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Akabot: 3d printing filament extruder

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SANTA CLARA UNIVERSITY

Department of Mechanical Engineering

Date: June 11, 2014

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Emily Albi, Kevin Kozel, Daniel Ventoza and Rachel Wilmoth

ENTITLED

AKABOT: 3D PRINTING FILAMENT EXTRUDER

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

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Advisor

Department Chair

AKABOT: 3D PRINTING FILAMENT EXTRUDER

By

Emily Albi, Kevin Kozel, Daniel Ventoza and Rachel Wilmoth

THESIS

Submitted in Partial Fulfillment of the Requirements for the
Bachelor of Science Degree in
Mechanical Engineering in the School of Engineering
Santa Clara University, 2014

Santa Clara, California

Abstract

3D printing could usher in a new age of localized manufacturing in places like Uganda, where three of our senior design team members spent the summer of 2013. Motivated by a concept for our senior design project, one of our team members interned with Village Energy, a small electronics business in Kampala, Uganda, as it piloted the use of a 3D printer to manufacture enclosures for its solar lights. The need for our project arose when we realized that although the 3D printer proved a viable method of manufacturing enclosures, Village Energy could not afford to continue 3D printing with filament imported from abroad.

The goal of our project is to provide companies like Village Energy with a solution to the problem of importing expensive filament. We aim to take plastic water bottles (in abundance in Kampala but generally burned as trash) melt and extrude them as filament for a 3D printer.

We present our filament maker, named the AkaBot. In this paper, we will discuss the AkaBot subsystems, design process, testing process, and results. This project has successfully built a machine that can melt and extrude plastic water bottle shreds, but the filament made from our machine still requires improved mechanical properties.

We will also discuss related issues such as business plan, economics, social impact, environmental impact, ethics, health and safety, and sustainability.

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Chapter 1: Introduction

1.1 Project Motivation

In September 2011, United Nations Secretary-General Ban Ki-Moon shared his vision for making sustainable energy for all a reality by 2030 [1]. Access to clean, sustainable energy enables the poorest of the poor to work their way out of poverty by improving their health and well-being, as well as increasing the number of productive hours in their day [2]. Currently, 92% of Ugandans lack access to grid electricity, and many turn instead to kerosene lamps [3]. A growing body of research has examined the effects of using kerosene as a fuel for lighting. The widely-referenced 2010 Lighting Africa report, *Off-grid lighting for the Base of the Pyramid*, finds that there are significant advantages to replacing kerosene lights with sources of clean energy [4]. Kerosene emits approximately two and a half kilograms of carbon dioxide per liter burned, which, given the scale of kerosene usage, means there is a compelling environmental argument for its replacement. Chronic illness due to indoor air pollution, as well as the risk of burns from overturned kerosene lamps, constitute a health and safety motivation for replacing kerosene. Proper lighting also gives people more productive hours in a day, which has economic advantages. Finally, kerosene must be purchased on a regular basis, with its price projected to increase by 4% annually [5]. A picture of a standard kerosene lamp is shown below in Figure 1.

Figure 1: Kerosene light: expensive, polluting, dangerous [6].

The distributed clean energy movement afoot in Africa proposes to spread the use of solar lanterns and solar home systems in order to combat the lack of a formal energy infrastructure. A small electronics company in Kampala, Village Energy, is among the few social enterprises built in Uganda with the aim of developing solar lights for even their most remote fellow Ugandans. Although Village Energy's solar lanterns function well, initially they were not selling well on the crowded Ugandan solar market. Inexpensive but poorly designed products from abroad have flooded the African solar market, leaving consumers wary of cheap knockoff products. Village Energy found that Ugandans wanted plastic-enclosed solar lights, which they associated with quality products. Shown below in Figure 2 is a sampling of some high-quality solar lights for sale in Uganda.

Figure 2: Solar lights available in Uganda [7].

As part of Village Energy's social mission, all manufacturing needed to be kept local. In order to manufacture plastic enclosures using minimal infrastructure, Village Energy experimented with 3D printing. Our senior design team worked alongside Village Energy to develop the prototype solar lantern enclosure made with a 3D printer. Shown below is the original Village Energy enclosure, made of sheet metal, and the 3D printed enclosures made of plastic.

Figure 3: On left, Village Energy sheet metal solar lantern enclosure. On the right is solar lantern enclosure improved aesthetics from 3D printing.

However, Village Energy could not afford to continue to buy filament from abroad to use as input plastic material for the 3D printers. Purchasing filament from abroad was expensive, and the unreliable Ugandan postal system would both add significant shipping costs and slow down production. Based on our observations from our summer in Uganda and with Village Energy, we thought the best way to help Village Energy bring clean, sustainable energy to Uganda was to help their manufacturing process. Village Energy could sell more solar lights if they had a process to recycle abundant waste plastic water bottles (normally burned as trash in Kampala) into plastic filament for use in their 3D printer. We named our project the “AkaBot”, to abbreviate “akaveera”, which means “plastic” in the native language of central Uganda. The AkaBot intakes shredded bits of plastic water bottles, melts and mixes them, then extrudes the plastic as filament for a 3D printer.

1.2 Literature Review

1.2.1 Plastic Processing

Basic production methods that are used to form plastic parts are blow molding, coating, calendaring, injection molding and extrusion. However, over 66% of plastic is processed through injection molding and extrusion. Injection molding consists of heating and homogenizing plastic, which is then injected into a cold mold, where it takes the shape of the mold cavity. In old methods, the plastic was homogenized and a cylinder and then injected using a ram. In current methods, a screw is used to heat, homogenize, and inject the plastic. An advantage of the screw method is that it continues to add material, which compensates for material shrinkage. Further advancements in injection molding are co-injection, gas-assisted, water-assisted, injection-compression, rubber injection, and structural foam injection molding [8].

Extrusion, the most common method, is a continuous process in which plastic pellets are fluidized and homogenized by a screw inside a barrel, and the melted plastic is pushed under constant pressure through a shaping die. The product, or extrudate, forms to the shape of the die. Furthermore, extrudate swell is an expansion process that occurs when the plastic exits the nozzle. Extrudate swell is caused by the change of velocity distribution, inertia effect, and viscoelastic behavior of the plastic melt. The extrusion process forms long shapes of consistent profile shapes. These products can also be cut into many small shapes that are cut from the long extruded filament [9].

In an ordinary extruder there are seven elements: the feed hopper, the barrel, the screw, the motor and gear reduction, the screen pack and breaker plate, the die, and instrumentation elements for monitoring variables such as pressure, temperature, and screw revolutions. Characterization of single-screw extruders is often done by the length-to-diameter ratio of the screw, the number of stages, the compression ratio, and the meter ratio. Extrusion has the highest output rate of any plastics process [10].

The last method to be covered is blow molding. This process consists of melting plastic pellets, forming a tube, and introducing air or other gas to expand the tube until it takes shape of the hollow mold around it. The tube is usually made through extrusion or injection molding. The combination of injection molding and blow molding, injection blow molding, is common because it allows for mass production, does not require postfinishing, has better tolerances and wall thickness, and can be made unsymmetrical. There is typically a reheating stage in between the injection molding and blow molding. Wall thickness distribution is a big concern for blow molding because it influences the integrity, performance, and material cost of the final part. Bottles represent roughly 80% of the blow molding market [11].

1.2.2 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) is a testing technique often used in plastic analysis; the machine heats a small sample (10-15mg) past the melting point, and then cools it again to room temperature. The heating rate and cooling rate are adjustable. The heat flow in and out of the sample versus the temperature are recorded and graphed.

Using DSC results, the glass transition temperature, melting temperature, and percent crystallinity can be calculated. The glass transition temperature is where the plastic changes from elastic to brittle. The melting temperature is the point when the plastic fully melts [12]. PET is a semi-crystalline thermoplastic polymer, which means that it has crystalline and amorphous regions; an illustration of a semi-crystalline polymer is shown below in Figure 4. A representation of the amount of crystalline to amorphous regions is the percent crystallinity.

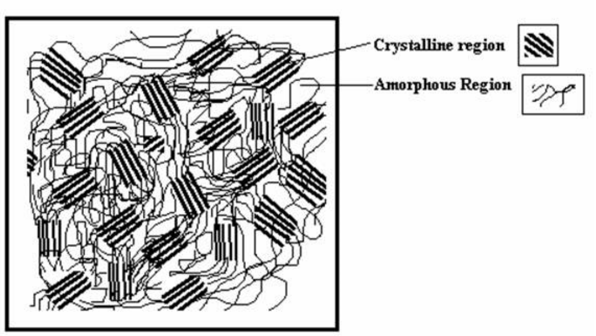


Figure 4: Crystalline vs. amorphous regions of a semi-crystalline polymer [13].

On a DSC graph, there are a few characteristics, which are shown below in Figure 5.

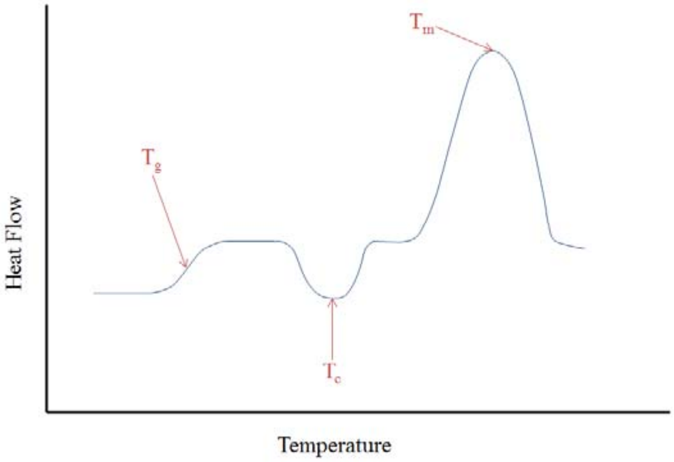


Figure 5: A general DSC graph showing the glass transition temperature (T_g), cold crystallization temperature (T_c), and melting temperature (T_m).

The glass transition temperature (T_g) is shown by an increase in heat flow as the polymer's specific heat increases. Since it occurs over a range, the glass transition temperature is calculated as the middle of the range. The cold crystallization temperature (T_c) is the lowest point on the crystallization dip; the dip in graph represents an exothermic process as the polymer gives off heat while the crystalline structures align. The melting temperature, (T_m) is the highest point on the melting peak, which is an endothermic process as the polymer absorbs heat to melt.

The areas under the two peaks represent a change in enthalpy, and are integrated to find the cold crystallization area (ΔH_c) and heat of melting area (ΔH_m). Every polymer has a reference melting enthalpy (ΔH_m°) which is the melting heat if it were 100% crystalline; this value for PET is 140.1 J/g [14].

1.3 Project Objectives

The goal of this project is to design and build an extrusion machine that makes 3D printing filament from water bottles. The application is for any business using 3D printing in a developing country with the intent to make the 3D printing sustainable and economical. The deliverable is a frugal and rugged machine that intakes polyethylene terephthalate (PET) plastic water bottle shreds, melts and mixes them, and then extrudes them as homogeneous filament. Although PET plastic is difficult to recycle, it was chosen for our project because it is the most commonly availabe waste plastic in Uganda. Our design requirements and customer needs are discussed in more detail in the Systems-Level Chapter.

Chapter 2: System-Level

2.1 System Level Requirements

We worked closely with our customer in Uganda to establish system requirements for our machine. Since the water bottles in Uganda are made of PET, or polyethylene terephthalate, we chose it as our input material.

Using PET sets us apart from other non-industrial extruders. Other extruders use plastics with much lower melting temperatures like ABS and PLA. A summary of the eight system requirements can be found in Table 1.

- We wanted to extrude filament with a diameter of 3.00 mm; one of two standard sizes.
- Our goal was to produce a 1 kg spool of filament in a 10 hour work day, which resulted in a production rate of 12inch/min.

- In order to ensure compatibility with the 3D Stuffmaker Mega Prusa printer, our extruded filament needed to exhibit similar mechanical properties as existing filament.
- Additionally, we wanted to extrude filament that was both homogenous and uniform with a tolerance of 0.1 mm.
- Finally, our customer wanted to keep the price of our machine under $300.

Table 1: System requirements for the AkaBot

Baseline	Requirement
Input Material	Polyethylene Terephthalate (PET)
Filament Size	3.00 mm
Production Rate	12 inch/min
Compatibility	3D Stuffmaker Mega Prusa
Filament Mechanical Properties	Strain at fracture ~.4%
Filament Quality	Homogenous and uniform
Filament Tolerance	+/- 0.1 mm
Cost	$300

2.2 Customer Needs

Along with the baseline requirements of the AkaBot, additional parameters must be met in order to fully satisfy the needs of the customer. The AkaBot is intended for Village Energy to use for their manufacturing of solar light enclosures. By working in Uganda alongside Village Energy technicians, shown below in Figure 6, our team had a good sense of what is necessary for this product to be a successful addition to Village Energy's business. In order to ensure we knew what specifically would make a successful product, the head technician of Village Energy, Paola DeCecco, was interviewed to get some specific customer requirements.

Figure 6: Village Energy staff, with Paola DeCecco three from the left.

The questions and answers from the interview with Paola DeCecco are summarized below in Table 2.

Table 2: Summary of the feedback received from Paola DeCecco

Question	Answer
What color filament is a priority?	Green and White
Are there any size limitations for the machine?	No
Would you prefer to have a part that may not be optimal that can be bought or made in Uganda, or one that works better but must be imported?	All parts should be sourced cheaply from : Aliexpress.com for detail and ALIBABA.COM for bulk in order to be able to deliver to Uganda
Can it be designed to run off of AC power supply from an outlet? What voltage?	240V AC is preferred but a converter can be used
Any specifications that you can think of from the electrical standpoint that you see as being important before we get started designing them?	Built in protections for power surges and spikes would be an added bonus

Poala requested that the filament be either green or white. Additionally, all parts should be sourced cheaply from Aliexpress.com and Alibaba.com to allow Village Energy to ship replacement parts directly to Uganda in the future. The AkaBot should also run off of 240 V AC power with built in protections for power surges and spikes in order to guard against the sporadic and unreliable power in Uganda.

2.3 Benchmarking Results

Comment [ema1]: kevin

With the increasing popularity of 3D printing, hobbyists and recreational users continue to change the rapidly growing technology. Due to the expensive nature of the hobby, many people have developed new and innovative ways to make the process cheaper. The “ink cartridges” for 3D printers come in the form of 1 kg spools of plastic filament. A single spool can cost as much as $50. Hobbyists have created machines that melt ABS and PLA pellets that they can then extrude as filament at much lower prices. Product specifications of three filament extruders: Lyman Extrusion v2, STRUdittle, and ExtrusionBot, can be found in Appendix A. These three machines are similar to the AkaBot in appearance and function, but the key difference is that our machine is meant to extrude PET rather than ABS or PLA. Furthermore, our machine uses shredded plastic bottles rather than virgin pellets.

There are numerous characteristics of these three machines that can be used for comparison. However, we focused on the production rate, filament tolerance, overall size, machine orientation, and nozzle sizes. The fastest production rate is achieved by the ExtrusionBot at 36 in/min, but we set our goal at 12 in/min to accommodate a 1 kg spool made in a standard 10 hour work day. The STRUdittle has the best filament tolerance at +/- 0.025mm with automatic spooling and +/-0.05mm without automatic spooling. Because automatic spooling was outside the scope of our project, we aim to achieve a tolerance of +/-0.1mm. The overall size and machine orientation were not extremely important to us, as long as it could fit in a work area and successfully extrude. Finally, all of the machines had the capability of swapping out nozzles in order to extrude both 1.75mm and 3mm filament. We focused on producing a high quality 3mm filament before making interchangeable nozzles.

2.4 Functional Analysis

Comment [D2]: Differentiate between overview and functional analysis
Subsystem order is incorrect

Comment [ema3]: daniel

The AkaBot consists of six main subsystems:

1. Electronics
2. Power Transfer
3. Auger and Motor
4. Chamber and Hopper
5. Heating Element
6. Nozzle

Figure 7 illustrates a physical configuration sketch with the various components of the subsystem labeled.

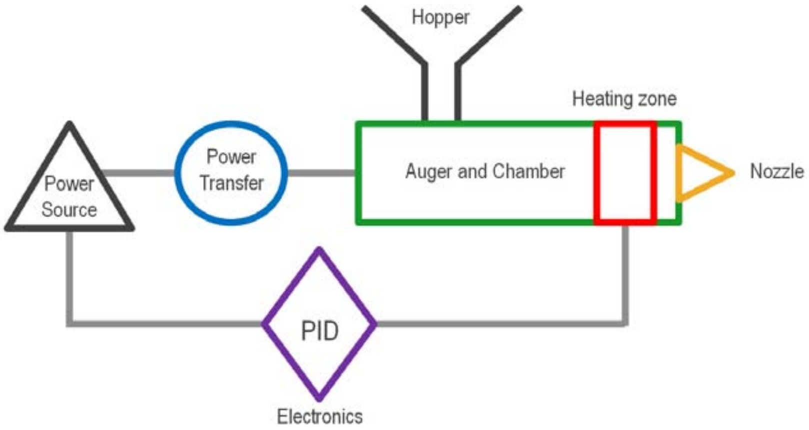


Figure 7: Schematic of AkaBot machine with major subsystems.

The AkaBot is plugged into a standard 120 V AC outlet which will power all the electronics including the 12 V DC motor. A simple converter can help the AkaBot run on Uganda's power grid. A chain drive provides the necessary power transfer between the motor and the auger. The auger, which is enclosed by the chamber, provides the required mixing and pumping power for the plastic shreds as fed into the chamber through a hopper. The heating zone provides the necessary energy in order to melt the plastic shreds as they move along the length of the chamber. The filament nozzle aids in the cooling process as the filament is extruded. A 3D rendering of the AkaBot is shown in Figure 8.

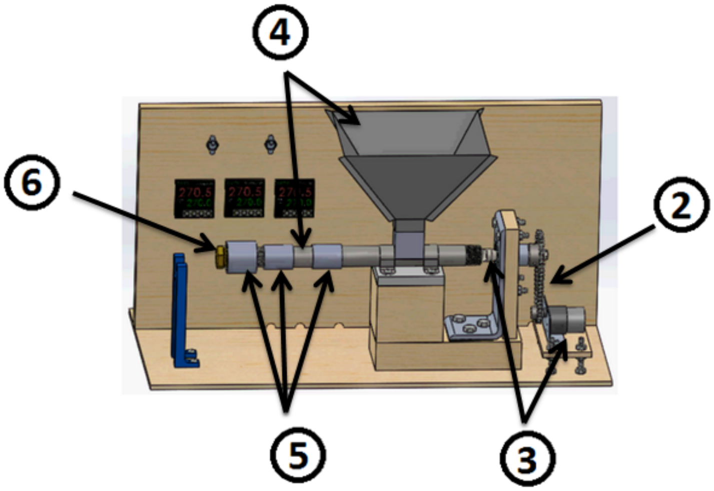


Figure 8: 3D rendering of AkaBot machine. (Not pictured: electronics)

A summary of the function, inputs and outputs for the six main subsystems can be found in Table 3. The numbers in Figure 8 above refer to their order in Table 3 below.

Table 3: Summary of subsystems and their functionality

	Component	Function	Input	Output
1	Electronics	Controls the temperature of the heating zone and speed of the motor	120v AC	12v DC circuit 120v AC circuit
2	Power Transfer	Connects the motor to the auger	6 RPM	2.4 RPM
3	Motor and Auger	Provides the required mixing and pumping power for the plastic shreds	12v DC	12 inch/min
4	Chamber and Hopper	Hopper feeds plastic into the chamber; Chamber encloses the auger and contains the melting process	Plastic	Plastic
5	Heating Zone	Provides the necessary energy to melt the plastic shreds	550 W	Melted plastic
6	Filament Nozzle	Extrudes filament at a desired diameter	Melted plastic shreds	3.00 mm plastic filament

2.5 Key System Level Issues

Comment [ema4]: daniel

There were tradeoff choices that were made in each subsystem. All detailed analyses of the tradeoffs can be found in their respective subsystem chapter.

In designing the electronics, we chose between using an Arduino to control the heaters and individual pre-set PID controllers. The Arduino is less expensive, but requires much more coding to adjust the temperatures, which reduces the usability of the product. At this stage, our design is a prototype that is intended to be used for testing and design iterations, which involves constant adjustment of the heater temperatures. For this reason, we chose to use the individual PID controllers in order to have the most flexibility while testing.

The power delivery mechanism to the auger is another major tradeoff analysis our team had to do. Essentially, the comparison was between a gear train, a sprocket and chain, and a v-belt. Although all three systems could deliver power from the motor to the auger, the sprocket and chain prevailed in our comparison because the parts are available in Uganda, there are lower stress concentrations on the teeth and higher speed accuracy, the installation is easier, and it is not affected by high temperatures and grease.

The geometry of the auger was also a key system level issue, as it dictates the size of the chamber and the power necessary to extrude the plastic. An in-depth tradeoff analysis was done involving multiple auger geometries for comparison. The pumping power for different combinations of auger and motor was calculated by setting different motors to the rotational speed necessary to extrude at 12 inch/min, and using the geometric measurements of different augers. The most important dimensions of the auger were the outside diameter, which determines the size of the chamber, and the helix angle, which has the most effect on the pumping power. After selecting augers which all worked with one size of pipe, the auger with the smallest helix angle was determined to be the best for its higher pumping power.

The chamber material choice involves tradeoffs in cost, durability, and heat transfer. Because the chamber must reach the high temperatures necessary to melt PET, but also maintain a heating profile, it was necessary to balance the material choice with its cost and availability in Uganda. Threaded stainless steel pipe was used for the chamber for its ease in connecting to the nozzle, and its low conductivity to allow a wider temperature distribution and reduce heat transfer to the sprocket, chain, and motor.

The two types of heaters pursued were band heaters and coils. Since a controllable heat distribution along the length of the chamber and flexibility in changing the temperature of the heaters was desired, heating bands were used.

The main tradeoff decision for the nozzle design was the material choice. A key purpose of the nozzle is to start the cooling process of the plastic, and a high cooling rate was wanted. For this reason, a material with a higher thermal conductivity than the chamber material, which was stainless steel, was desired. By having a more conductive nozzle, more heat from the plastic is lost to the environment, thus increasing the cooling rate of the plastic. Instead of using stainless steel, which has a very low conductivity, brass was used, since it has a significantly higher conductivity.

2.6 Team and Project Management

2.6.1 Project Challenges and Constraints

There were two major system-level challenges to overcome for designing our 3D printer filament extruder, and they were material and sourcing challenges. The material challenge that we faced was related to the problem that Polyethylene Terephthalate (PET) is a not often used for 3D printing, so creating a working filament out of this material was difficult. Although many 3D printers have adjustable settings, none are designed specifically to print PET filament. Our project mission was to use water bottle shreds, but since water bottle plastic has already been manufactured, the quality has been slightly compromised. To counteract this, virgin PET pellets were also tested with the intention of eventually mixing with the in order to improve the overall quality of the filament.

The second major system-level challenge was the customer requirement that all parts be sourced inexpensively from the (few) websites that deliver to Uganda, like Alibaba.com and Aliexpress.com. For the purpose of our project, it is absolutely necessary that the parts are replaceable and the AkaBot is maintainable in Uganda. However, practically speaking, the sparse information and extremely slow delivery on Aliexpress.com prevented it from being an option for the fast-paced and time-constrained development of the AkaBot. We addressed this issue by continuing forward with the design of our system using parts easily available to us in California. We knew that before the product was usable in Uganda, the parts would have to be sourced from other places, like Aliexpress.com. The constraint on our project was that we did not have the time to go through design iterations with Aliexpress.com parts, but we consider the AkaBot prototype a working model, from which the final parts can more easily be selected and found on Aliexpress.com.

2.6.2 Budget

Comment [dfv5]: Update

Comment [ema6]: daniel

We have sought a total of $37,501 and have received $8,261. The majority of our funding came from the Center of Science and Technology and Society (CSTS). We did not receive the requested $20,000 to travel to Uganda. The School of Engineering committed $1,311 to cover the costs of building materials of our machine. The undergraduate travel awards committed $2,000 for travel to Uganda. Together, the American Society of Mechanical Engineering (ASME) and the Santa Clara Entrepreneurs Organization (SCEO) committed an additional $750.00. A summary of the expenses is shown below in Table 4.

Table 4: Sources of funding for the AkaBot

INCOME			
Category	**Source**	**Sought**	**Committed**
Grant	CSTS	$24,940.00	$4,200.00
	School of Engineering	$1,311.00	$1,311.00
	ASME SCVS	$500.00	$500.00
	UG Travel Awards - SCU	$10,500.00	$2,000.00
Competition	SCEO	$250.00	$250.00
TOTAL		**$37,501.00**	$8,261.00

2.6.3 Timeline

Comment [dfv7]: REWRITE

The timeline is broken up into three distinct sections:

- Fall Quarter – Funding
- Winter Quarter – Design
- Spring Quarter – Testing

The Gantt chart can be found in Appendix B.

We overcame several setbacks during the testing and design phase. There were unforeseen issues that delayed the projects which included:

- Delivery times
- Auger re-design
- Electronic re-design
- Control over cooling process
- Limited Ugandan water bottle supply

2.6.4 Design Process

Comment [ema8]: kevin

There are several hobbyist-level 3D printer filament makers that have been made in the past few years. However, they all use ABS plastic pellets for the feedstock material, while the AkaBot uses PET plastic. Because of this, some of our design process was based on the existing filament makers' results and design processes, but many parts had to be re-designed to fit our needs, since the melting temperature of PET is much higher than ABS. We deviated from the processes recorded by the hobbyists by making our own theoretical calculations, which informed our purchasing decisions.

Another key aspect of our design process was testing. We went through several design iterations of machine parts, motor speed, and temperature settings. We also used a Differential Scanning Calorimetry (DSC) machine to analyze the plastic properties of the plastic during our first design phase and after each subsequent iteration to understand the changes in the plastic properties.

2.6.5 Risks and Mitigations

Comment [ema9]: rachel

The basis of our project is that we wanted to recycle water bottles to make 3D printing filament. Although this was our goal, it was also a risk. When plastic is manufactured, it changes the plastic properties and can make it difficult to get usable plastic properties even after melting again and extruding. For this reason, we might not get usable filament with just water bottle plastic. We have known from the start that it may be necessary to mix the water bottle shreds with virgin PET. Although this detracts from the completely sustainable model of using only water bottles, importing some pellets to mix is still easier and less expensive for Village Energy than importing the spools of filament. Another avenue to explore is adding plasticizers to the water bottle plastic, which may also result in a better filament, which is left as an option for future teams.

2.6.6 Team Management

Our team management style was highly collaborative, based on our extensive experience working together over the past three years of undergraduate Mechanical Engineering. In general, we discussed as a group what needed to get done, with tasks assigned to team members based on their skill and level of interest. We took ownership of different tasks at the early stages of design, and continued to work with those tasks in all aspects of the project.

The collaborative style hinges on communicating early and often about intersecting subsystems, as well as project deadlines and due dates. We communicated through regular team meetings and weekly team work sessions. Team writing and presentation projects were clearly divided up, and team members were aware of what was expected each time. Work was always divided up in such a way that each team member knew who has been assigned each section, in order to create accountability amongst the team.

Our most effective form of communication has been a large calendar we made as a team and hung on the wall in the lab where we work on our design project. On the calendar we put every relevant due date we could think of, overlaid with personal unavailability and class times. Given the busy nature of each of our schedules as we finish our college careers and look for jobs, the personal unavailability helps us know when a team member should work on a project early, as well as why he or she may not be reachable. The class schedule was helpful for planning team meetings, so we did not repeat the same scheduling constraints every time an irregular meeting needed to be scheduled. One glance at this calendar tells a team member what is coming up, as well as who can work on it and when.

Chapter 3: Electronics

Comment [EA10]: kevin update

The electronics were designed to give us the most flexibility and control over the final filament properties. Since this machine will be implemented in Uganda, a 240 V plug would be ideal. However, for all our design and testing we only had access to 120 volt outlets. Therefore, a

240 V to 120 V adapter will need to be connected so we can plug our machine into the wall. Within our system, a 12 V 5 A power supply is used to separate the circuit into AC and DC parts. The DC circuit is shown below in Figure 9.

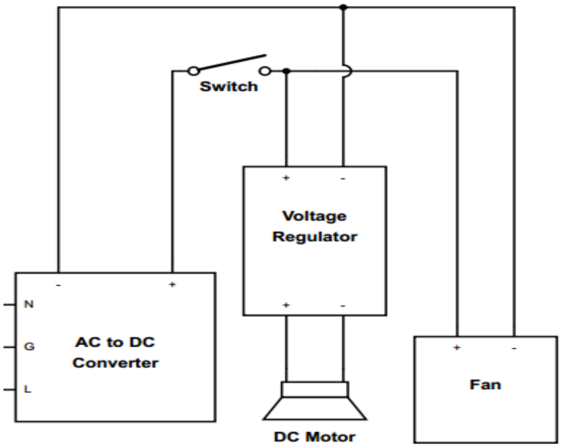


Figure 9: DC Circuit.

The power supply is necessary to step down from 120 V AC to 12 V DC. The 12 V DC output from the power supply powers the voltage regulator, 12 V motor, 12 V to 5 V adapter, and 5 V fan. A second design iteration was exchanging the 5 V fan for a 12 V fan, which eliminated the need for the adapter. The fan is used to cool the filament as it exits the nozzle, and runs at a constant speed. The motor speed, however, can be adjusted using the voltage regulator. The voltage regulator can output anywhere from 0-12 volts and controls the motor speed proportionally.

The AC circuit, shown in Figure 10, is spliced from the wires before they reach the power supply. It powers three separate heaters and temperature controllers. Each one requires a heater, PID controller, solid state relay, and thermocouple. PID stands for proportional, integral, derivative: three separate control parameters. The PID controller displays two values: the point value and set value. The point value is the actual temperature being read by the thermocouple, and the set value is the desired temperature input by the user. The PID controller regulates the temperature of the heater based on the input from the thermocouple. Using its PID control algorithm, the heater is either turned on or off using the solid state relay. The PID controller can be manually tuned to adjust the PID gains, but its automatic tuning provides greater accuracy.

The controller was set for the temperature to be slightly higher than the melting point of PET plastic to compensate for the heat loss through the pipe and to the environment.

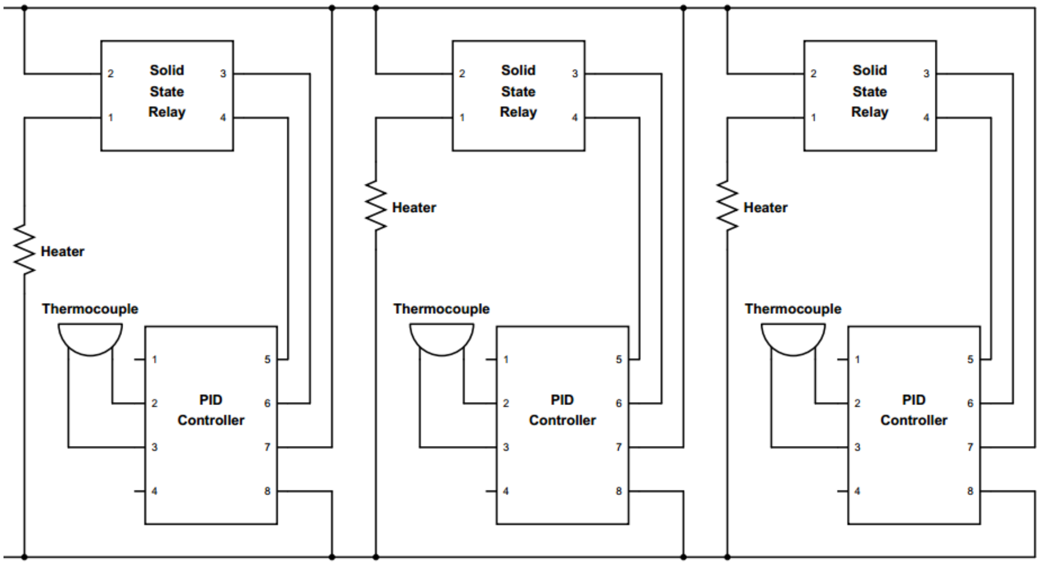


Figure 10: AC Circuit.

In the testing phase, there are two electronic parameters that can be adjusted: temperatures of the three heaters and motor speed. The motor speed can be adjusted by raising or lowering the value on the voltage regulator, which sends more or less voltage to the DC motor. However, the motor speed should remain high enough to obtain our desired output of 12 in/min. The heat received by the plastic can be changed by either adjusting the heater temperatures or the heater placement. Once the heater placement is determined, the individual heater temperatures can be changed to give us the desired heating profile. The speed that the plastic moves through the chamber and the amount of heat it receives from each of the heating bands is crucial to the final filament properties. This is why the circuit was designed such that these two variables can be adjusted during testing.

Chapter 4: Power Transfer

Comment [EA11]: Daniel update

The connection between the motor and the auger provides power transfer between two parallel shafts. The following three methods were compared for the best compatibility in the extrusion process and in Uganda.

- Gear train
- Belt drive (v-belt)
- Chain drive

The table below shows six parameters that were compared for the three different methods of power transfer. They are listed in order of importance.

Table 5: Comparison between gears, v-belts and chain drives

	Gears	**V-Belt**	**Chain**
Parts cost	High	Low	Moderate
Reliability life of parts	Longest	Medium	Long
Misalignment tolerance	Slight	Considerable	Moderate
Max recommended speed (m/s)	50	30	15
Speed ratio accuracy	High	Moderate	High
Drive mechanism	Positive	Friction	Positive

The first three parameters: parts cost, reliability life of parts, and misalignment tolerance, were specifically chosen to accommodate for a frugal and rugged design in Uganda. The last three parameters: maximum recommended speed, speed ratio accuracy and drive mechanism, were specifically compared when designing the extrusion process.

The chain drive was chosen for the following reasons:

- Balance between parts cost and reliability life of parts
- Moderate misalignment tolerance allows for easier installation
- Positive drive mechanism does not experience creep or slippage

The biggest challenge in using a chain drive was ensuring that there was proper tension in the chain. As a result, a simple method was devised that used a combination of nuts and bolts to manually adjust the height of the motor mount. The figure below illustrates the frugality of the motor mount.

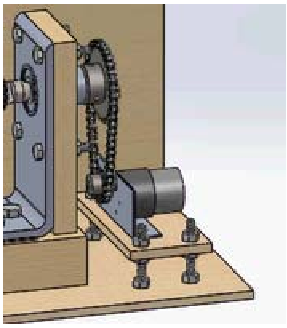


Figure 11: Chain drive design.

A chain drive also was compatible with the extrusion process since it has a resistance to higher temperatures as well as oils and greases.

Chapter 5: Auger and Motor

5.1 Auger

The auger, which acts as a screw pump, fits inside the chamber. The function of the auger is to move the plastic bits inserted through the hopper along the length of the chamber. As the plastic progresses horizontally down the chamber, the heating element melts it, and the auger therefore also functions to mix the plastic during melting. The auger plays a large role in ensuring homogeneity of the filament, which is one of our system requirements.

Shown below in Figure 12 is a diagram of a typical auger, with the channel depth, helix angle, and flighted length labeled.

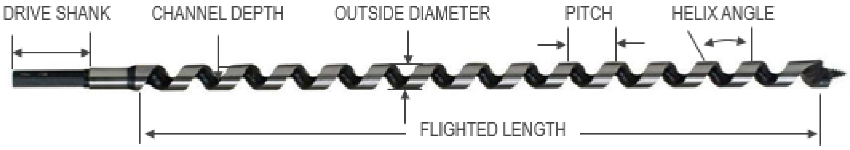


Figure 12: Diagram of an auger with geometric properties.

Equation 1 below gives the relationship between significant auger geometric properties.

$$Q = \alpha N - \frac{\beta}{\mu}\frac{\Delta P}{L} \tag{1}$$

The parameter Q is the volumetric flow rate, N is the screw speed, μ is the melt viscosity of the plastic undergoing extrusion, ΔP is the axial pressure rise, and L is the axial length of the screw pump, also known as the flighted length. The parameters α and β are comprised of geometric properties of the auger, namely, diameter, D, channel depth H, and helix angle, ϕ. The relationships for α and β are shown below as Equations 2 and 3, respectively.

$$\alpha = \frac{\pi^2}{2} D^2 H (sin\phi)(cos\phi) \tag{2}$$

$$\beta = \frac{\pi}{12} D H^3 (sin^2\phi) \tag{3}$$

A summary of the parameters above is given below in Table 6.

Table 6: Parameters used in the calculation of Equations 1, 2, and 3

Symbol	Parameter	Units
Q	Volumetric flow rate	m^3/s
N	Screw speed	rev/s
D	Chamber diameter	m
μ	Melt viscosity	P
H	Channel depth	m
ϕ	Helix angle of flight	rad
$\Delta P/L$	Axial pressure rise	Pa/m
L	Axial length of screw pump	m

These equations were used to calculate the pressure change necessary through the chamber. Because the screw speed is included in these equations, the capacity of the motor must also be accounted for.

Each parameter was considered in the design of the auger, but the two most important for its performance in the AkaBot were outside diameter and helix angle. The outside diameter determines the tolerance within the chamber. A close tolerance builds the pressure necessary for extrusion. The outside diameter of the auger was chosen to be ¾", which made it simple to find a corresponding chamber.

The helix angle is inversely related to the pressure an auger can build. Our first auger design used an auger with a 60^{o} helix angle, but due to lack of pressure build, we later chose an auger with a 30^{o} angle. We chose several commercially available augers, obtained geometric specifications from the manufacturer, and then compared the necessary axial pressure rise for each auger. In calculating the pressure capacity of an auger, it was necessary to assume a motor speed. Therefore, we calculated pressure rise for a variety of auger-motor pairs, then selected the most cost-effective pair from the resulting options. The table showing the choices is available in Appendix C.

5.2 Motor

The purpose of the motor is to provide the power and torque to drive the auger. It is an important part of the AkaBot because the torque must provide enough force to push the plastic through the length of the chamber, and the speed setting governs the extrusion speed of the filament through the die. The speed of the motor is regulated by a voltage divider, explained in further detail in the Electronics section.

Comment [EA12]: Maybe we can refer specifically to section # here

Since the motor and auger are connected, they are co-dependent and both contribute to the available speed and force to push the plastic through the chamber. Using Equation 1 as shown in the Auger section, the change in pressure was calculated from the geometric properties of the auger. The speed of rotation, N, which is related to motor speed, (RPM) is also needed for the calculation of the change in pressure for Equation 1. A test matrix was used to obtain the results of using different combinations of augers and motors. Using the change in pressure, the

Comment [EA13]: Same here as above

pumping power and torque needed for each auger-motor combination were calculated using Equations 4 and 5 below.

$$Pumping\ Power\ (PP) = \Delta PxQ \tag{4}$$

$$Torque\ (T) = \frac{PP \times 5252}{RPM} \tag{5}$$

This needed torque was compared with the available torque as given by the specifications for each motor, and combinations were selected that worked with our other system requirements. The test matrix showing the torque values is shown in Appendix C.

From these viable choices, the auger and motor combination was selected based on a few other factors. A brushless motor is much quieter than a brush motor, and since this extrusion machine is meant to be running during an ordinary workday, it is ideal to use a brushless motor in order to minimize the disturbance to a work environment. Additionally, one goal is to limit the voltage and power necessary to operate the AkaBot. This was taken into account when selecting the motor, with the hope of selecting the most energy-efficient motor. The final decision was made based on cost, with the goal of making the AkaBot as inexpensive as possible.

Chapter 6: Chamber and Hopper

6.1 Chamber

Comment [EA14]: Visually messy and could reorganize for brevity

The chamber provides the housing for the auger. The plastic shreds are fed into the chamber through the hopper as illustrated in Figure 13 below.

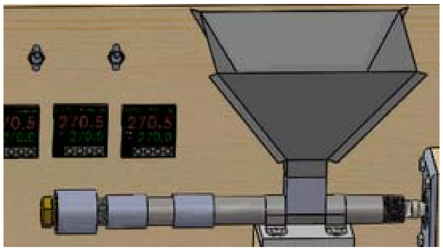


Figure 13: Hopper connection with chamber.

The melting and mixing of the plastic occurs within the chamber before filament is extruded through the nozzle. Since the chamber experiences high temperatures during the extrusion process, the following parameters were used in order to choose the material. Table 7 summarizes the five parameters used in determining the material of the chamber.

Table 7: Chamber Material Parameters

Temperature Range	Working temperature of the material
Tolerance	Clearance between auger and inner diameter of the chamber
Availability	"Off-the-shelf" product
Conductivity	Heat transfer that will occur across the material
Price	Cost of linear foot of material

Comment [dfv15]: Heat Transfer book

Four different types of pipe were compared using the chamber material parameters:

- Black Steel Pipe
- Aluminum
- Stainless Steel – Schedule 40
- Stainless Steel – Schedule 80

After comparing the four different options of pipe, it was determined that stainless steel, schedule 80 pipe best fit the chamber material parameters for the following reasons:

- The melting temperature of PET is 245^{o}C. Metals like black steel pipe experience embrittlement at these temperatures [15].
- Tolerance was quantified by comparing the clearance with industrial extrusion processes using Equation 6 [16]:

$$C_r = 0.001 \; x \; D_b \tag{6}$$

where C_r is the clearance and D_b is the diameter of the barrel or auger. Using Equation 6, the minimum required clearance is 6.6e-4" using an auger with a barrel diameter of 0.66". This precision was not reasonable given the customer requirements previously mentioned so as a result, the focus was to achieve the smallest possible

Comment [dfv16]: Reference to minimal machining clearance between the chamber and the auger. The inner diameter of the stainless steel, schedule 80 pipe is 0.742", 0.1" smaller than that of the stainless steel, schedule 40, aluminum and black steel pipe.

- Availability was essential when selecting the material of the chamber in order to meet the customer needs. It was important that any part bought was readily available so as to facilitate easy replace ability. All four pipe options can be found on McMaster.com.
- The conductivity of the pipe is essential in helping to control the heating zone. A lower thermal conductivity restricts the heat transfer throughout the rest of the chamber. Stainless steel has a thermal conductivity of 19.8 W/m·K. Aluminum can exhibit a thermal conductivity as high as 231 W/m·K.
- Although price was a parameter in determining the material of the chamber, it ended up having a minimal weight on the final decision. Stainless steel, schedule 80 pipe was the most expensive at $40.53 per foot with threaded ends, compared to aluminum schedule 40, which was $15.35 per foot with threaded ends.

Providing support for the chamber proved to be a challenge when designing for a frugal and rugged extrusion machine. In an effort to provide flexibility in replicating and replacing parts in the AkaBot, specialized and customized parts were avoided. Figure 14 illustrates a 3D rendering of the AkaBot.

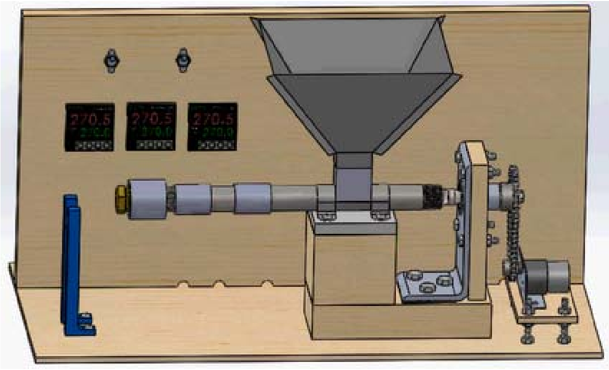


Figure 14: 3D rendering of the AkaBot.

The majority of the supports consist of wood, either 2'x4's or 4'x4's. Both are commonly manufactured sizes of lumber. Additionally, stainless steel pipe clamps were used to secure the pipe to the supports.

6.2 Hopper

The hopper feeds the plastic shreds to the auger and chamber for extrusion. It needs to feed the plastic into the chamber at a steady rate with no obstructions, have structural integrity, withstand temperatures of 80°C, and be easily removable. Taking these factors into consideration, we made the following decisions in building the hopper:

- Opening size
- Shape
- Material
- Connections

The opening size needed to be large enough to allow the shreds to feed in without jamming; however, a smaller chamber means more pipe length is available to be part of the heating zone. We designed the opening size to be 1.25 inches. Since the length of one full "scoop" of the auger, or the pitch, was about one inch, we made the opening slightly larger to allow some extra room for plastic shreds to enter the chamber. Additionally, an opening size of 1.5 inches on the chamber was the largest that could be machined with the available tools in the machine shop. Since one common goal throughout this project was to keep the design inexpensive and simple, we wanted to avoid buying any additional tools in order to keep the total cost down, and adhere to our mission of simplicity in machining.

Once the opening length was decided, the overall shape was designed to be a rectangular funnel that expands outward to about seven inches on each side with a height of about four inches. A 3D rendering of our design is shown below in Figure 15. A prototype was constructed from cardstock and a test run with the plastic shreds and auger was conducted to see if the angle was steep enough to maintain a constant flow of plastic. The test confirmed that the shape of the hopper worked successfully as a container to hold the plastic while feeding it into the chamber at a steady rate.

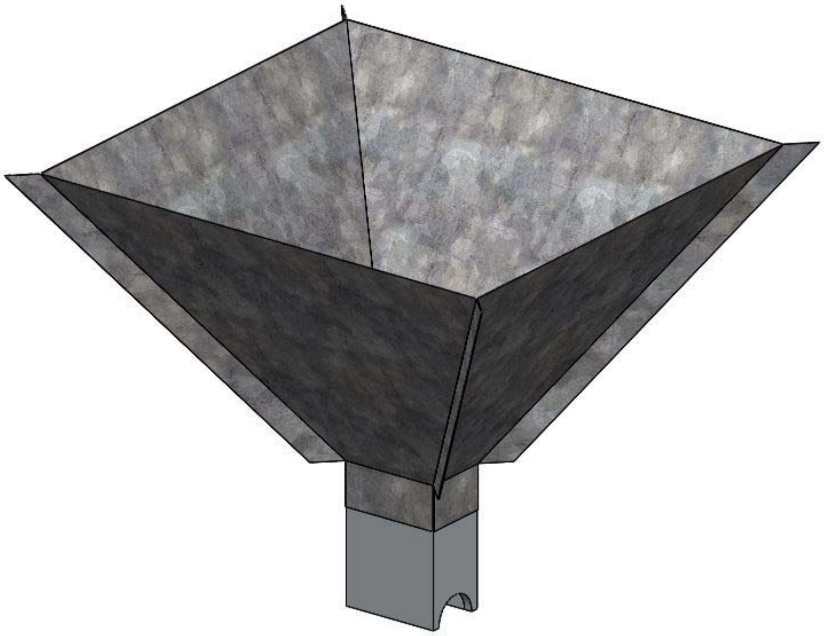


Figure 15: Hopper design.

In conjunction with making decisions about the opening size and shape of the hopper, different materials were explored. Initially, we wanted to 3D print the hopper, so it would be easily replaceable in Uganda, but since we knew from Finite Element Analysis that it could reach a temperature of 70°C, we didn’t want to risk using a material with a relatively low melting temperature. Therefore, we decided to make the hopper from metal. The funnel shape shown above in Figure 15 has many bends, and sheet metal was chosen since it is relatively easy to cut and bend. Galvanized sheet metal was used since it resists rusting, which is vital because the surface that the plastic is fed in through must be clean in order to not add any foreign materials to the PET plastic. We wanted the base of the hopper to be permanently fastened to the tubing which serves as a connection to the chamber, but removable from the chamber for cleaning purposes. In order to reduce the amount of heavy machining necessary, aluminum rectangular tubing was used; a piece was cut and the hopper was designed to fit snugly around the base.

Connecting the parts was the last machine design consideration to be made. Each side of the hopper was cut and bent as an individual piece of sheet metal. Each piece was then connected to other pieces of bent sheet metal as well as to the base. The hopper sides were designed to have flanges bent outwards at 45^{o} angles that connect to each other as shown in Figure 15. There were two types of connections that were considered: rivets and welding. Rivets would require drilling holes on each flange at precisely the same distances in order for the holes to line up. To reduce the amount of machining, welding instead was instead chosen, but since galvanized sheet metal cannot be welded, a welding substitute called JB Weld was used. JB Weld is an epoxy that sets within 24 hours and hardens with strength and stiffness properties similar to metal. Each flange was attached together with the JB Weld, and the base was connected to the funnel shape in the same way. The machined slot in the chamber and the outer dimensions of the base of the hopper were designed to have a small tolerance so that the base would fit tightly inside the opening of the chamber. This design made the hopper easily removable from the chamber, which allows both the hopper and chamber to be more easily cleaned.

Chapter 7: Heating Element

The heating element subsystem consists of the heaters that wrap around the chamber and provide heat to the inside in order to melt the plastic. Two types of heaters were initially considered: heating bands and heating coils. The aspects for each that were considered in the decision-making process are shown below in Table 8.

Table 8: The tradeoff analysis for the heating bands vs. heating coils

Item	Quality
Heating bands	• Adjustable individual heater temperatures • Concentrated heat • Lower power necessary
Heating coils	• Adjustable coil power • Distributed heat • Higher power necessary

We wanted to have the most flexibility with the temperature profile along the chamber, which favors the heating bands since we could place them along the chamber with different set temperatures, whereas the heating coil would take more surface area and be set with only one power setting. Lower power requirements are favorable since electricity is expensive in Uganda; this consideration also favored the heating bands. For these reasons, we decided to use heating bands as our heating element.

7.1 Theoretical Heat Transfer Calculations

Heating bands of a given diameter may still have different widths and total power output. Because of this, we needed to carry out some heat transfer calculations in order to know what to order. All variables, descriptions, values, and units used in the following equations are shown in Appendix D. A simplified model of the heating element is shown below in Figure 16.

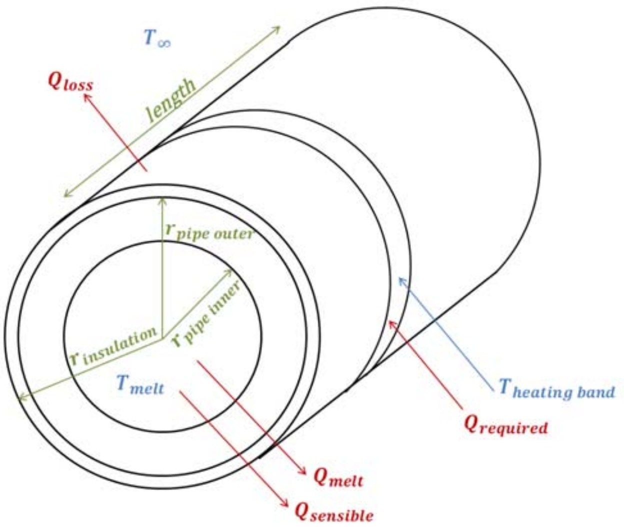


Figure 16: A simplified model of the chamber, heating element (a single heating band), and the interior plastic used for the heat transfer calculations.

Engineering theory was used to predict the necessary amount of heat and the required length of pipe for heating at a set extrusion speed of 12 in/minute. Using this extrusion speed and the cross sectional area of both the nozzle and the pipe, the speed inside the chamber was calculated using the following equation:

$$A_1V_1 = A_2V_2 \tag{7}$$

where A_1 and A_2 are the cross sectional areas [m^2] of the nozzle and pipe respectively. Similarly, V_1 and V_2 are the velocities [m/s] inside the nozzle and pipe respectively. Using the velocity inside the pipe and the cross sectional area of the pipe, the mass flow rate inside the pipe, $\dot{m}$, was calculated to be 5.1x10^{-5} kg/s using the following equation:

$$\dot{m} = \rho \cdot A_{pipe} \cdot V_{pipe} \tag{8}$$

where ρ is the density of PET. In order to find the total heat required to melt the plastic throughout the chamber, the following equation was used:

$$q_{total} = q_{sens} + q_{melt} + q_{loss} \tag{9}$$

where q_{sens}, q_{melt}, and q_{loss} each represent a different portion of the heating process and have units of Watts. The first one, q_{sens}, is given by the following equation, and represents the amount of heat needed to raise the temperature of the PET from room temperature (22°C) to melting temperature (260°C).

$$q_{sens} = \dot{m}c_p(T_m - T_i) \tag{10}$$

Room temperature is T_i, the melting temperature is T_m, and c_p is the specific heat of PET. The second heating part of Equation 9 is q_{melt}, and represents the amount of heat needed for phase transition of the PET from solid to liquid. This amount of heat is given by the following equation:

$$q_{melt} = L_m \cdot \dot{m} \tag{11}$$

where L_m is the latent heat of melting of PET. The third part of Equation 3 is q_{loss} and represents the heat loss to the environment. This heat loss was calculated by finding the overall heat transfer coefficient, UPL, using the following equation:

$$UPL = \left(\frac{1}{hA} + \frac{\ln(r_o/r_i)}{2\pi Lk}\right)^{-1} \tag{12}$$

where h is the heat transfer coefficient due to natural convection and is assumed to be 10 W/m^{2}K, A is the surface area of convection [m^2], r_o and r_i are the outer and inner radii [m] of the pipe respectively, L is the length of the pipe [m], and k is the thermal conductivity of the pipe which is stainless steel 304. Using the overall heat transfer coefficient, UPL, the heat loss to the environment, q_{loss} was calculated using the following equation:

$$q_{loss} = UPL(T_{band} - T_i) \tag{13}$$

where T_i is the initial temperature (22°C) and T_{band} is the temperature of the heating band and was set to 400°C. Once the overall heat needed was calculated using Equation 9, the length required for this heat transfer was back-calculated. This was accomplished by solving the following equation for the new length, L.

$$P = UPL\Delta T = \dot{m}\left(c_p \Delta T + L_m\right) \tag{14}$$

Using the approach described above, the required amount of heat was found to be 113 W, over a length of 3.2 inches. The MATLAB code and results of these calculations can be found in Appendix E. All equations and theory are from Bergman, T.L., Frank O. Incropera [17].

The following are the assumptions used in calculating the necessary heat and length to melt the plastic:

- Steady-state
- No insulation
- 2-dimensional heat transfer (no axial heat gradient along length of chamber)

Knowing that the results are purely theoretical, we ordered nine total heating bands:

- Three 100W, 1-inch width
- Three 150W, 1.5-inch width
- Four 250W, 2-inch width

By ordering extra heating bands of higher power capabilities than the theoretical calculations concluded we needed, we were prepared to substitute the lower power for higher power ones if experimental results showed we weren't providing enough heat to the plastic in order to fully melt it.

7.2 Three-Dimensional Heat Transfer Analysis using Finite Element Analysis

As stated above, one of the assumptions used in the theoretical heat transfer calculations was that the heat transfer was 2-dimensional. Realistically, it is in three dimensions, and in order to model the 3-dimensional heat transfer before fully designing the AkaBot, Finite Element Analysis (FEA) was used. FEA is a computer method of modeling thermal or mechanical properties of a design. We decided that we would start our modeling and testing with three heating bands; having three bands would allow us some flexibility in controlling the heating profile and distribution, but would also fit comfortably along the length of the chamber from the hopper to the nozzle while still allowing some space in between each heater. One heat transfer concern we had was that the heating bands would heat the pipe so much that the back end of the auger and chamber would become too hot for the sprocket and hopper connections. The sprocket connected to the chain and motor, which shouldn't exceed 80°C; the hopper connection is where the plastic shreds are fed in, and we didn't want to start the melting process until they actually reached the chamber. Because of this concern, we considered building the chamber with an insulation flange in between the hopper connection and heaters, as shown below in Figure 17 in exploded and assembled view.

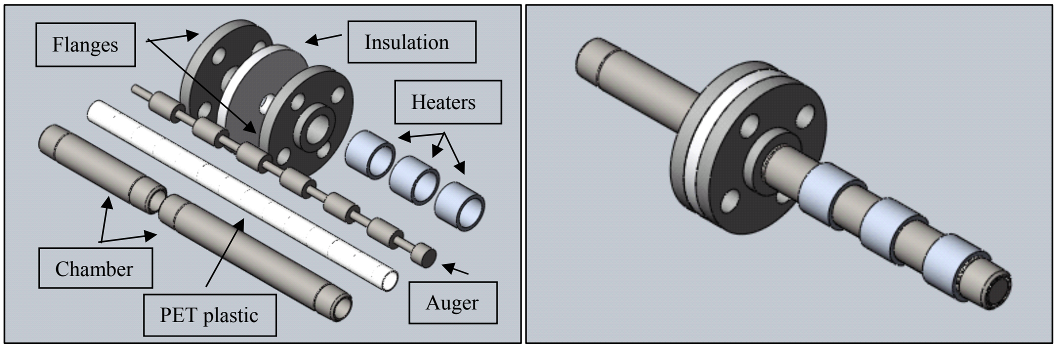


Figure 17: On the left, an exploded view of the flanged system. On the right, an assembled view of the same system. The heaters are the source of the heating power modeled in FEA simulations.

We compared this flanged system to a non-flanged system shown below in Figure 18 with exploded and assembled views.

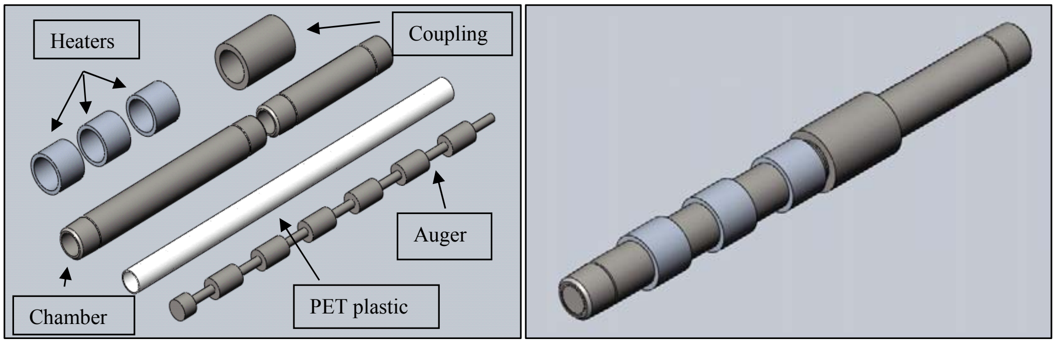


Figure 18: On the left, an exploded view of the non-flanged system. On the right, an assembled view of the same system. The heaters are the source of the heating power modeled in FEA simulations.

The materials used to model both the flanged and non-flanged AkaBot system were 304 stainless steel, 1060 aluminum alloy, PET plastic, and ceramic porcelain. Their significant properties for the thermal analysis are thermal conductivity, specific heat, and density. Each of these properties is shown in Appendix F for each type of material used in this test.

The chamber was made of stainless steel 304, and the auger, although actually stainless steel 307, was modeled as 304 because of the limits of SolidWorks FEA material choices. The plastic was PET, and the insulation was ceramic porcelain. The flanges were modeled as aluminum 1060, as were the heaters.

As can be seen in Figures 17 and 18, the system was simplified in order to conduct the FEA simulations and these simplifications are listed as:

- Auger treated as block-shaped
- Plastic modeled to fill the void left between the auger and the chamber
- All threading removed
- Nozzle removed

In all models, the ambient temperature was set to 20°C. Also in all models, the convective heat transfer coefficient was set to 10 W/mK, an average term for free convection in air. The heaters were set to different locations and power settings, with and without the insulation, and the temperature distribution along the chamber was graphed using FEA. The heater settings and temperature results for all the tests are compiled and shown in Appendix G. From these tests, it was concluded that axial insulation was not necessary, since the temperature decreased to at least 80°C by the time it would reach the hopper entrance with and without the insulation. Two test temperature distribution results are shown below in Figures 19 and 20 to illustrate this conclusion.

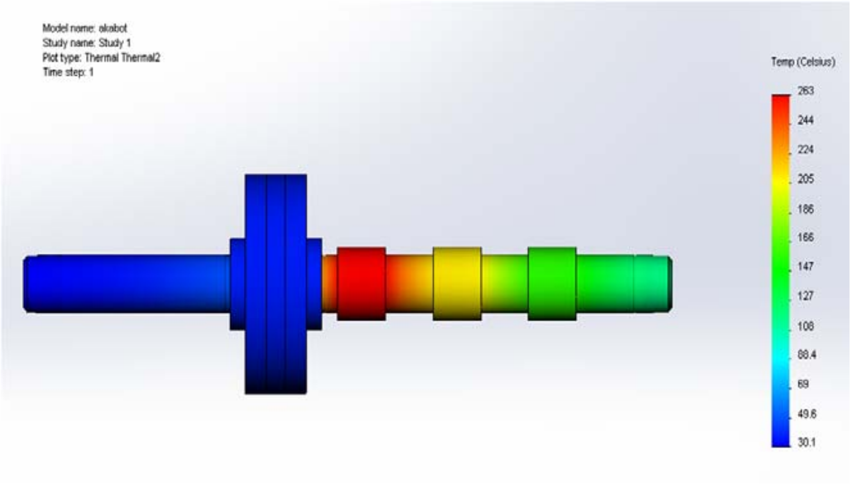


Figure 19: Thermal modeling results for Setup 6: flanged, insulated AkaBot with heaters at 1 inch, 50 W, at 3 inches, 20 W, and at 5 inches, 10 W.

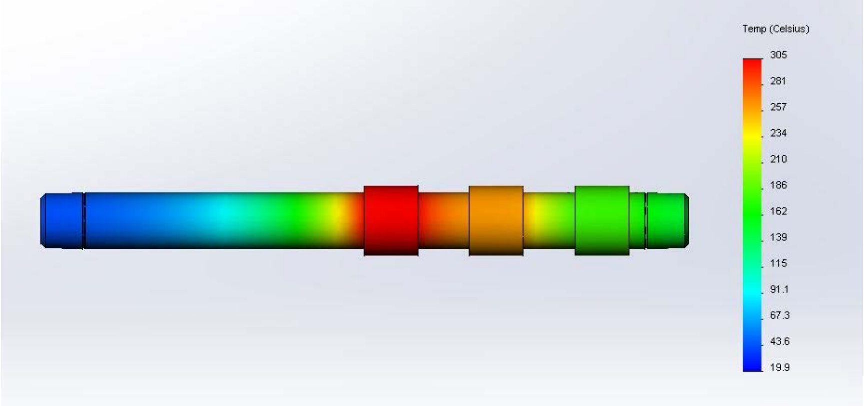


Figure 20: Thermal modeling results for Setup 12: un-flanged, uninsulated AkaBot with heaters at 1 inch, 50 W, at 3 inches, 20 W, and at 5 inches, 10 W.

Since the FEA simulations concluded that the temperature of the chamber at the hopper entrance would decrease to 80°C with or without axial insulation, it was decided to not use it. Adding the insulation would increase the cost of the product and require more precision when assembling the machine, so in line with our goal to keep the AkaBot frugal and rugged, we decided against the insulation.

Chapter 8: Nozzle

The function of the nozzle is to bring the plastic to size as it cools and exits the chamber. In designing the nozzle, three main parameters were important:

- Simplicity in machining
- Cooling rate
- Smooth plastic flow

A solid brass plug was chosen for its simplicity and conductivity. The exterior threads of the plug made it easy to attach to the threaded chamber using a coupling, eliminating the need for machining a connection. This also allowed it to be easily removable in order to clean the chamber. A 3D rendering of the brass plug is shown in Figure 21.

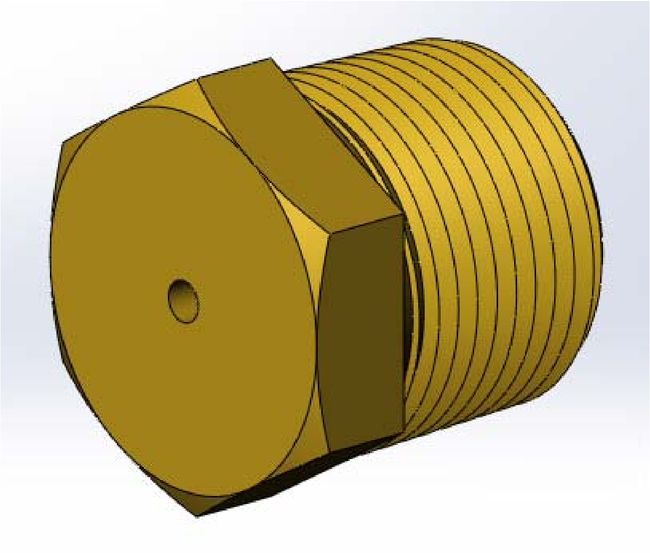


Figure 21: 3D rendering of the brass plug used as a nozzle.

The conductivity of brass was desirable to help the heat transfer out of the plastic, in order to cool it and begin to drop it below melting temperature. Brass was chosen because it is more conductive than stainless steel, but not as conductive as a material like copper. This allowed us room to adjust the material of the nozzle as more or less conductivity was required by the desired cooling rate.

Because the nozzle was purchased off the shelf as a solid brass plug, it needed to be machined to allow for plastic to flow through it and extrude as a continuous cylinder. The interior shape of the nozzle was designed for smooth plastic flow and desired final filament diameter. The options for inner profile of the nozzle were square, parabolic, and conical. A square profile would cause pockets to form in the corners and would induce turbulence, which would then cause inconsistencies in the filament due to disturbances in the flow. The parabolic shape is the next best option, but does not have a very consistent pressure profile since it is an exponential curve. The conical nozzle is the best option since it has a linear profile and will not cause any turbulence in the flow. The conical nozzle creates a steady velocity increase while eliminating fluid stall points, which ensures the optimal extrusion conditions. The exact angle of the conical entrance was dictated by the availability of machine tools, given the goal of roughly half an inch of depth. A one inch diameter, 90^{o} counterbore tool was used to create the conical entrance shape. A diagram of the brass plug nozzle's inner geometry is shown in Figure 22, and a 3D rendering of the inner geometry is shown in Figure 23.

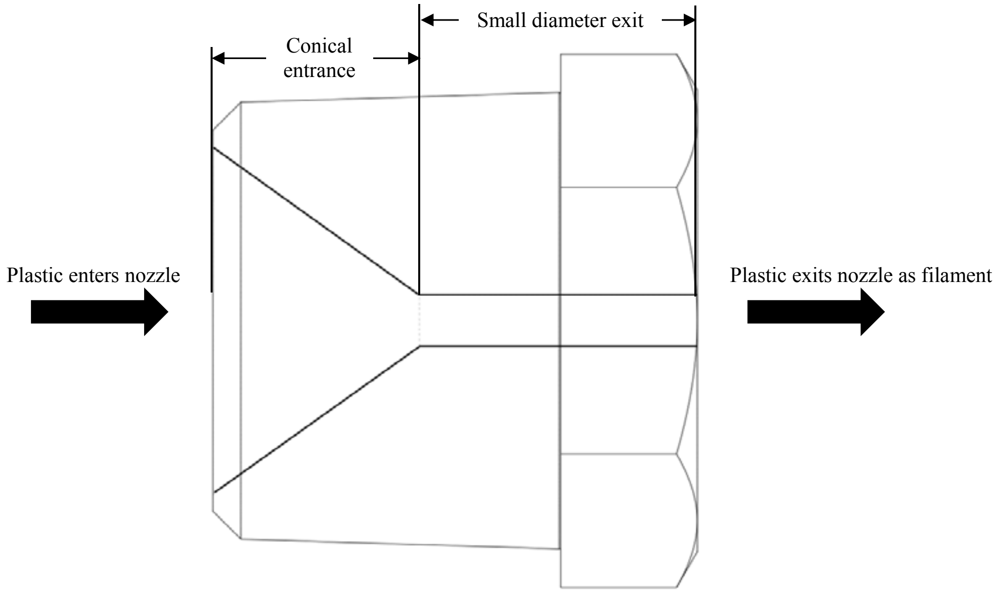


Figure 22: Diagram of inner geometry of the brass plug nozzle.

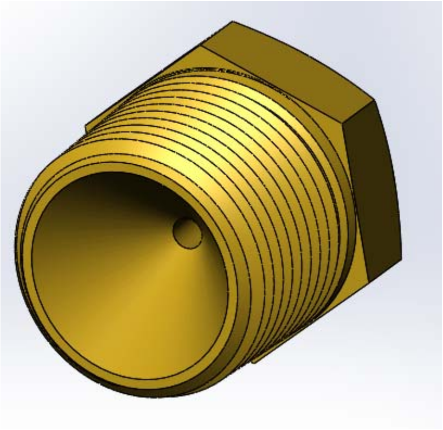


Figure 23: 3D rendering of inner geometry of the brass plug nozzle.

The desired final diameter of the filament is related to the small diameter in the nozzle. Because plastic swells as it cools, the small diameter of the nozzle must be smaller than the desired final diameter. The system requirements dictate the final diameter should be 3.00mm within a given tolerance. The square of the exact shear swelling ratio in the radial direction, B_{SR}^2, is described in Equation 15[18]:

$$B_{SR}^2 = \frac{area\ of\ swollen\ extrudate}{area\ of\ capillary} \tag{15}$$

To determine the value of B_{SR}^2, and therefore, the small diameter of the nozzle, a couple key assumption had to be made about the plastic. The first assumptions is that the plastic behaves as a Newtonian fluid, and the second is that PET's modulus of elasticity is valid at high temperatures. Neither of those assumptions is true; therefore, the analytical calculation of B_{SR}^2 carries very little weight. Instead, the small diameter was determined by using benchmarking data from existing extruders of other plastic types. The analytical calculations can be found in Appendix I.

Chapter 9: System Integration, Test and Results

9.1 Design Iterations

Several adjustments and modifications were made during the testing process. The results and the changes are summarized below:

Design 1 – Difficulty in determining the necessary melting temperature and motor speeds resulted in burnt plastic.

Design 2 – Removing the coupling and nozzle allowed us to see the plastic melt and record the corresponding temperatures.

Design 3 – Using the pre-recorded temperatures from Design 2 did not result in extruded filament.
– The heat loss in the stainless steel coupling solidified the plastic before reaching the filament nozzle.

Design 4 – Localized heating was increased by placing a heater directly on the coupling that connects the filament nozzle to the chamber.
– The resulting filament extruded was very brittle.

Design 5 – Virgin PET pellets were tested, intended to be used as a mixing agent to improve the mechanical properties of the filament.

Figure 24 summarizes the plastic results from each of the design iterations. Design 5 shows the initial testing phase using virgin PET pellets before using them as a mixing agent with the water bottles.

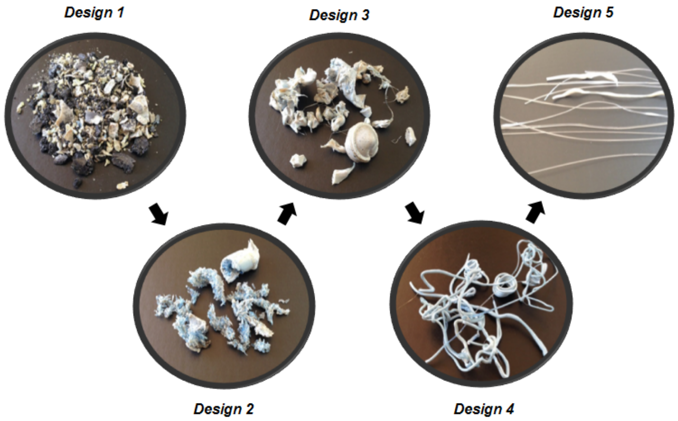


Figure 24: Plastic results from design iterations 1-5.

9.2 Plastic Testing

Plastic testing was conducted throughout the design iterations of the AkaBot in order to experimentally obtain the glass transition temperature, melting temperature, and percent crystallinity. The glass transition temperature is the point where the plastic changes from elastic to brittle. We need to reach the melting temperature inside the chamber in order to fully melt the plastic. However, past the melting temperature, the plastic degrades. The percent crystallinity is directly related to the mechanical properties of the plastic.

Testing of the plastic was done with a Differential Scanning Calorimetry (DSC) machine, and using the results, the glass transition temperature, melting temperature, and percent crystallinity can be found. The percent crystallinity is calculated using the following equation [19]:

$$\%\,Crystallinity = \frac{\Delta H_m - \Delta H_c}{\Delta H_m^{\circ}} \cdot 100 \tag{16}$$

A higher percent crystallinity results in a more brittle plastic. Knowing this, the goal throughout our project was to lower the crystallinity of the filament we produce. The Rwenzori water bottles from Uganda were tested before and after extruding. Multiple trials were carried out for each, and the clearest graph for each is shown below in Figures 25 and 26. All additional graphs are shown in Appendix J. Tables 9 and 10 show the results for each test and the average values for the $\Delta H_c, \Delta H_m$, percent crystallinity, melting temperature, and mid glass transition temperature.

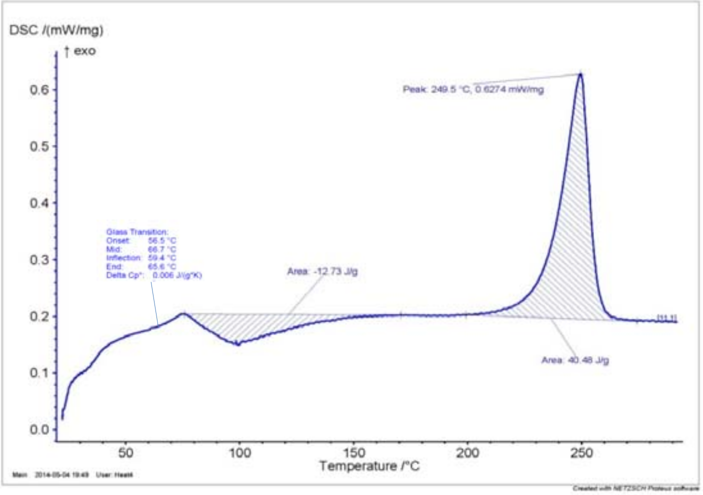


Figure 25: The DSC graph from the Rwenzori water bottle test before extruding (Sample 1).

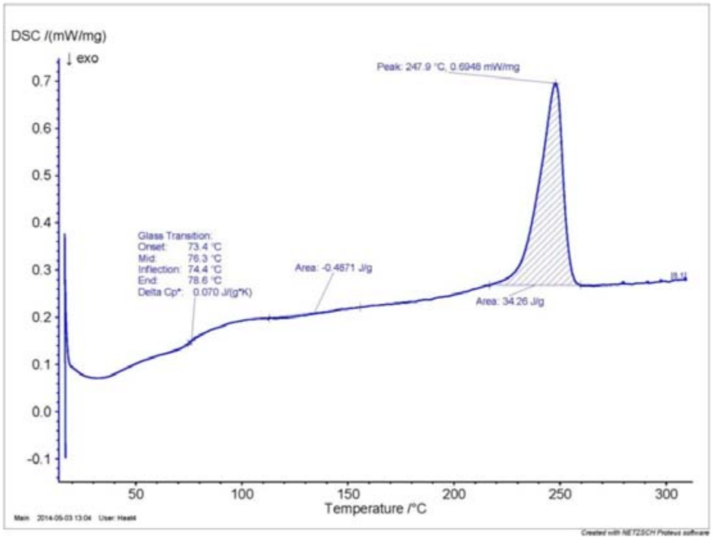


Figure 26: The DSC graph from the Rwenzori water bottle test after extruding (Sample 1).

Table 9: The results and average values of the ΔH_c,ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature for the Rwenzori water bottle before extruding

Sample	**Mass (mg)**	**ΔHc (J/g)**	**ΔHm (J/g)**	**ΔHm° (J/g)**	**Percent Crystallinity (%)**	**Melting Temperature (°C)**	**Mid Glass Transition (°C)**
1	16.2	12.73	40.48	140.1	19.81	249.5	60.6
2	14.5	16.78	41.02	140.1	17.30	248.1	66.7
3	14.2	13.27	42.91	140.1	21.16	249.4	Data Inadequate
Average		**14.26**	**41.47**		**19.42**	**249.0**	**63.7**

Table 10: The results and average values of the ΔH_c,ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature for the Rwenzori water bottle after extruding

Sample	**Mass (mg)**	**ΔHc (J/g)**	**ΔHm (J/g)**	**ΔHm° (J/g)**	**Percent Crystallinity (%)**	**Melting Temperature (°C)**	**Mid Glass Transition (°C)**
1	11.7	0.4871	34.26	140.1	24.11	247.9	76.3
2	11.9	0.7009	33.78	140.1	23.61	247.7	75.7
Average		**0.59**	**34.02**		**23.86**	**247.8**	**76.0**

The most important conclusion to be made from these DSC tests was the increase in percent crystallinity. It increased from an average of 19.42% before extrusion to 23.86% after extruding. This means that we extruded plastic that is more brittle than it was as a water bottle. Tensile tests were also carried out on the filament we extruded and the results are shown below in Table 11 along with the tensile tests for other filaments.

Table 11: Tensile test results

	PET+ MadeSolid	AkaBot Filament	PET Pellet Filament	Water Bottle
Diameter (mm)	2.8	2.12	1.04	1.20
Yield Strength (Pa)	33.4	6.03	29.5	20.8
Modulus of Elasticity (Pa)	480	255	366	178
Elongation at Fracture (mm)	13	1.45	3.48	1.20
Strain at Fracture (%)	0.4	0.02	0.14	0.12

The strain at elongation of the filament we made from the water bottles was 0.02%, while the strain at elongation of an existing PET filament is 0.4% as shown above in Table 11. Clearly, the filament we produced is much too brittle, and to reduce the brittleness, the percent crystallinity needs to be reduced.

There are a couple ways to experiment with lowering the percent crystallinity, and one option is to mix the water bottle plastic with virgin PET pellets. Since the pellets have not gone through the same manufacturing processes as the water bottles, the plastic properties are superior to the water bottles, and it's more likely to produce a usable filament. DSC tests were conducted on the pellets before extruding and after extruding and the clearest graph of the trials for each is shown below in Figures 27 and 28, while additional graphs are shown in Appendix J. The results and average values for the ΔH_c, ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature and shown in Tables 12 and 13.

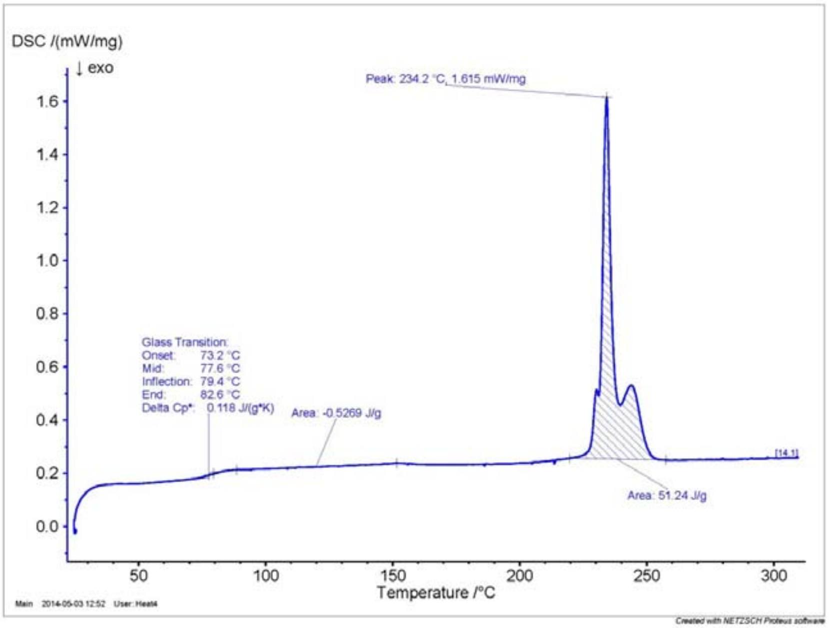


Figure 27: The DSC graph from the PET pellets test before extruding.

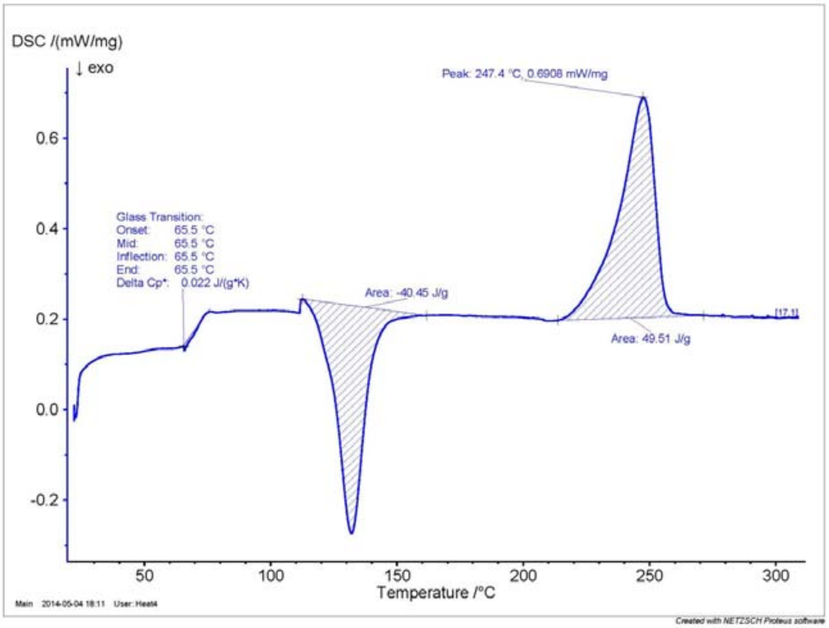


Figure 28: The DSC graph from the PET pellets test after extruding (Sample 1).

Table 12: The results and average values of the ΔH_c,ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature for the PET pellets before extruding

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	11.6	0.5269	51.24	140.1	36.20	234.2	77.6
2	11.2	0	49.97	140.1	35.67	233.7	76.1
Average		**0.26**	**50.61**		**35.93**	**234.0**	**76.9**

Table 13: The results and average values of the ΔH_c,ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature for the PET pellets after extruding

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	14.4	40.45	49.51	140.1	6.47	247.4	65.5
2	18	40.02	47.59	140.1	5.40	248.1	64.6
Average		**40.24**	**48.55**		**5.94**	**247.8**	**65.1**

The results from the PET pellets test before extrusion were particularly helpful in knowing that the melting temperature of the pellets was about 15 °C lower than the melting temperature of the water bottles. Because of this, when extruding, the heater temperatures were lowered. As can be seen from Tables 12 and 13, the percent crystallinity decreased from an average of 35.93% before extruding to 5.94% after extruding. The tensile test confirmed that the filament produced with the pellets was much more ductile since the strain at fracture was 0.14%, which is much higher that the water bottle filament results. The tensile test results and data are shown above in Table 11.

Increasing the cooling rate of the filament directly decreases the percent crystallinity. We concluded that one reason why the percent crystallinity was significantly lower when extruding with the PET pellets was that since the melting temperature was lower, the lower temperature settings of the heaters resulted in a lower extrusion temperature, which meant the filament cooled faster to room temperature.

PET filament produced industrially was purchased and tested in order to have an existing product to compare for. The results are shown below in Figure 29.

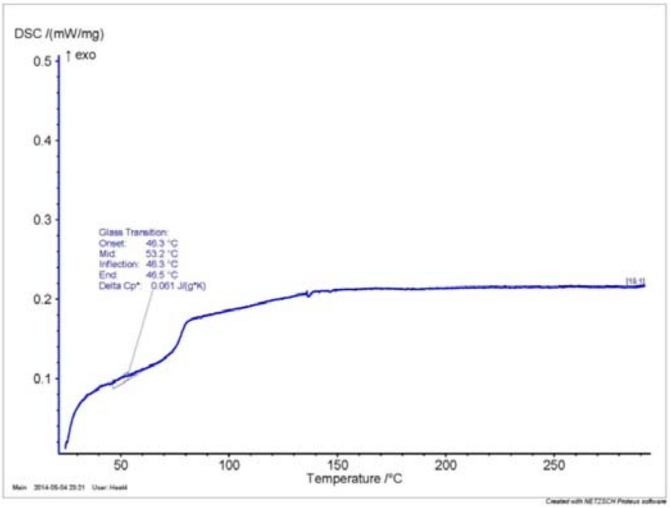


Figure 29: The DSC graph from the PET filament made by MadeSolid.

From this test, it was apparent that the PET filament made by MadeSolid was completely amorphous with no crystalline structures. This is shown by no melting peak. The company confirmed that their filament has additives, but since it is a trade secret, we don't know the specifics. These conclusions were useful in thinking of future work—plasticizers may need to be added in order to lower the glass transition temperature and reduce the crystallization.

In thinking of future testing, we also conducted a DSC test of Costco water bottles, since they are the highest available PET water bottles in the U.S. The results are shown below in Figure 30 and Table 14.

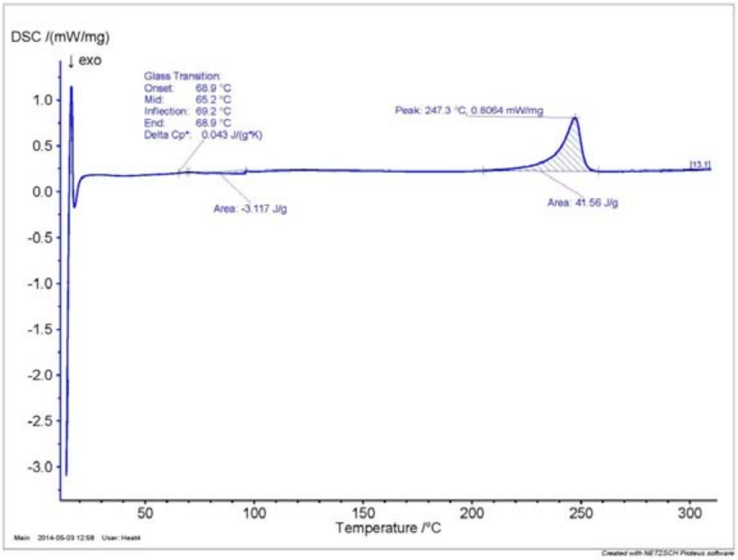


Figure 30: The DSC graph from the Costco water bottles (Sample 2).

Table 14: The results and average values of the ΔH_c, ΔH_m, percent crystallinity, melting temperature, and mid glass transition temperature for Costco water bottles

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	13.1	3.135	41.23	140.1	27.19	247.3	56.7
2	10.9	3.117	41.56	140.1	27.44	247.3	65.2
Average		**3.13**	**41.40**		**27.32**	**247.3**	**61.0**

Since the melting temperature of the Costco water bottles is essentially the same as for the Ugandan Rwenzori water bottles, we concluded from this test that the temperature, motor, and cooling settings used in design iterations of the AkaBot would work for both types of water bottles.

Chapter 10: Economic Analysis

The economic considerations for this project emerge in two main ways. First, the cost of the prototype versus our budget for development. Second, the tradeoff analysis for our customer between using the AkaBot and continuing to import filament from the suppliers abroad.

Keeping the cost low is important for our project because it is intended for emerging markets. Although our target cost was $300, the cost of our prototype was $485. Although we were well within our budget for development, the cost of the prototype is much too high. In order to get the cost down, parts must be sourced more cheaply, and electronics could be streamlined for lower cost.

The most important economic consideration is the tradeoff analysis the customer makes in deciding whether to purchase the AkaBot. In order to help any company like Village Energy save money on 3D printing, the AkaBot needs to be the clear victor in a side-by-side economic comparison.

Assuming that Village Energy uses one kilogram spool of filament per week, the cost of importing filament costing $30 per spool (plus shipping) was calculated over the course of a year. The cost of making filament using the AkaBot, including all the related costs of labor and maintenance, etc., was also calculated for the same consumption pattern. Shown in Figure X is a plot of the two options that Village Energy has moving forward, as they decide whether to import filament of make it themselves. The plot shows the cumulative cost over the course of a year for each option.

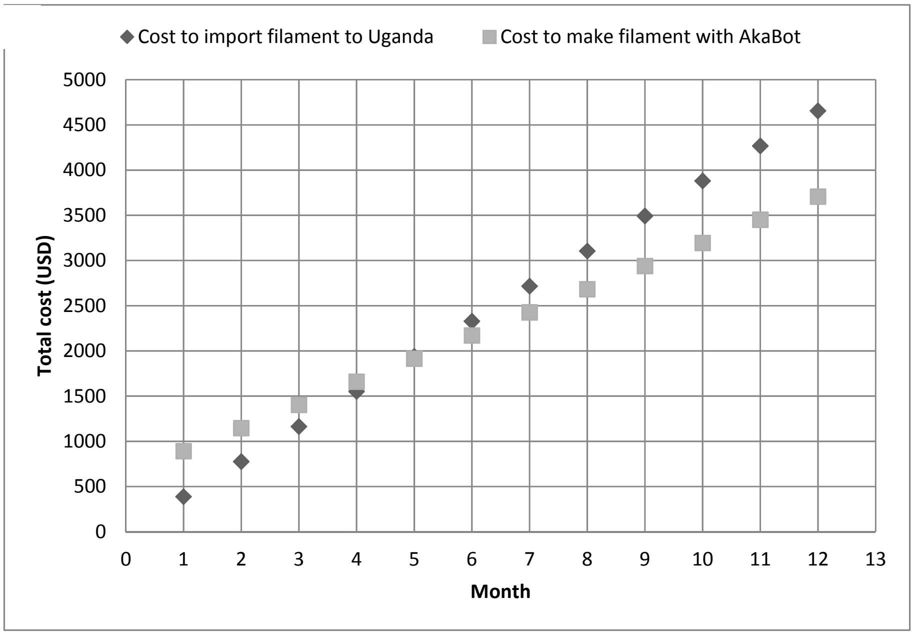


Figure 31: Village Energy cumulative costs over the course of a year to import or make filament.

As can be seen in Figure 31, the AkaBot is more expensive than importing filament for the first four months. After four months, they are equal, and past that, the AkaBot is less expensive than importing filament. This is a strong economic argument for using the AkaBot, even with the cost at $485. If the AkaBot cost were $300, break-even would happen after three months, instead of after four. The full list factors that went into the cost of importing filament versus using the AkaBot can be found in Table 15, in the Business Plan chapter.

Chapter 11: Business Plan

11.1 Introduction

The AkaBot: 3D Printing Filament Extruder is a machine with the potential to create disruptive innovation. Our product takes waste plastic water bottles, melts them, and extrudes them as filament for a 3D printer. The idea for this product emerged when a small electronics company in Kampala, Uganda, experimented with 3D printing enclosures for its solar lights. In order to develop a sustainable supply chain, this company needed a way to make its own filament. The AkaBot is the result of an engineering effort to help reduce poverty in Uganda by enabling economic development, helping establish recycling infrastructure, and creating meaningful jobs in the developing world.

Although there are other small-scale 3D printing filament extruders on the market, none make polyethylene terephthalate (PET) filament. Furthermore, none are designed specifically for the requirements of the developing world. The AkaBot is designed for the marketplace of rural Uganda, but could be applied to other places where entrepreneurs need manufacturing infrastructure that requires a relatively low investment.

The AkaBot executive team is well-experienced in the 3D printing world, having studied Mechanical Engineering at Santa Clara University, and done a year-long project developing the AkaBot. Furthermore, three members of the leadership team at AkaBot have spent significant time working with Village Energy in Uganda, piloting their usage of a 3D printer for their manufacturing needs. This has given the leadership team a deep familiarity with the customer requirements. With an excellent group of mechanical, electrical, and chemical engineers, the team at AkaBot is determined to make a difference in the lives of rural villagers who want access to economic development.

11.2 Objectives

AkaBot's mission is to make 3D printing a viable manufacturing option for the world's poor. By recycling waste plastic into filament for a 3D printer, AkaBot wants to help those at the bottom of the pyramid help themselves and the environment at the same time. The team at AkaBot believes strongly in the social and environmental mission of the company.

11.3 Product Description

The AkaBot is the original small scale PET filament extruder. Unlike other filament extruders, the AkaBot intakes shredded bits of plastic water bottles, (PET) melts them, and extrudes them as filament for a 3D printer.

Shredded bits of plastic enter a heated chamber through a hopper. They are pushed and mixed down the length of the chamber, before they exit as filament through a conical nozzle. The filament cools with the help of a fan. The AkaBot, pictured below in Figure 32, allows the user to control motor speed and temperature of each of the three heaters.

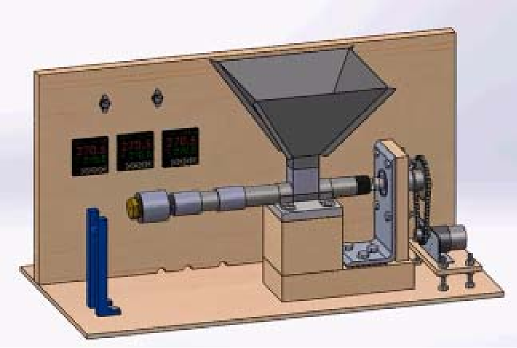


Figure 32: 3D rendering of the AkaBot prototype.

An AkaBot user has a distinct advantage over the average 3D printer customer. Most 3D printer users regularly buy filament, at a cost that quickly begins to add up. The AkaBot allows customers to cut that expense, instead making 3D printing not only extremely low-cost, but also beneficial to the environment, as waste plastic can be used as input material.

AkaBot's unique heating design for PET plastic is currently in the process of receiving a patent.

11.4 Product Economics

In order to help customers save money on 3D printing, the AkaBot needs to be the clear victor in the comparison between making or importing filament.

Since Village Energy was the inspiration for the AkaBot, we will use it as an example. Assuming that Village Energy uses one kilogram spool of filament per week, the cost of importing filament costing $30 per spool (plus shipping) was calculated over the course of a year. The cost of making filament using the AkaBot, including all the related costs of labor and maintenance, etc., was also calculated for the same consumption pattern. Table 15 shows the unit costs and inputs for each option. The comparison between the resulting costs over time is shown in Figure 31.

Table 15: Village Energy unit costs to import or make filament

	Description	Units	Value
Option 1: Import Filament	Cost of 1kg spool PLA	$/kg	30
	Shipping cost (DHL)	$/5kg	315
	Total Cost of 1kg PET	$/kg	97
	Consumption rate of 1kg*	kg/week	1
	Total cost/month of importing filament	$/month	388
	Lag time per spool	days	4
	Hassle factor rating	1 to 10	4
Option 2: Make Filament using AkaBot	Water bottles to make 1 kg	#/kg	180
	Cost per water bottle	$	0.05
	Cleaning supplies (oil, soap)	$/month	10
	Maintenance cost	$/month	10
	Labor cost	$/month	200
	Hair dryer	$	10
	Shredder	$	150
	AkaBot price	$	447
	Total fixed costs	$/month	635
	Lag time per spool	days	2
	Hassle factor rating	1 to 10	10

As can be seen in Figure 31, the AkaBot is more expensive than importing filament for the first four months. After four months, they are equal, and past that, the AkaBot is less expensive than importing filament. This is a strong economic argument for using the AkaBot. The full list factors that went into the cost of importing filament versus using the AkaBot can be found in Appendix K.

The cost to manufacture the AkaBot is $485 for the prototype, but will significantly drop if parts are ordered in bulk. If AkaBot is manufacturing 50 machines a year, the cost will be only $388. With a profit margin added in of 15%, the price to the consumer is $447.

11.5 Potential Markets

An example of a customer would be Village Energy in Uganda. Village Energy 3D prints solar lanterns and would use our machine to produce low cost filament. However, the versatility of 3D printing opens up our potential market to numerous other companies. Any company that is using 3D printing and has access to large volumes of plastic can use our AkaBot machine.

Although the machine was designed for developing countries, it can be used in the developed world as well. A company in the developing country would profit more per kilogram of filament produced due to the added expense of importing. However, a company in the developed world could have a larger production volume and would have a larger overall profit. Furthermore, this machine could be sold to companies that aren't directly using 3D printing, but rather are distributors of filament. An ideal location for an AkaBot user would be a place where there is access to large amounts of waste plastic.

11.6 Competition

Using waste plastic into 3D printer filament is a very new concept so there are not very many competitors in the market. The main competition would come from machines like the Legacy Filament Extruder, Filabot, Filastruder, ExtrusionBot, and many others. What sets us apart from the competition is that none of these machines have successfully extruded PET plastic.

Other companies like the Perpetual Plastic Project (PPP), Protoprint Solutions, and Plastic Bank could be potential competitors. PPP is targeting corporations with the vision of accepting broken plastic products and turning them into a new spool of filament. Protoprint Solutions and Plastic Bank are in the area of collecting waste plastic and turning it into filament. These companies could be customers if they wanted to buy our machine, but that is unlikely since they have already built their own extruders. Once again what sets us apart from these companies is that none of them are successfully extruding PET filament.

11.7 Sales and Marketing Strategies

Our business will operate with minimal advertising. We will market primarily to groups involved in social entrepreneurship, like Santa Clara University's Global Social Benefit Institute.

We will publish in social entrepreneurship journals and news sources, which we hope will get the conversation about 3D printing in developing markets to gain more momentum.

We plan to have one salesperson on our team whose job will be to network with potential customers, pitch the AkaBot concept, and make sales. This person will be based at headquarters in Northern California, but will travel to Africa or India on a regular basis. This person will receive a base salary with bonuses based on sales volumes.

11.8 Manufacturing Plans

We will sell the AkaBot as a self-assembly kit. Like many 3D printers commercially available today, buyers will assemble the AkaBot upon purchase. This will make it easier to ship to places in the developing world. In order to do this, we must perform minimal machining on parts before they go into the package, which we will do at our lab in Northern California. We will keep enough inventory on hand to produce five machines per month. It will take $2500 to get started with supplies. We will need to purchase tools for machining, most notably a milling machine. We will expand as is necessary to keep up with sales by possibly contracting out the machining work, and focusing on distribution and product development.

11.9 Financial Plan

Although the cost of the prototype was $485, once machines are produced on a larger scale this price will be greatly reduced. Assuming a production cost of $388 and a sales price of $447, the profit per unit will be $59. Also, it is expected that 50 machines will be sold per year.

In order to compensate for a strict demand, 10 machines will be produced prior to sales and then a machine is constructed per purchase after that. With this financial plan, the company will break even after 67 units are sold assuming 10 units are in the inventory at any time.. If the company continues to sell 50 machines a year for 5 years, the profit will be $10,811. This is all shown in Figure 33.

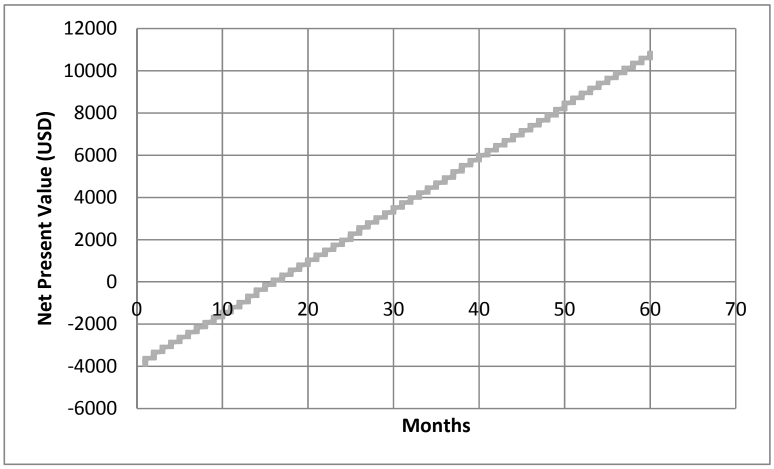


Figure 33: Return on investment over five years.

The money required to construct the first 10 machines will be the $3880. After that, no more funds are required after 67 units have been sold. If the projections are accurate, 67 units will be sold after about 16 months. The initial funds will come 20% from personal funds and 80% from venture capital.

The key financial assumptions are that the mass produced machine will cost $388, the sale price will be $447, that 50 machines will be sold in the first year, and that the majority of funding will come from venture capital. The assumptions of the machine cost and sales price are imperative to the pricing plan. Any reduction in sale price or increase in machine cost will result in a smaller profit margin. Furthermore, assuming that 50 units will be sold per year is crucial to the initial payback period and affects the projected profits. Lastly, the source of the funding is important for our personal finances but is not a big factor as long as the initial investment is fully funded.

The net present value of the company will continue to grow as long as more units are sold. Assuming a constant sale rate of 50 units per year, the net present value will be $14,750 after 10 years.

The contingency plan for this venture is to sell all assets to any company or university that will accept our machines. If the sale price is 50%, then the final sales gave to begin before 67 units have been sold. Prior to that number any plans will result in a loss of capital.

Chapter 12: Engineering Standards and Realistic Constraints

12.1 Health and Safety

One engineering standard that was taken into account in our design is the American Society of Mechanical Engineers (ASME) Fundamental canon concerning the health and safety of the public, augmented by the ASME canon concerning environmental consciousness. The ASME fundamental canons have given us a lens to evaluate our project in the context of health, safety, and the environment.

The ASME fundamental canons address public health and safety in a number of ways, but what we found most salient was the simplicity of canon number one. The first fundamental canon of ASME states that, "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties" [20]. In addition to the societal health and safety implications previously discussed, the AkaBot raises health and safety concerns for the direct user. The AkaBot will take plastic shreds to about 250^{o}C, which is far too hot for humans to touch. Because of this, we have insulated as much of the machine as we can, and will include simple, pictorial guides for the user that illustrate how long the AkaBot should be left to cool before it can be touched, et cetera.

Another health and safety concern the direct user faces is inhaling toxic fumes. In order to combat against that, we have enclosed the portion of the machine where the plastic will be melting. Also, we are not taking the plastic to a high enough temperature to release the toxic fumes that are emitted when the plastic is fully burned. This is both necessary to our design's functionality as well as a health and safety concern. Therefore, there is no ethical dilemma.

We did, however, face a decision that involved ethics pitted against design optimization. When melted and extruded, our plastic water bottles were proving too brittle to be immediately used in a 3D printer. In industry, plasticizers, or additives that increase the fluidity of a plastic, are usually added to plastic that needs to become more ductile. These plasticizers generally release toxic fumes—which left us with a decision to make. If we added the plasticizers, our product would work, but at the cost of the health of the AkaBot operator. If we did not, we would have to search for another way to make our plastic more ductile. We chose to continue to search for another way to make our filament less brittle. We recognized the importance of eliminating inhaled toxic fumes, if our project was to have its desired impact. This decision was based on the first fundamental canon of the ASME code of ethics.

12.2 Ethics

From the conception and design phases of our project through to testing and implementation, two ethical claims have informed our work. The first is the inalienable dignity of all peoples, which provides the underlying fundamental ethical motivation for our work. The second ethical claim that has informed our work is an awareness of the interaction between technology and society, known as Techno-Social sensitivity. A deep knowledge and understanding of the way a technology will be used in the developing world has been central to the ethical basis of our project.

The rights approach to understanding ethics is central to the ethical motivation for our project. The notion that all people have the right to choose freely what kind of life to lead, as well as the notion that there is dignity rooted firmly in human nature, has inspired us in building the AkaBot. Article 25 of the Universal Declaration of Human Rights [21] claims that all men have "the right to a standard of living adequate for the health and well-being of himself and of his family". The right to a standard of living that allows for communal health is reflected in our project. The AkaBot supports manufacturing in developing countries, helps reduce toxic fumes in city air, and also helps a solar light company bring clean energy to remote communities. Clean energy, clean air, and economic development are all components of a healthy economy, as well as healthy citizens who no longer breathe toxic fumes. In a strong economy, more citizens have the chance to take control of their lives, whereas in a failing economy, more people are forced to focus solely on survival. By supporting localized manufacturing efforts in Uganda, and cutting some pollution out of the air, we are helping Ugandans build up their economy and free themselves from the burden of poverty.

While there is a strong argument for the role of aid money and charities in development, we believe there is ethical value in supporting an economy by supporting its businesses, instead of providing direct aid from a third party. We see Ugandans as smart, enterprising people who have been dealt a difficult hand. Instead of looking at the poor as helpless recipients of aid, considering them active members in a developing economy allows us to focus on their human dignity and inherent worth. This is a major reason why our project is designed as a component in a Kampala-based business, not a charity or a handout. We believe that socially oriented business can play a large part in development, especially because it respects the dignity of the poor by giving them a chance to build up their own economies using the technical knowledge of the developed world. The respect for the dignity of all persons is found in many ethical frameworks, but most relevant for us is Catholic Social Teaching [22], which emphasizes the worth and distinction of all people.

The second ethical consideration in our senior design project relates to what we have learned about what it means to be a good engineer. Charles E. Harris Jr.'s The Good Engineer: Giving Virtue its Due in Engineering Ethics [23] defines the virtue ethics in engineering to counter the trend of encountering ethics as merely a list of negative rules. One of the ethics that Harris brings to the discussion is the issue of Techno-Social Sensitivity. In contrast to the rights and dignity of all peoples, and the health and safety considerations, Techno-Social Sensitivity is a lesser known ethical consideration, but one that is increasingly relevant in everyday life. Harris presents Techno-Social Sensitivity as an awareness of the way technology affects society and the way social forces in turn affect the evolution of technology. There are two themes within the philosophy of technology that we find relevant to the AkaBot project. The first relates to how social forces play into technical design, and the second relates to how technology itself can exert a profound social influence.

The technical design of our machine was based primarily on the desire to melt and extrude plastic to a desired shape, with a certain tolerance, at a certain speed. It is easy to interpret the design work as primarily technical, when in fact, social forces are at play at nearly every turn. The speed of extrusion was not solely dictated by how the plastic would react to a given speed, but also by the need for the operator to obtain a one kilogram spool of filament in the course of a normal workday. The materials and layout of our design have been chosen to be replaceable and maintainable in Uganda, using what tools and materials are available in Kampala. This means we, as engineers, cannot pick the most "efficient" or even the cheapest design, but must instead focus on what constitutes the best design for operation in Uganda. Furthermore, our project itself is motivated by social forces, as described earlier in this paper. It is impossible to disconnect social and value factors from technical design.

Perhaps the more interesting Techno-Social Sensitivity is the way in which technology exerts a profound social influence, even reaching into implications of the distribution of power. Engineers invested primarily in the functionality of their products can lose sight of the greater significance of their technologies, so it is important to periodically reflect on the social implications new technologies may have. In some cases, technology can be used as a weapon, and engineers in that situation would rely on an ethic of preventing harm through proper design decisions. In our case, the technology we are developing could help distribute power where it should more rightfully be—in the hands of a disadvantaged population. We believe that the Techno-Social Sensitivity is in fact a motivating ethic for our project, since we see the AkaBot as a means to increasing the power of ordinary people to participate in a formal economy. Increasing power through engineering is normally thought of in a technical sense, but its non-technical applications are just as important.

12.3 Social Impact

We believe the AkaBot has the potential to facilitate energy access in Uganda as well as create job opportunities. This potential is based on a number of assumptions regarding the infrastructure surrounding the machine. We first define our scope of influence to be Village Energy's work within Uganda. This constitutes a pilot program in which the viability of a 3D printing manufacturing system used with the AkaBot can be tested.

The assumptions regarding the AkaBot surrounding infrastructure are fairly aspirational. In order for the AkaBot to maximize its social impact, there first need to be companies in the developing world using 3D printing for some part of their value chain. Second, these companies need to be located in areas with an abundance of plastic waste, like water bottles. Third, these companies need to be willing to undergo the switching costs and "hassle factor" associated with making their own filament for their 3D printer using the AkaBot. There needs to be a supply chain for used PET water bottles established in the places where the AkaBot is used. Finally, successful use of the AkaBot assumes a fairly reliable power source.

The overarching assumption of this analysis is that the AkaBot functions well in the Ugandan environment, undergoes any required maintenance, and is operated by a qualified attendant.

The three most pertinent social impact metrics associated with the AkaBot are increased revenue for Village Energy, number of people reached with solar energy access, and employment opportunities generated. These three metrics are key performance indicators for Village Energy's social and financial stakeholders.

Shown in Table 16 are the parameters, values, and units associated with the projection for increased revenue Village Energy would likely receive when using the AkaBot to improve its product aesthetics. Based on information from Village Energy, the customer and pilot company for the AkaBot, as well as supplementary data from the Uganda Bureau of Statistics, it was possible to calculate the current estimated revenue for Village Energy, as well as the expected revenue with improved aesthetics. The basic calculation was based on the price of the solar product, the number of potential customers who see a demonstration every year, the current yield of buyers from those who see demonstrations, and the projected increase in yield based on improved aesthetics. The data for increased revenue projections comes from Village Energy. Based on the provided parameters, the AkaBot and 3D printer together enable Village Energy to increase their revenue by 50%, bringing the annual revenue to 67,500 USD.

Table 16: Village Energy increased revenue with improved product aesthetics

Parameter	Value	Unit	Source
Sales yield	12.5%	buyers/people shown the product in a demonstration	Village Energy
Villages visited in a year	120	Villages/year	Village Energy
Number exposed per village	40	people shown the product in a demonstration	Village Energy
Expected increase multiplier in buyers per village w/ improved aesthetics (k)	1.5	scalar multiplier	Village Energy
Sales price of a VE light	75	USD	VE marketing material
Current revenue of Village Energy	45,000	USD/year	N/A
Projected VE Revenue w/ improved aesthetics	**67,500**	**USD/year**	**N/A**

The second relevant social impact metric is increased solar energy access. Based on the Village Energy provided data, the number of people who are likely to buy solar lights with improved aesthetics can be isolated. Assuming those people did not already have access to solar energy, and extrapolating the impact based on family size data from the Uganda Bureau of Statistics, the number of people with access to solar energy because of improved aesthetics was found to be 1,470 per year. These metrics are summarized in Table 17.

Table 17: Village Energy increased energy access impact with improved product aesthetics

Parameter	Value	Unit	Source
People buying solar lights because of aesthetics	2.5	people buying b/c of aesthetics per village	Village Energy
Number of villages visited	120	villages/year	Village Energy

in a year			
Average number of dependents	4.9	# of dependents/buyer	Uganda Bureau of Statistics
People/year with energy access because of aesthetics	**1,470**	**# of people reached / year**	**N/A**

The third prominent social impact metric associated with the AkaBot is increased employment opportunity. In order to quantify the opportunity, the working assumption is that if there is revenue enough to cover a salary, there will be plenty of work Village Energy would benefit from. In this analysis, the assumption is that increased revenue goes directly to new hire salaries. Based on the increase in revenue and the average salary in Kampala, according to the Uganda Bureau of Statistics, Village Energy can afford to hire four new people per year. The parameters involved in this are shown below in Table 18.

Table 18: The increased employment opportunity at Village Energy based on increased revenue

Parameter	Value	Unit	Source
VE new revenue/year	22500	USD/year	*Previous calc
Average yearly income in Kampala, 2009/2010	4560	USD/year	Uganda Bureau of Statistics
Number of people employable with new income	**4**	**# people**	**N/A**

The conclusion from evaluating social impact metrics is that the AkaBot can have a significant effect on one company's reach and economics. If social enterprises in the developing world with similar needs follow in the footsteps of Village Energy, the AkaBot could have an even more significant social impact.

12.4 Environmental Impact

One of the key aspects to the AkaBot is that it uses recycled water bottles for its feedstock material. The environmental effect of this can be measured by the metric of crude oil use. The production and transportation of PET water bottles is assumed to be similar to the process to make and transport PET filament, and by reusing water bottles instead of using PET filament, the AkaBot cuts down on crude oil use.

Table 19 shows the parameters, values, and units that were used to calculate the amount of crude oil that wouldn't be used as a result of recycling PET water bottles with the AkaBot. Data from the United Nations, National Geographic, and Village Energy was used. It was concluded that it would require 1201 barrels a year to produce the filament that Village Energy uses to manufacture their solar lights. However, by using already produced water bottles, the AkaBot reduces the amount of crude oil use by this amount every year.

Table 19: The reduction of the use of crude oil

Parameter	Unit	Value	Source
Population in U.S.	million people	300	UN data [24]
Population in Kampala	million people	1.2	UN data
Water bottles used in U.S. annually	million	29000	National Geographic [25]
Water bottles used in Kampala annually	million	116	N/A
Crude oil equivalent (transport + production) in U.S.	million barrels/year	67	National Geographic
Crude oil equivalent (transport + production) in Kampala	million barrels/year	0.268	N/A
Recycling rate in U.S.	percent	0.13	UN data
Recycling rate in Kampala	percent	0.01	Village Energy
Water bottles as trash annually in U.S.	million	25230	N/A
Water bottles as trash annually in Kampala	million	114.84	N/A
Production rate filament for Village Energy	spool/year	260	Village Energy
Weight water bottle	gram	5	Village Energy
Spool weight	gram	1000	Village Energy
Water bottles used by Village Energy	WB/spool	200	N/A
Water bottles used by Village Energy	WB/year	52000	N/A
Crude oil reduction	**barrels/year**	**1201**	**N/A**

12.5 Sustainability

The goal of the AkaBot is to create a sustainable supply chain for any company using 3D printing in the developing world, like Village Energy in Uganda. Although 3D printing has improved Village Energy's sales, it is also very expensive for them to import the filament in order to produce more units. This is where the AkaBot comes in. By replacing purchased filament with the filament produced by our machine, Village Energy will be able to continue operation without having to worry about constantly importing filament.

From our experience spending two months in Uganda, there is an abundance of water bottles. Plastic bottles are prevalent particularly in the capital where Village Energy is located, mainly due to the high population of immigrants that would get sick from drinking the tap water. The AkaBot would be able to capitalize on the excess of bottled water and turn that into a working filament. By utilizing the resource of plastic bottles that would otherwise be thrown away or burned, our customer is gaining a seemingly endless supply of filament. There are several details to be worked out in terms of the bottle collection and cleaning process, but the bottles are essentially an inexpensive untapped resource. Furthermore, since Village Energy is 3D printing solar lanterns, they are spreading the use of sustainable energy sources. Energy poverty is a big issue facing the developing world right now, and as sustainable energy sources continue to grow, so will Village Energy's business. The AkaBot is an integral part of spreading sustainability throughout Uganda, both through its reduction of plastic waste and its role in creating more solar lanterns.

Chapter 13: Summary and Conclusions

Overall, this project has been a successful foundation for future development. The goal of the project was to develop a machine that could intake PET plastic water bottle shreds and melt and extrude them as filament for a 3D printer. Over the course of this year, we have built the machine, developed a cleaning process for the plastic, and successfully extruded plastic shreds. However, they are not yet usable in a 3D printer. We have experimented with virgin PET pellets, and concluded that mixing PET pellets with PET water bottle shreds could help improve the mechanical properties of the extruded filament.

There are six suggestions we have for the future work on this project:

- First, and most important, is to improve the mechanical properties of the PET filament. As previously mentioned, this can be done through mixing PET pellets with PET water bottle shreds, but could also be achieved through a faster cooling rate.
- The second improvement suggestion we have is to develop an automatic spooling system that will be able to coil extruded filament at the same rate it is extruded. This will help ensure a constant diameter, but will require a new nozzle to be machined with a larger diameter, since the automatic spooling will somewhat stretch the cooling plastic.
- Third, we suggest creating specific heater and motor settings that can extrude different types of plastic filament, like HDPE, ABS, and PLA. This would make the AkaBot more versatile.

- Our fourth suggestion is to collaborate with the chemistry department to customize the filament color using dyes. The original motivation of this product was to help improve a company’s aesthetics, so the color of the filament is very important.
- Our fifth suggestion is to develop interchangeable filament dies that can produce either 1.75mm or 3.00mm filament. This will help make the AkaBot more versatile, since most 3D printers use either 1.75mm or 3.00mm filament.
- Our sixth and final suggestion is to source all machine parts from suppliers like Alibaba.com, that deliver to Uganda. In order to help make the AkaBot cost the target of $300, the electronics should be redesigned to steamline for cost.

References

[1] "About Us - Sustainable Energy for All." *Sustainable Energy for All About Us Comments*. United Nations, n.d. Web. 06 June 2014.

[2]"Energy Access Transforms Lives." *Practical Action*. N.p., n.d. Web. 6 June 2014.

[3]"Energy Profile of Uganda." *Energy Profile of Uganda*. The Encyclopedia of Earth, n.d. Web. 06 June 2014.

[4]"Energy Access Transforms Lives." *Practical Action*. N.p., n.d. Web. 6 June 2014.

[5] *Lighting Africa Market Trends Report 2012: Overview of the Off-Grid Lighting Market in Africa*. Rep. N.p.: International Finance Corporation, n.d. Print.

[6] Yundt, Victoria. *Photograph of Kerosene Light*. 2012. Uganda.

[7] Yundt, Victoria. *Photograph of Solar Lanterns at Solar Sister*. 2012. Kampala, Uganda.

[8] Iler, H. Darrell, Eric Ruff, and Seth Althoff. "An Introduction to Polymer Processing, Morphology, and Property Relationships through Thermal Analysis of Plastic PET Bottles." Journal of Chemical Education 83.3 (2006): 439-42. Mar. 2006. Web. Oct. 2013.

[9] Turng, Lih-Sheng, and Sidney H. Goodman. "Plastics Processing." AccessScience (2012): www.accessscience.com. McGraw-Hill Education, 2012. Web. Oct. 2013.

[10] George, Andrew, and Brent Strong. "Composite Materials." AccessScience (2012): www.accessscience.com. McGraw-Hill Education, 2012. Web. 2013.

[11] “Plastic Processing” (Turng, Lih-Sheng, Goodman)

[12] *Differential Scanning Calorimetry Investigation of Polymers*. Rep. N.p.: Humboldt-Universitat Zu Berlin, n.d. Print

[13] Hegde, Raghavendra R., M. G. Kamath, and Atul Dahiya. *Polymer Crystallinity*. Rep. N.p.: n.p., n.d. Print.

[14] Sichina, W.J., “DSC as Problem Solving Tool: Measurement of Percent Cyrstallinity of Thermoplastics” Perkin Elmer Inc., 2000

[15] Callister, William D. and Rethwisch, David G. *Materials Science and Engineering: An Introduction.* 2009.

[16] Myers, Jeff A., and Puhalla, Mike. “Barrel Alignment – A Critical Factor in Reducing Extruder Wear.”

[17] Bergman, T.L., Frank P. Incropera, Adrienne S. Lavine, and David P. Dewitt.*Fundamentals of Heat and Mass Transfer*. 7th ed. Hoboken, NJ: Wiley, 2011. Print

[18] Crawford, R. J. *Plastics Engineering*. Oxford: Pergamon, 1987.

[19] Sichina, W.J., “DSC as Problem Solving Tool: Measurement of Percent Cyrstallinity of Thermoplastics” Perkin Elmer Inc., 2000

[20] ASME. "Code of Ethics of Engineers." *American Society of Mechanical Engineers*. ASME, n.d. Web. 6 June 2014.

[21] "The Universal Declaration of Human Rights, UDHR, Declaration of Human Rights, Human Rights Declaration, Human Rights Charter, The Un and Human Rights." *UN News Center*. UN, n.d. Web. 04 June 2014.

[22] "Catholic Social Teaching." *Catholic Social Teaching*. N.p., n.d. Web. 05 June 2014.

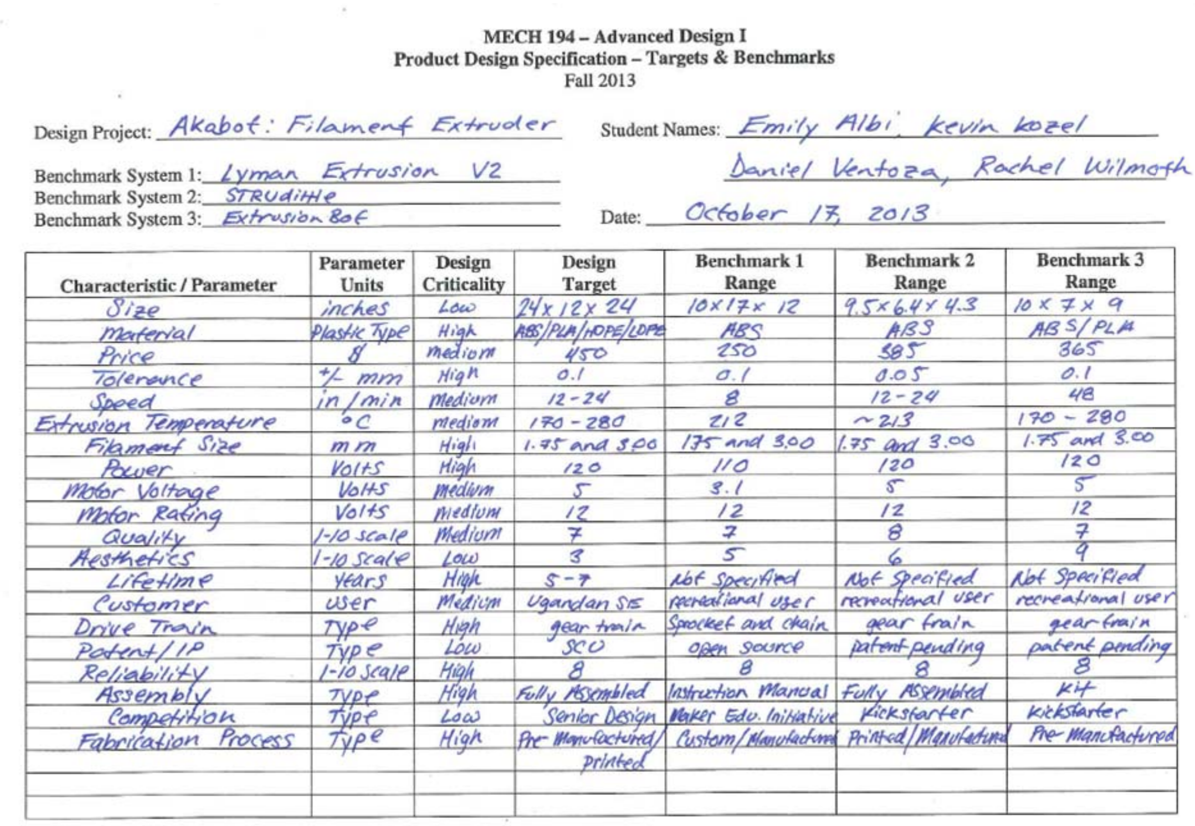
[23] Harris, Charles E. "The Good Engineer: Giving Virtue Its Due in Engineering Ethics." *Science and Engineering Ethics* 14.2 (2008): 153-64. Web.

[24] "UNdata." *UNdata*. N.p., n.d. Web. 14 May 2014.

[25] "Water Bottle Pollution -- National Geographic Kids." *National Geographic*. N.p., n.d. Web. 11 May 2014.

Appendices

Appendix A: PDS



MECH 194 – Advanced Design I
Product Design Specification – Targets & Benchmarks
Fall 2013

Design Project: Akabot: Filament Extruder
Student Names: Emily Albi, kevin kozel, Daniel Ventoza, Rachel Wilmoth
Benchmark System 1: Lyman Extrusion V2
Benchmark System 2: STRUdittle
Benchmark System 3: Extrusion Bot
Date: October 17, 2013

Characteristic / Parameter	Parameter Units	Design Criticality	Design Target	Benchmark 1 Range	Benchmark 2 Range	Benchmark 3 Range
Size	inches	Low	24x12x24	10x17x12	9.5x6.4x4.3	10x7x9
Material	Plastic Type	High	ABS/PLA/HDPE/LDPE	ABS	ABS	ABS/PLA
Price	$	medium	450	250	385	365
Tolerance	+/- mm	High	0.1	0.1	0.05	0.1
Speed	in/min	Medium	12-24	8	12-24	48
Extrusion Temperature	°C	medium	170-280	212	~213	170-280
Filament Size	mm	High	1.75 and 3.00	175 and 3.00	1.75 and 3.00	1.75 and 3.00
Power	Volts	High	120	110	120	120
Motor Voltage	Volts	medium	5	3.1	5	5
Motor Rating	Volts	medium	12	12	12	12
Quality	1-10 scale	Medium	7	7	8	7
Aesthetics	1-10 scale	Low	3	5	6	9
Lifetime	years	High	5-7	Not Specified	Not Specified	Not Specified
Customer	user	Medium	Ugandan SS	recreational user	recreational user	recreational user
Drive Train	Type	High	gear train	Sprocket and chain	gear train	gear train
Patent/IP	Type	Low	SCU	open source	patent pending	patent pending
Reliability	1-10 scale	High	8	8	8	8
Assembly	Type	High	Fully Assembled	Instruction Manual	Fully Assembled	Kit
Competition	Type	Low	Senior Design	Maker Edu. Initiative	Kickstarter	Kickstarter
Fabrication Process	Type	High	Pre-Manufactured/ Printed	Custom/Manufactured	Printed/Manufactured	Pre-Manufactured

Figure A1: Product Design Specifications.

Appendix B: Gantt Chart

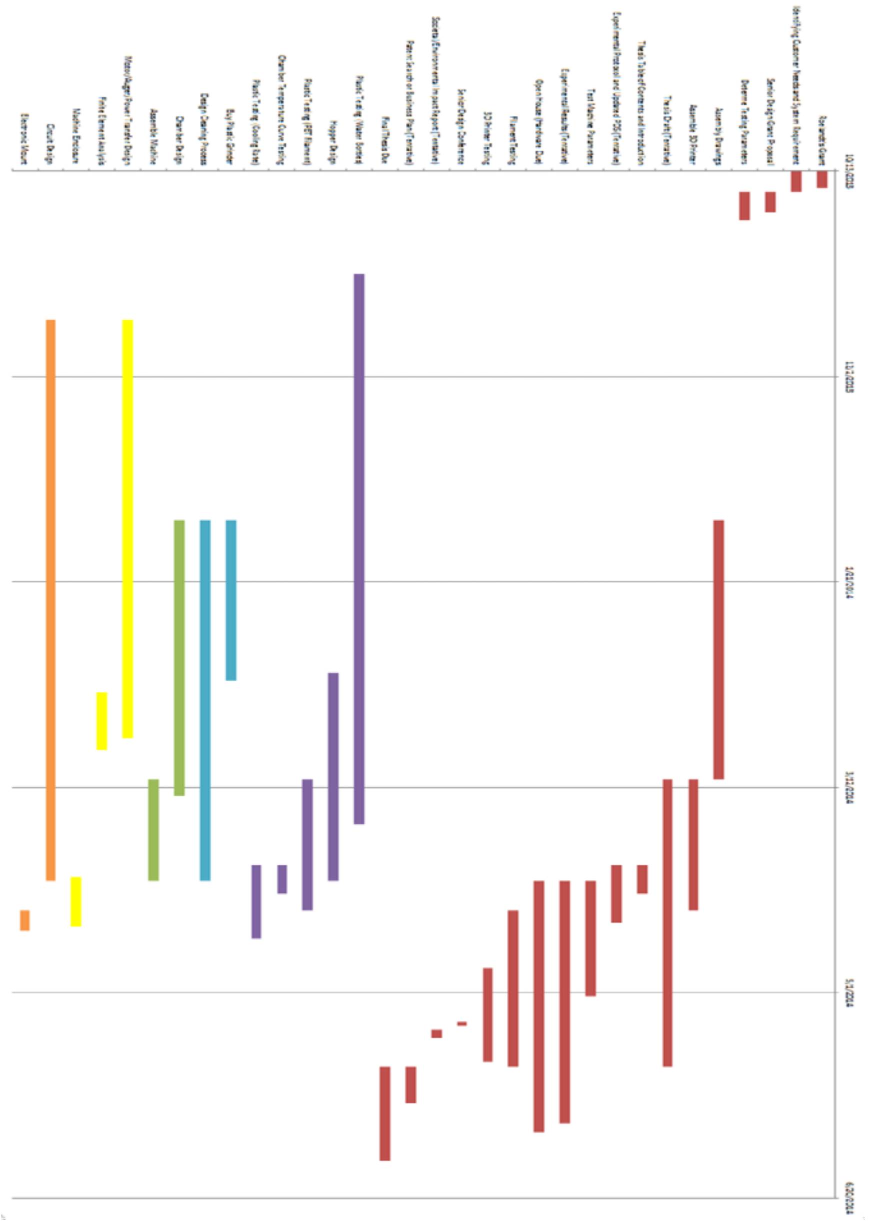
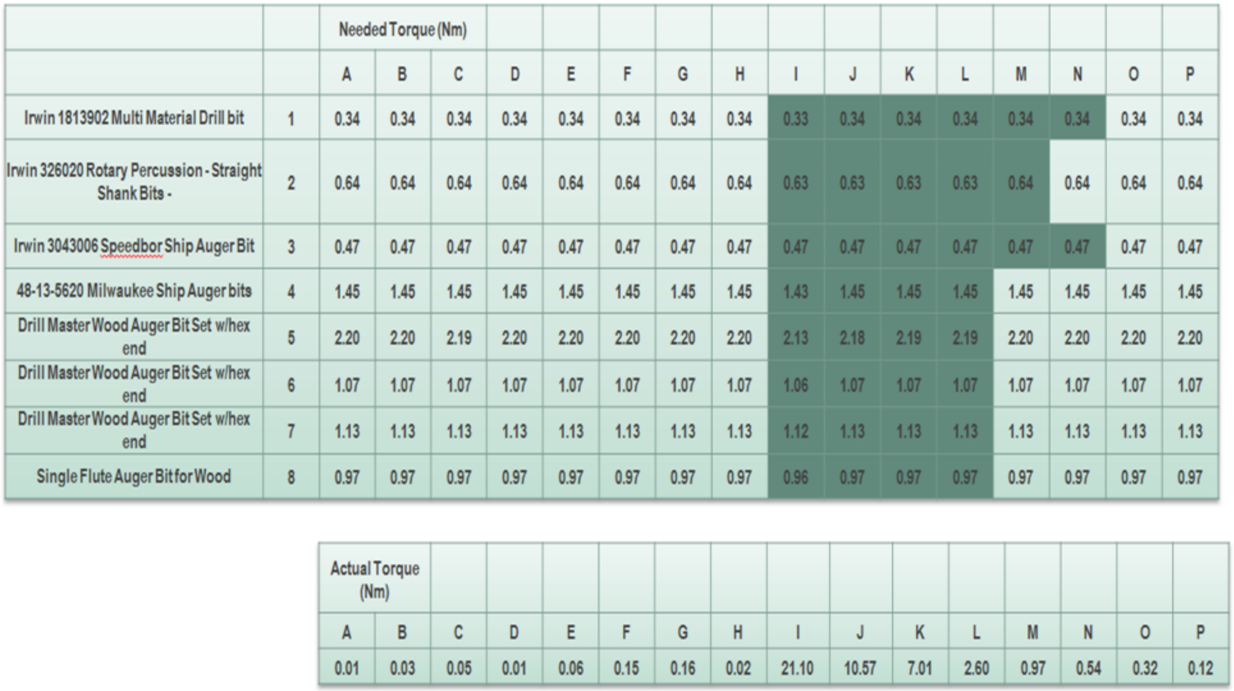


Figure A2: Gantt Chart.

Appendix C: Auger Motor Calculations

Table A1: Spreadsheet used to determine suitable auger and motor combinations



		Needed Torque (Nm)															
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Irwin 1813902 Multi Material Drill bit	1	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Irwin 326020 Rotary Percussion - Straight Shank Bits -	2	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.63	0.63	0.63	0.63	0.64	0.64	0.64	0.64
Irwin 3043006 Speedbor Ship Auger Bit	3	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
48-13-5620 Milwaukee Ship Auger bits	4	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.43	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Drill Master Wood Auger Bit Set w/hex end	5	2.20	2.20	2.19	2.20	2.20	2.20	2.20	2.20	2.13	2.18	2.19	2.19	2.20	2.20	2.20	2.20
Drill Master Wood Auger Bit Set w/hex end	6	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.06	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Drill Master Wood Auger Bit Set w/hex end	7	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Single Flute Auger Bit for Wood	8	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97

Actual Torque (Nm)															
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0.01	0.03	0.05	0.01	0.06	0.15	0.16	0.02	21.10	10.57	7.01	2.60	0.97	0.54	0.32	0.12

Appendix D: Heat Transfer Variables

Table A2: The variables, descriptions, values, and units for all properties and dimensions used in heat transfer calculations

Variable	Description	Value	Units
A_1	Cross sectional area of nozzle	$7.0686 \text{x} 10^{-6}$	m^2
A_2	Cross sectional area of inner pipe	$2.7897 \text{x} 10^{-4}$	m^2
V_1	Velocity out of nozzle	0.0051	m/s
V_2	Velocity in pipe	$1.2872 \text{x} 10^{-4}$	m/s
ρ	Density of PET	1420	kg/m^3
T_m	Melting temperature of PET	260	°C
T_i	Room temperature	22	°C
c_p	Specific heat of PET	1140	J/kgK
L_m	Latent heat of melting of PET	50	J/g
h	Heat transfer coefficient due to natural convection	10	W/m^2K
r_o	Outer radius of pipe	0.0133	m
r_i	Inner radius of pipe	0.0094	m
L	Length of pipe	0.3048	m
k	Thermal conductivity of stainless steel 304	15.8	W/mK
T_{band}	Temperature of heating band	400	°C

Appendix E: MATLAB code

Matlab Code

```
>> analysis_report
q_sens =
   13.8346
q_melt =
    2.5495
UPL =
    0.2546
q_loss =
   96.2553
q_total =
  112.6394
L_inches =
    3.2441
```

```
%Defining Constants/Assumptions
Cp = 1140;
%Specific heat of PET [J/kgK]   *Used from book from Sepehrband
p = 1420;
%Density of PET [kg/m3]         *plastic-products.com/part12.htm
v = 12;
%Velocity of extrusion [in/min]
Tm = 260;
%Melting temp of PET [C]
Ti = 22;
%Initial temp of PET [C]
Lm = 50 * 1000;
%Latent heat of melting PET [kJ/kG]
L = 12 * 0.0254;
%Length of pipe [m]
k_pipe = 16;
%Thermal conductivity of Stainless Steel 304 at 600K [W/mk]
h = 10;
%Heat transfer coefficient for natural convection [W/m2K]
ID = 0.742 * 0.0254;
%Inner diameter of chamber [m]
OD = 1.05 * 0.0254;
%Outer diameter of chamber [m]
T_band = 400;
%Temp of heating bands [C]

%Conversions
v_die = (v*0.0254)/60;
%Velocity of extrusion [m/s]
D_die = 3*10^-3;
%Diameter of die [m]
```

```
A_pipe = (ID/2)^2*pi ;
%Cross sectional area of chamber [m2]
A_die = (D_die/2)^2*pi;
%Cross sectional area of die [m2]

%Finding velocity of plastic in chamber
v_pipe = (A_die * v_die)/A_pipe ;
%Velocity of plastic in chamber [m/s]  *USING A1V1=A2V2 from die to chamber
% v_pipe = v_die
%NOT USING A1V1=A2V2 from die to chamber

%Finding mass flow rate
m = p * A_pipe * v_pipe;
%Mass flow rate [kg/s]

%Finding q_sens
q_sens = m * Cp * (Tm - Ti)
%[W]

%Finding q_melt
q_melt = Lm * m
%[W]

%Finding q_loss
UPL = ((1/(L*pi)) * ((1/(h*OD)) + (log(OD/ID)/(2*k_pipe))))^(-1)
%Overall heat transfer coefficient
q_loss = UPL * (T_band - Ti)
%[W]

%Finding total heat needed
q_total = q_sens + q_melt + q_loss
%[W]

%Back-calculating length to achieve the heating needed
UP = UPL/L;
L = (m*(Cp*(Tm - Ti) + Lm))/(UP * (Tm - Ti));
%[m]
L_inches = L/0.0254
```

Appendix F: Finite Element Analysis Variables

Table A3: The materials used in the AkaBot system FEA thermal modeling and significant properties

	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)
Stainless Steel 304	16.0	500	8000
Aluminum 1060 Alloy	200	900	2700
PET plastic	0.26	1140	1420
Ceramic porcelain	1.49	878	2300

Appendix G: Finite Element Analysis Table

Table A4: The heater wattages with the minimum, maximum, and nozzle temperatures shown in axial position for each loading condition. Setups 1-10 involve thermal analysis on the flanged, insulated system, while Setups 11-13 involve thermal analysis on the non-flanged, non-insulated systems.

	1 in	2 in	3 in	4 in	5 in	6 in	Total Watts (W)	Min Temp (°C)	Max Temp (°C)	Nozzle Temp (°C)
Setup 1	50 W		50 W				100	32.5	322	129
Setup 2		50 W		50 W			100	28.7	328	160
Setup 3	60 W		35 W				95	32.9	330	120
Setup 4		60 W		35 W			95	29.0	329	150
Setup 5	35 W		60 W				95	30.0	550	200
Setup 6	50 W		20 W		10 W		80	30.1	263	110
Setup 7	60 W		30 W		10 W		100	32.6	322	130
Setup 8	50 W		30 W		20 W		100	31.4	293	150
Setup 9		50 W		30 W		20 W	100	27.9	294	230
Setup 10		60 W		30 W		10 W	100	28.8	322	175
***Setup 11**	50 W		50 W				100	19.9	346	135
***Setup 12**	50 W		20 W		10 W		80	19.9	287	120
***Setup 13**	60 W		30 W		10 W		100	19.9	350	140

Appendix H: Finite Element Analysis Figures

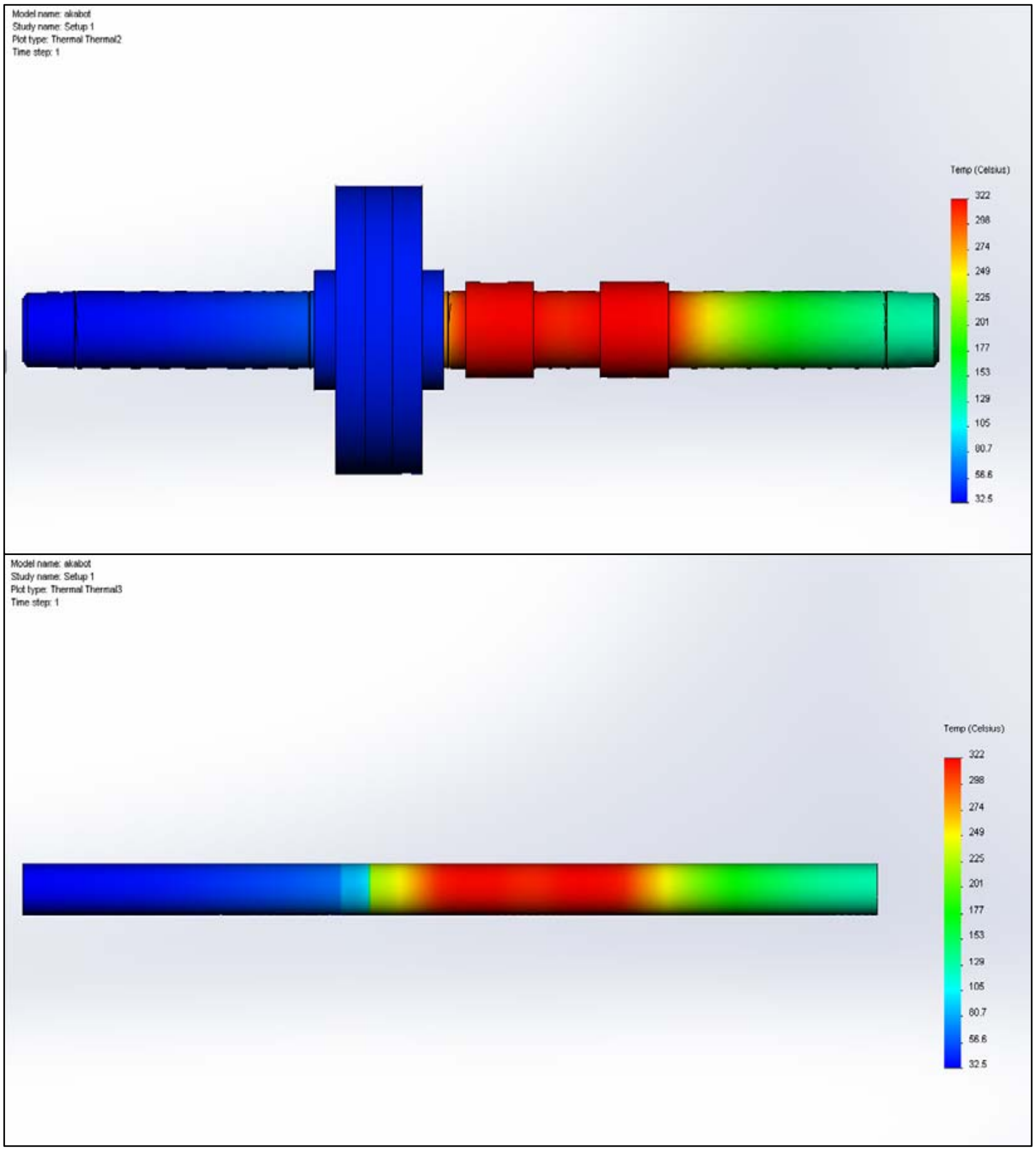


Figure A3: Thermal modeling results for Setup 1: flanged, insulated AkaBot with heaters at 1 inch, 50 W, and at 3 inches, 50 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

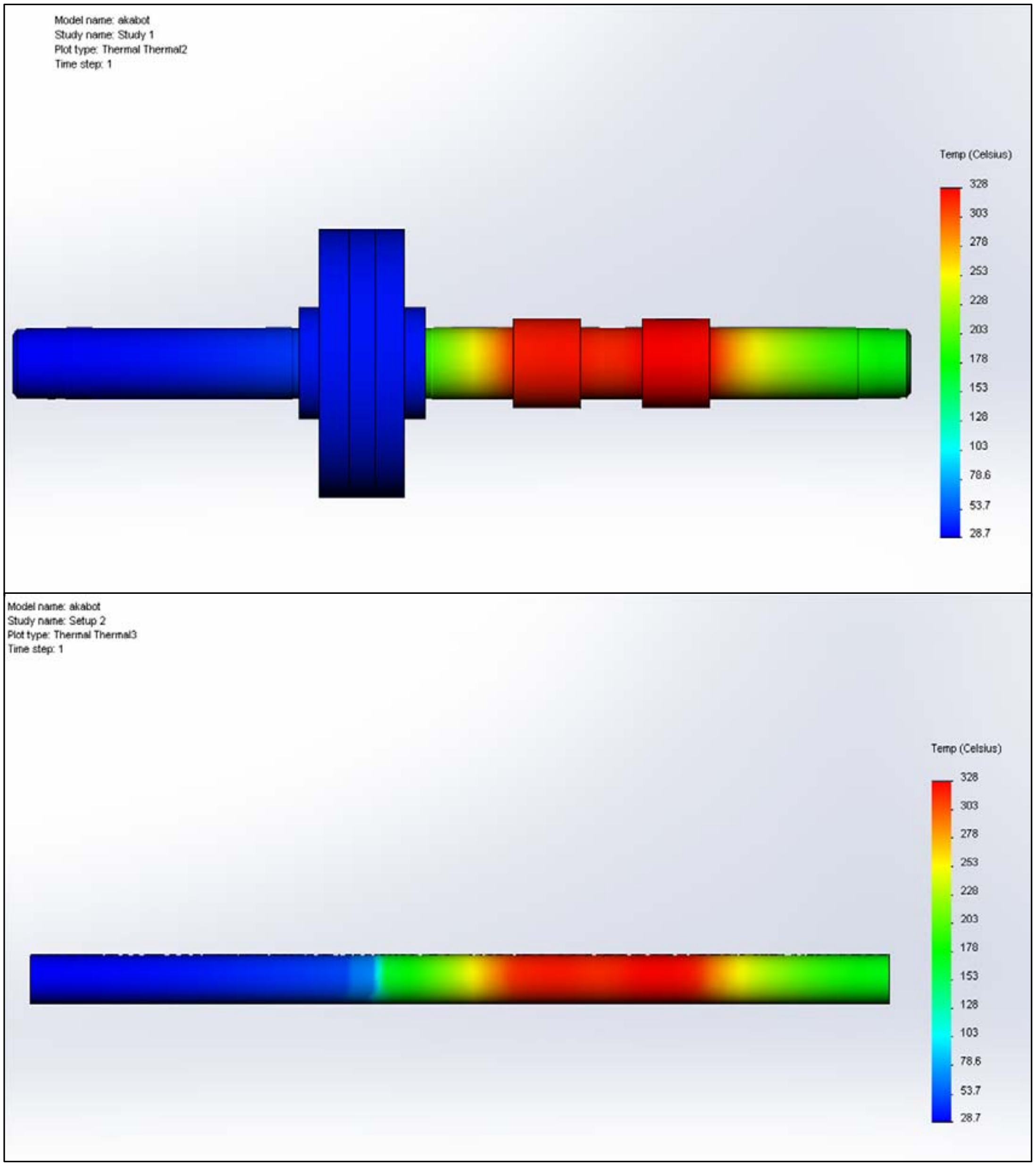


Figure A4: Thermal modeling results for Setup 2: flanged, insulated AkaBot with heaters at 2 inches, 50 W, and at 4 inches, 50 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

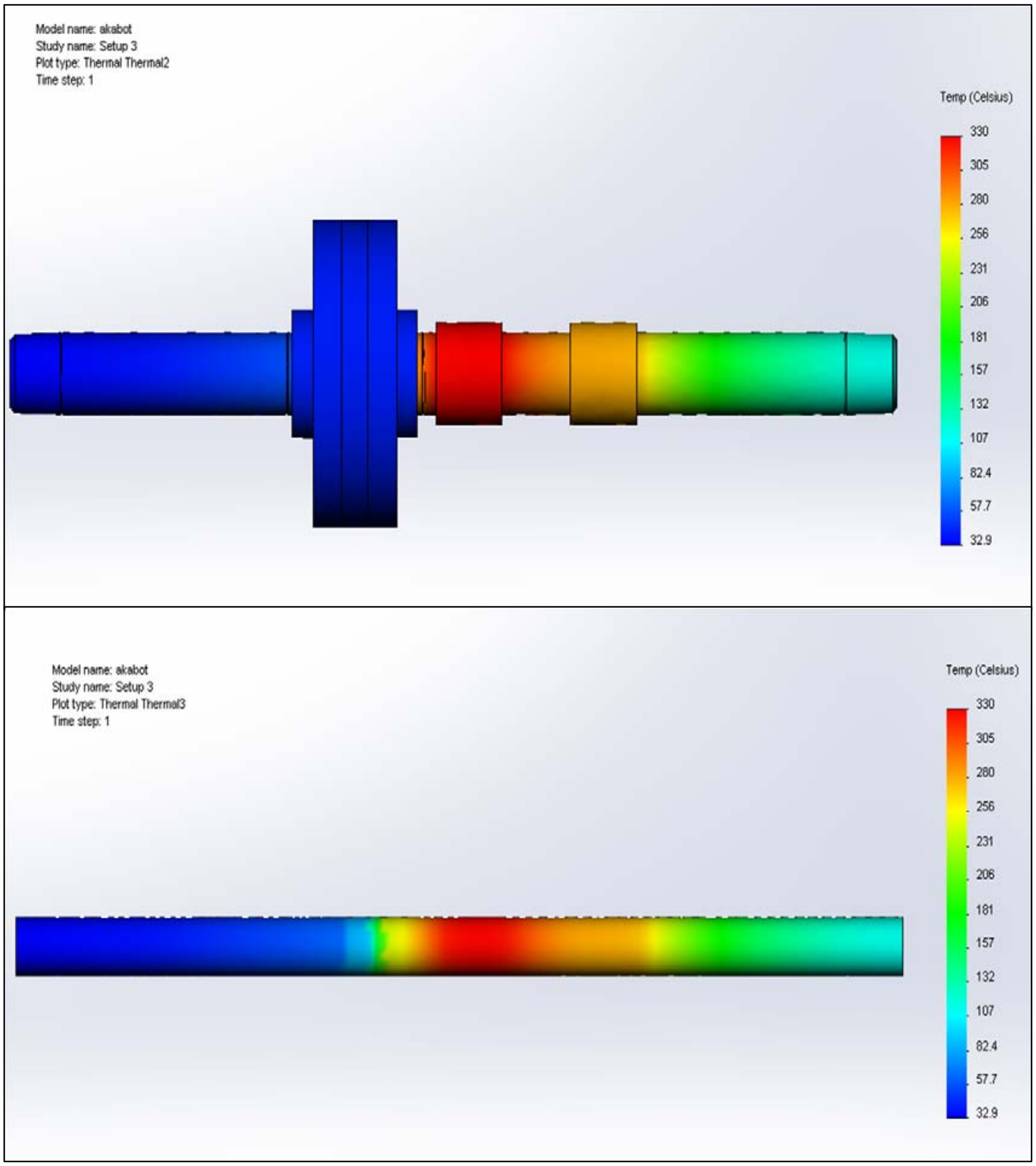


Figure A5: Thermal modeling results for Setup 3: flanged, insulated AkaBot with heaters at 1 inch, 60 W, and at 3 inches, 35 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

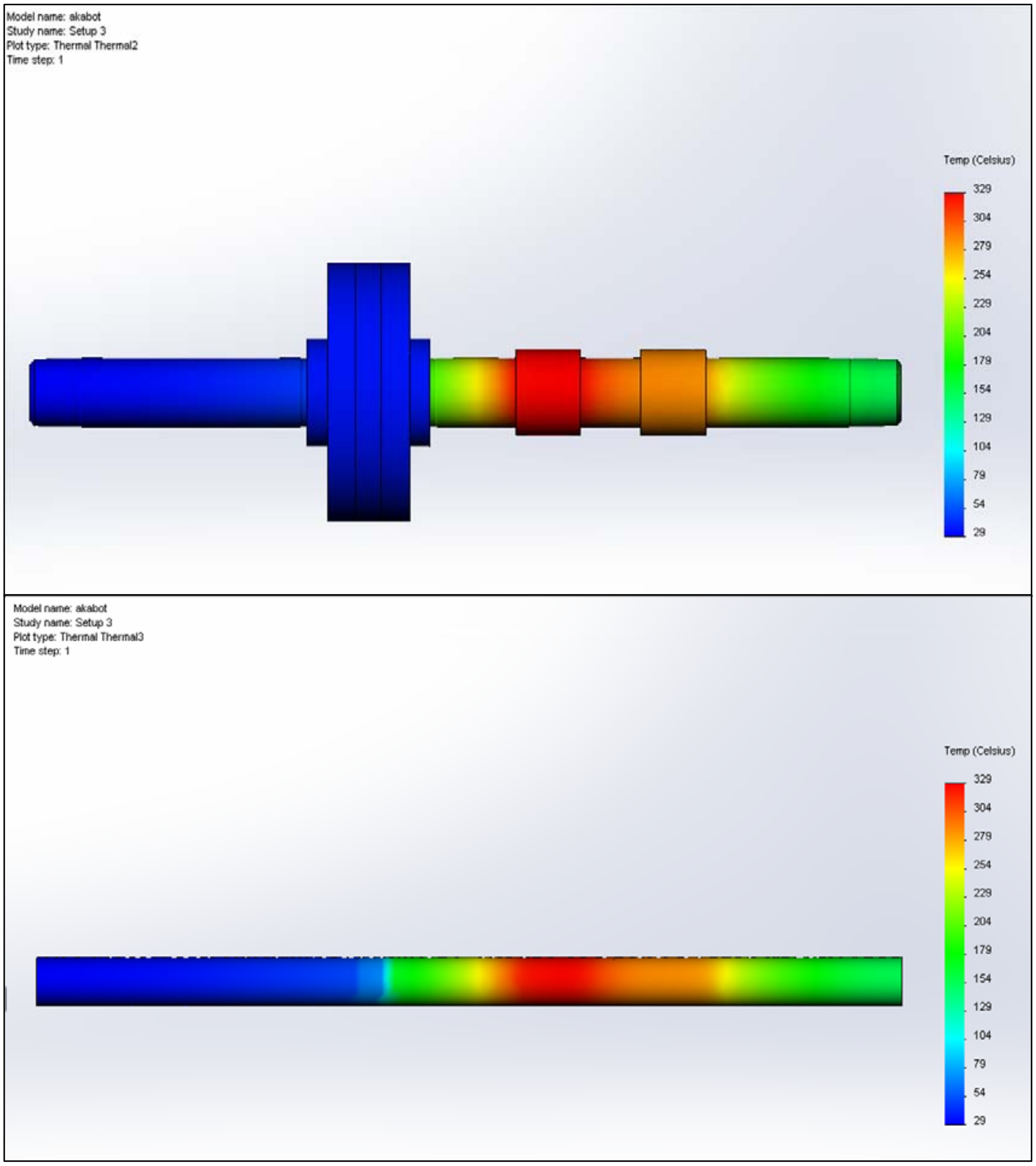


Figure A6: Thermal modeling results for Setup 4: flanged, insulated AkaBot with heaters at 2 inches, 60 W, and at 4 inches, 35 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

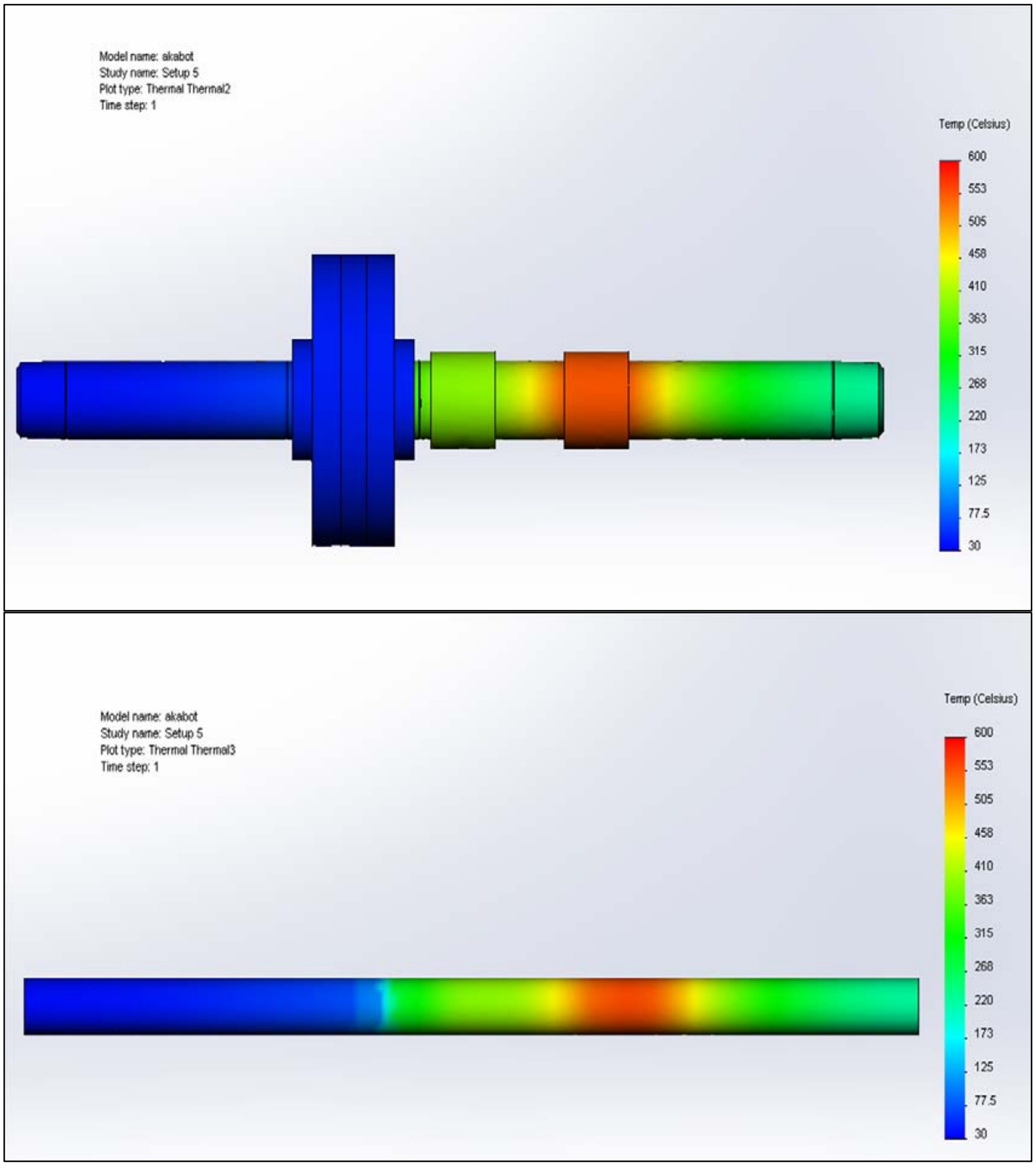


Figure A7: Thermal modeling results for Setup 5: flanged, insulated AkaBot with heaters at 1 inch, 35 W, and at 3 inches, 60 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

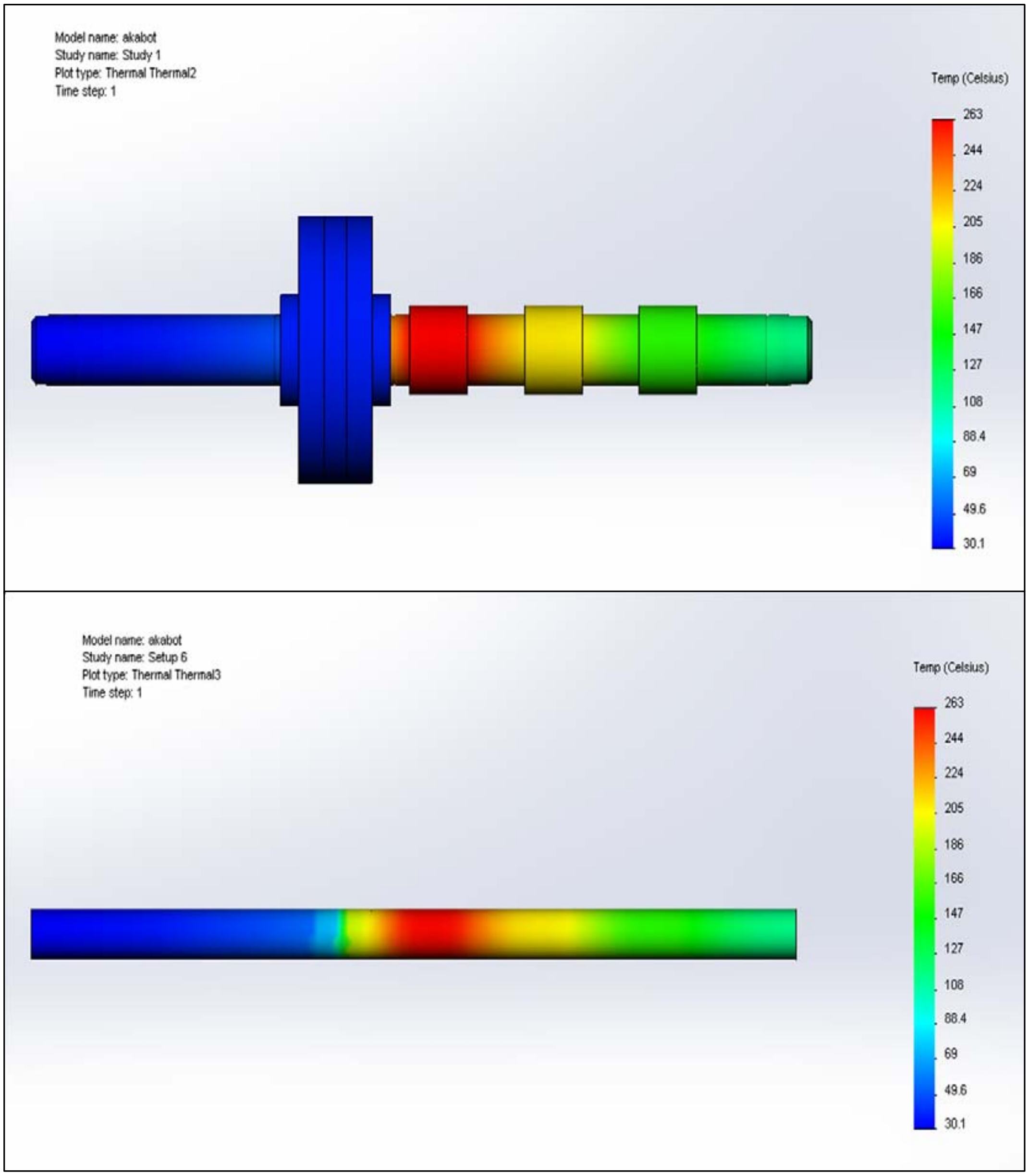


Figure A8: Thermal modeling results for Setup 6: flanged, insulated AkaBot with heaters at 1 inch, 50 W, at 3 inches, 20 W, and at 5 inches, 10 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

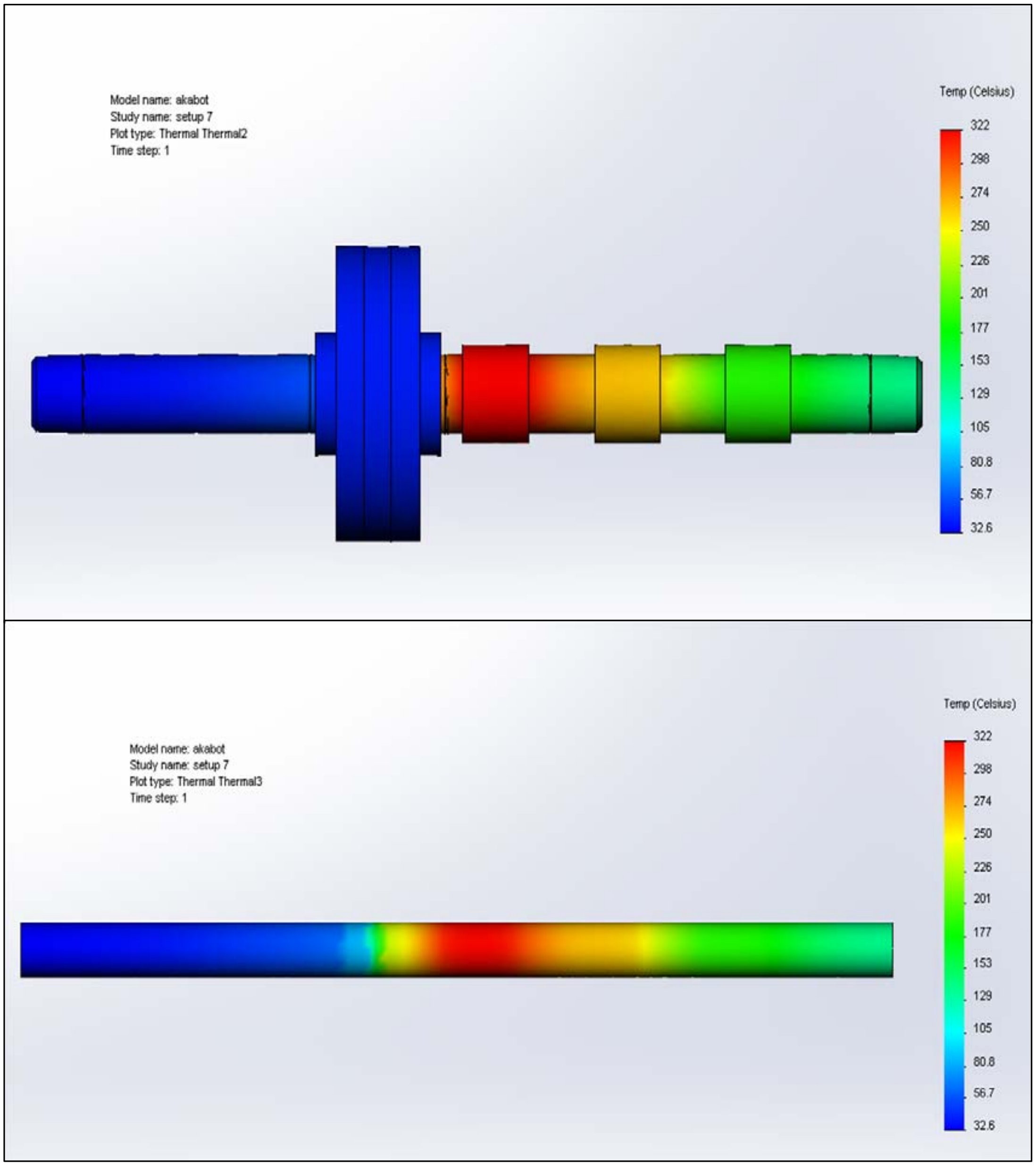


Figure A9: Thermal modeling results for Setup 7: flanged, insulated AkaBot with heaters at 1 inch, 60 W, at 3 inches, 30 W, and at 5 inches, 10 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

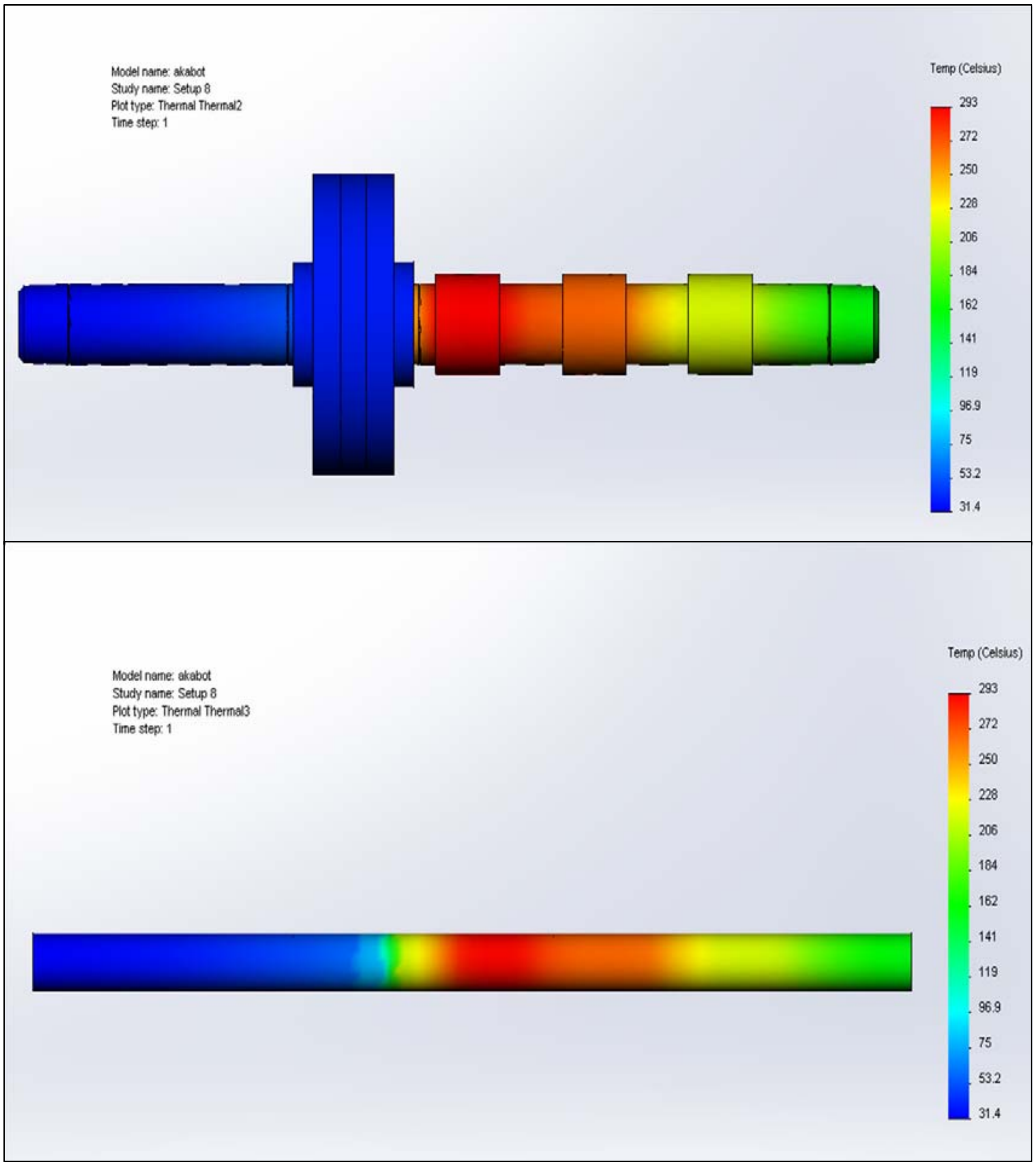


Figure A10: Thermal modeling results for Setup 8: flanged, insulated AkaBot with heaters at 1 inch, 50 W, at 3 inches, 30 W, and at 5 inches, 20 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

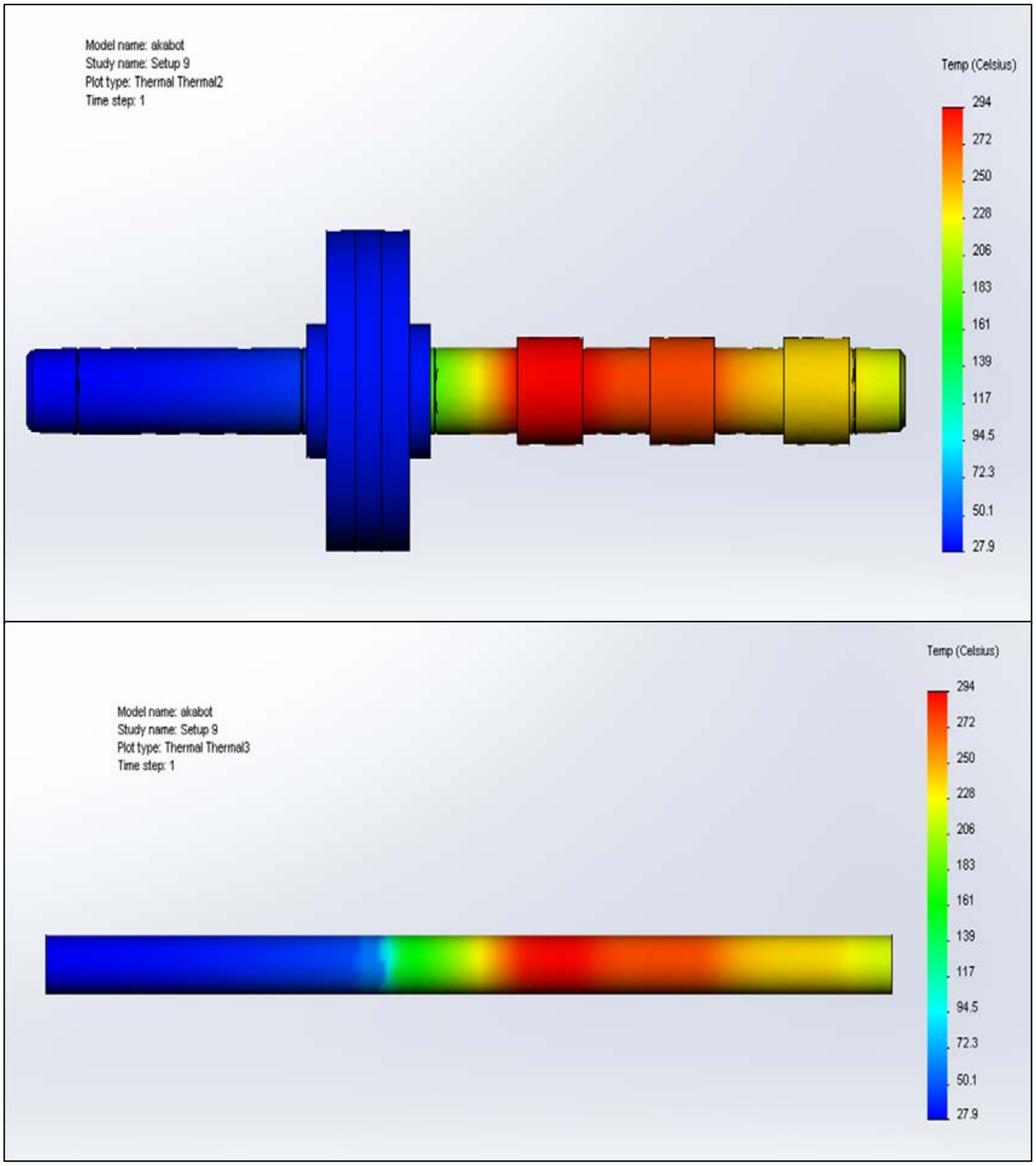


Figure A11: Thermal modeling results for Setup 9: flanged, insulated AkaBot with heaters at 2 inches, 50 W, at 4 inches, 30 W, and at 6 inches, 20 W. Above is the full flanged machine, and below is the PET plastic in an isolated view.

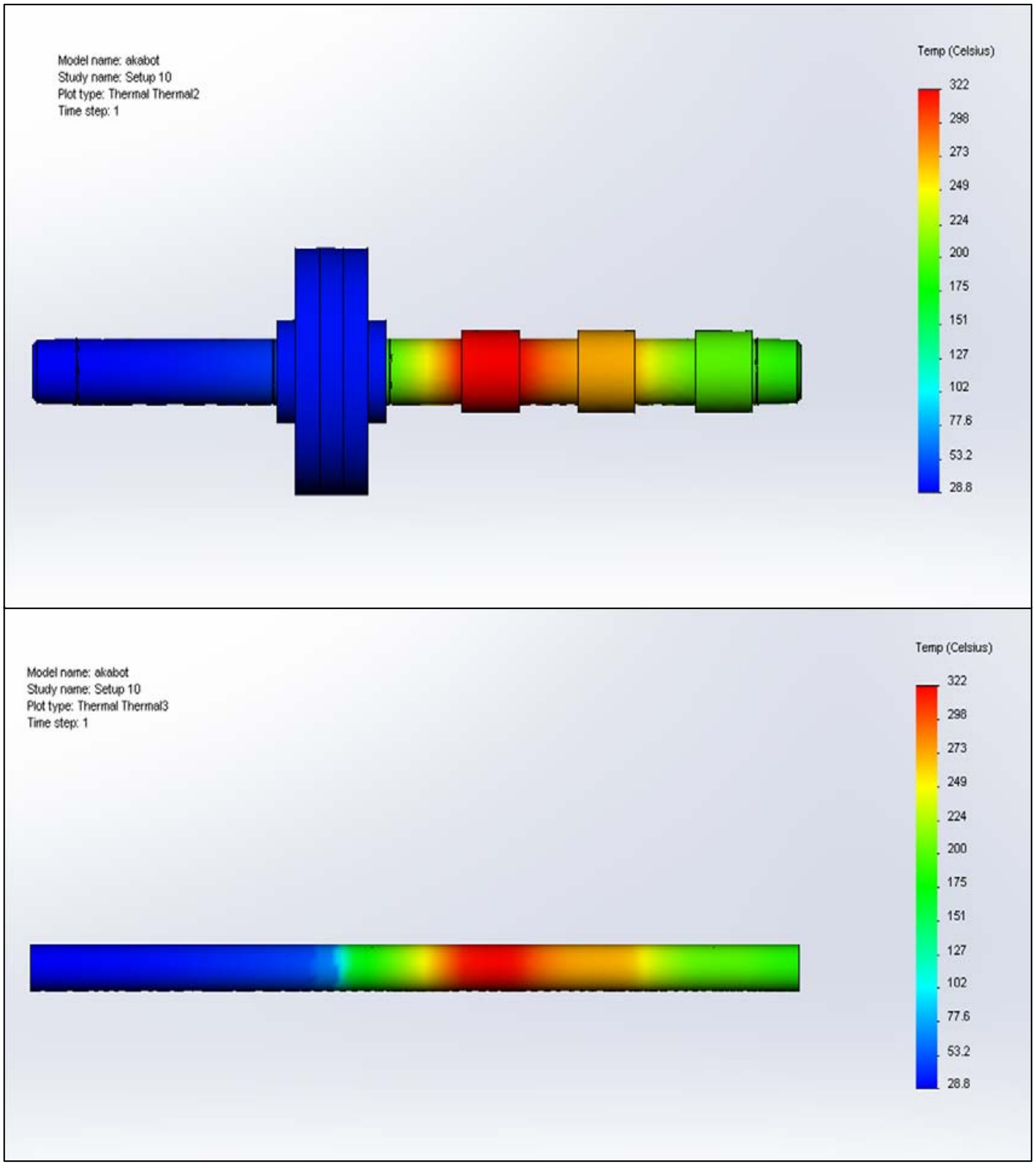


Figure A12: Thermal modeling results for Setup 11: un-flanged, uninsulated AkaBot with heaters at 1 inch, 50 W, and at 3 inches, 50 W. Above is the full machine, and below is the PET plastic in an isolated view.

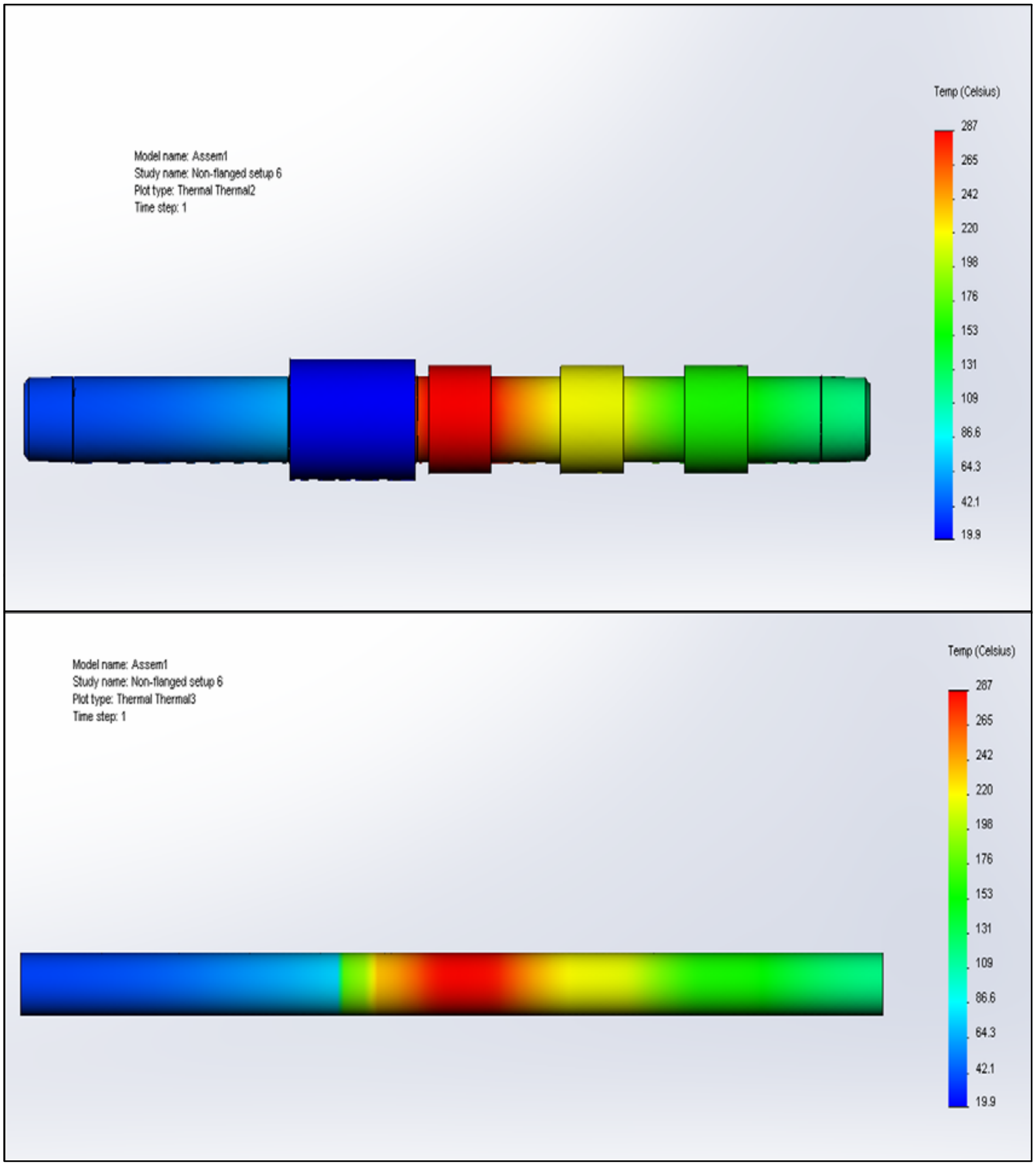
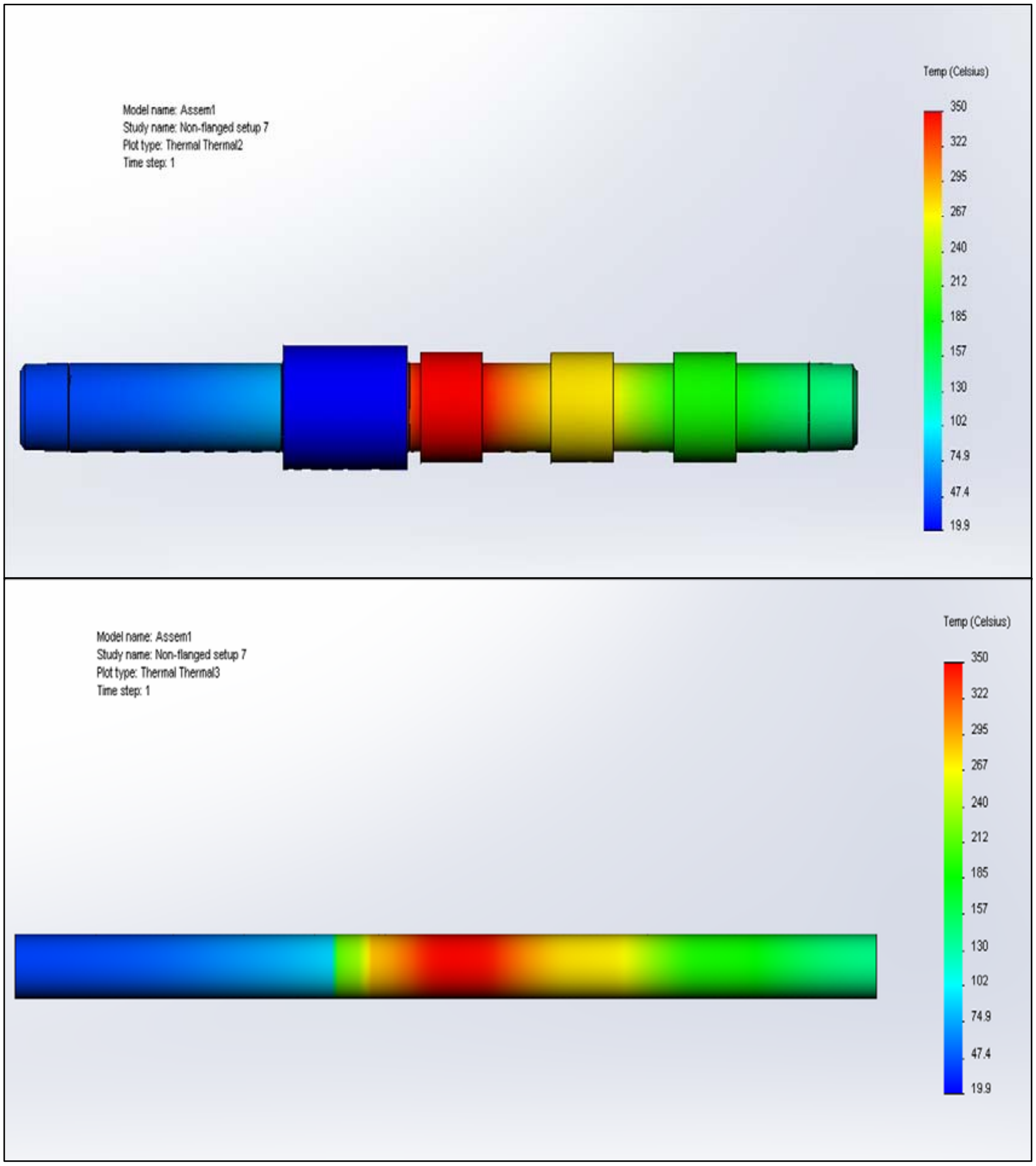


Figure A13: Thermal modeling results for Setup 12: un-flanged, uninsulated AkaBot with heaters at 1 inch, 50 W, at 3 inches, 20 W, and at 5 inches, 10 W. Above is the full machine, and below is the PET plastic in an isolated view.

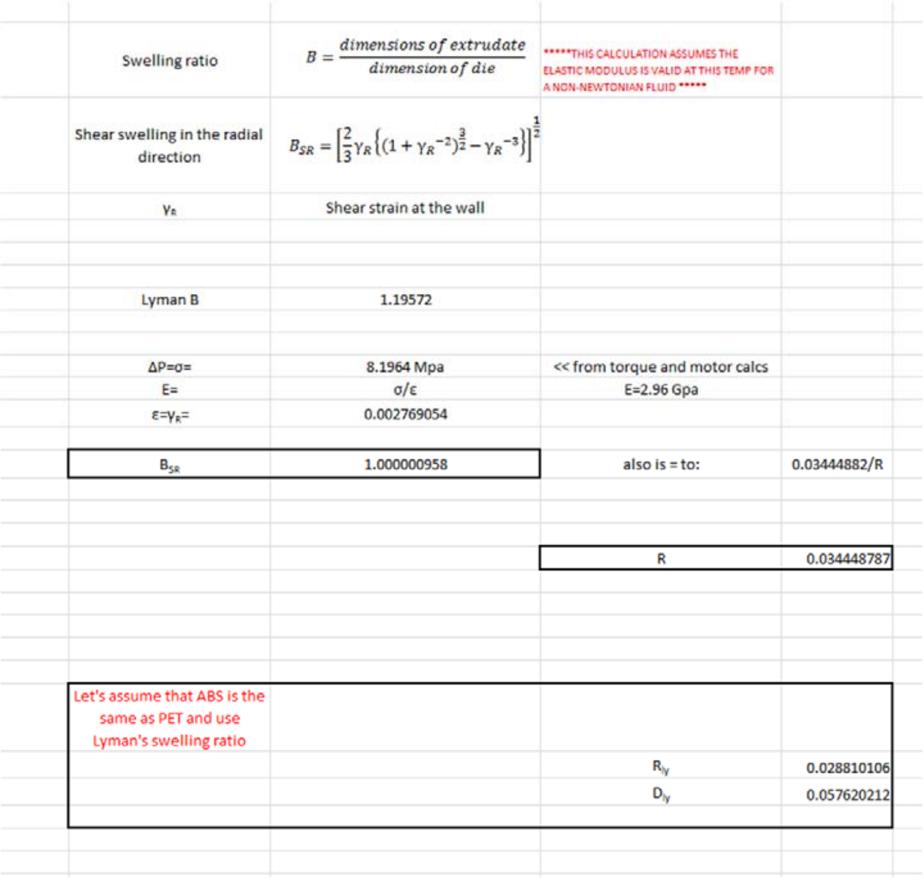


Model name: Assem1
Study name: Non-flanged setup 7
Plot type: Thermal Thermal2
Time step: 1

Model name: Assem1
Study name: Non-flanged setup 7
Plot type: Thermal Thermal3
Time step: 1

Figure A14: Thermal modeling results for Setup 13: un-flanged, uninsulated AkaBot with heaters at 1 inch, 60 W, at 3 inches, 30 W, and at 5 inches, 10 W. Above is the full machine, and below is the PET plastic in an isolated view.

Appendix I: Die Swell Calculations



Swelling ratio	$B = \frac{dimensions\ of\ extrudate}{dimension\ of\ die}$	*****THIS CALCULATION ASSUMES THE ELASTIC MODULUS IS VALID AT THIS TEMP FOR A NON-NEWTONIAN FLUID *****	
Shear swelling in the radial direction	$B_{SR} = \left[\frac{2}{3}\gamma_R\left\{(1+\gamma_R{}^{-2})^{\frac{3}{2}} - \gamma_R{}^{-3}\right\}\right]^{\frac{1}{2}}$		
γ_R	Shear strain at the wall		
Lyman B	1.19572		
$\Delta P=\sigma=$	8.1964 Mpa	<< from torque and motor calcs	
E=	σ/ε	E=2.96 Gpa	
$\varepsilon=\gamma_R=$	0.002769054		
B_{SR}	1.000000958	also is = to:	0.03444882/R
		R	0.034448787
Let's assume that ABS is the same as PET and use Lyman's swelling ratio			
		R_{ly}	0.028810106
		D_{ly}	0.057620212

Figure A15: Die Swell calculations.

Appendix J: DSC Graphs

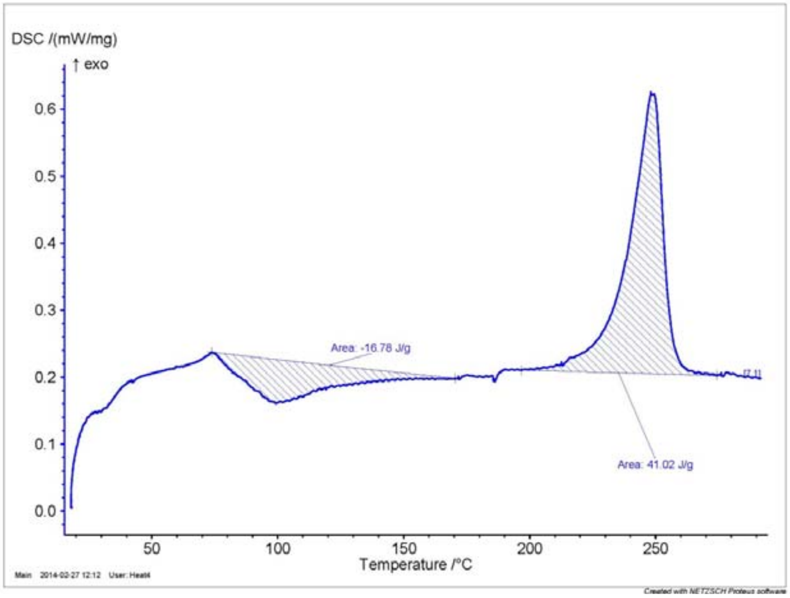


Figure A16: The DSC graph from the Rwenzori water bottle test before extruding (Sample 2).

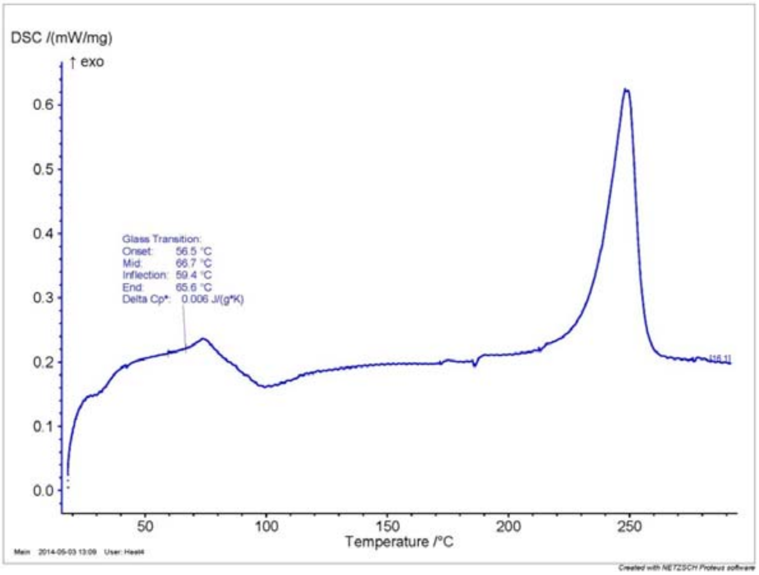


Figure A17: The DSC graph from the Rwenzori water bottle test before extruding (Sample 2).

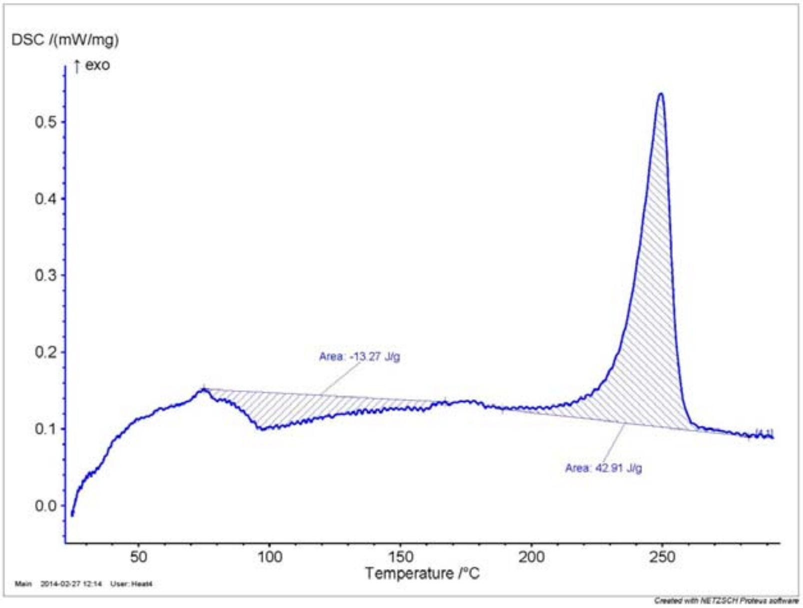


Figure A18: The DSC graph from the Rwenzori water bottle test before extruding (Sample 3).

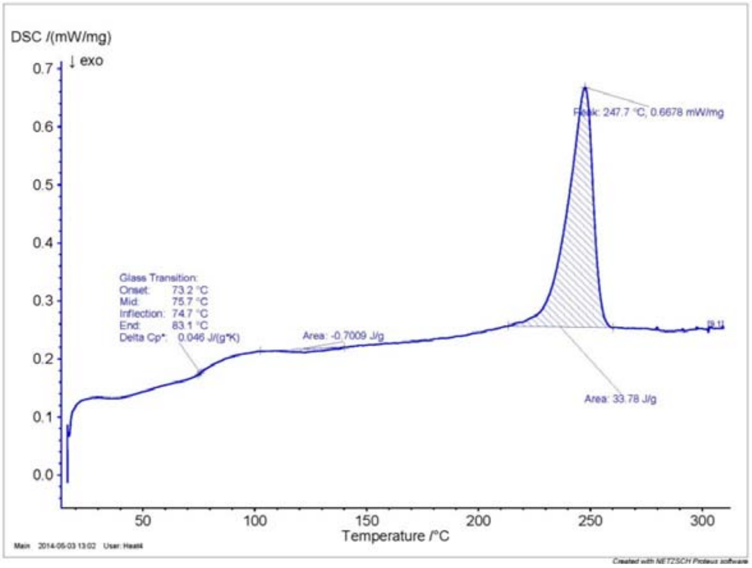


Figure A19: The DSC graph from the Rwenzori water bottle test after extruding (Sample 2).

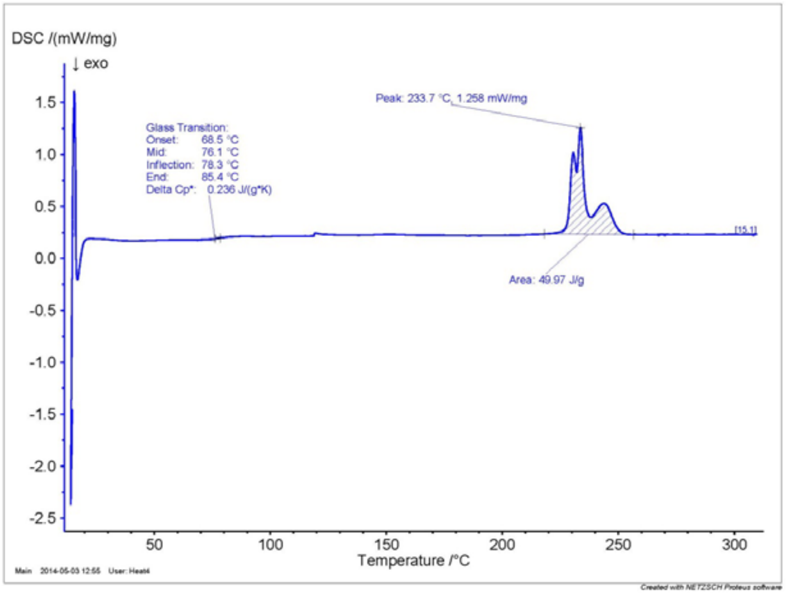


Figure A20: The DSC graph from the PET pellets before extruding (Sample 2).

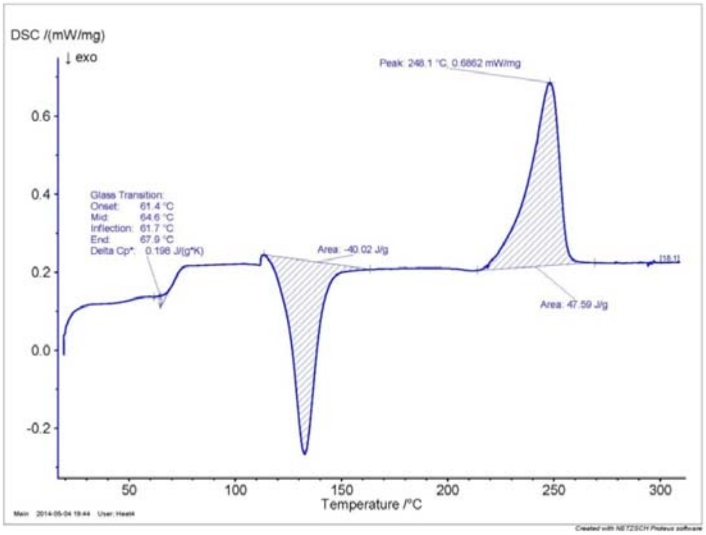


Figure A21: The DSC graph from the PET pellets test after extruding (Sample 2).

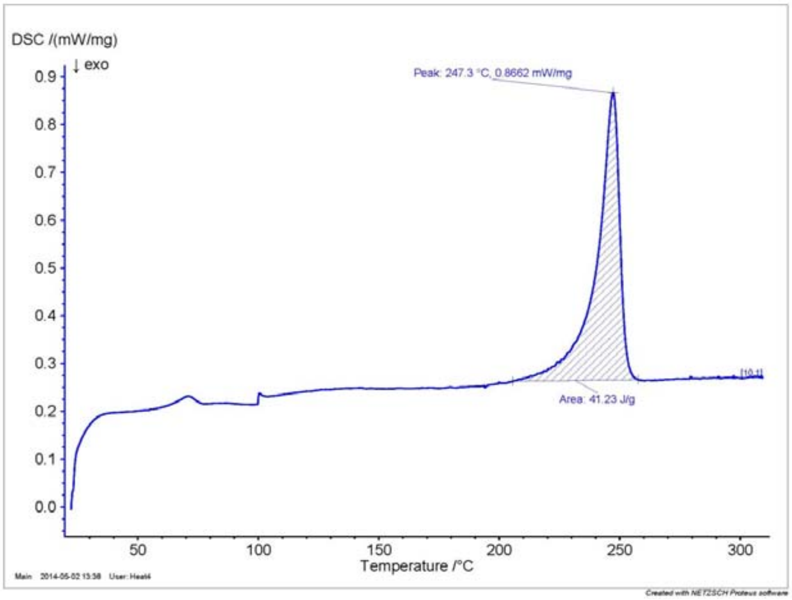


Figure A22: The DSC graph from the Costco water bottle test before extruding (Sample 1).

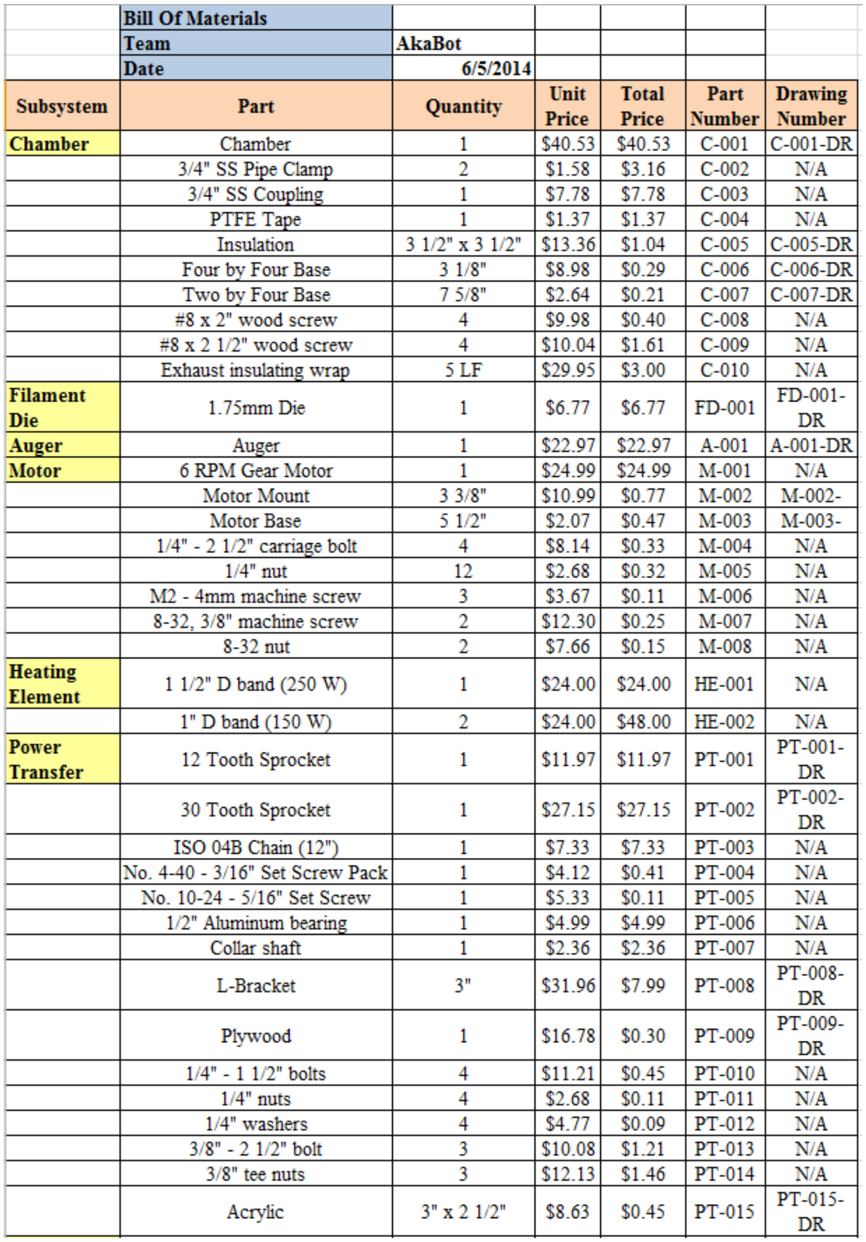
Appendix K: Economic Analysis Variables

Table A5: Factors used in economic analysis

	Description	Units	Value
Option 1: Import Filament	Cost of 1kg spool PLA	$/kg	30
	Shipping cost (DHL)	$/5kg	315
	Total Cost of 1kg PET	$/kg	97
	Consumption rate of 1kg*	kg/week	1
	Total cost/month of importing filament	$/month	388
	Lag time per spool	days	4
	Hassle factor rating	1 to 10	4
Option 2: Make Filament using AkaBot	Water bottles to make 1 kg	#/kg	180
	Cost per water bottle	$	0.05
	Cleaning supplies (oil, soap)	$/month	10
	Maintenance cost	$/month	10
	Labor cost	$/month	200
	Hair dryer	$	10
	Shredder	$	150
	AkaBot price	$	447
	Total fixed costs	$/month	635
	Lag time per spool	days	2 days
	Hassle factor rating	1 to 10	10

Appendix L: Bill of Materials

Table A6: Bill of Materials for AkaBot

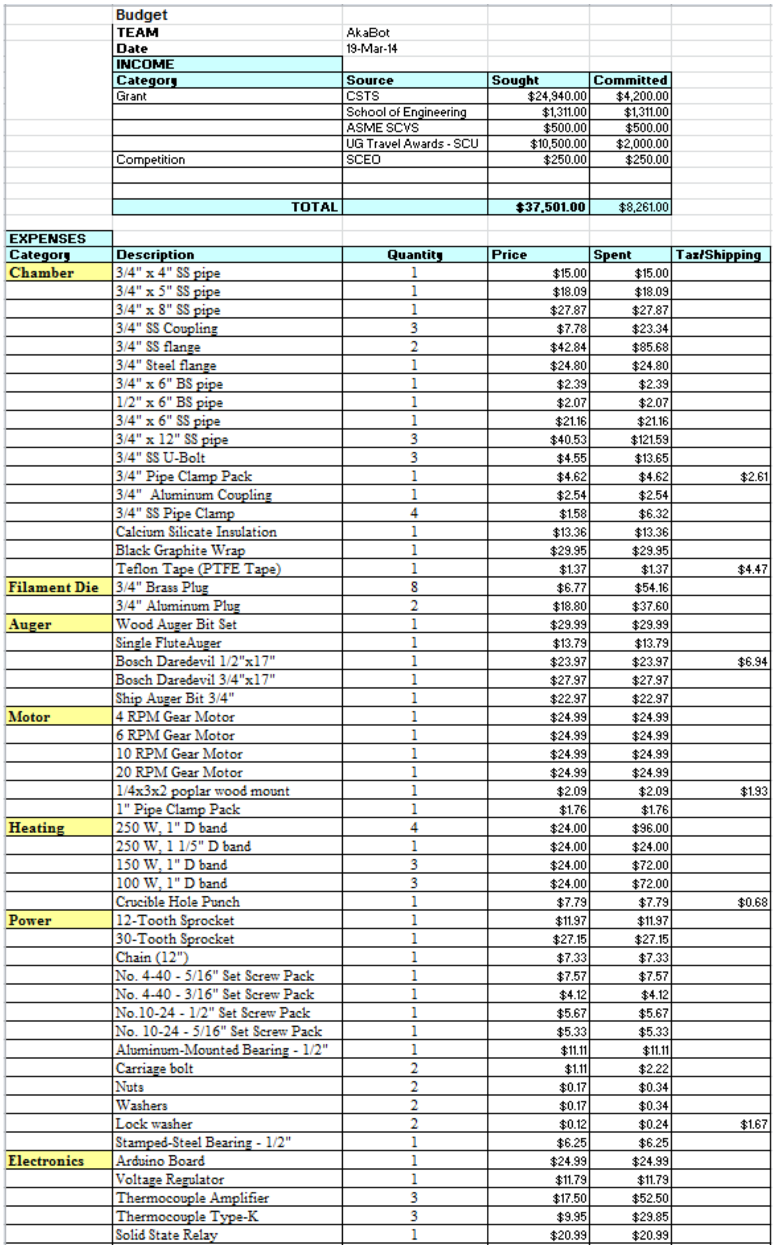


	Bill Of Materials					
	Team	**AkaBot**				
	Date	**6/5/2014**				
Subsystem	**Part**	**Quantity**	**Unit Price**	**Total Price**	**Part Number**	**Drawing Number**
Chamber	Chamber	1	$40.53	$40.53	C-001	C-001-DR
	3/4" SS Pipe Clamp	2	$1.58	$3.16	C-002	N/A
	3/4" SS Coupling	1	$7.78	$7.78	C-003	N/A
	PTFE Tape	1	$1.37	$1.37	C-004	N/A
	Insulation	3 1/2" x 3 1/2"	$13.36	$1.04	C-005	C-005-DR
	Four by Four Base	3 1/8"	$8.98	$0.29	C-006	C-006-DR
	Two by Four Base	7 5/8"	$2.64	$0.21	C-007	C-007-DR
	#8 x 2" wood screw	4	$9.98	$0.40	C-008	N/A
	#8 x 2 1/2" wood screw	4	$10.04	$1.61	C-009	N/A
	Exhaust insulating wrap	5 LF	$29.95	$3.00	C-010	N/A
Filament Die	1.75mm Die	1	$6.77	$6.77	FD-001	FD-001-DR
Auger	Auger	1	$22.97	$22.97	A-001	A-001-DR
Motor	6 RPM Gear Motor	1	$24.99	$24.99	M-001	N/A
	Motor Mount	3 3/8"	$10.99	$0.77	M-002	M-002-
	Motor Base	5 1/2"	$2.07	$0.47	M-003	M-003-
	1/4" - 2 1/2" carriage bolt	4	$8.14	$0.33	M-004	N/A
	1/4" nut	12	$2.68	$0.32	M-005	N/A
	M2 - 4mm machine screw	3	$3.67	$0.11	M-006	N/A
	8-32, 3/8" machine screw	2	$12.30	$0.25	M-007	N/A
	8-32 nut	2	$7.66	$0.15	M-008	N/A
Heating Element	1 1/2" D band (250 W)	1	$24.00	$24.00	HE-001	N/A
	1" D band (150 W)	2	$24.00	$48.00	HE-002	N/A
Power Transfer	12 Tooth Sprocket	1	$11.97	$11.97	PT-001	PT-001-DR
	30 Tooth Sprocket	1	$27.15	$27.15	PT-002	PT-002-DR
	ISO 04B Chain (12")	1	$7.33	$7.33	PT-003	N/A
	No. 4-40 - 3/16" Set Screw Pack	1	$4.12	$0.41	PT-004	N/A
	No. 10-24 - 5/16" Set Screw	1	$5.33	$0.11	PT-005	N/A
	1/2" Aluminum bearing	1	$4.99	$4.99	PT-006	N/A
	Collar shaft	1	$2.36	$2.36	PT-007	N/A
	L-Bracket	3"	$31.96	$7.99	PT-008	PT-008-DR
	Plywood	1	$16.78	$0.30	PT-009	PT-009-DR
	1/4" - 1 1/2" bolts	4	$11.21	$0.45	PT-010	N/A
	1/4" nuts	4	$2.68	$0.11	PT-011	N/A
	1/4" washers	4	$4.77	$0.09	PT-012	N/A
	3/8" - 2 1/2" bolt	3	$10.08	$1.21	PT-013	N/A
	3/8" tee nuts	3	$12.13	$1.46	PT-014	N/A
	Acrylic	3" x 2 1/2"	$8.63	$0.45	PT-015	PT-015-DR

Subsystem	Part	Quantity	Unit Price	Total Price	Part Number	Drawing Number
Electronics	Fan	1	$7.79	$7.79	E-001	N/A
	Step Down Converter	1	$8.00	$8.00	E-002	N/A
	Power Supply (3-prong)	1	$9.99	$9.99	E-003	N/A
	PID + Solid State + Thermo	3	$39.88	$119.64	E-004	N/A
	Wire Nuts	1	$3.49	$3.49	E-005	N/A
	Wire	1	$8.49	$8.49	E-006	N/A
	Switches	2	$3.95	$7.90	E-007	N/A
	Thermocouple Type-K	3	$9.95	$29.85	E-008	N/A
	Electronics Panel	23.75" x 24"	$7.97	$4.01	E-009	E-009-DR
	2 1/2" Corner brace	1	$4.79	$3.59	E-010	N/A
Feed Hopper	Hopper Small	1	$10.48	$10.48	FH-001	FH-001-DR
	Hopper Big	1	$10.48	$10.48	FH-002	FH-002-DR
	J-B Weld	1	$5.67	$5.67	FH-003	N/A
	Hopper Entrance	2"	$8.34	$1.39	FH-004	FH-004-DR
Enclosure	Machine Base	23.75" x 12"	$19.97	$5.02	EN-001	EN-001-DR
Grand Total				**$484.28**		

Appendix M: Budget

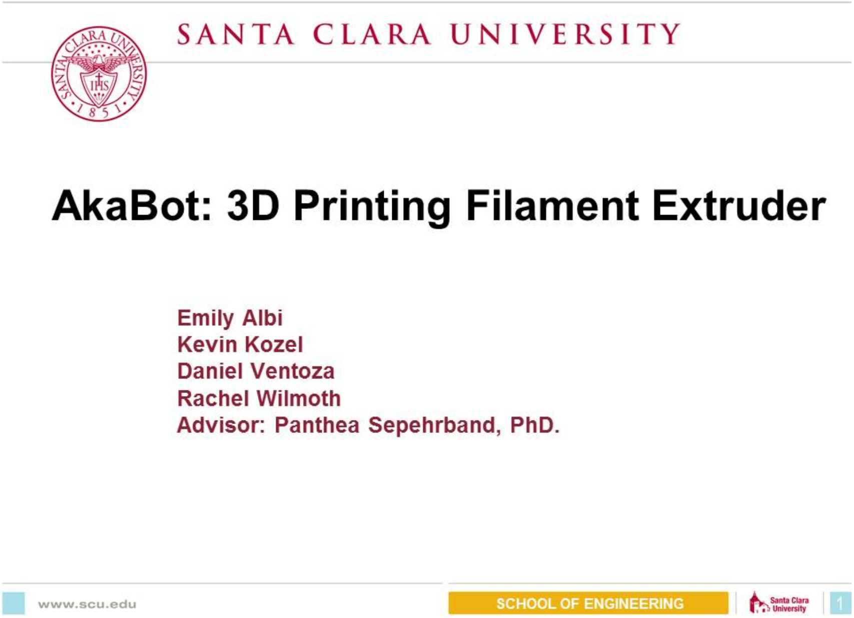
Table A7: Budget



	Budget				
	TEAM	AkaBot			
	Date	19-Mar-14			
	INCOME				
	Category	**Source**	**Sought**	**Committed**	
	Grant	CSTS	$24,940.00	$4,200.00	
		School of Engineering	$1,311.00	$1,311.00	
		ASME SCVS	$500.00	$500.00	
		UG Travel Awards - SCU	$10,500.00	$2,000.00	
	Competition	SCEO	$250.00	$250.00	
	TOTAL		**$37,501.00**	$8,261.00	
EXPENSES					
Category	**Description**	**Quantity**	**Price**	**Spent**	**Tax/Shipping**
Chamber	3/4" x 4" SS pipe	1	$15.00	$15.00	
	3/4" x 5" SS pipe	1	$18.09	$18.09	
	3/4" x 8" SS pipe	1	$27.87	$27.87	
	3/4" SS Coupling	3	$7.78	$23.34	
	3/4" SS flange	2	$42.84	$85.68	
	3/4" Steel flange	1	$24.80	$24.80	
	3/4" x 6" BS pipe	1	$2.39	$2.39	
	1/2" x 6" BS pipe	1	$2.07	$2.07	
	3/4" x 6" SS pipe	1	$21.16	$21.16	
	3/4" x 12" SS pipe	3	$40.53	$121.59	
	3/4" SS U-Bolt	3	$4.55	$13.65	
	3/4" Pipe Clamp Pack	1	$4.62	$4.62	$2.61
	3/4" Aluminum Coupling	1	$2.54	$2.54	
	3/4" SS Pipe Clamp	4	$1.58	$6.32	
	Calcium Silicate Insulation	1	$13.36	$13.36	
	Black Graphite Wrap	1	$29.95	$29.95	
	Teflon Tape (PTFE Tape)	1	$1.37	$1.37	$4.47
Filament Die	3/4" Brass Plug	8	$6.77	$54.16	
	3/4" Aluminum Plug	2	$18.80	$37.60	
Auger	Wood Auger Bit Set	1	$29.99	$29.99	
	Single FluteAuger	1	$13.79	$13.79	
	Bosch Daredevil 1/2"x17"	1	$23.97	$23.97	$6.94
	Bosch Daredevil 3/4"x17"	1	$27.97	$27.97	
	Ship Auger Bit 3/4"	1	$22.97	$22.97	
Motor	4 RPM Gear Motor	1	$24.99	$24.99	
	6 RPM Gear Motor	1	$24.99	$24.99	
	10 RPM Gear Motor	1	$24.99	$24.99	
	20 RPM Gear Motor	1	$24.99	$24.99	
	1/4x3x2 poplar wood mount	1	$2.09	$2.09	$1.93
	1" Pipe Clamp Pack	1	$1.76	$1.76	
Heating	250 W, 1" D band	4	$24.00	$96.00	
	250 W, 1 1/5" D band	1	$24.00	$24.00	
	150 W, 1" D band	3	$24.00	$72.00	
	100 W, 1" D band	3	$24.00	$72.00	
	Crucible Hole Punch	1	$7.79	$7.79	$0.68
Power	12-Tooth Sprocket	1	$11.97	$11.97	
	30-Tooth Sprocket	1	$27.15	$27.15	
	Chain (12")	1	$7.33	$7.33	
	No. 4-40 - 5/16" Set Screw Pack	1	$7.57	$7.57	
	No. 4-40 - 3/16" Set Screw Pack	1	$4.12	$4.12	
	No.10-24 - 1/2" Set Screw Pack	1	$5.67	$5.67	
	No. 10-24 - 5/16" Set Screw Pack	1	$5.33	$5.33	
	Aluminum-Mounted Bearing - 1/2"	1	$11.11	$11.11	
	Carriage bolt	2	$1.11	$2.22	
	Nuts	2	$0.17	$0.34	
	Washers	2	$0.17	$0.34	
	Lock washer	2	$0.12	$0.24	$1.67
	Stamped-Steel Bearing - 1/2"	1	$6.25	$6.25	
Electronics	Arduino Board	1	$24.99	$24.99	
	Voltage Regulator	1	$11.79	$11.79	
	Thermocouple Amplifier	3	$17.50	$52.50	
	Thermocouple Type-K	3	$9.95	$29.85	
	Solid State Relay	1	$20.99	$20.99	

EXPENSES					
Category	**Description**	**Quantity**	**Price**	**Spent**	**Tax/Shipping**
	Fan 5v	1	$7.78	$7.78	
	Step Down Converter	1	$8.00	$8.00	
	Power Supply (2-prong)	1	$8.00	$8.00	
	12v 6a Power Supply	1	$9.50	$9.50	
	PID + Solid State + Thermo	3	$39.88	$119.64	
	5mmx23.75x47.75 mount	1	$8.04	$8.04	$0.70
	Wire Strippers	1	$23.45	$23.45	
	12v 5a Power Supply	1	$11.50	$11.50	$1.01
	Wire Nuts	1	$3.49	$3.49	
	Thin Wire	5LF	$0.17	$0.85	
	Thick Wire	2LF	$0.59	$1.18	
	50 gauge White Wire	10LF	$0.17	$1.70	$0.15
	Electical Tape	2	$0.99	$1.98	$0.57
	Switches	2	$3.95	$7.90	$0.59
	Multicolored wire	1	$8.49	$8.49	
	Cable ties	1	$3.99	$3.99	$0.74
	Gold Kapton Tap	1	$8.49	$8.49	
Feed Hopper	Galvanized Sheet 22 Guage	2	$10.48		$20.96
	J B weld	1	$5.67	$5.67	
Miscellaneous	3D Printer	1	$795.00	$795.00	
	12v 5a Power Supply	1	$7.73	$7.73	
	10 lbs PET Pellets	2	$40.00	$80.00	
	PET Filament (1.75mm)	1	$69.99	$69.99	$16.25
	PET Filament (3.00mm) 0.5 kg	1	$79.95	$79.95	
	Grinder	1	$199.99	$199.99	
	Ultrasonic Bath	1	$759.00	$759.00	
	Canola Oil	1	$2.99	$2.99	
	Canola Oil	3	$5.79	$17.37	
	Canola Oil	1	$6.59	$6.59	
	40pk water bottles	1	$3.89	$3.89	$2.00
	Dish Detergent	1	$1.99	$1.99	
	Tri Fold	1	$7.99	$7.99	
	Glue stick	1	$2.49	$2.49	
	Clips	1	$9.79	$9.79	$1.77
	Paper Towels	1	$0.99	$0.99	
	Cleaning Pads	1	$2.49	$2.49	
	Tooth Brush	1	$1.99	$1.99	$0.17
	Steel Wool Soap Pads	1	$2.29	$2.29	
	Plastic Container	1	$3.29	$3.29	$0.49
	Cleaning Buckets	2	$2.78	$5.56	
	Beaker	1	$6.00	$6.00	$0.53
	Sheet Pad Sander	1	$29.97	$29.97	
	Sanding Pads	2	$3.97	$7.94	
	Multimeter	1	$79.97	$79.97	$7.74
	Small container	1	$6.99	$6.99	
	Scour Pad	1	$1.94	$1.94	
	Small container	1	$2.19	$2.19	
	Isopropyl	3	$1.97	$5.91	$0.88
	Fiberglass screen	1	$6.78	$6.78	
	Nuts/Bolts/Washers	N/A	N/A	$35.34	$3.00
	12v Fan	1	$20.49	$20.49	$1.79
	Wire Basket	1	$23.50	$23.50	
Enclosure	Wood Screw	6	$1.09	$6.54	$0.10
	Wood Screws	2	$1.19	$2.38	
	23/32x23.75x47.75 base	1	$20.16	$20.16	
	4x4x10 lumber	1	$11.33	$11.33	
	2x4x96 lumber	1	$5.54	$5.54	$1.95
	4x4x8 lumber	1	$9.06	$9.06	
	Corner brace	3	$3.49	$10.47	
	TOTAL			$3,823.13	$79.69
	GRAND TOTAL				$3,902.82
	Net Reserve (Deficit)			$2,437.87	

Appendix N: PowerPoint Slides



SANTA CLARA UNIVERSITY

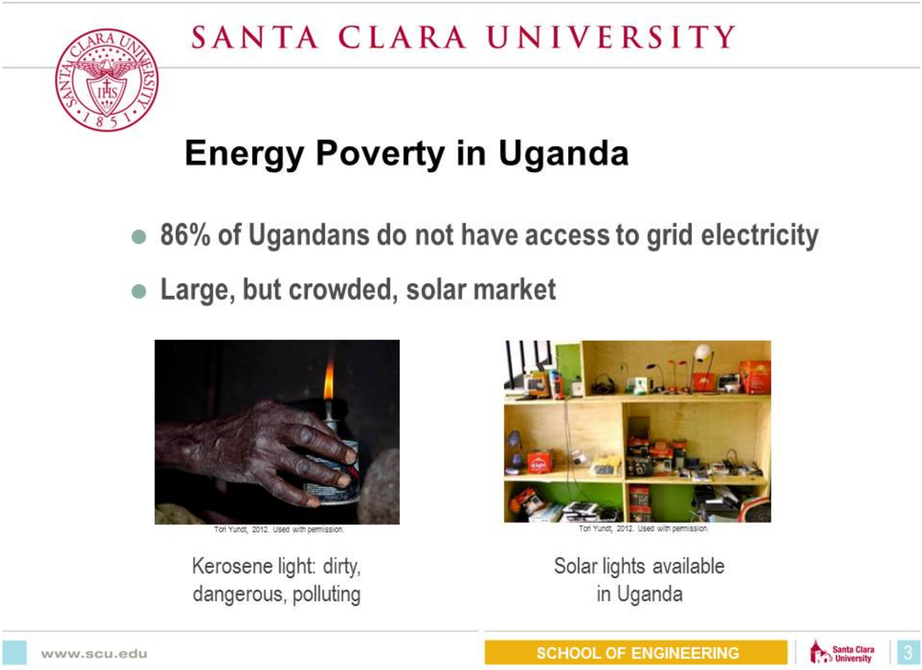
AkaBot: 3D Printing Filament Extruder

Emily Albi
Kevin Kozel
Daniel Ventoza
Rachel Wilmoth
Advisor: Panthea Sepehrband, PhD.

SANTA CLARA UNIVERSITY

Presentation Overview

- Problem statement
- System-level project overview
- Subsystem design process and analytical work
- Design iterations
- Testing framework
- Results and conclusion
- Next steps



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Energy Poverty in Uganda

- 86% of Ugandans do not have access to grid electricity
- Large, but crowded, solar market

Tori Yundt, 2012. Used with permission.

Kerosene light: dirty,
dangerous, polluting

Tori Yundt, 2012. Used with permission.

Solar lights available
in Uganda

www.scu.edu

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Village Energy Problem Statement

- Initial problem: uncompetitive aesthetics
- Initial solution: 3D print
- Our problem: imported filament unsustainable
- Our solution: filament made in Uganda

Picture taken by Team AkaBot, 2013.

Before

Picture taken by Team AkaBot, 2013.

After

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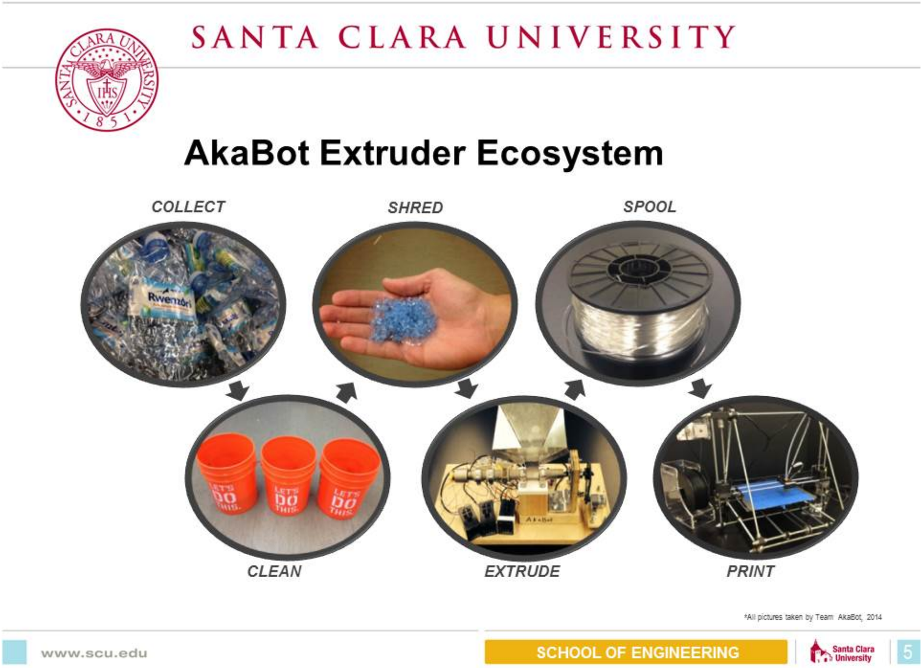

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AkaBot Extruder Ecosystem

*All pictures taken by Team AkaBot, 2014

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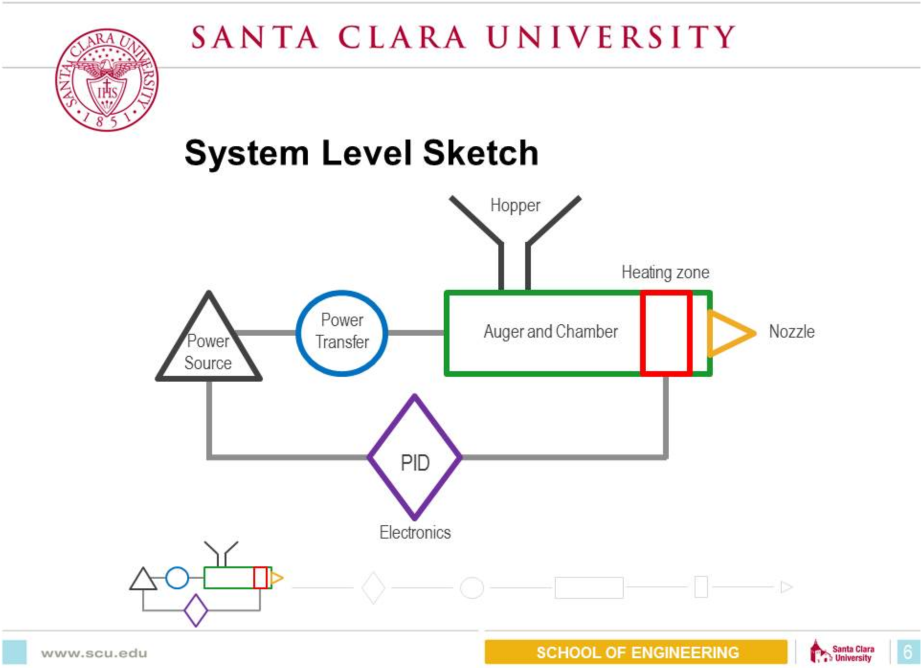

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System Level Sketch

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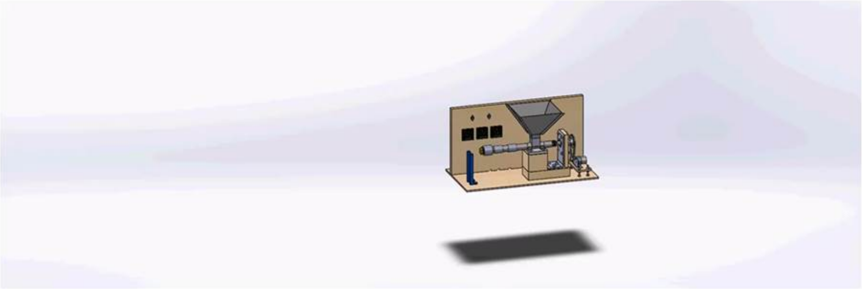
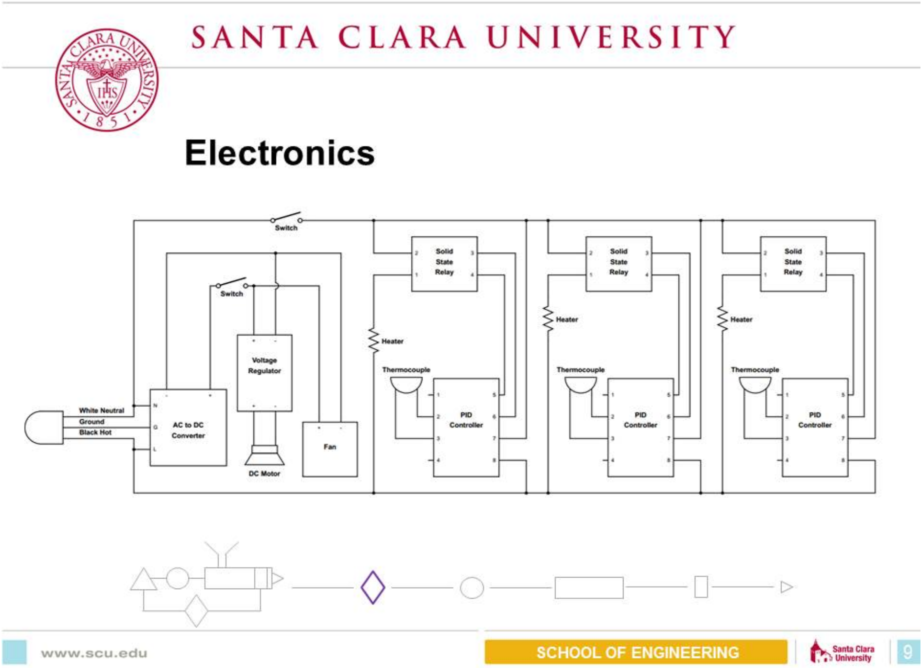
AkaBot 3D Model



System Requirements

Baseline	Requirement
Input Material	Polyethylene Terephthalate (PET)
Filament Size	3.00 mm
Production Rate	12 inch/min
Compatibility	3D Stuffmaker Mega Prusa
Filament Mechanical Properties	Ex. strain at fracture ~.4%
Filament Quality	Homogenous and uniform
Filament Tolerance	+/- 0.1 mm
Cost	$300



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Electronics

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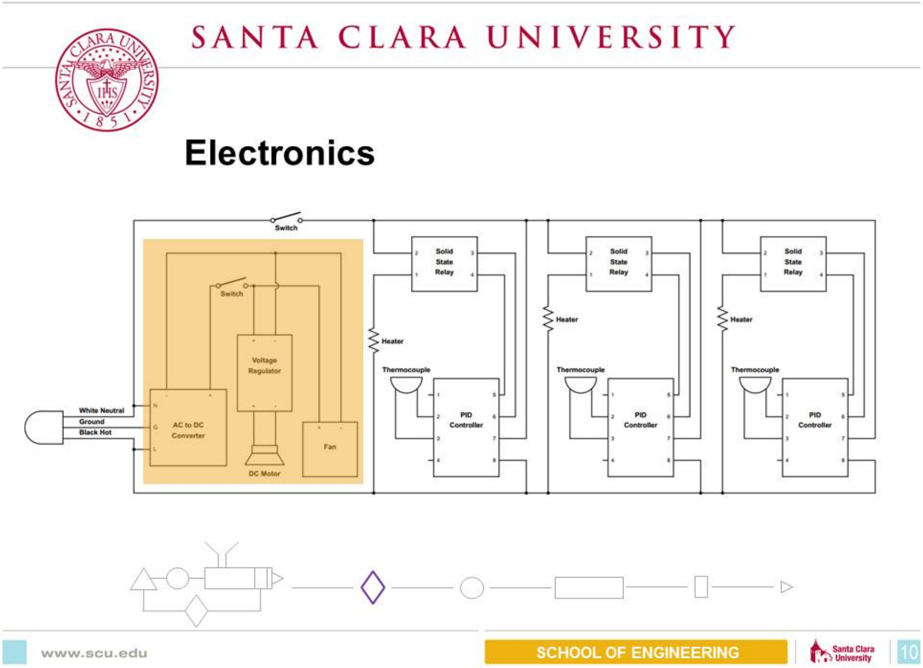

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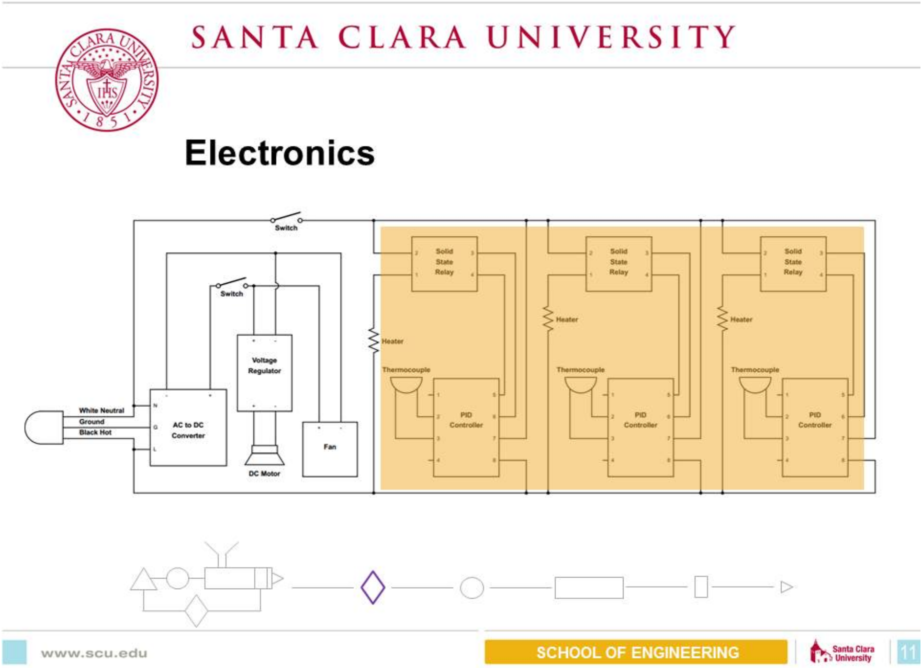

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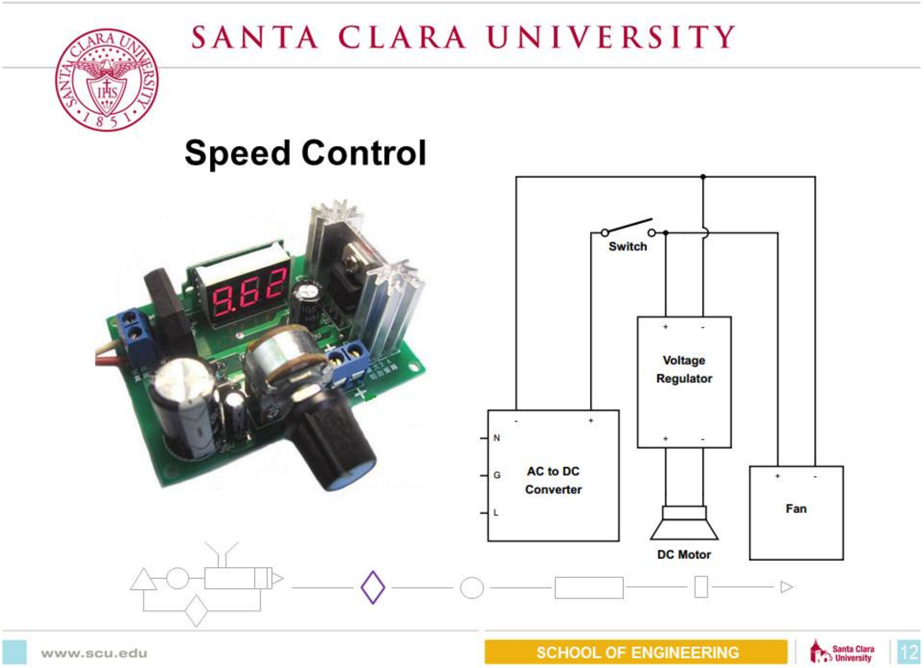

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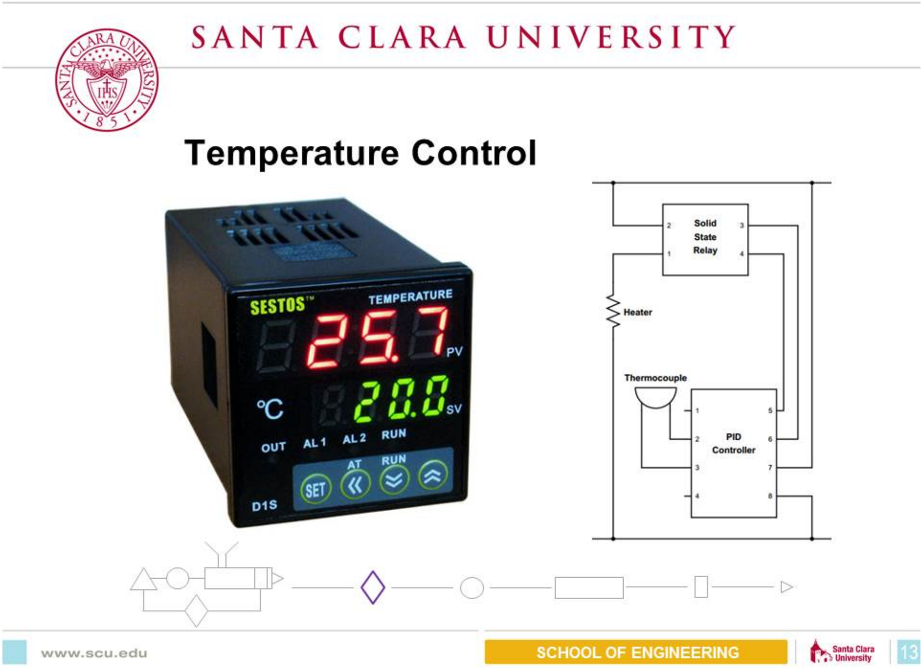
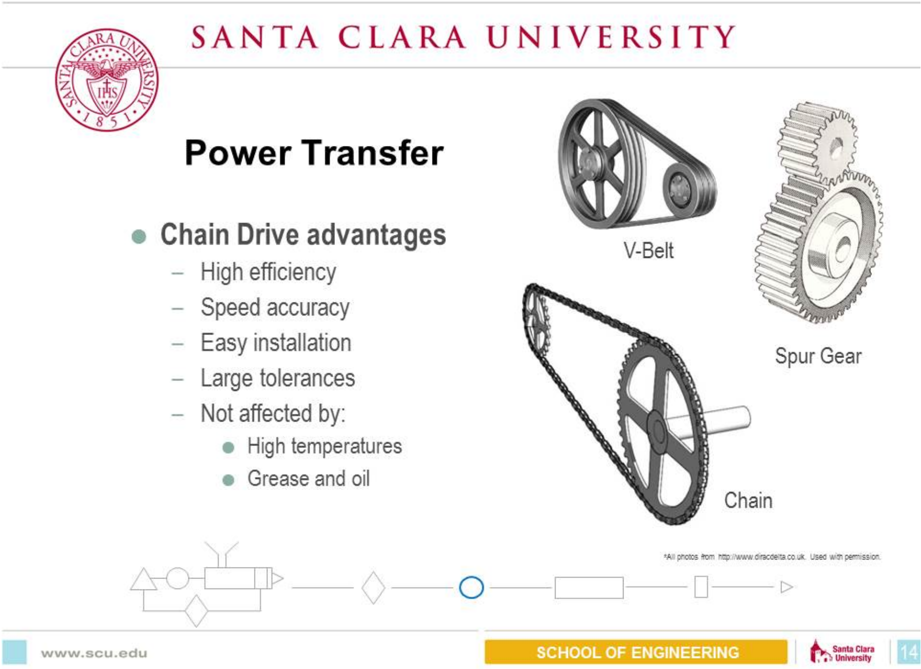
Speed Control



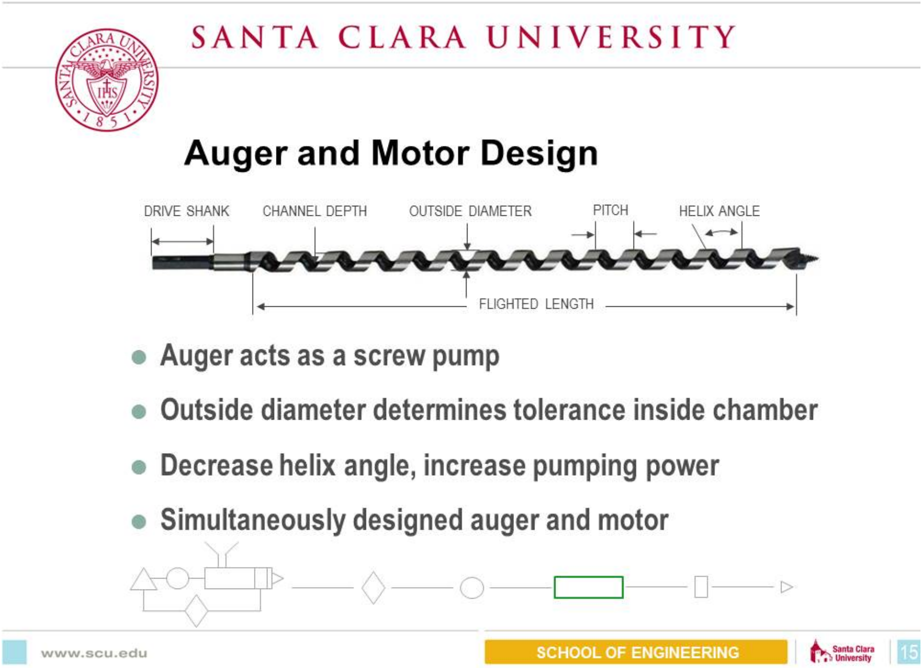
Temperature Control



Power Transfer

- Chain Drive advantages
  - High efficiency
  - Speed accuracy
  - Easy installation
  - Large tolerances
  - Not affected by:
    - High temperatures
    - Grease and oil

*All photos from http://www.diracdelta.co.uk. Used with permission.



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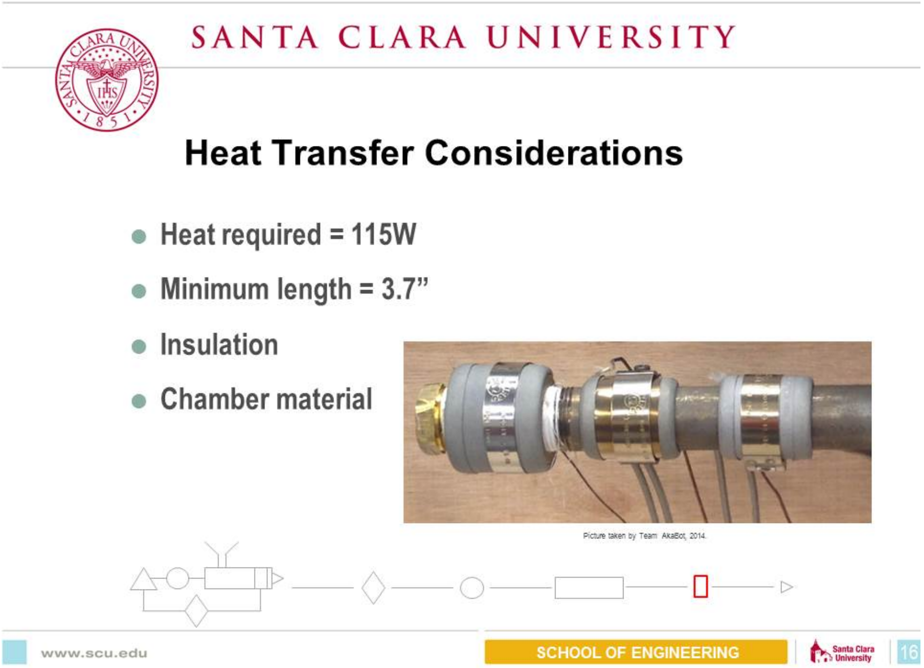
Auger and Motor Design

- Auger acts as a screw pump
- Outside diameter determines tolerance inside chamber
- Decrease helix angle, increase pumping power
- Simultaneously designed auger and motor



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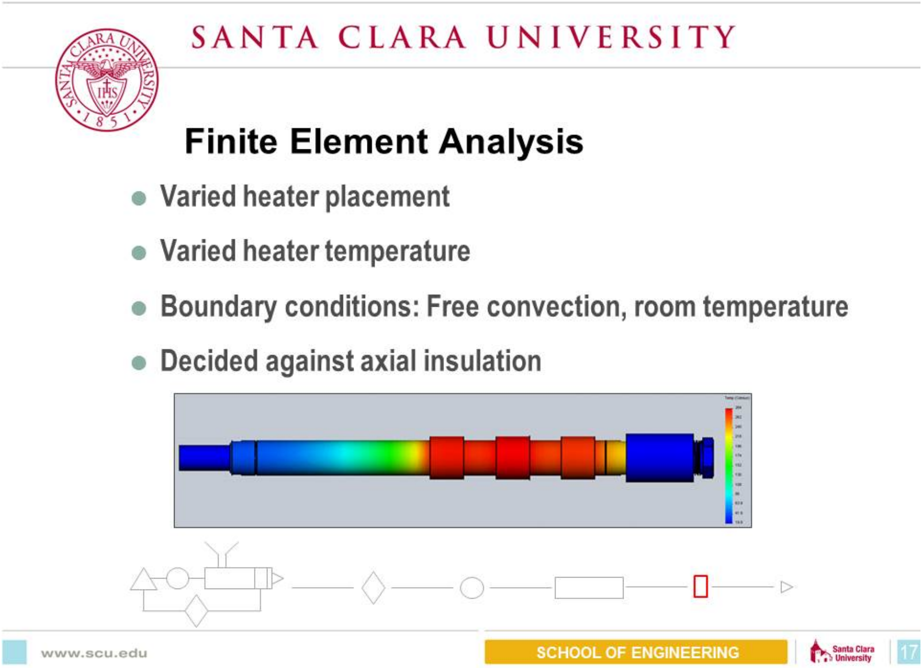
Heat Transfer Considerations

- Heat required = 115W
- Minimum length = 3.7”
- Insulation
- Chamber material

Picture taken by Team AkaBot, 2014.



Finite Element Analysis

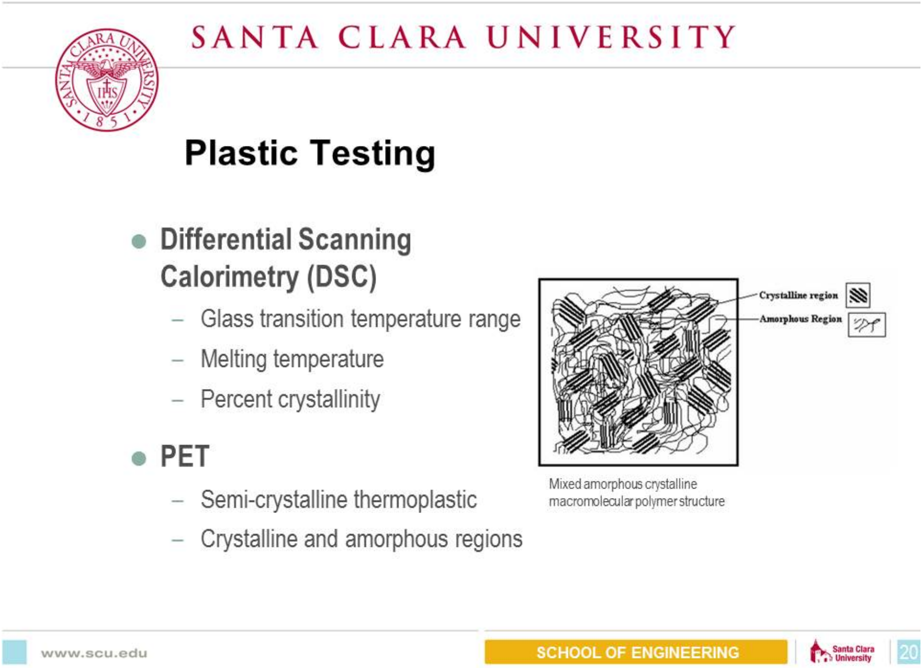
- Varied heater placement
- Varied heater temperature
- Boundary conditions: Free convection, room temperature
- Decided against axial insulation

Nozzle Design

- Brass plug advantages
  - Conductivity
  - Simplicity
- Conical shape
- Plastic should begin cooling in the nozzle
- Shear swelling ratio

Design Modification Process

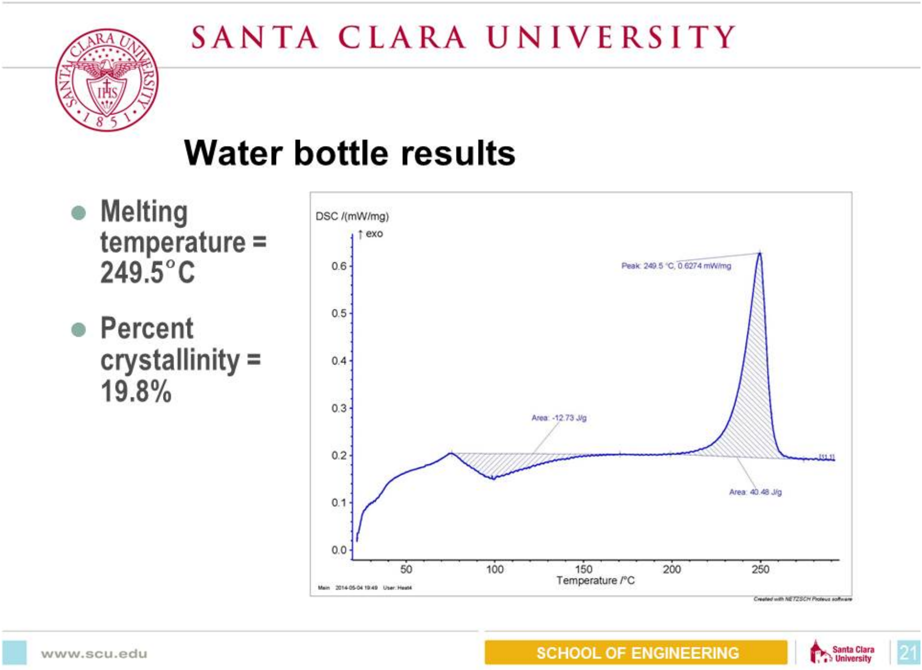
*All pictures taken by Team AkaBot, 2014



Plastic Testing

- **Differential Scanning Calorimetry (DSC)**
  - Glass transition temperature range
  - Melting temperature
  - Percent crystallinity
- **PET**
  - Semi-crystalline thermoplastic
  - Crystalline and amorphous regions

Mixed amorphous crystalline macromolecular polymer structure



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Water bottle results

- Melting temperature = 249.5°C
- Percent crystallinity = 19.8%

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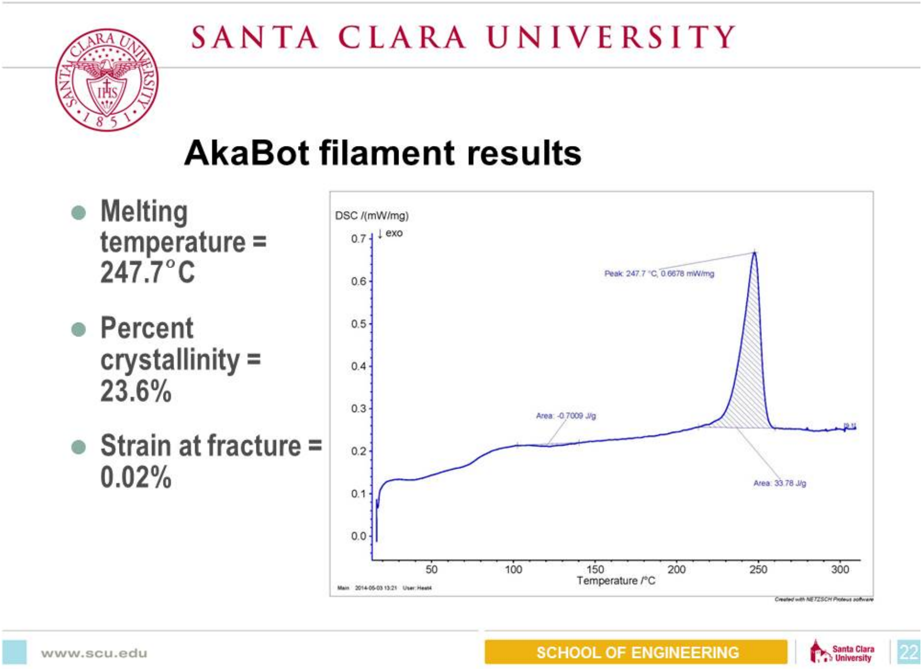

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AkaBot filament results

- Melting temperature = 247.7°C
- Percent crystallinity = 23.6%
- Strain at fracture = 0.02%

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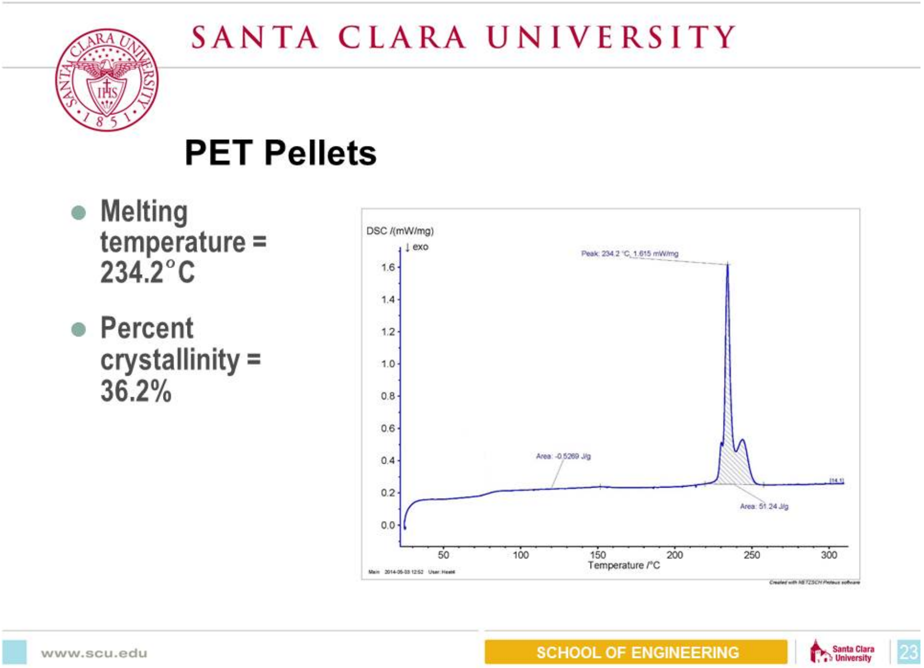

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PET Pellets

- Melting temperature = 234.2°C
- Percent crystallinity = 36.2%

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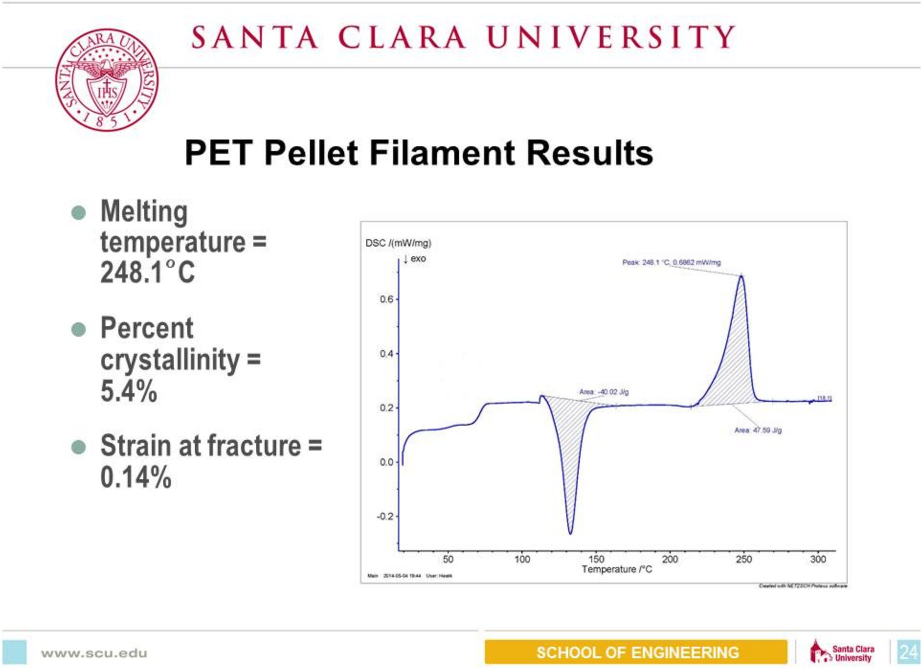

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PET Pellet Filament Results

- Melting temperature = 248.1°C
- Percent crystallinity = 5.4%
- Strain at fracture = 0.14%

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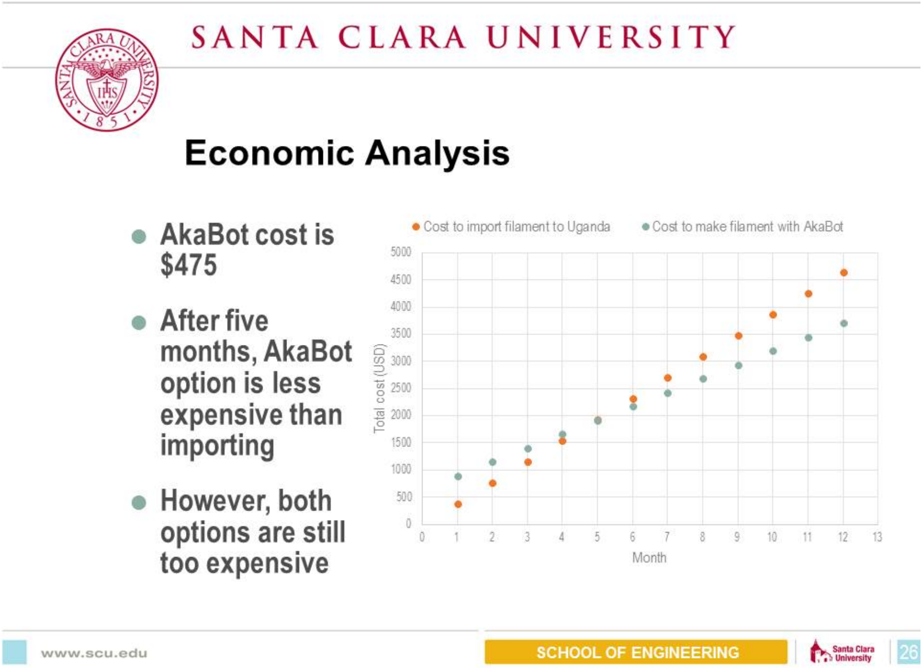
Goals for the Remainder of the Quarter

- Mix PET pellets with water bottles
- Tolerance
- Mass per length
- 3D Printer compatibility

Picture taken by Team AkaBot, 2014.

3D Stuffmaker Mega Prusa



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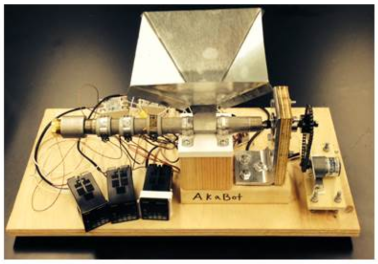
Economic Analysis

- AkaBot cost is $475
- After five months, AkaBot option is less expensive than importing
- However, both options are still too expensive

Work for Future Teams

- Improving PET filament
  - Cooling rate
  - Adding plasticizer
- Automatic spooling
- HDPE, ABS, and PLA plastic types
- Interchangeable die for 1.75mm filament
- Sourcing inexpensive parts from Alibaba



Picture taken by Team AkaBot, 2014.

Acknowledgements

- Center for Science, Technology, and Society Roelandts Grant
- School of Engineering
- American Society of Mechanical Engineers
- Santa Clara Entrepreneurs Organization
- Panthea Sepehrband
- Hohyun Lee
- Donald MacCubbin
- Timothy Hight
- Shoba Krishnan
- Terry Shoup
- Bernadette Tong

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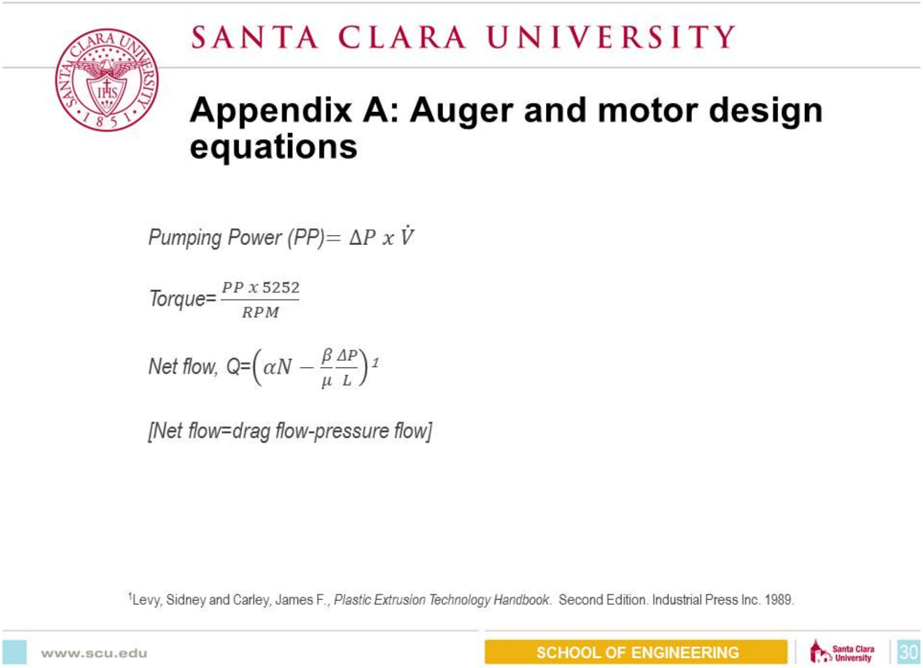
Questions?

Picture taken by Team AkaBot, 2013.

Rachel with Village Energy Kampala employees



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Appendix A: Auger and motor design equations

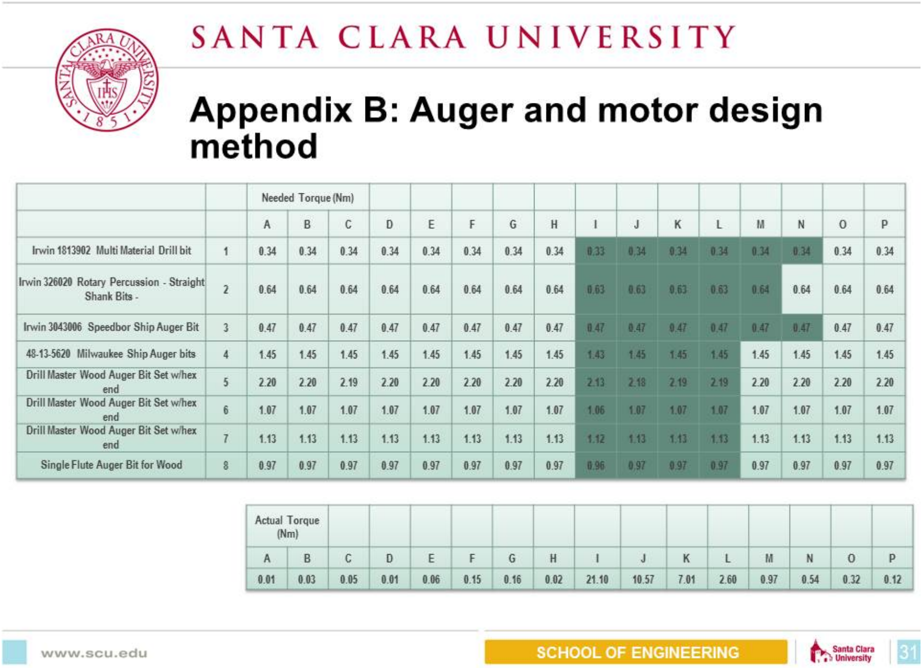
Pumping Power (PP)= $\Delta P \; x \; \dot{V}$

Torque= $\frac{PP \; x \; 5252}{RPM}$

Net flow, Q=$\left(\alpha N - \frac{\beta}{\mu}\frac{\Delta P}{L}\right)$[1]

[Net flow=drag flow-pressure flow]

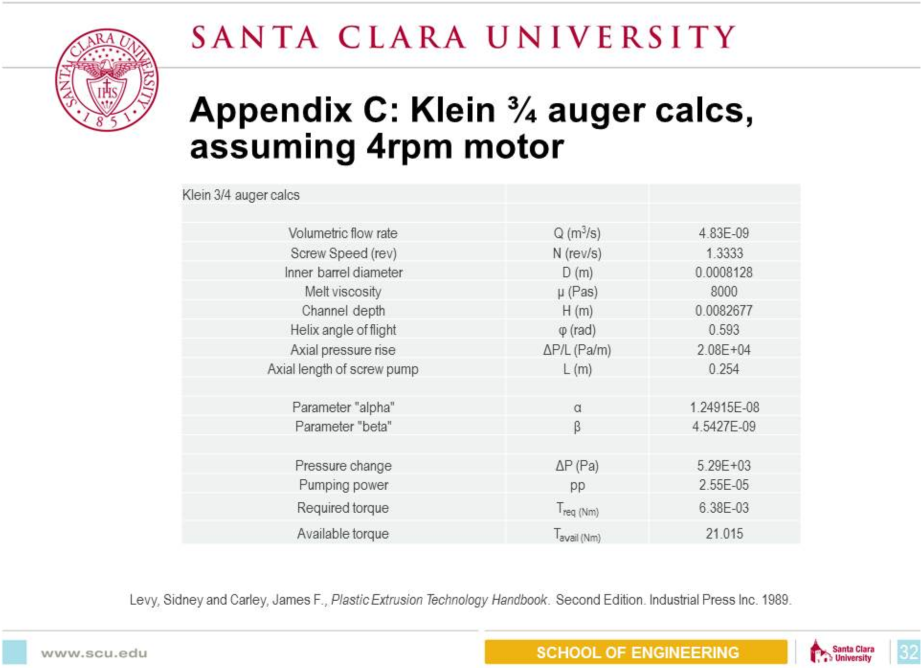
[1] Levy, Sidney and Carley, James F., *Plastic Extrusion Technology Handbook*. Second Edition. Industrial Press Inc. 1989.



Appendix B: Auger and motor design method

		Needed Torque (Nm)															
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Irwin 1813902 Multi Material Drill bit	1	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Irwin 326020 Rotary Percussion - Straight Shank Bits -	2	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.63	0.63	0.63	0.63	0.64	0.64	0.64	0.64
Irwin 3043006 Speedbor Ship Auger Bit	3	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
48-13-5620 Milwaukee Ship Auger bits	4	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.43	1.45	1.45	1.45	1.45	1.45	1.45	1.45
Drill Master Wood Auger Bit Set w/hex end	5	2.20	2.20	2.19	2.20	2.20	2.20	2.20	2.20	2.13	2.18	2.19	2.19	2.20	2.20	2.20	2.20
Drill Master Wood Auger Bit Set w/hex end	6	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.06	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Drill Master Wood Auger Bit Set w/hex end	7	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Single Flute Auger Bit for Wood	8	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97

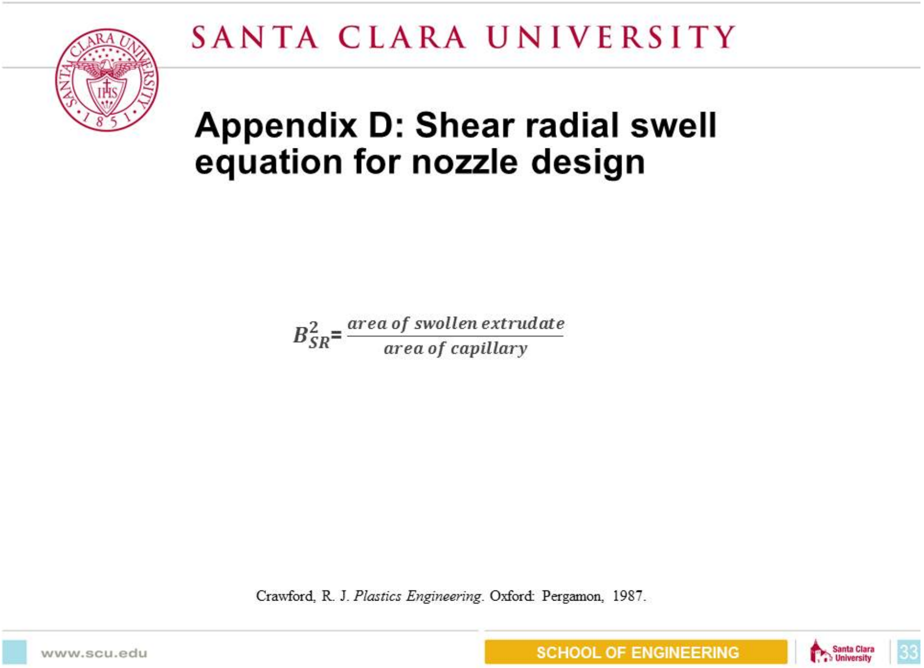
Actual Torque (Nm)															
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
0.01	0.03	0.05	0.01	0.06	0.15	0.16	0.02	21.10	10.57	7.01	2.60	0.97	0.54	0.32	0.12



Appendix C: Klein ¾ auger calcs, assuming 4rpm motor

Klein 3/4 auger calcs		
Volumetric flow rate	Q (m^3/s)	4.83E-09
Screw Speed (rev)	N (rev/s)	1.3333
Inner barrel diameter	D (m)	0.0008128
Melt viscosity	μ (Pas)	8000
Channel depth	H (m)	0.0082677
Helix angle of flight	φ (rad)	0.593
Axial pressure rise	ΔP/L (Pa/m)	2.08E+04
Axial length of screw pump	L (m)	0.254
Parameter "alpha"	α	1.24915E-08
Parameter "beta"	β	4.5427E-09
Pressure change	ΔP (Pa)	5.29E+03
Pumping power	pp	2.55E-05
Required torque	$T_{req\ (Nm)}$	6.38E-03
Available torque	$T_{avail\ (Nm)}$	21.015

Levy, Sidney and Carley, James F., *Plastic Extrusion Technology Handbook*. Second Edition. Industrial Press Inc. 1989.



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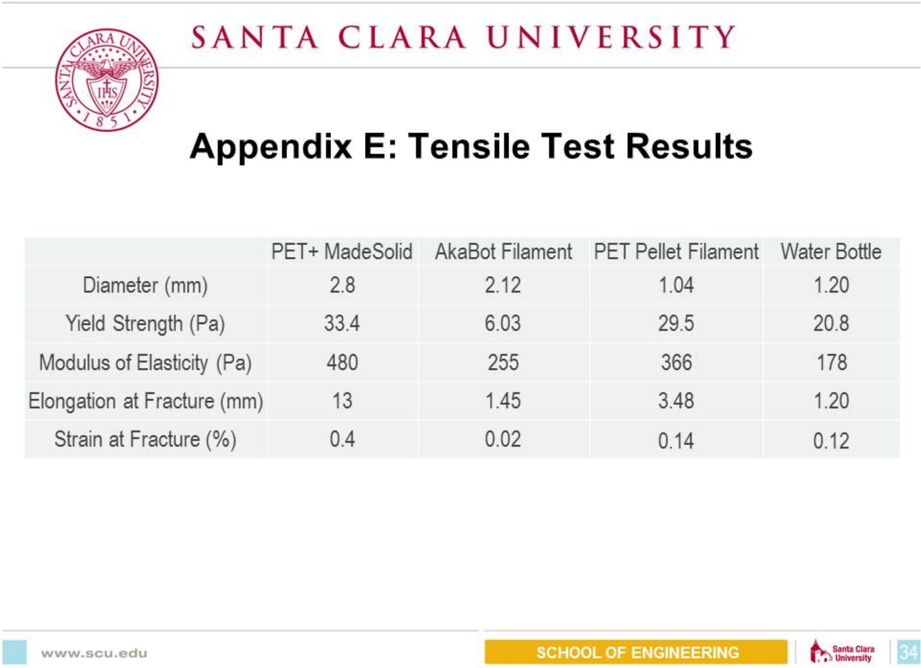
Appendix D: Shear radial swell equation for nozzle design

$$B_{SR}^2 = \frac{\text{area of swollen extrudate}}{\text{area of capillary}}$$

Crawford, R. J. *Plastics Engineering*. Oxford: Pergamon, 1987.



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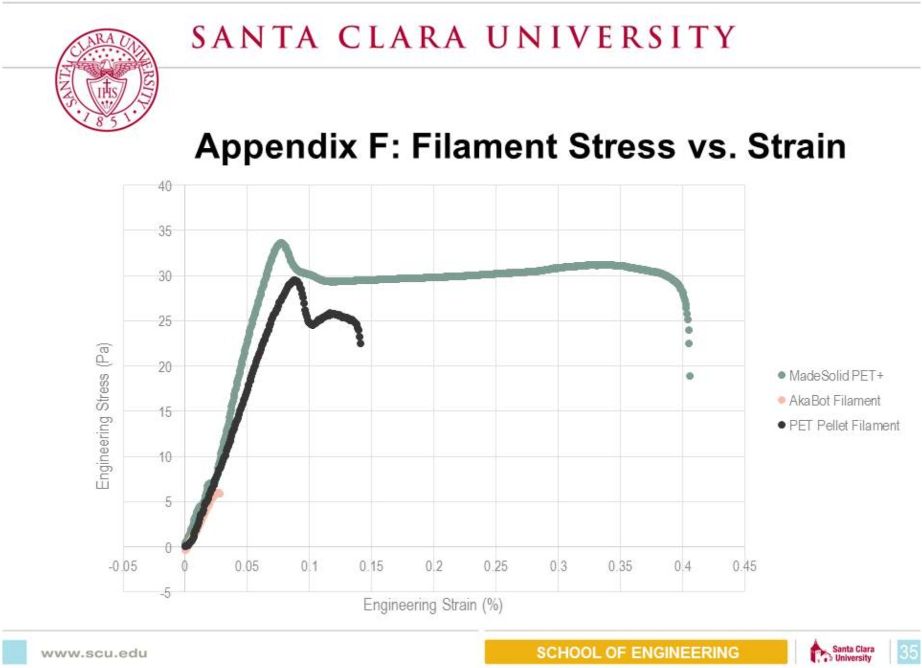
Appendix E: Tensile Test Results

	PET+ MadeSolid	AkaBot Filament	PET Pellet Filament	Water Bottle
Diameter (mm)	2.8	2.12	1.04	1.20
Yield Strength (Pa)	33.4	6.03	29.5	20.8
Modulus of Elasticity (Pa)	480	255	366	178
Elongation at Fracture (mm)	13	1.45	3.48	1.20
Strain at Fracture (%)	0.4	0.02	0.14	0.12



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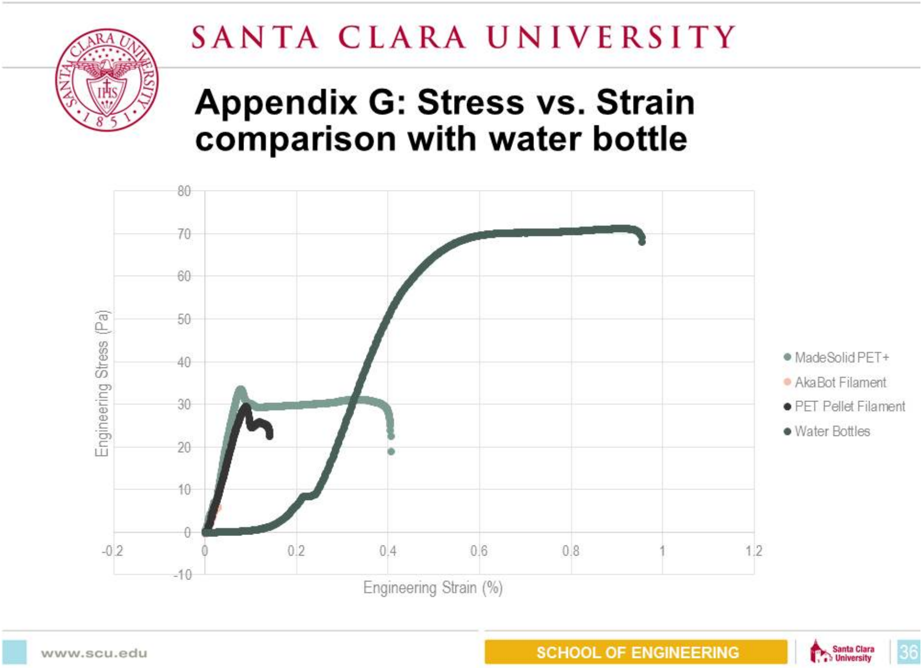
Appendix F: Filament Stress vs. Strain



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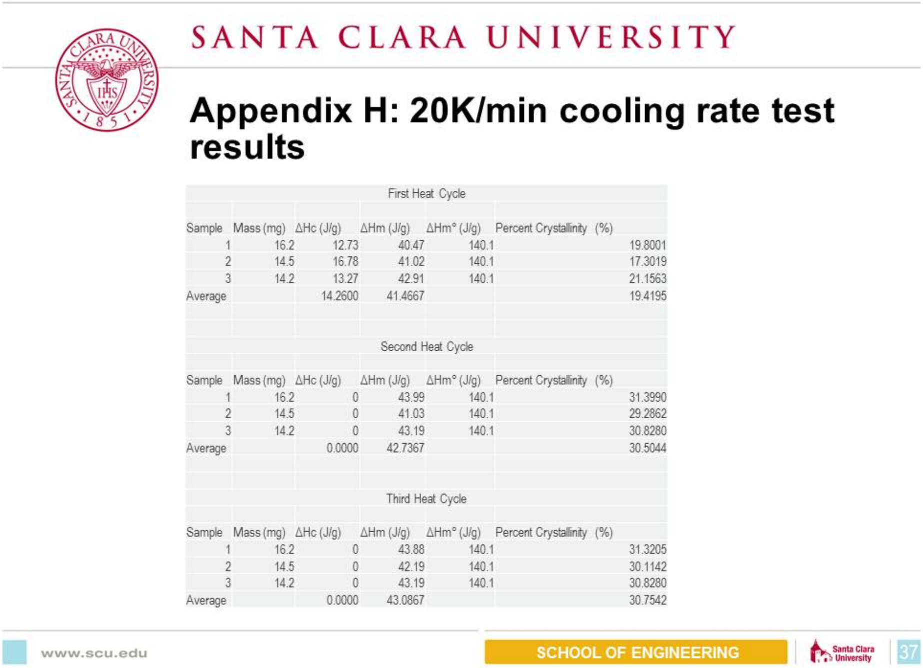
Appendix G: Stress vs. Strain comparison with water bottle



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Appendix H: 20K/min cooling rate test results

First Heat Cycle

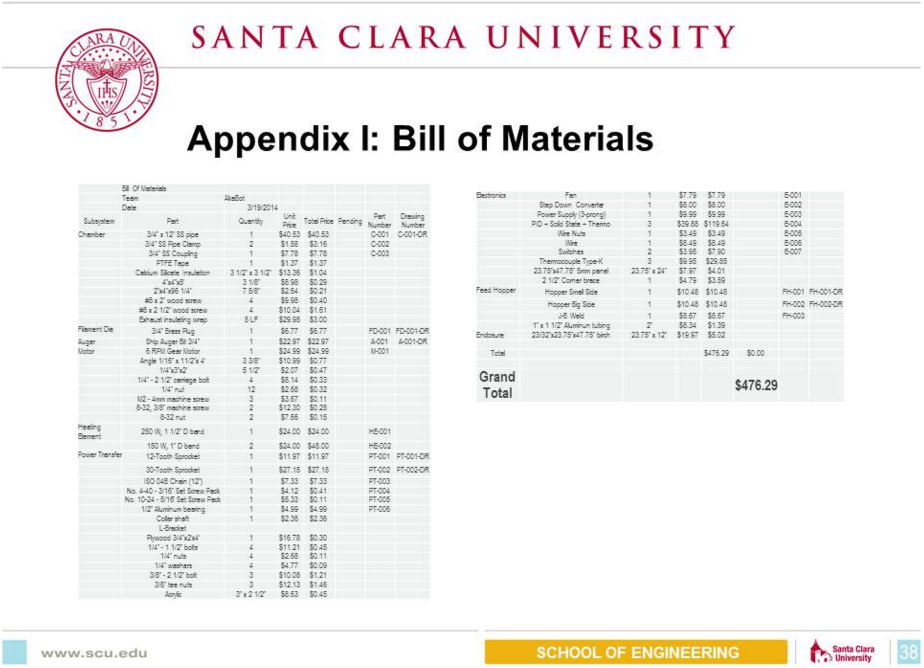
Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)
1	16.2	12.73	40.47	140.1	19.8001
2	14.5	16.78	41.02	140.1	17.3019
3	14.2	13.27	42.91	140.1	21.1563
Average		14.2600	41.4667		19.4195

Second Heat Cycle

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)
1	16.2	0	43.99	140.1	31.3990
2	14.5	0	41.03	140.1	29.2862
3	14.2	0	43.19	140.1	30.8280
Average		0.0000	42.7367		30.5044

Third Heat Cycle

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)
1	16.2	0	43.88	140.1	31.3205
2	14.5	0	42.19	140.1	30.1142
3	14.2	0	43.19	140.1	30.8280
Average		0.0000	43.0867		30.7542



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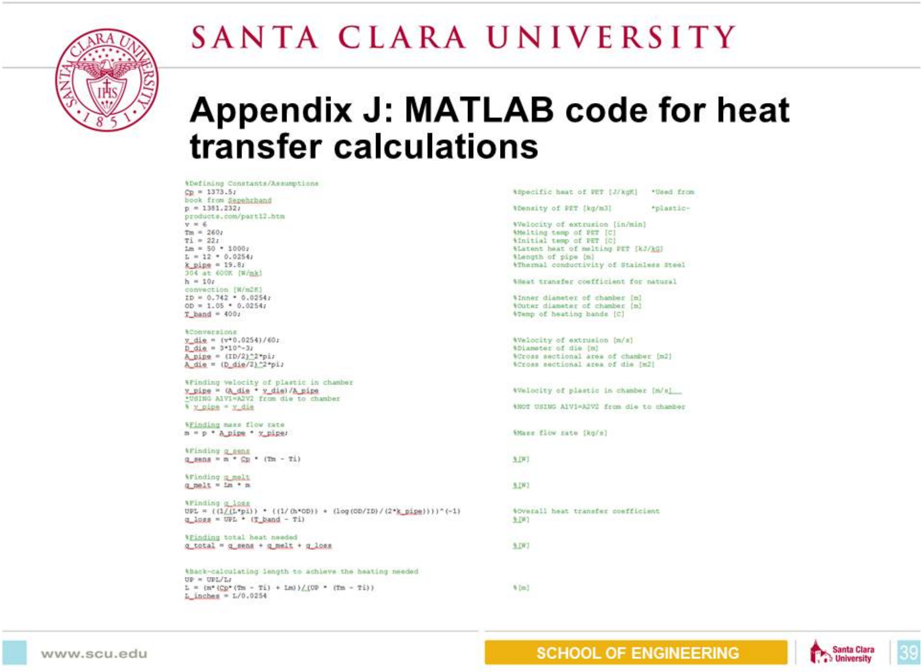
Appendix I: Bill of Materials

	Bill Of Materials						
	Team	AkaBot					
	Date	3/19/2014					
Subsystem	Part	Quantity	Unit Price	Total Price	Pending	Part Number	Drawing Number
Chamber	3/4" x 12" SS pipe	1	$40.53	$40.53		C-001	C-001-DR
	3/4" SS Pipe Clamp	2	$1.58	$3.16		C-002	
	3/4" SS Coupling	1	$7.78	$7.78		C-003	
	PTFE Tape	1	$1.37	$1.37			
	Calcium Silicate Insulation	3 1/2" x 3 1/2"	$13.36	$1.04			
	4"x4"x8'	3 1/8"	$8.98	$0.29			
	2"x4"x96 1/4"	7 5/8"	$2.64	$0.21			
	#8 x 2" wood screw	4	$9.98	$0.40			
	#8 x 2 1/2" wood screw	4	$10.04	$1.61			
	Exhaust insulating wrap	5 LF	$29.95	$3.00			
Filament Die	3/4" Brass Plug	1	$6.77	$6.77		FD-001	FD-001-DR
Auger	Ship Auger Bit 3/4"	1	$22.97	$22.97		A-001	A-001-DR
Motor	6 RPM Gear Motor	1	$24.99	$24.99		M-001	
	Angle 1/16" x 11/2"x 4'	3 3/8"	$10.99	$0.77			
	1/4"x3"x2'	5 1/2"	$2.07	$0.47			
	1/4" - 2 1/2" carriage bolt	4	$8.14	$0.33			
	1/4" nut	12	$2.68	$0.32			
	M2 - 4mm machine screw	3	$3.67	$0.11			
	8-32, 3/8" machine screw	2	$12.30	$0.25			
	8-32 nut	2	$7.66	$0.15			
Heating Element	250 W, 1 1/2" D band	1	$24.00	$24.00		HE-001	
	150 W, 1" D band	2	$24.00	$48.00		HE-002	
Power Transfer	12-Tooth Sprocket	1	$11.97	$11.97		PT-001	PT-001-DR
	30-Tooth Sprocket	1	$27.15	$27.15		PT-002	PT-002-DR
	ISO 048 Chain (12")	1	$7.33	$7.33		PT-003	
	No. 4-40 - 3/16" Set Screw Pack	1	$4.12	$0.41		PT-004	
	No. 10-24 - 5/16" Set Screw Pack	1	$5.33	$0.11		PT-005	
	1/2" Aluminum bearing	1	$4.99	$4.99		PT-006	
	Coller shaft	1	$2.36	$2.36			
	L-Bracket						
	Plywood 3/4"x2'x4'	1	$16.78	$0.30			
	1/4" - 1 1/2" bolts	4	$11.21	$0.45			
	1/4" nuts	4	$2.68	$0.11			
	1/4" washers	4	$4.77	$0.09			
	3/8" - 2 1/2" bolt	3	$10.08	$1.21			
	3/8" tee nuts	3	$12.13	$1.46			
	Acrylic	3" x 2 1/2"	$8.63	$0.45			
Electronics	Fan	1	$7.79	$7.79		E-001	
	Step Down Converter	1	$8.00	$8.00		E-002	
	Power Supply (3-prong)	1	$9.99	$9.99		E-003	
	PID + Solid State + Thermo	3	$39.88	$119.64		E-004	
	Wire Nuts	1	$3.49	$3.49		E-005	
	Wire	1	$8.49	$8.49		E-006	
	Switches	2	$3.95	$7.90		E-007	
	Thermocouple Type-K	3	$9.95	$29.85			
	23.75"x47.75" 5mm panel	23.75" x 24"	$7.97	$4.01			
	2 1/2" Corner brace	1	$4.79	$3.59			
Feed Hopper	Hopper Small Side	1	$10.48	$10.48		FH-001	FH-001-DR
	Hopper Big Side	1	$10.48	$10.48		FH-002	FH-002-DR
	J-B Weld	1	$5.67	$5.67		FH-003	
	1" x 1 1/2" Aluminun tubing	2'	$8.34	$1.39			
Enclosure	23/32"x23.75"x47.75" birch	23.75" x 12"	$19.97	$5.02			
Total				$476.29	$0.00		
Grand Total					**$476.29**		



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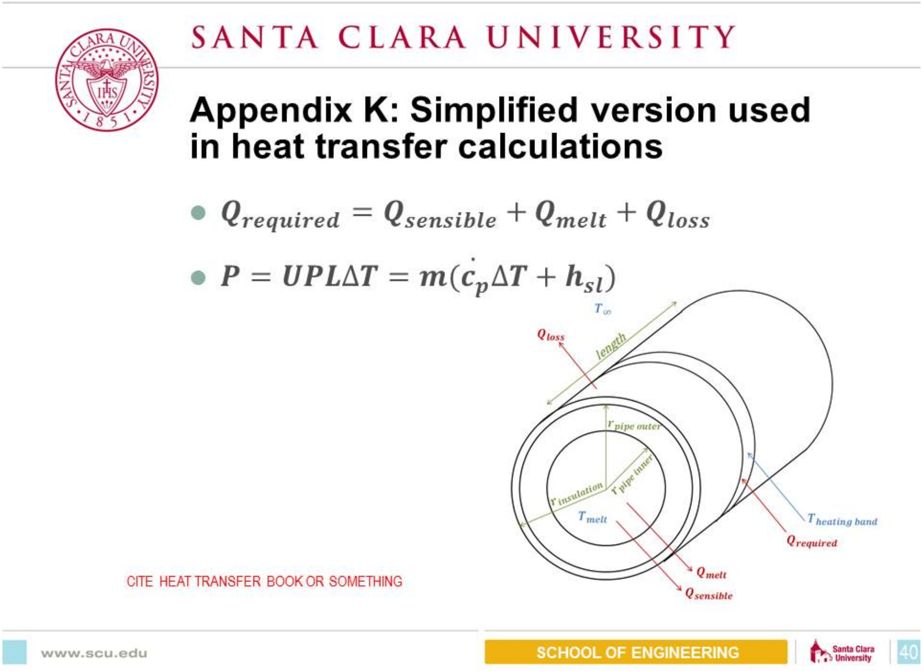
Appendix J: MATLAB code for heat transfer calculations

```
%Defining Constants/Assumptions
Cp = 1373.5;                                          %Specific heat of PET [J/kgK]   *Used from
book from Sepehrband
p = 1381.232;                                         %Density of PET [kg/m3]         *plastic-
products.com/part12.htm
v = 6                                                 %Velocity of extrusion [in/min]
Tm = 260;                                             %Melting temp of PET [C]
Ti = 22;                                              %Initial temp of PET [C]
Lm = 50 * 1000;                                       %Latent heat of melting PET [kJ/kG]
L = 12 * 0.0254;                                      %Length of pipe [m]
k_pipe = 19.8;                                        %Thermal conductivity of Stainless Steel
304 at 600K [W/mk]
h = 10;                                               %Heat transfer coefficient for natural
convection [W/m2K]
ID = 0.742 * 0.0254;                                  %Inner diameter of chamber [m]
OD = 1.05 * 0.0254;                                   %Outer diameter of chamber [m]
T_band = 400;                                         %Temp of heating bands [C]

%Conversions
v_die = (v*0.0254)/60;                                %Velocity of extrusion [m/s]
D_die = 3*10^-3;                                      %Diameter of die [m]
A_pipe = (ID/2)^2*pi;                                 %Cross sectional area of chamber [m2]
A_die = (D_die/2)^2*pi;                               %Cross sectional area of die [m2]

%Finding velocity of plastic in chamber
v_pipe = (A_die * v_die)/A_pipe                       %Velocity of plastic in chamber [m/s]
%USING A1V1=A2V2 from die to chamber
% v_pipe = v_die                                      %NOT USING A1V1=A2V2 from die to chamber

%Finding mass flow rate
m = p * A_pipe * v_pipe;                              %Mass flow rate [kg/s]

%Finding q_sens
q_sens = m * Cp * (Tm - Ti)                           %[W]

%Finding q_melt
q_melt = Lm * m                                       %[W]

%Finding q_loss
UPL = ((1/(L*pi)) * ((1/(h*OD)) + (log(OD/ID)/(2*k_pipe))))^(-1)     %Overall heat transfer coefficient
q_loss = UPL * (T_band - Ti)                          %[W]

%Finding total heat needed
q_total = q_sens + q_melt + q_loss                    %[W]


%Back-calculating length to achieve the heating needed
UP = UPL/L;
L = (m*(Cp*(Tm - Ti) + Lm))/(UP * (Tm - Ti))          %[m]
L_inches = L/0.0254
```



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Appendix K: Simplified version used in heat transfer calculations

- $Q_{required} = Q_{sensible} + Q_{melt} + Q_{loss}$
- $P = UPL\Delta T = m(\dot{c_p}\Delta T + h_{sl})$

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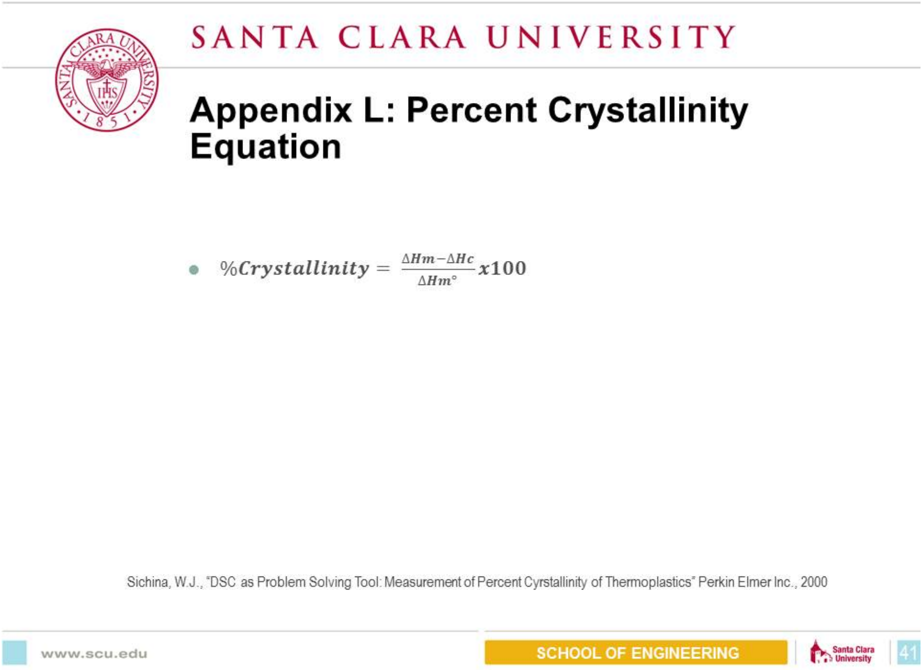

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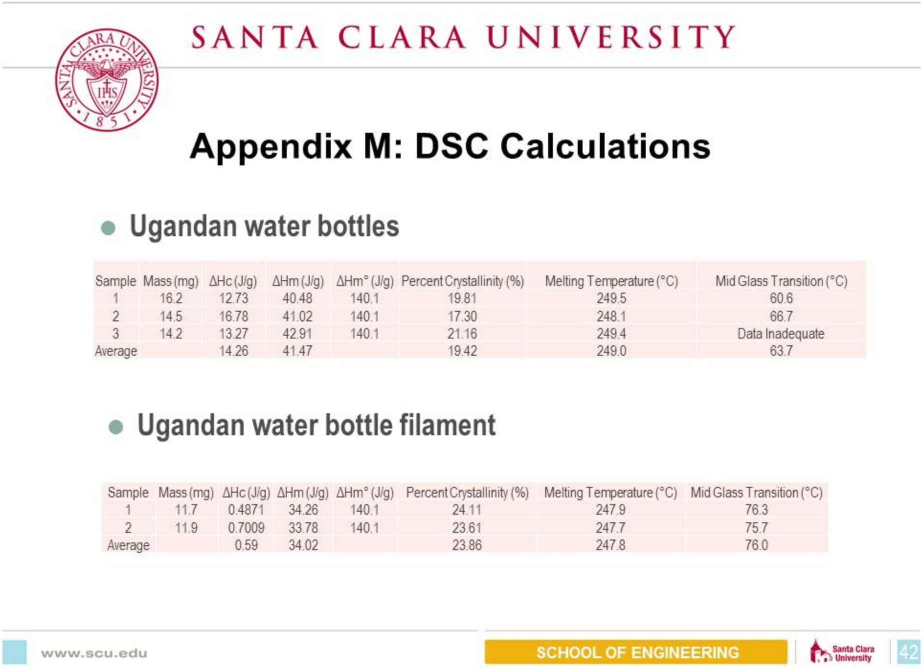
Appendix L: Percent Crystallinity Equation

- $\%Crystallinity = \frac{\Delta Hm - \Delta Hc}{\Delta Hm^{\circ}} x100$

Sichina, W.J., "DSC as Problem Solving Tool: Measurement of Percent Cyrstallinity of Thermoplastics" Perkin Elmer Inc., 2000



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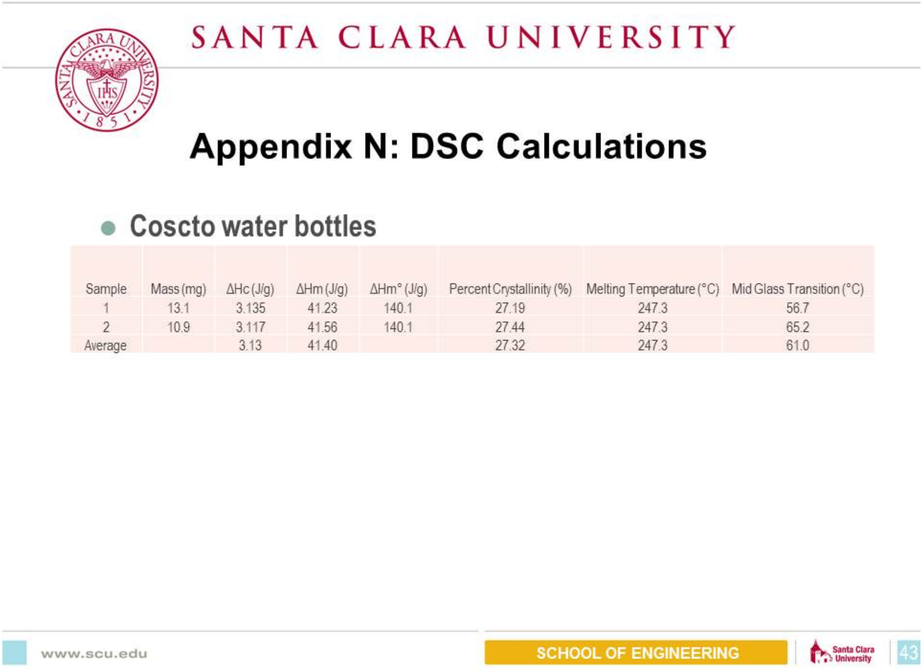
Appendix M: DSC Calculations

- **Ugandan water bottles**

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	16.2	12.73	40.48	140.1	19.81	249.5	60.6
2	14.5	16.78	41.02	140.1	17.30	248.1	66.7
3	14.2	13.27	42.91	140.1	21.16	249.4	Data Inadequate
Average		14.26	41.47		19.42	249.0	63.7

- **Ugandan water bottle filament**

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	11.7	0.4871	34.26	140.1	24.11	247.9	76.3
2	11.9	0.7009	33.78	140.1	23.61	247.7	75.7
Average		0.59	34.02		23.86	247.8	76.0



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Appendix N: DSC Calculations

- **Coscto water bottles**

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	13.1	3.135	41.23	140.1	27.19	247.3	56.7
2	10.9	3.117	41.56	140.1	27.44	247.3	65.2
Average		3.13	41.40		27.32	247.3	61.0

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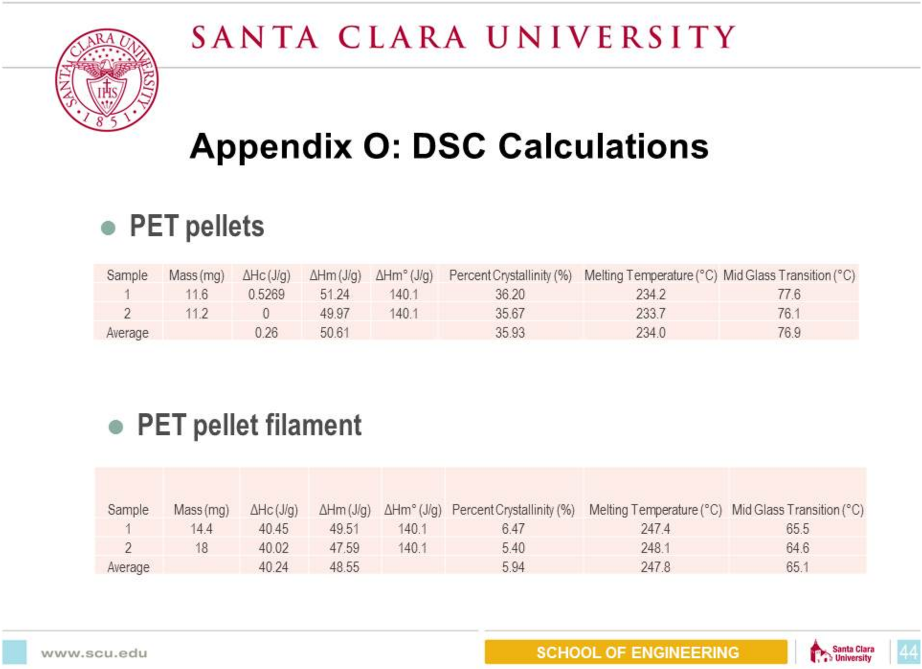

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Appendix O: DSC Calculations

- **PET pellets**

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	11.6	0.5269	51.24	140.1	36.20	234.2	77.6
2	11.2	0	49.97	140.1	35.67	233.7	76.1
Average		0.26	50.61		35.93	234.0	76.9

- **PET pellet filament**

Sample	Mass (mg)	ΔHc (J/g)	ΔHm (J/g)	ΔHm° (J/g)	Percent Crystallinity (%)	Melting Temperature (°C)	Mid Glass Transition (°C)
1	14.4	40.45	49.51	140.1	6.47	247.4	65.5
2	18	40.02	47.59	140.1	5.40	248.1	64.6
Average		40.24	48.55		5.94	247.8	65.1

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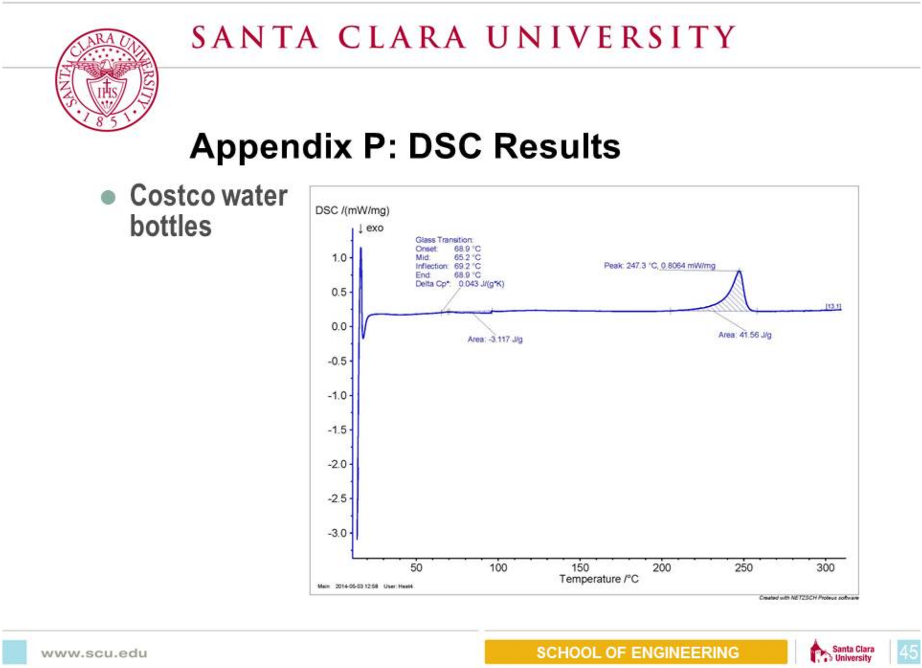

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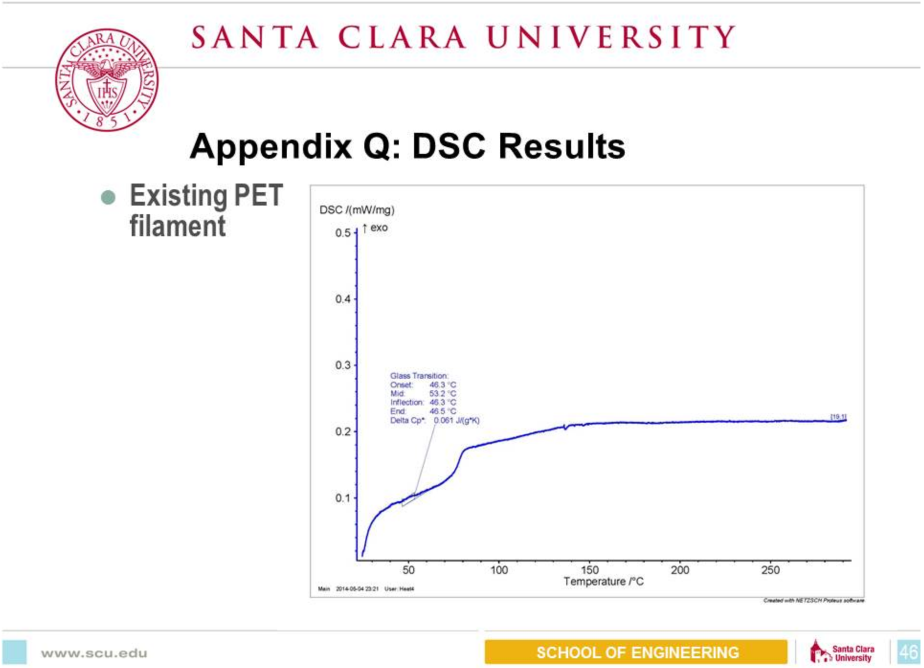
Appendix P: DSC Results

- **Costco water bottles**



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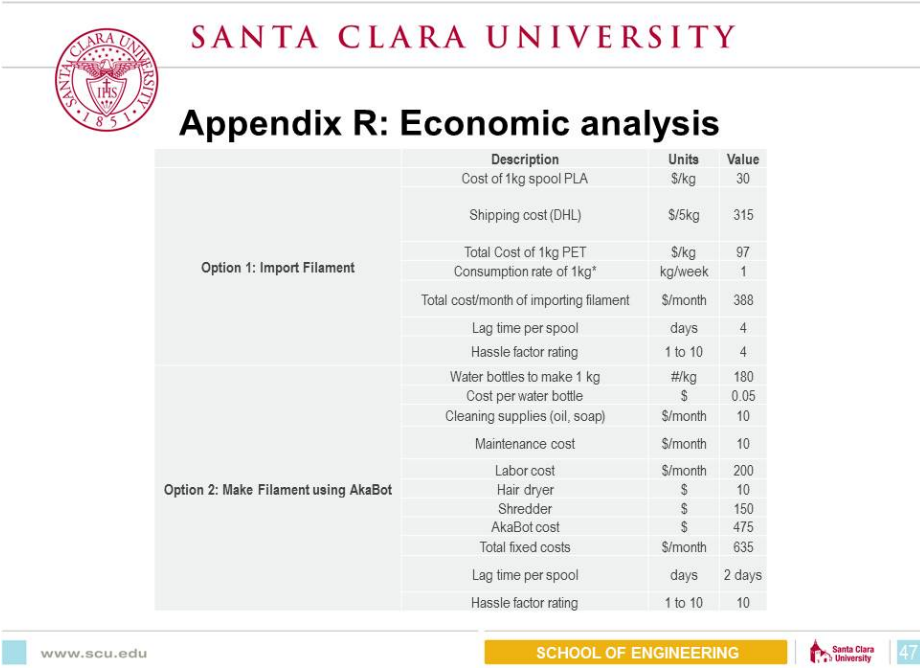
Appendix Q: DSC Results

- **Existing PET filament**



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Appendix R: Economic analysis

	Description	Units	Value
Option 1: Import Filament	Cost of 1kg spool PLA	$/kg	30
	Shipping cost (DHL)	$/5kg	315
	Total Cost of 1kg PET	$/kg	97
	Consumption rate of 1kg*	kg/week	1
	Total cost/month of importing filament	$/month	388
	Lag time per spool	days	4
	Hassle factor rating	1 to 10	4
Option 2: Make Filament using AkaBot	Water bottles to make 1 kg	#/kg	180
	Cost per water bottle	$	0.05
	Cleaning supplies (oil, soap)	$/month	10
	Maintenance cost	$/month	10
	Labor cost	$/month	200
	Hair dryer	$	10
	Shredder	$	150
	AkaBot cost	$	475
	Total fixed costs	$/month	635
	Lag time per spool	days	2 days
	Hassle factor rating	1 to 10	10

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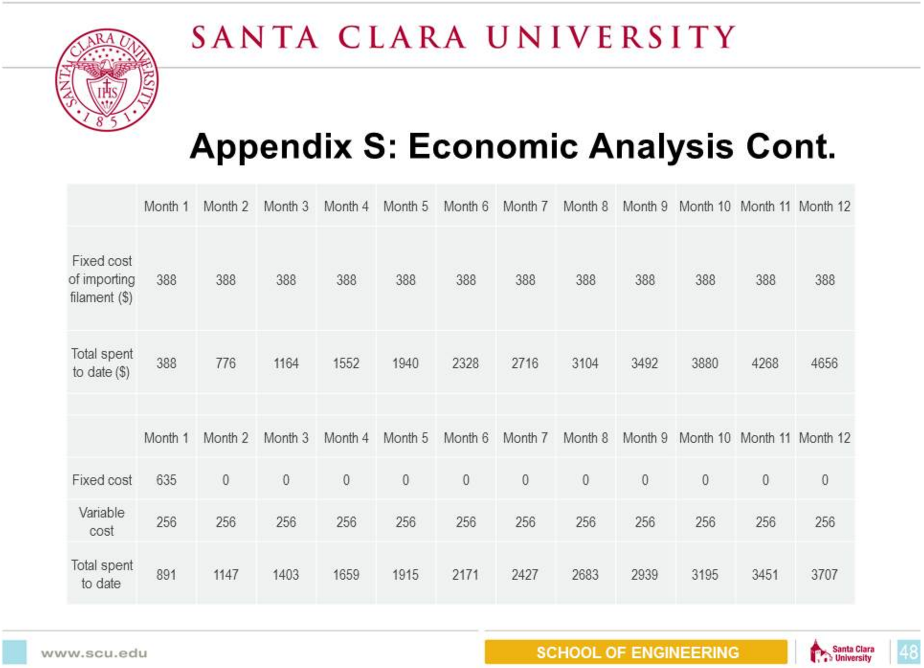

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Appendix S: Economic Analysis Cont.

	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Fixed cost of importing filament ($)	388	388	388	388	388	388	388	388	388	388	388	388
Total spent to date ($)	388	776	1164	1552	1940	2328	2716	3104	3492	3880	4268	4656

	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Fixed cost	635	0	0	0	0	0	0	0	0	0	0	0
Variable cost	256	256	256	256	256	256	256	256	256	256	256	256
Total spent to date	891	1147	1403	1659	1915	2171	2427	2683	2939	3195	3451	3707

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