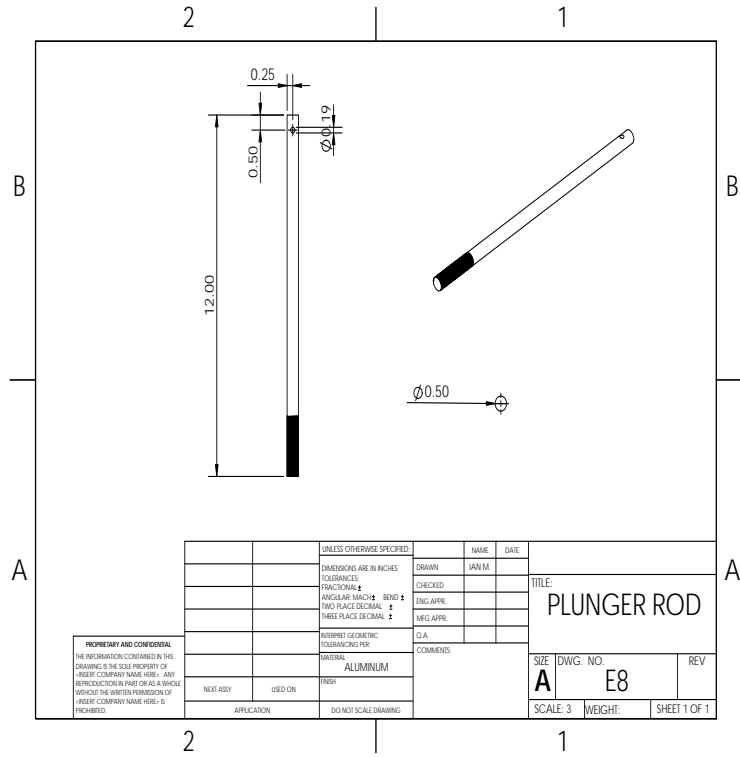


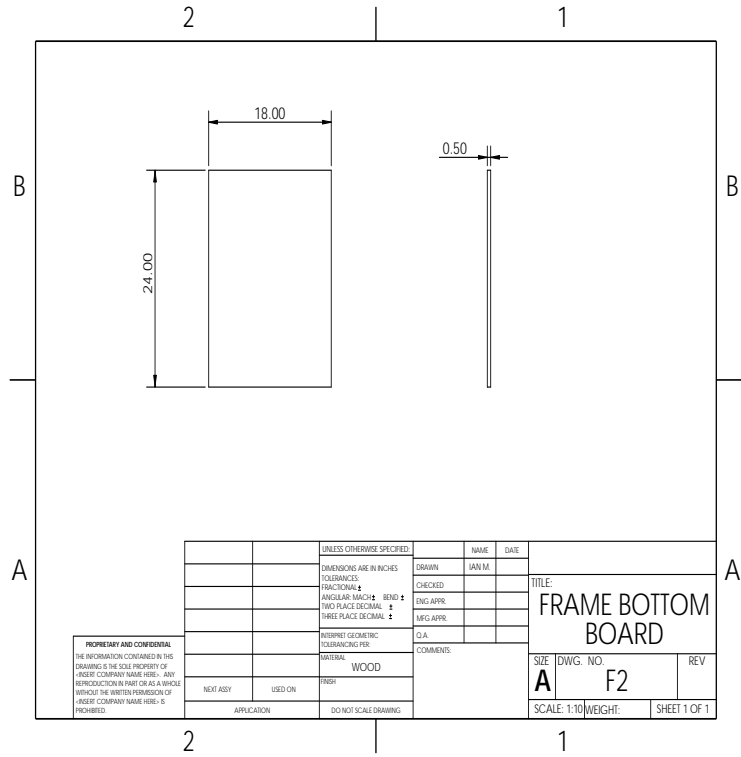


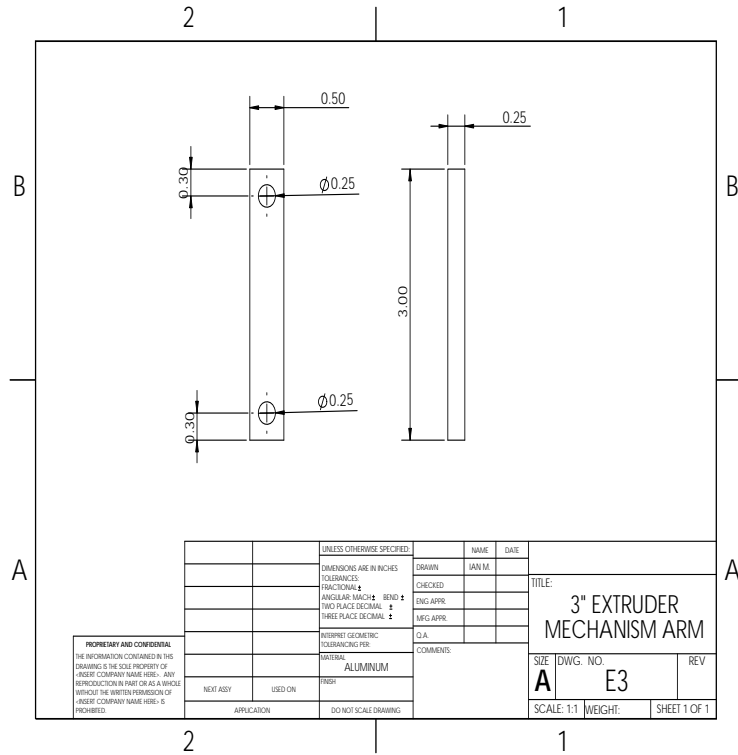












B

△

<COMPANY NAME>
TITLE:
**HEATING SYSTEM
ASSEMBLY**
\$REV DWG. NO. REV
A
SCALE: 1:10 \$SHEET 1 OF 1

Appendix F: Presentation Slides

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Poly Pelletizer

A Solution to Polyethylene Terephthalate (PET) Pollution

Team: Ian Maltzer, James Martino & Logan Costa-Smith
Advisor: Dr. Panthea Sepehrband

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Agenda:

- Project Background
- Objectives and Motivations
- Specifications
- Testing and Results
- Takeaways
- Q & A

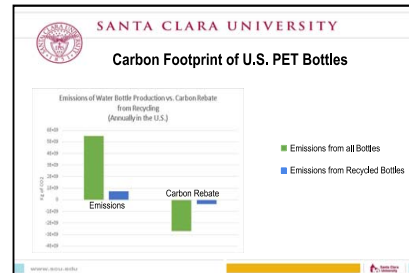
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Problems with PET Bottles

- Millions of barrels of petroleum annually for plastic production
- Only about 25% of plastic bottles in the U.S. are recycled
- Damage environment through pollution, leaching, and harming wildlife



Long Beach, California



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The Need

- Bring industrial recycling to local scale
- Expand recycling practices worldwide
- Develop means of utilizing plastic pollution




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Our Objectives

- Help manufacturers build sustainably
- Increase incentives to recycle
- Promote innovation that reduces carbon footprint
- Produce PET pellets for widespread applications



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What is the Poly Pelletizer?

- Recycles water bottle shreds into PET pellets
- Implements dual heating and pressure system



2

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Helping Manufacturers in Developing Communities

- Limited access to manufacturable materials
 - Expensive to import materials
 - Remote areas
- Limited alternatives available



3

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Uses for PET Pellets

- Used in nearly all major recycling processes
- Can be used for 3D printer filament
- Exportable product



9

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Previous Projects



Akabot 1: Horizontal configuration resulted in issues generated pressure to extrude filament



Akabot 2: Improved filament, but inconsistent results when working with shredded water bottles

10

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Initial Design Ideas

Melting Pot

Pros:

- Large Batch
- Inexpensive
- Simple Design

Cons:

- Inadequate temperature control
- Mixing is difficult due to large diameter of system
- No pressure generation to push resin through die

Vacuum System

Pros:

- Removes air from heating system, to allow for more even melting

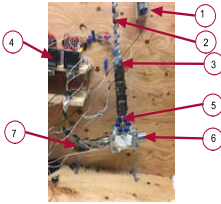
Cons:

- Expensive
- Difficult to implement

11


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Final Design



Part Number	Part Name
1	Motor
2	Auger
3	Band Heater
4	Controllers
5	Valve
6	Plunger
7	Die

12

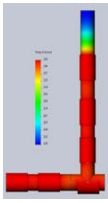


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Finite Element Analysis

Assumptions:

- Convection with the ambient environment
- Perfect heat transfer between band heater and chamber
- Insulation will minimize heat loss



13





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System Specifications

14





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System level Sketch



- Heating and Melting
- Temperature Control
- Pressure system

15





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Melting Subsystem

- 10 RPM gear motor
- Torque Stall 368 oz-in
- 1 inch diameter
- IRWIN Speedbor
- 300 Watt Heating Bands
- 1 1/2 inch diameter
- Copper Foil for better fit
- Fiber glass insulation
- Ball valve




16





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Temperature Control System




17





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Pressure Subsystem





18



65

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Testing and Results

19

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Preliminary Processes


- Ideal PET shreds
- Cleaning process
- Shredding Processes



20

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Initial Test



- All testing done in Vacuum hood
- Hardware and Electronics test
- Resulted in rewiring of Gear motor power source

21

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Test: $\frac{7}{8}$ " Auger and 12" Brass tube



- Resulted in cold spots
- Unmelted PET would fall to bottom of heating subsystem

22

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Test: 1" Auger and 6" Brass tube




- No longer solidifies on auger
- Too much plastic added to the system stalling gear motor
- First complete melt in melting subsystem

23

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Test: Allowing System to have Preliminary Heat Up




- Allowed for extra heat up time before adding PET
- Optimized melting subsystem
- Backup and overflow due to valve


24

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Final Test: 1" Auger and 12" Pipe with no Valve



- Consistent flow of plastic
- First successful extrusion of plastic
- Began burning plastic



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Further Work to be Done



- Different Temperature gradients
- Differential scanning calorimetry testing on pellets produced
- Creating PET pellets with desirable material properties

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Takeaways

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Potential Impact of Poly Pelletizer

- Project has the potential to significantly change how we recycle
 - Bring sustainable manufacturing to disadvantaged communities
 - Make large-scale recycling processes available on a smaller scale for individual companies



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Lessons Learned

- Invaluable experience in problem-solving
- Broadened our knowledge beyond mechanical background
- Difference between theoretical and physical testing




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Acknowledgements



- Dr. Sepehrband
- Miller Center for Social Entrepreneurship
- Santa Clara School of Engineering



31

32

33

34



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Additional Authors

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Printed Name: Ian Maltzer

Date: 6/14/17

Additional Authors

Signed: _____

Printed Name: _____

Date: _____

Additional Authors

Signed: Logan Costa-Smith

Printed Name: Logan Costa-Smith

Date: 6/14/2017

Additional Authors

Signed: _____

Printed Name: _____

Date: _____

Additional Authors

Signed: _____

Printed Name: _____

Date: _____