

THE DESIGN OF A HYBRID ROCKET ENGINE

BY

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ABSTRACT

In this thesis a hybrid rocket engine will be designed and built to experimentally test different materials which can be used for fuel. Hybrid rockets contain both a solid propellant such as hydroxyl-terminated polybutadiene (HTPB) or paraffin wax and a gaseous oxidizer such as liquid oxygen (O_2). The most recent research has been using Acrylonitrile butadiene styrene (ABS) as the solid propellant. The advantages of using ABS plastic are that it produces a thrust comparable to other propellants, it is affordable, and it can be three dimensionally printed to transform into any shape. Disadvantages of using ABS are its low melting point, causing a lower thrust, and it burns faster than traditional hybrid rocket propellants. Due to its low melting point and faster burn rates, an experiment was conducted where ABS and aluminum nanoparticle flakes were combined to solve this problem. A small scale hybrid rocket stand was designed in Solidworks™ and then built. The next step was to discover a method that would make the combined ABS and aluminum nanoparticles into a shape that could be used in the 3D printer. A filament extruder was then designed and built. ABS was dissolved with acetone and mixed with aluminum to become a plastic/metal propellant for the hybrid rocket. Once that plastic/metal material was bound together, it was then able to undergo heat and pressure in the filament extruder to become a 1.75 millimeter in diameter string that could be 3D printed. Once this plastic/metal material is able to be 3D printed, the aluminum will achieve higher melting temperatures producing greater thrust values.

INTRODUCTION

Traditionally there have been two main types of rocket propulsion systems. These include liquid rocket engines and solid rocket motors. Hybrid rocket engines are a third rocket propulsion system that is also popular. These rockets are designed with characteristics from both liquid and solid rockets. Hybrid rockets will be compared to liquid and solid rockets in the following sections.

A. Background On Rockets

A rocket is a missile, spacecraft, aircraft or vehicle that exerts thrust from a rocket engine. These engines push the aircraft forward by expelling their exhaust in the opposite direction at a high speed. The difference between a rocket and a jet engine is a jet needs air to operate whereas rockets carry their oxidizer alongside of their fuel. This allows rockets to work in space where there is no oxygen. Rockets are relatively lightweight and powerful, capable of generating large acceleration. Chemical rockets are the most common type of high power rocket. They create a high speed exhaust by the combustion of fuel with an oxidizer. The stored propellant can be a simple pressurized gas or liquid. Chemical rockets are categorized into three different groups: liquid rockets, solid rockets, and hybrid rockets.

1. Liquid Rocket Engines

Liquid rocket engines are complex systems that consist of pressure regulators, pumps, valves, and injectors. With all of these parts included in liquid rockets, it is crucial that they work together correctly to perform in the desired manner. The fuel and oxidizer are both liquid, and are stored in different tanks. They deliver the fuel and oxidizer to the thrust chamber through complex plumbing. After reaching the thrust chamber, the liquids combine and are ignited. The hot combustion gases then expand through the nozzle and provide thrust. Liquid rockets can be throttled, meaning they are able to start, stop, and start again. They can also provide varying thrust values unlike other conventional rockets. A common choice for fuel is liquid hydrogen and for oxidizer, liquid oxygen. This is the fuel and oxidizer used by National Aeronautics and Space Administration (NASA) for space shuttles into orbit. These rockets, when launched, are environmentally friendly.

However, these rockets can be high priced to build and maintain. They are also heavy from the complex components, liquid fuel, and oxidizers. Storing the fuel and oxidizer is also a concern because they are extremely flammable.

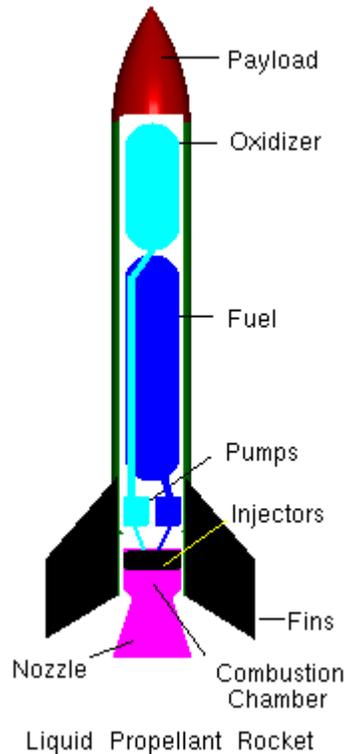


Figure 1. Liquid rocket diagram.

2. Solid Rocket Motors

Solid Rockets are simple in nature. They operate by using a solid fuel grain that consists of both a fuel and an oxidizer. This mixture is often molded and burned with the exhausting gas expanding through the nozzle. These rockets have much larger thrust value than liquid or hybrid rockets. These rockets have several disadvantages though. They cannot be throttled, meaning they operate like a fire cracker; once they are ignited, there is no shut down. Another drawback is that they are difficult to store. If these rockets were exposed to an open flame they could experience an unplanned launch resulting in severe damage and fatal injuries. The last problem that is seen is that most of the gasses that these rockets emit are toxic. An example of these toxic chemicals would be hydrogen chloride gas. This gas is a pollutant to the environment. Hydrogen chloride gas is highly

corrosive and will damage metal structures and buildings or monuments made of limestone. If high levels of hydrogen chloride gas dissolve in a water body, aquatic organisms will be harmed or even killed. This gas is also dangerous for humans. Inhalation of air containing low levels of hydrogen chloride over short periods of time can cause throat irritation. Exposure to higher levels may result in effects including rapid breathing, blue coloring of the skin, fluid accumulation in the lungs and in extreme cases severe swelling of the throat, suffocation and death.

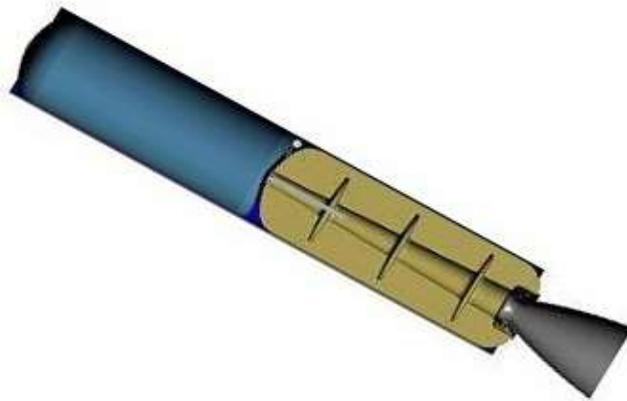


Figure 2. Solid rocket diagram.

3. Hybrid Rocket Engines

The first recorded effort, as a forerunner to the hybrid rocket, was reported by Sergei P. Korolev and Mikhail K. Tikhonravov within the scope of the Russian GIRD.^[9] This flight was made on August 17 of 1933. This rocket was roughly 7 inches in diameter and 8 feet long. In 1975, William Avery and coworkers at the Applied Physics Laboratory of John Hopkins University conducted burning tests with a reverse hybrid rocket propellant system.^[9] The propellant that was used in their experiment was benzene and jet propellant fuel. Since that was the propellant, potassium perchlorate, ammonium nitrate, and ammonium perchlorate were its oxidizers. This was difficult to burn. More recently, the SpaceShipOne vehicle was built on September 29th in the year 2004. This hybrid rocket

was a nitrous oxide/Hydroxyl Terminated Polybutadien (HTPB) motor that was a sub orbital manned vehicle.



Figure 3. SpaceDev.^[8]

Hybrid rockets use a solid fuel and a gaseous oxidizer. Common solid fuels used in hybrid rockets are hydrocarbons such as HTPB, kerosene, and plastics of various types (acrylonitrile butadiene styrene (ABS), for example). The most common oxidizer used for a hybrid rocket is nitrous oxide. In a hybrid rocket, a central combustion chamber is created in the hollowed out center of the fuel grain. The fuel grain forms a pressure chamber between an oxidizer injector and the nozzle. An ignition system is used to vaporize the inside of the fuel grain. The heat of the combustion of the fuel vapor maintains vaporization of the remaining fuel. The combustion gas then expands through the nozzle to produce thrust. Through this process, the oxidizer and the fuel remain separate; this means the rocket can be stopped, restarted, and throttled. It is safe to store these materials that make hybrid rockets. Storing oxidizers are nothing more than storing a compressed gas cylinder and plastics can be safely stored anywhere as well. The largest concern in hybrid rockets is the higher levels of carbon monoxide.

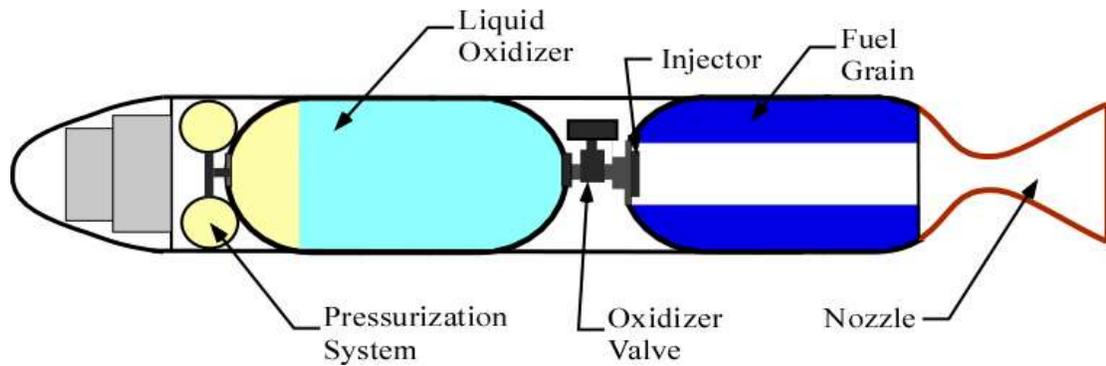


Figure 4. Hybrid rocket diagram.

4. The Advantages Of Hybrid Rockets

Hybrid rockets hold several advantages over both liquid and solid rockets. Some of these advantages are an ability to throttle, less complicated designs, and less expensive to design and build. It was due to these reasons that research was begun in the field of hybrid rockets at Alfred University.

Hybrid and liquid rockets share the throttling advantage over solid rockets, however hybrids have multiple advantages over liquid rockets. One advantage is the complexity of their design. Liquid rockets, as described earlier, have a complicated layout of pumps, pipes, valves, and pressure regulators. Hybrids have one pipe with a regulator that transports the oxidizer from storage to the combustion chamber. They are much simpler in design due to their fuel being solid which reduces the plumbing dramatically.

In addition to having a simpler design than liquid rockets, hybrids are more cost efficient to design and build. It is not surprising that they are less expensive to build due to hybrids being less complicated in design. Less pipes, valves, regulators, and storage tanks aid the designing process. Since hybrid rockets are designed and assembled for a more economical price with all the advantages of a liquid rocket, they are the better choice.

B. Background On 3D Printing

The process of three dimensional printing (3D printing) is recent to the field of manufacturing. 3D printing is defined as the process of making any three dimensional shape from a digital file. The creation of a 3D object is obtained through a process called the additive process. This process is when an object is created by layers of material placed in succession.

1. History Of 3D Printing

The first 3D printer was built in 1984 by Charles W. Hull. He worked for a company called 3D Systems Corp™ where he conducted research and produced his 3D printer. When these printers first came out to the production line, they were expensive and not feasible to be purchased by the general market. Over the past two decades, the price for 3D printers has decreased dramatically. Today a 3D printer can be purchased for as low as \$1000.

2. How 3D Printing Is Used Today

The process of 3D printing is used for multiple applications today in both schools and industry. In high schools and colleges 3D printing is used to teach Computer Aided Design (CAD) programs. In industry, 3D printing is used to create prototypes for various projects. Many people might go so far to say, 3D printing is the future of manufacturing. More specifically, in the year 2014 SpaceX™ launched Falcon 9 rocket with 3D printed main oxidizer valves.

3. The Makerbot™

The Makerbot™ is one of the most popular 3D printers on the market. The company Makerbot™ began in the year 2009. It was founded by Adam Mayer, Zach Smith, and Bre Pettis. Through the years of designing and developing 3D printers three different models were produced. The first was the Cupcake CNC™ (seen in the figure below). This 3D printer was designed and sold in 2009. This was one of the first 3D printers that allowed the user to build from their own sketches. After the success of the Cupcake CNC™, a year later an upgrade was designed called the Thing-O-Matic™ (also seen in the figure below). Then two years later in 2012, the Replicator™ entered the market. The Replicator™ offered more than double the build envelope than the Thing-O-Matic™.

The Replicator was the 3D printer that was bought and used for the research conducted in this project.

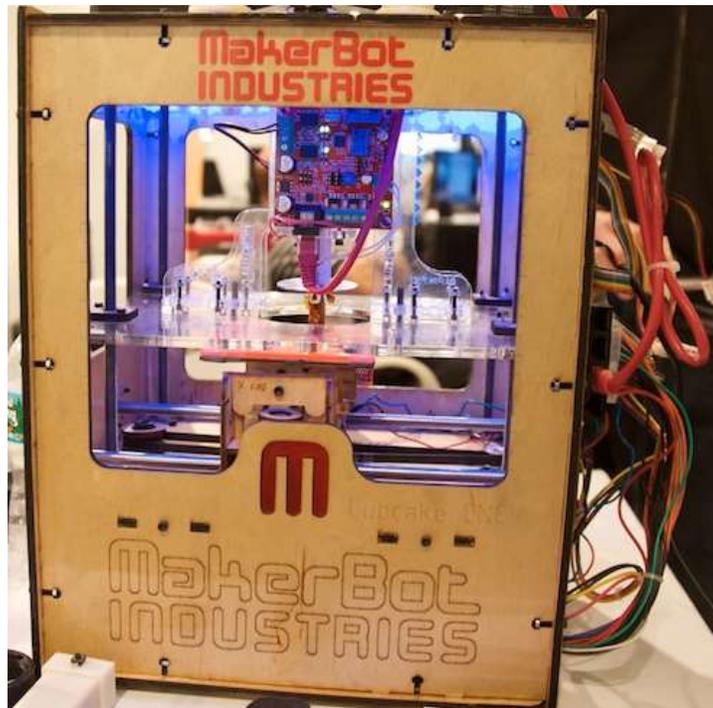


Figure 5. Makerbot Cupcake™.



Figure 6. Thing-O-Matic™.

C. Background On The Research Done At Alfred University

Hybrid rocket research has been an ongoing project at Alfred University since the year 2002. It was in that year that a small scale hybrid rocket was designed and built. This rocket was a project from a class offered at Alfred called ‘Aspects of Rocket Engine Design’. The hybrid rocket contained basic design components that were developed at the Stennis Space Center at NASA. Then in 2004 a new group of students made the hybrid rocket their senior design project. It was then that they analyzed some of the safety concerns, flaws in the design, and problems collecting data when launched. After the group investigated these problems and made various attempts to fix them, they added an additional endplate so two grains could be launched at the same time. When the group concluded a two semester long endeavor to improve the rocket, there were still a few problems such as the seal from the grain to the endplates, the nozzle that leaked out the sides, and the instrumentation did not collect data quarterly. Then in 2012, as a part of a Fluid Mechanics course at Alfred, a group of students desired to redesign the entire hybrid rocket. Their work will be discussed in greater detail later in chapters to come.

1. How The Ongoing Research At Alfred University Will Improve Hybrid Rockets

The research that was conducted at Alfred University consisted of design and building a small scale hybrid rocket that used ABS plastic as its fuel. This was different that in other experiments at schools such as Pennsylvania State University (Penn State). At Penn State, they used paraffin wax as a fuel source. The oxidizer that was used was liquid oxygen that was sent in to the rocket at 100 Pounds per square inch absolute (psia). ABS was chosen due to it being the material that is mostly used when 3D printing. The second way this was different was the most essential part of this research project, combining ABS and aluminum together to 3D print fuel. Adding some aluminum nanoparticles to the ABS accomplished two key goals, the first goal began, it had the possibilities of achieving higher thrust.

The ideal velocity characteristic for hybrid rockets, C^*_{ideal} , can be found equation (1)^[8]

$$c^* = \frac{g\gamma R(T_c)_{ns}}{\gamma \sqrt{\frac{2}{\gamma+1} \frac{\gamma+1}{\gamma-1}}} \quad (1)$$

where R is the universal gas constant, γ is the specific heat ratio, g is the acceleration due to gravity, and T_c is the temperature. In a system with sonic velocity at the throat, the quantity c^* reflects the effective energy level of the propellants and the design quality of injector and combustion chamber.^[8] This equation indicates that as the temperature increases the velocity characteristic will increase as a square root. Therefore, adding aluminum nanoparticles to the ABS fuel will give an increased velocity characteristic since aluminum burns hotter than ABS.

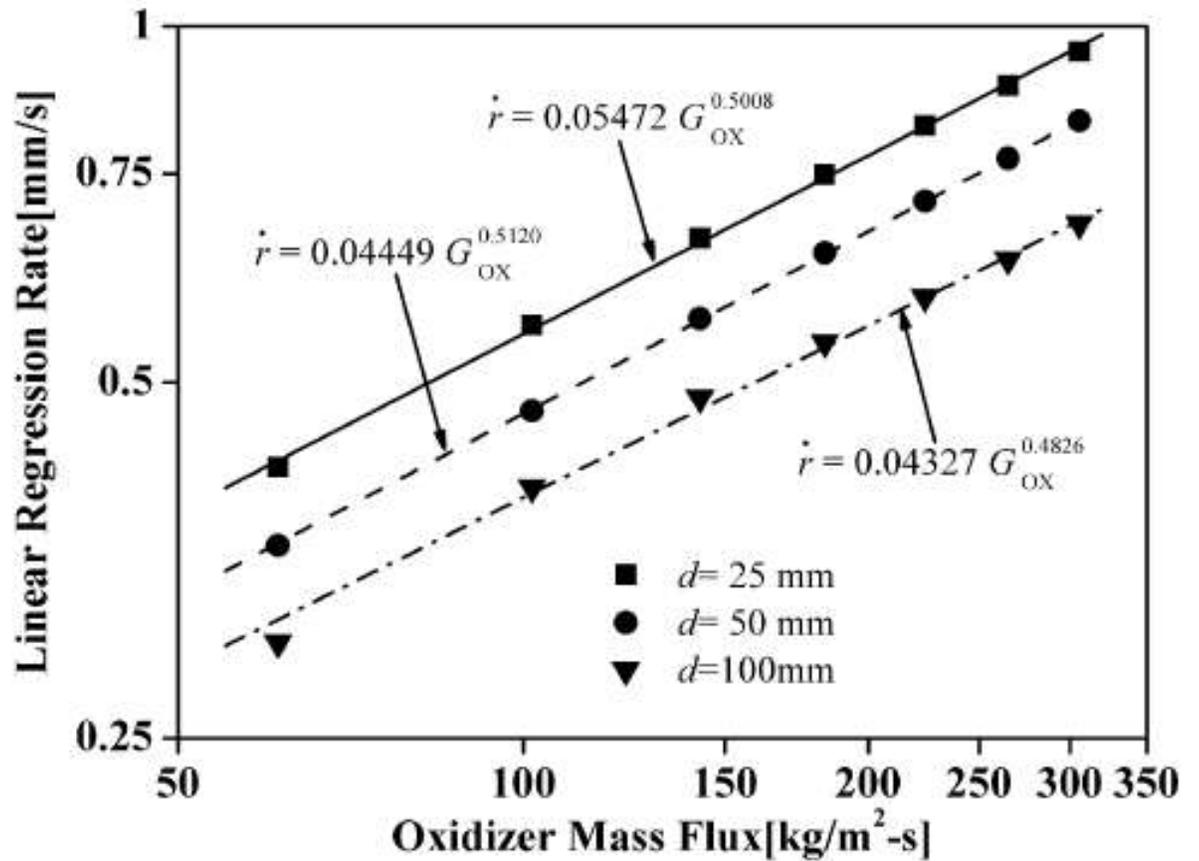


Figure 7. Fuel regression rate in different size motors.²

Aside from burning hotter, the aluminum also provides a higher regression rate. In hybrid rocket engine, the fuel regression rate is the rate that the fuel surface recedes over the course of a burn and this quality has a first order impact on the configuration (i.e. combustion chamber length and diameter) and therefore the performance of a motor.⁴ When the hybrid rocket is launched, the ABS fuel burn-rate is modeled as a regression rate. The regression graph was modeled by the equation

$$\dot{r} = \alpha G_0^n \quad (2)$$

where \dot{r} is the regression rate, G_0 is the oxidizer mass, n is the flux exponent, and α is the regression rate coefficient. In most cases, the thicker the fuel the lower regression curve. This can be seen from figure 7 where a paraffin wax material is molded into a hybrid

rocket grain at different diameters (25 mm, 50 mm, and 100 mm). For all three size motors, the non-dimensional chamber length was held constant at $L/D = 20$, the ratio of oxidizer inlet diameter to fuel port diameter was set as 0.8, and the fuel port diameter of the three motors are respectively 25 mm, 50 mm, and 100 mm.² As the fuel is enlarged, the regression rate decreases. Therefore, it was assumed since aluminum has a higher burning temperature than paraffin wax or ABS plastic, it will give a higher regression rate.

2. Thesis Statement

The goal of this project was to 3D print with ABS plastic and a small, evenly distributed amount of aluminum nanoparticles to improve the duration of fuel for a small scale hybrid rocket.

LITERATURE REVIEW

A. Regression Rates

The goal of this research project was to 3D print a grain for the hybrid rocket made out of both ABS plastic and aluminum nanoparticles. This is believed help the hybrid rocket have a higher average regression rate. The space-time averaged regression rate for a given test is estimated from initial port diameter and consumed fuel mass measurements.¹ The average regression rate consists of all the points of data from the normal regression rate and places a line as close to all the points as possible. The fuel regression rate is the key parameter that influences the design of hybrid rocket grains and the overall motor design, thus an understanding of the regression process is essential for the motor design.² In most cases for hybrid rockets, the higher the oxidizer mass flux, the higher the regression rate.

The fuel surface regression rate (\dot{r}) has been modeled by several equations all depending on the author. However, the following equation has been agreed upon by most experts.

$$\dot{r} = a \frac{G^n}{x^m} \quad (3)$$

Where x is the location, a is the empirical constant determined by the choice of fuel and oxidizer, and G is the local mass flux and equals

$$G = \frac{\dot{m}_{port}}{\pi r^2} = \frac{\dot{m}_{ox} + \dot{m}_f}{\pi r^2} \quad (4)$$

Where m is the mass flow rate and r is the radius. The dependence of regression rate on the mass flux G and the coordinate x comes from the dependence of the skin friction and heat transfer rate on Reynolds number which comes from the distance along the port. The regression rate is governed by turbulent heat and mass transfer in the reacting boundary layer.

In the following figure, the fuel regression rate of three different sized motors were taken and plotted against each other. This graph demonstrates that the regression rate

decreases as the fuel port increases in diameter. The reasoning behind this is as the fuel port opens, the flame expands further apart, causing the temperature to decrease. Effects of initial port diameter, fuel grain length, and the addition of AP and aluminum were investigated with respect to the regression rate of the solid fuel.² For the experiment that will be discussed in this thesis, the grain length, port diameter, and aluminum addition will be evaluated.

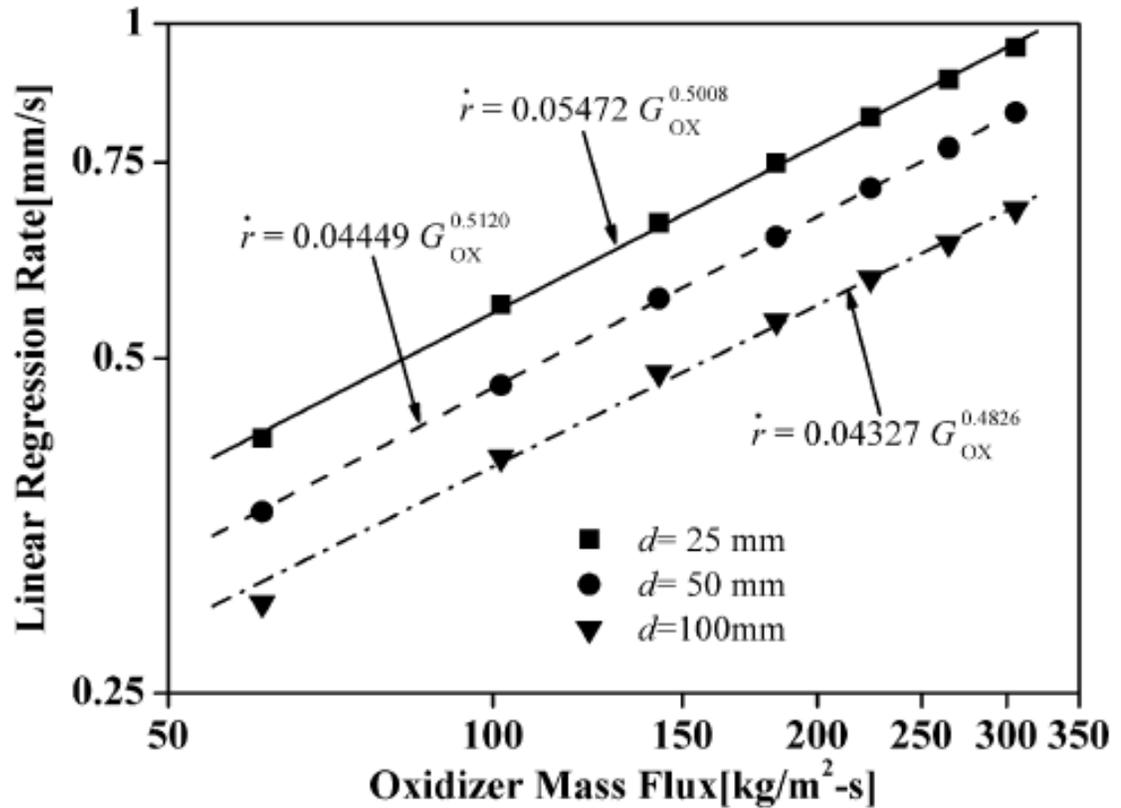


Figure 7. Fuel regression rate in different size motors.²

The following figure is an average regression rate on comparing two rocket grains of two different materials. The first material is Hydroxyl Terminated Polybutadiene (HTPB), one of the most commonly used for hybrid rockets. The other material is paraffin wax, a material that has recently been experimented with to learn how it performs compared to HTPB. When these two materials were compared, they were graphed using the average regression rate. A curve fit to the data points, that is, both laboratory-scaled and larger

scale, results in a mass flux exponent of 0.62.¹ Normally the mass flux exponent (n) ranges from 0.3 to 0.8, the exact number will always depend on the material used for the propellant and oxidizer.

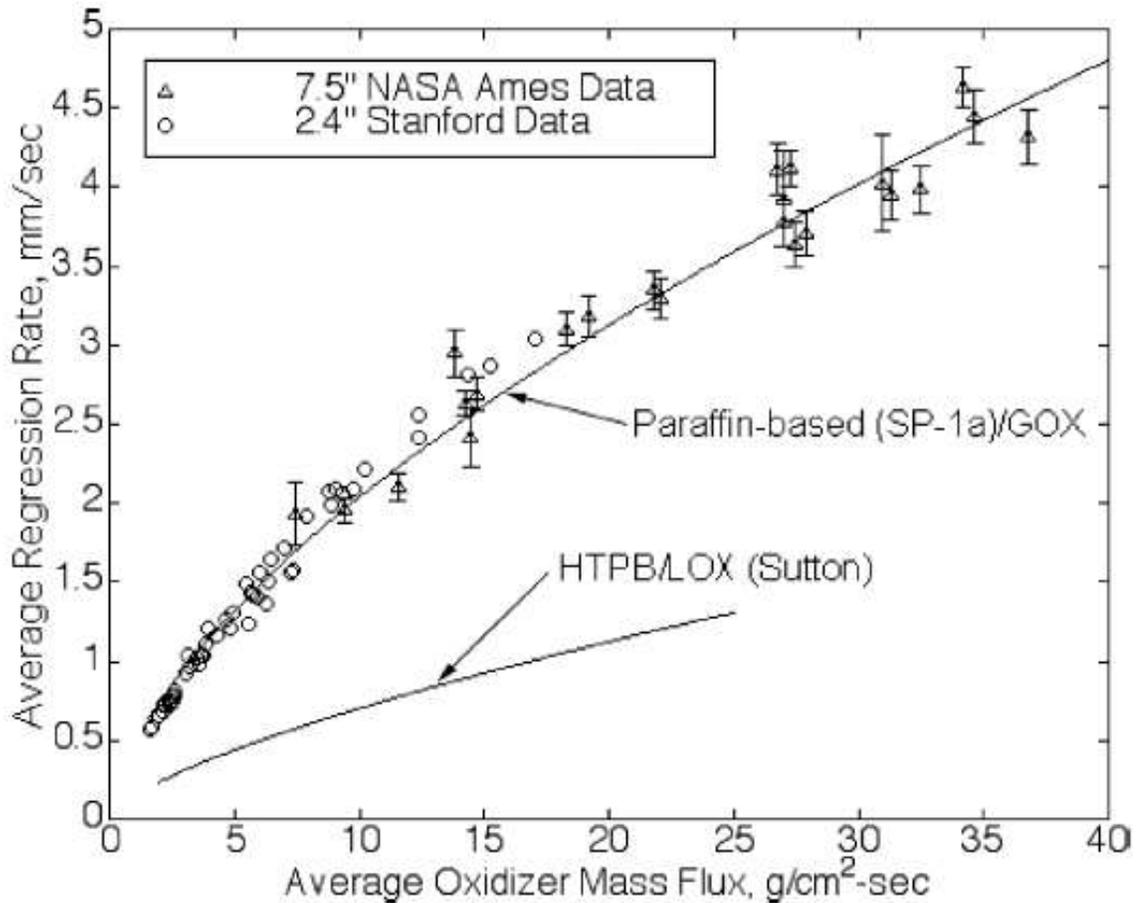


Figure 8. Average regression rate.

As hybrid rocket research continues, exchanging the rocket grains materials has been a popular area investigated. In the previous figure, two materials were compared were HTPB and paraffin. HTPB will be compared to ABS plastic to examine the regression rates of these materials. In all cases the ABS formulation burns with an almost identical mass flow but produces slightly less burn energy than does the HTPB materials.⁶ As seen in the figure below, there are two mean (or average) regression rates, once for HTPB and the other for ABS. Both materials contained results from diameter regression and mass regression. When ABS is compared to HTPB the regression rates are almost the same,

but ABS produces less energy. However, since it is far simpler to produce a rocket grain made from ABS, additional research will be required to rule out the use of ABS.

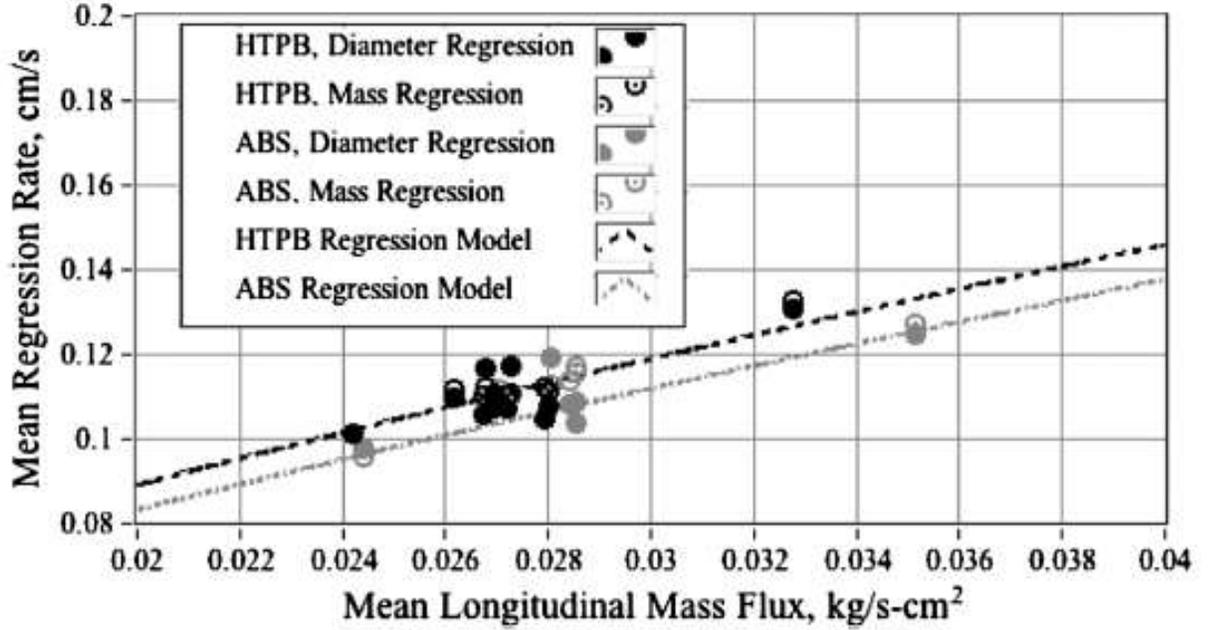


Figure 9. ABS vs HTPB regression rates.^[7]

B. Heat Transfer

To further understand regression rates in hybrid rocket grains, the heat and mass transfer must be discussed. One of the key areas to understand with this hybrid rocket grains is boundary layers. In fluid mechanics, there are two different types of boundary layers, laminar and turbulent. Whether the boundary layer is laminar or turbulent depends on the value of the critical Reynolds number. When the Reynolds number exceeds 10^5 to 5×10^6 , then the boundary condition is turbulent. The most common equation for the critical Reynolds number is

$$Re_{x,c} \equiv \frac{\rho u_{\infty} x_c}{\mu} = 5 \times 10^5 \quad (5)$$

where x_c is the critical location, ρ is density, μ is viscosity, and u is velocity. One difference between laminar and turbulent boundary conditions is mixing. Laminar does

not mix, where turbulent boundary layers do. This is due to the large velocity and temperature gradients.

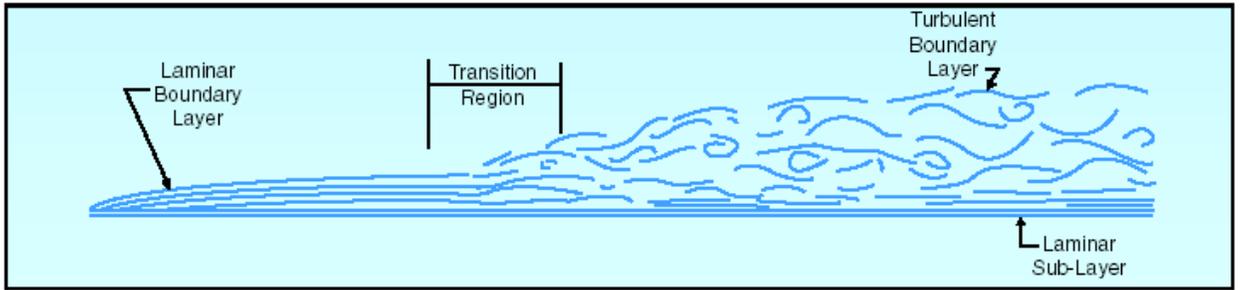


Figure 10. Mixing turbulent layers.

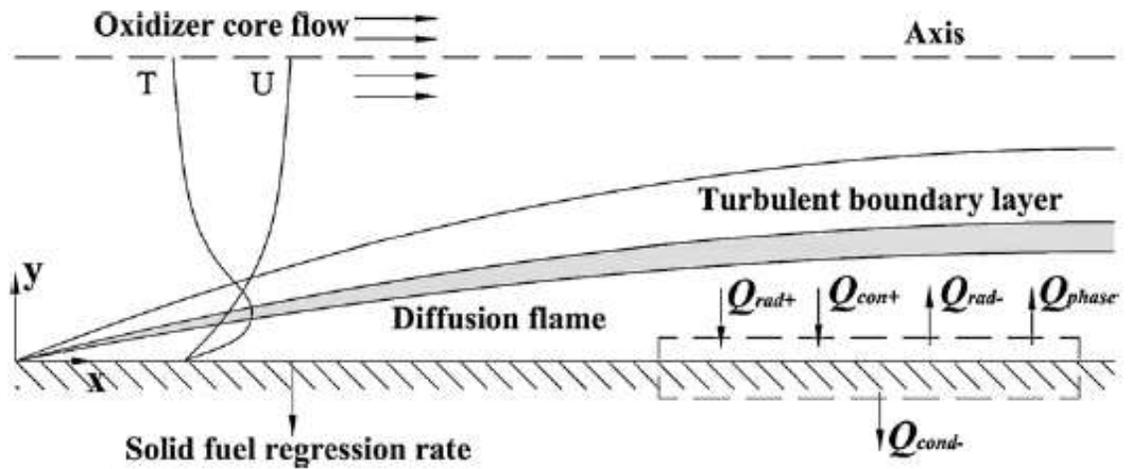


Figure 11. Boundary layer.

As seen above in figure 11, under the turbulent boundary layer there are several heat transfer rates (Q) occurring. The steady state energy balance is

$$\dot{Q}_{Total} = \dot{Q}_{con+} + \dot{Q}_{rad+} = \dot{Q}_{cond-} + \dot{Q}_{phase} + \dot{Q}_{rad-} \quad (5)$$

this can be written per unit surface area as:

$$k_g \frac{\delta T}{\delta y} \Big|_{y=0} + \alpha \epsilon_g \sigma T_f^4 = k_f \frac{\delta T}{\delta y} \Big|_{y=0} + \rho_f \dot{r} h_g + \epsilon_s \sigma T_s^4 \quad (6)$$

Where h_g is enthalpy, ρ is fuel density, r is instantaneous regression rate, ε is emissivity, σ is the Stefan-Boltzmann constant, and T is temperature. At the fuel surface, the rate of heat transfer per unit area converted from the flame sheet to the surface is modeled by the following equation.

$$Q_s = k_g \left. \frac{\delta T}{\delta y} \right|_{y=0} \quad (7)$$

This can be simplified by the following equation.

$$Q_s = \rho_f \dot{r} h_g \quad (8)$$

Determining the heat transfer rate Q_s is the pivotal point of the regression rate problem. In general, the heat transfer rate is dependent of many geometrical, combustion, and flow related factors. In addition, the complication in a hybrid rocket motor is that the vaporizing/liquid fuel leaving the surface of the grain substantially decreases the rate of heat transferred of the surface.

The final area examined in the combustion process are the droplets from the liquid-gas interface. As the oxidizer would ignite and travel through the rocket grain, the grain itself would transform from a solid material to a liquid gas mixture. With the high pressures of the oxidizer pushing though this mixture on the surface, little droplets would detach. This mechanism substantially increases the rate of the fuel mass transfer leading to a much higher regression rate than can be achieved with conventional polymeric fuels by a factor of three to five.³ This can be seen in the following figure.

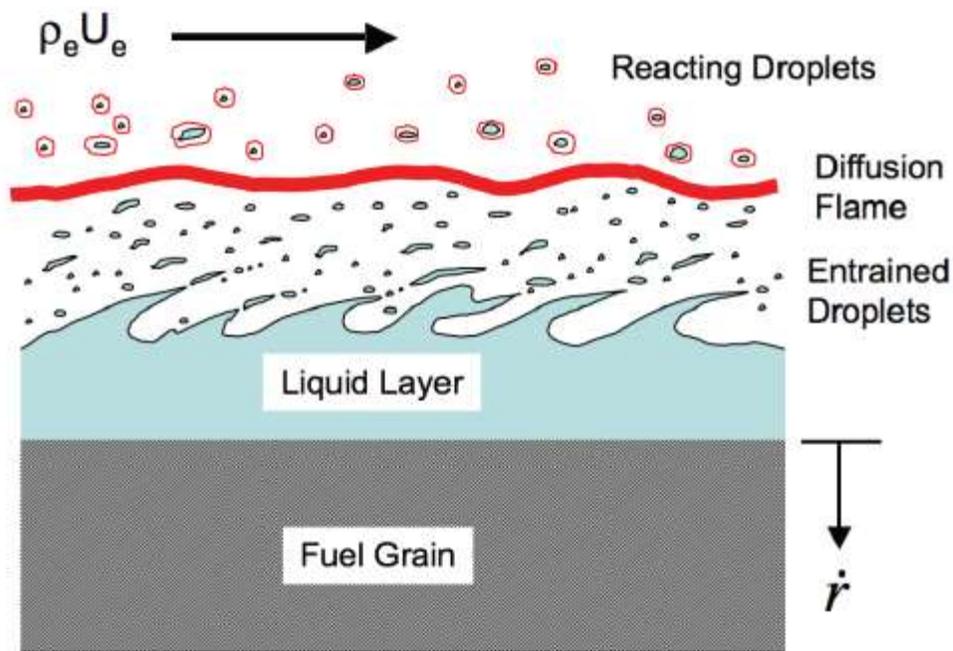


Figure 12. Reacting droplets.

C. Characteristic Velocity

Since the regression rates of HTPB and ABS were comparable in the previous section, the last area to examine is their performance. ABS is much more cost and time efficient from which to make rocket grain. The performance of these two materials were analyzed with different (oxygen to fuel) O/F ratios. Calculations for different mixture ratios were presented.⁶ When analyzing the performance many different areas are examined. One of these areas is the characteristic velocity (c^*) which can be seen in the equation

$$c^* = \frac{g\gamma R(T_c)_{ns}}{\gamma \sqrt{\frac{2}{\gamma+1} \frac{\gamma+1}{\gamma-1}}} \quad (9)$$

The characteristic velocity is defined as a measurement of the effectiveness with which the combustion in a rocket engine produces high temperature and pressure, equal to the exhaust velocity divided by the thrust coefficient. For the higher O/F ratio, 70% butadiene content results in an ABS c^* that exceeds the HTPB c^* for the same operating

pressure and O/F ratio.⁶ This means when the ABS plastic is burned lean, the combustion of the rocket reaches its most effective state.

In this section, the topics of regression rates, turbulent boundary layers, and the equation to find the characteristic velocity have been addressed. All the recent research in hybrid rocket fuel design have examined these areas in effort to design a hybrid rocket grain that burns longer, and has a greater amount of thrust. In the experiments that were done for this project, all of these areas were affected. By launching a 3D printed rocket grain that was made of both ABS plastic and aluminum nanoparticles, the regression would be changed. This can be seen in the figure below, as the aluminum is added to the HTPB, the regression rate is lower. Also, since aluminum has a different melting point than ABS, this will directly affect the boundary layers and the characteristic velocity. The difference between the experiments done in this paper and the experiments that have been conducted at other schools are the materials selected. The figure below shows aluminum combined with HTPB using O₂ as an oxidizer. Other graphs have shown regression rates of paraffin wax. But this is the only time that ABS has been mixed with aluminum nanoparticles and burned by O₂ oxidizer.

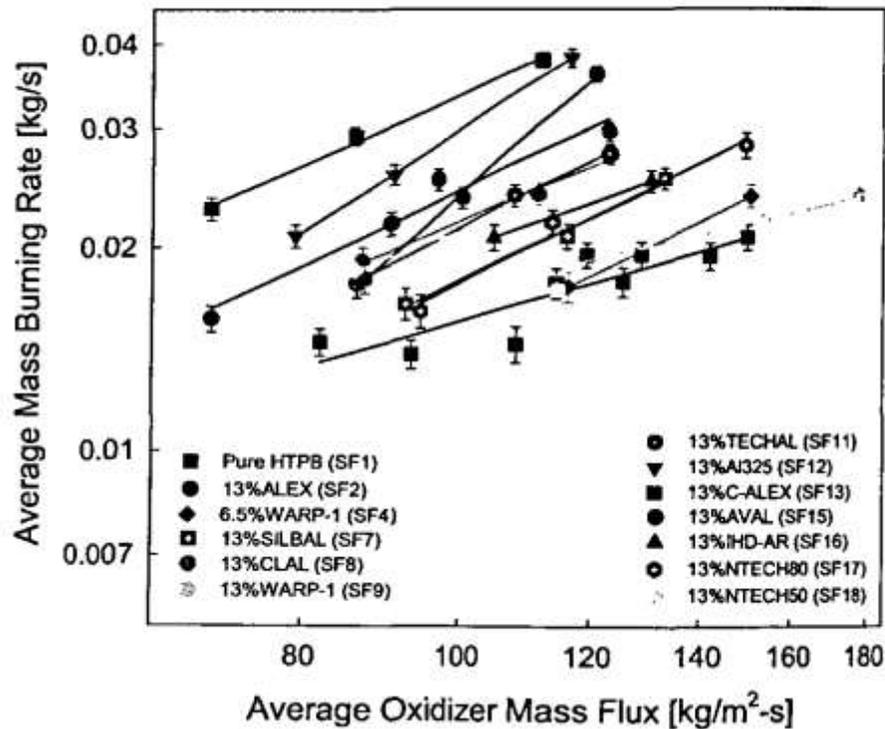


Figure 13. Nanoparticles in HTPB^[7].

As seen in the figure above, the mass burning rate for HTPB with 13% Alex® (aluminum) is higher than pure HTPB. Solid fuel containing Viton-A coated Alex® indicated the greatest enhancement in the mass burning rate at nearly 120% at an oxidizer mass flux of $112 \text{ kg/m}^2\text{-s}$, a representative value at which the average mass burning rates can be compared.⁷ Adding the aluminum increased the mass burning rate, however the combustion efficiency was lowered. It is uncertain as to what the regression rate of the material with aluminum is since there has been no research done. However, it is assumed that since the mass burning rate is increased, the regression rate will increase as well.

Hybrid Rocket Testing

A. The Rocket Stand

The objective in this section was to describe the AU small scale hybrid rocket test stand that has the force of the combustion pushing the rocket at the ground. The most logical way to achieve this was to design the rocket stand upside-down so the plume of the rocket points to the sky.

1. Designing And Constructing The Stand

The first step taken in designing the rocket stand was to see if anyone had done this before at Alfred University. There was a previous design that a student made, however it had several problems that prevented it from working properly. The students design however, provided an example of size, construction, and a basic apparatus. After examining the prior rocket design, it was clear that parts of the new hybrid rocket stand would require more attention than others. These parts were the nozzle and the endplates that would hold the fuel.

The nozzle was designed to look similar to the first hybrid rocket's nozzle. The material that was chosen for the nozzle needed to be able to withstand high temperatures. Graphite was then chosen as the material since it was readily available and was resistant to the conduction of heat. Another bonus to working with graphite is that it is easily machined, making this job ideal for the lathe.

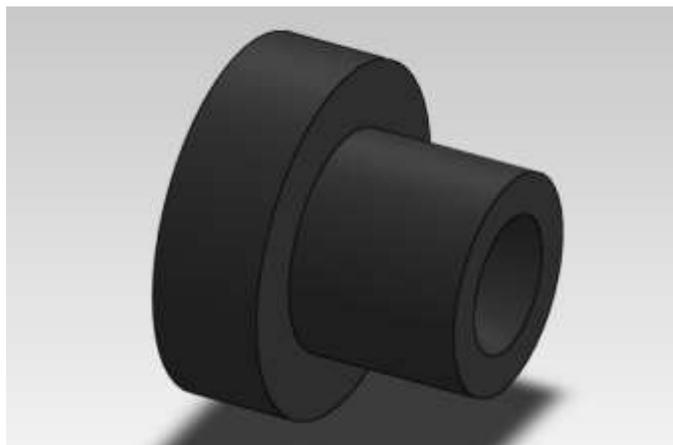


Figure 14. The nozzle modeled in the CAD program.

The endplates were the next step in the design process. The endplates were designed to be bolted six inches apart sandwiching the rocket grain in between them. The endplates needed to be airtight to the grains, and needed to obtain the combustion chamber letting the O₂ into the grain. To make these endplates air tight, tolerances of 0.001 of an inch was used so that the plates would not leak O₂ out before it reached the nozzle. The endplate that holds the nozzle is placed on top of the grain. This endplate does not need an O-ring since the O₂ will be pushing the nozzle into the endplate creating a tight seal.

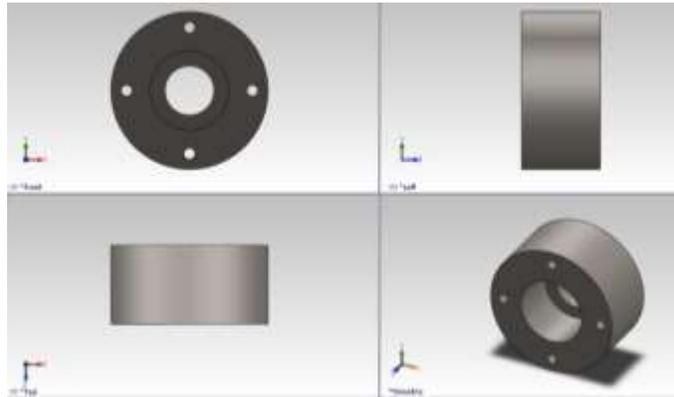


Figure 15. Top endplate without nozzle.

The bottom endplate requires an O-ring groove. The actual O-ring will be placed on the grain and slid into the bottom endplate. These grooves were not possible to make on the manual lathe. The CNC machine was the best way to cut the angles needed for the O-ring grooves. The O-ring design was following the Parker O-ring handbook which requires very small radius fillets and a very small angle for the walls of the groove. Not only are these features very difficult to do on a CNC machine but the radius and depth of the groove in the part made it impossible to cut with the tools available.

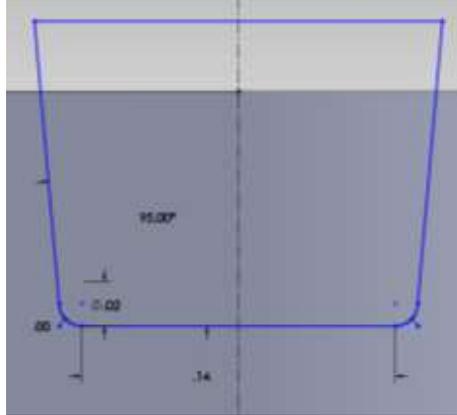


Figure 16. The O-ring design.

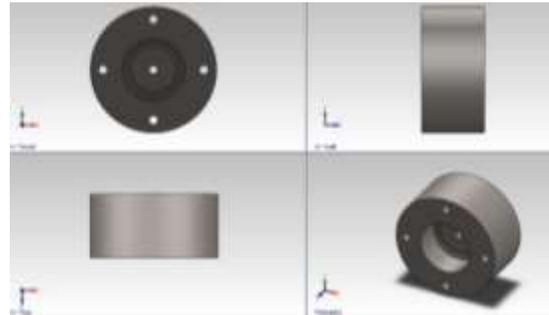


Figure17. Bottom endplate.

After the end plates were designed and machined in the CNC, the frame of the rocket stand was straightforward. Six inch long bolts were used to hold the top endplate to the bottom. One inch by one inch pieces of angle iron were used as horizontal side rails to connect the four vertical side rails. The vertical side rails were bolted to two six inch pieces of one by one inch angle iron. Two half inch wide by six inch long flat stock iron were placed on the horizontal side rails with a small spring on the end of both pieces of flat stock. The reason springs were implanted between the horizontal side rails and the flat stock was to create a place where the load cell could be placed. The load cell will be discussed later in this section. Most importantly, the nozzle was placed into the top endplate. The end result of the hybrid rocket stand design can be seen in the figure below.

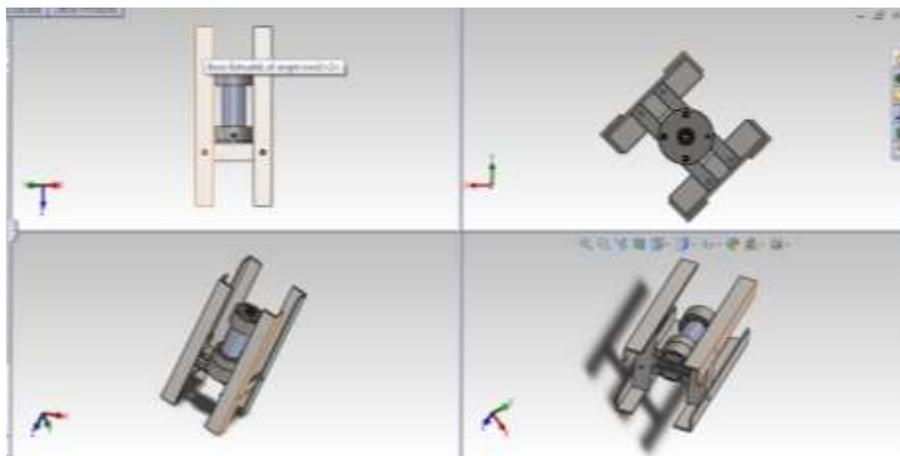


Figure 18. The final design of the rocket stand.

2. The Testing Procedure

Before the hybrid rocket was operated, a series of tasks were followed beforehand to insure safety to those who were testing rocket grains. The first piece that was required to fire the hybrid rocket was to install the rocket grain. The design of the rocket grain will be discussed later in this chapter. Once the grains were designed, the rocket was disassembled in order to install the grain. After the rocket was disassembled, the bolts were loosened that held the top and bottom endplates. Once that was done, the newly printed grain was placed between the endplates, with the new O-ring placed in the O-ring groove on the top of the grain. After the grain and the O-ring were in place, the bolts were inserted through the top and bottom endplates. Once the bolts were tightened, the rocket was then moved to a designated test pad. Before the rocket was fired, the computer and Data Acquisition (DAQ) were connected with an alligator clip to the power supply. Then the DAQ was connected to the computer with a Universal Serial Bus (USB) cable. After that, additional alligator clips were installed from the DAQ to the pressure transducer and load cell. Then the welding hose was attached from the oxygen tank to the rocket using the quick connects. Then the wire from the igniter was placed in the combustion chamber, and all cameras were placed on the test pad as desired. When the regulator on the oxygen tank was turned off, it was slowly opened again. Once the tank was opened, the regulator tank was slowly opened until the valve read 100 PSI. When the 100 PSI was in the regulator, the LABVIEW program was turned on. Finally, the valve that lets the oxygen from the regulator to the combustion chamber of the rocket was opened. The igniter button was pressed the pressure and force that the rocket is discharging was recorded on the DAQ. The rocket produced combustion for approximately 10 to 15 seconds. When the plume of the rocket got close to the edges of the grain and the plume began to pulsate, the oxygen was shut off.



Figure 19. The rocket approaching burnout.

3. The Improvements Made On The Stand

The hybrid rocket stand had several problems, one of which was that the load cell was under the top endplate, grain, and bottom endplate. This resulted in the load cell never zeroing out due to the weight of the grain and endplates. Another problem with the rocket stand was the load cell reading was never accurate. The resistance in the spring caused the load cell to not receive the total force dispersed by the rocket. As a result of these inaccuracies, the hybrid rocket stand was turned on its side. This involved modifying the design and construction of the rocket stand.



Figure 20. Rocket stand side view.



Figure 21. The horizontal rocket stand.

As seen in the pictures above, the rocket stand was mounted horizontally to eliminate the load cell bearing the weight of the endplates and grain. The grains and endplates were

placed on a horizontal slide with the load cell at the opposite side of the nozzle. Therefore the only opposing force was the friction of the slide. Once this was built, it was tested. The results from the firing the rocket on the new stand was as expected. The ABS performance can be seen below. Its results were comparable to the results vertical stand.

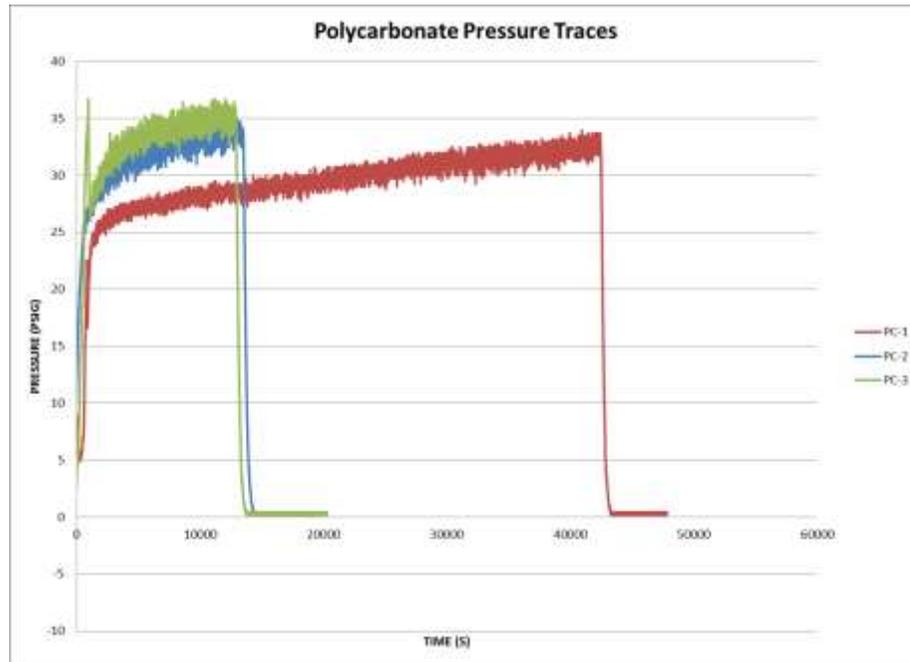


Figure 22. Polycarbonate pressure traces.

B. Hybrid Rocket Fuel

Some of the most common fuels used for hybrid rockets are paraffin waxes and polyethylene waxes. These waxes are predicted to have high regression rates at oxidizer mass fluxes covering a wide range of hybrid rocket applications. For this experiment, the material Acrylonitrile Butadiene Styrene (ABS) was used. The reason ABS plastic was chosen for this experiment was due to it being the material that is most commonly used in 3D printers. Being able to 3D print any shape, thickness, or spiral for fuel of the rocket was a large part of what was investigated. ABS has the chemical composition of $(C_3H_5 C_4H_6 C_3H_3N)_n$ and is a common thermoplastic. It has a transition temperature of 105 °C, yet it is amorphous meaning it does not have an exact melting point. The proportions of ABS plastic can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. This material was experimented on due to the low price and the improved regression rate (compared to paraffin). ABS can be bought in several forms; for this

experiment it was bought in filament form. This form can be used to make any shape desired, through the 3D printer.

1. The Combustion Of ABS+O₂

When the ABS filament was printed in the 3D printer, it produced a 2 inch in diameter cylinder that was 6 inches long. The cylinder had a ¼ inch hole bored through it. After the cylinder was 3D printed, it was then ready to be fired in the rocket. When the igniter lights the O₂ in the rocket and begins to burn the ABS grain, combustion then begins. Combustion by definition is rapid oxidation generating heat or both light and heat; also, slow oxidation accompanied by relatively little heat and no light. In the figure below, is a picture taken from a video recorded from the FLIR T440 infrared camera. The picture was taken when the rocket was being fired. The temperature of the physical rocket stand was low. However the plume of the rocket reached temperatures well over 150 degrees Celsius. The vertical bar, to the left in the figure below, showed the temperatures ranging from -8.4 to 150 degrees Celsius. The temperature around the plume decreases the further away it is read.

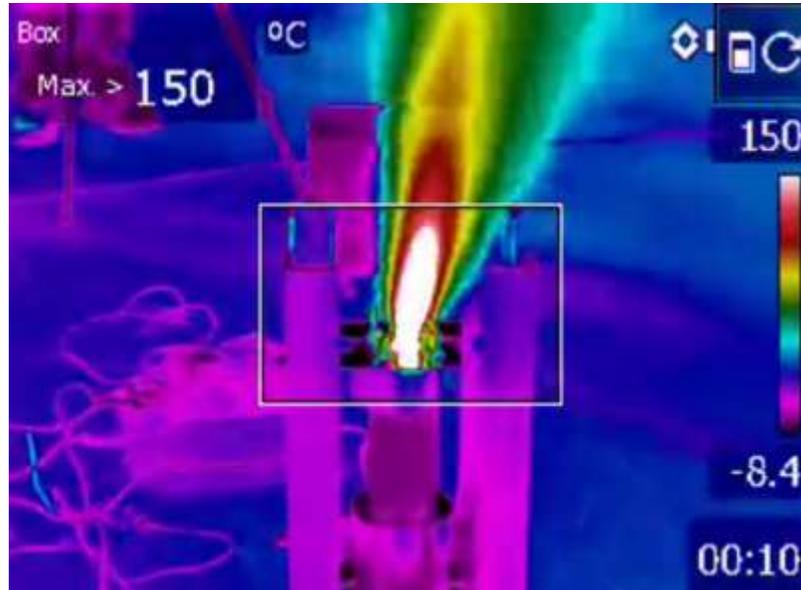


Figure 23. The thermal camera capturing the rocket.

This provides data in two ways: The first way is that it displays two sinusoidal waves that show the force and pressure. This wave is seen in the figure below. It does not record the data, however it shows it as it is being produced. Therefore, as the rocket is being fired the operator can read the force and pressure. The second way this program provides data is it sends the data taken to an Excel spreadsheet. Then with the Excel sheet, the data can be graphed over time. These excel graphs can be seen in the next section of this chapter.

3. Comparing Results of Different Fuel Designs

Part of the experiment with the hybrid rocket was to see how ABS grains would perform as a fuel. That led to making a baseline design of the rocket grain. The specifications of this baseline grain are as follows: 2 inch in diameter, 6 inch long, with 0.5 inch hole through the center. The baseline grain and the results of the grain when fired can be seen in Fig.(26). On the left is the design of the grain in a half section view. This shows the hole that was designed to be the throat of the rocket. The graphed results are on the right, showing the pressure over time. The pressure is measured in units of psia, and time in seconds. Once the baseline grain was designed and tested, dozens of grains were made varying in pattern, size, and number of ports. Shown below are some of the designs that achieved higher performance in pressure. All of the grains were fired under the same amount of time (roughly 60 seconds). The pressure of the oxygen proceeding to the combustion chamber was 65 psia.



Figure 25. Baseline design.

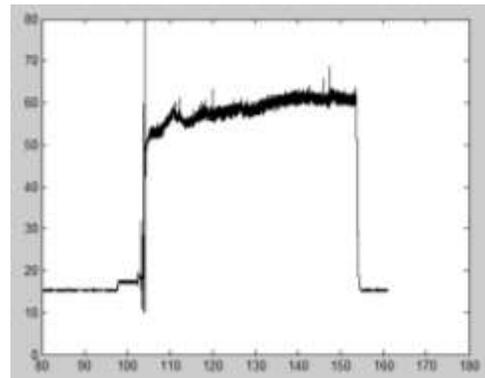


Figure 26. Baseline results.



Figure 27. Multiport design.

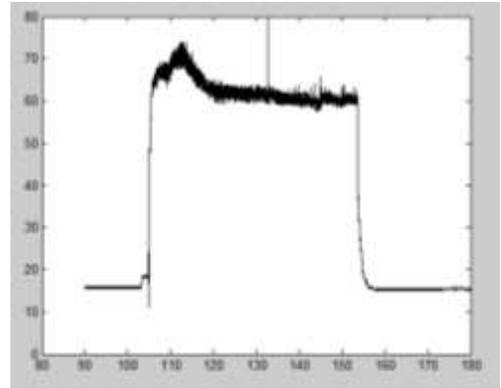


Figure 28. Multiport results.

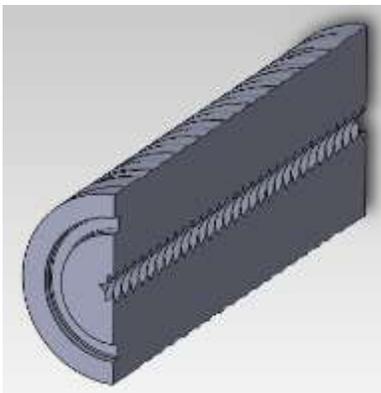


Figure 29. Star swirl design.

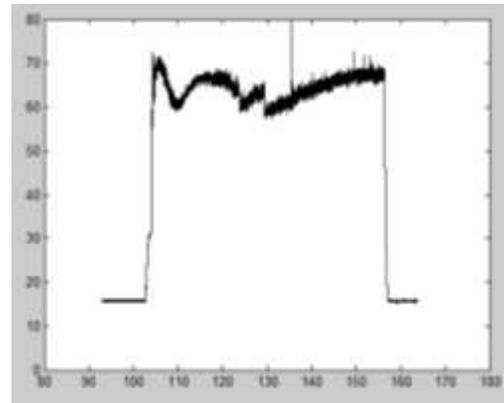


Figure 30. Star swirl results

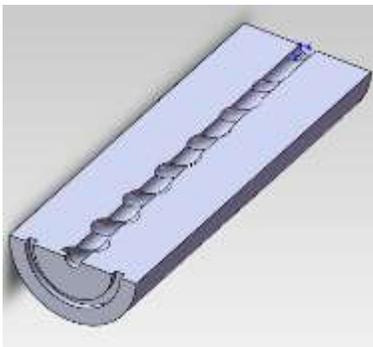


Figure 31. Tapered swirl design.

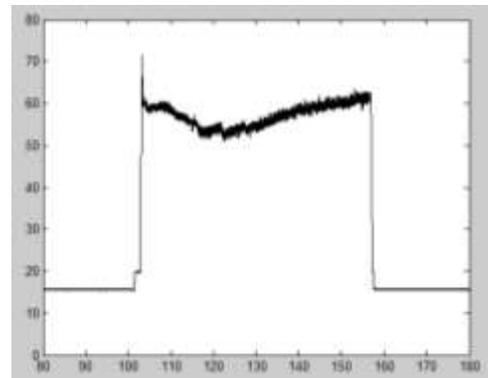


Figure 32. Tapered swirl results.

As seen in the figures above, the different grain designs (Baseline, Multiport, Star Swirl, and Tapered Swirl) each show comparable results. The star swirled design gave the highest pressure performance of them all. It achieved just over 70 psia whereas the

baseline got just over 60 psia. The tapered swirl design is comparable to the baseline design as it achieved approximately 60 psia. The multiport design started at 70 psia, but after 10 seconds it plummeted back to 60 psia. After firing these four rocket grains, the star swirled grain proved that when designing rocket grains to have different patterns, it does have a positive effect on the pressure.

C. 3D Printing Fuel Grains

To transform the shape of ABS from a filament to a cylinder, 3D printing is the only practical method. The advantage of 3D printing hybrid rocket grains is that the size and shape can be customized. The remainder of this chapter will discuss how to take grain design and transform it to a working product.

1. Designing ABS Grains

When designing grains for the hybrid rocket two areas were focused on. One of those areas is the inside of the rocket grain. One of the purposes for conducting this research was to see if there was any difference in performance between straight bored grains and ones with spiral design. To make these grains perform ideally, they must have the proper seal, hence an O-ring was needed. The spiral shape and the O-ring were to the two attributes of the grains that were focused on when designed.

a. Straight Vs Spiral Grains

The original grain design was a 2 inch in diameter by 6 inch long cylindrical grain with a 0.5 inch hole bored through the entire length. Then grains were designed to have a spiral pattern though the center. Several different spiraled patterns were designed and then made in the 3D printer. The idea was to fire different spiral patterns and the straight bored pattern in the rocket. Once they were fired, the plan was to compare the pressure and see if the spiraled grains had a higher performance than the straight grain.

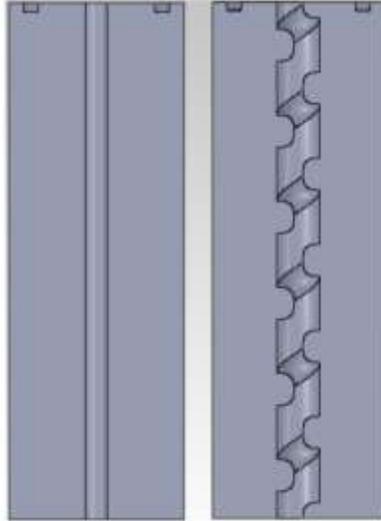


Figure 33. Cross-sectional view of straight vs spiral grain.

b. Designing The O-Ring

The last area that needed to be designed for the grains was the O-ring. The O-rings were designed by using the Parker O-ring Handbook, which requires very small radius fillets and a very small angle for the walls of the groove. The grains all needed to be designed with an O-ring groove that would fit the O-ring on the nozzle with a tolerance of 0.001 inch. The bottom of the O-ring groove was 0.14 inches and the small radius used to on the corners was 0.02 inches. The angle from the bottom of the groove to the sides was 95 degrees. These O-ring grooves were designed in Solidworks™ so that when the grains were printed on the 3D printer, it was ready for an O-ring to be installed.

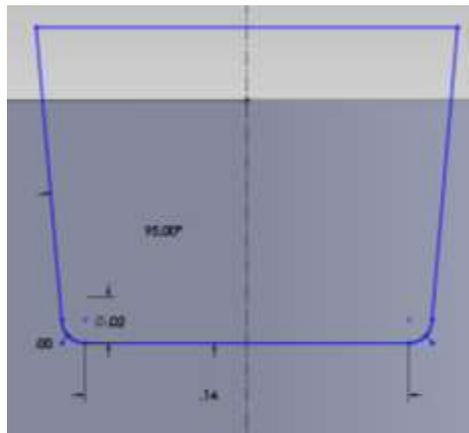


Figure 34. The O-ring design.

2. 3D Printing The Grains

Printing these grains is an important part of this experiment. The 3D printer that was used in this experiment was the MakerBot Replicator™. To convert a design from Solidworks™ to code that can be read on the Makerbot™, a program called Replicator G is needed.



Figure 35. The Makerbot™.

a. Replicator G

Replicator G™ is a program that converts a drawing from CAD programs to machine code (also called G code) that can be read by the Makerbot™. G Code is the generic name for a control language for CNC machines. It is a way for the user to tell the machine to move to various points at a desired speed, control the spindle speed, and turn on and off various coolants. It is a fairly standard and useful tool.

b. Converting Solidworks™ To Replicator G

To convert a design from Solidworks™ to Replicator G, the following procedure should be followed. Before a design can be converted, Replicator G needs to be downloaded, Python (a program that reads G code), and an SD card needs to be in the computer that is being used. The first activity that is needed is, the user needs to have a grain designed in Solidworks™. Once the grain is designed, save the design in a .STL format. Open Replicator G™, go to file, open, and select the grain design that was saved in .STL. Once this is done, the grain that was designed should be displayed in the Replicator G™. Move the grain to the center of the platform and set the part of the

platform. After all these procedures are achieved, click the command ‘Generate G-Code’. A display box will appear where it will show the temperature, feed rate, etc. It is not recommended to change the temperature or anything else in this display box. Click ‘Build to file’ and this will generate G code and send it to the SD card.

3. Operational Procedure For The Makerbot™

Before using the Makerbot™, check and make sure there is ABS filament attached to the head of the printer where the nozzle is located. Also, take a foam paint brush and a glass cup with some acetone in it. Brush some of the acetone on the platform. This will help the ABS stick to the platform when it is printed. Take the SD card that has the G code on it and place it in the slot on the left side of the Makerbot™. Turn the Makerbot™ on, click ‘print from SD card’. Then the grain design in G code will be there, click it and the printer will begin to heat up. Once the Makerbot™ has heated up, it will begin printing the rocket grain. After the Makerbot™ is done printing, the part that was designed should be made and ready to be used.

FILAMENT EXTRUDER

The filament extruder is a machine that converts plastic (in this case ABS) chips into a thin filament that is 1.75 mm in diameter. The filament is then rolled up on a spool and fed into a 3D printer. Filament extruders turn plastic chips into a thin filament by transporting the plastic through the port in a nozzle. As the plastic travels through the pipe to get to the nozzle the heat should increase such that, when the material reaches the nozzle it should be at the desired temperature. In this case, the temperature was 120 degrees Celsius. Understanding how filament extruders work and are built was important to the research that was conducted on this experiment. The object of the experiment was to produce a 3D printed rocket grain that would consist of mostly ABS and some aluminum nanoparticles. The only way to construct a rocket grain with both of these materials was to combine them before it was 3D printed.

A. The Design

When the designing process for the filament extruder began, research led to the Lyman filament extruder. In 2013, Hugh Lyman won ‘the desktop factory competition’ for his design of the Lyman filament extruder. This machine made ABS pellets into filament. Since the objection for this project was to construct a filament that contained plastic and metal, the Lyman filament extruder made an adequate starting point. The designing procedure for the new filament extruder for this project was categorized into three sections, Lyman’s design, a new design, and the final design. The Lyman design was analyzed to start, then it was broken down to the basics to see how it worked. After that, a new design for this project was made. This new design was based on Lyman’s design, but simplified to make the machine more affordable. The final design was made after some research went into what materials were available and what the easiest method of manufacturing was.

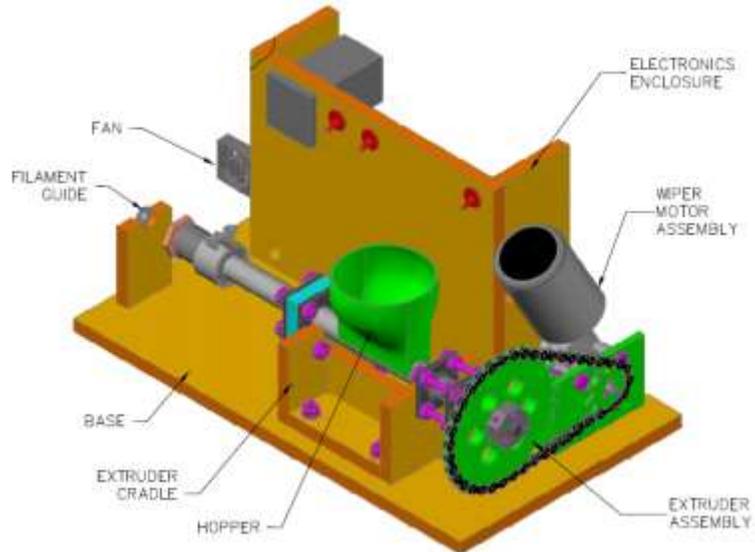


Figure 36. Lyman's extruder design.

1. Different Stages In Designing The Filament Extruder

The Lyman Filament Extruder was used as a baseline in this experiment. As it was carefully examined there were parts that were not necessary towards it producing a filament. These parts were discarded and a new design was made. This new design, which can be seen in figure 37, contained the essential parts that moved and heated the ABS into a filament. These selected parts were the auger bit, the $\frac{3}{4}$ inch pipe that the auger was inside, the metal brackets that held the pipe in place, the 30 tooth sprocket, the 10 tooth sprocket, the motor, and most importantly the nozzle.

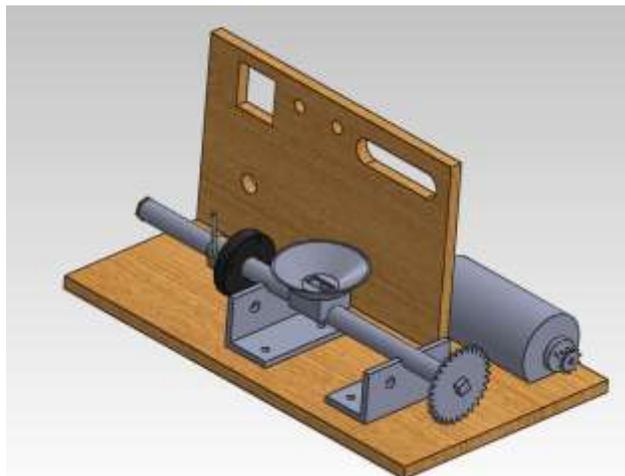


Figure 37. The initial design.

After researching what parts were available and affordable, the final design, which can be seen in figure 38 and 39, was made. The following design was built: The base of the extruder was made of $\frac{3}{4}$ inch plywood as well as the vertical divider. The front bracket, pipe brackets, and motor bracket were all made of iron. The two sprockets shown, differ in size, the one from the motor was 10 teeth, and the other 30 tooth. The motor used to drive the 10 tooth sprocket came from an 89 Volkswagen Rabbit windshield wiper motor. The pipe that was selected for this design was $\frac{3}{4}$ inch black steel. Inside the pipe was a $\frac{5}{8}$ inch auger drill bit. The one inch band heater on the opposing end of the sprockets was bought from PE Products. The nozzle was brass and was machine on the manual lathe in a machine shop. The nozzle and the end of the pipe that contained the nozzle were threaded to be $\frac{3}{4}$ -11. All of the drawings for each part of the extruder can be further viewed in the appendix. In addition to these machined parts, the filament extruder design consisted also of a temperature controller, an external thermocouple, and a variable DC (Direct Current) power supply.

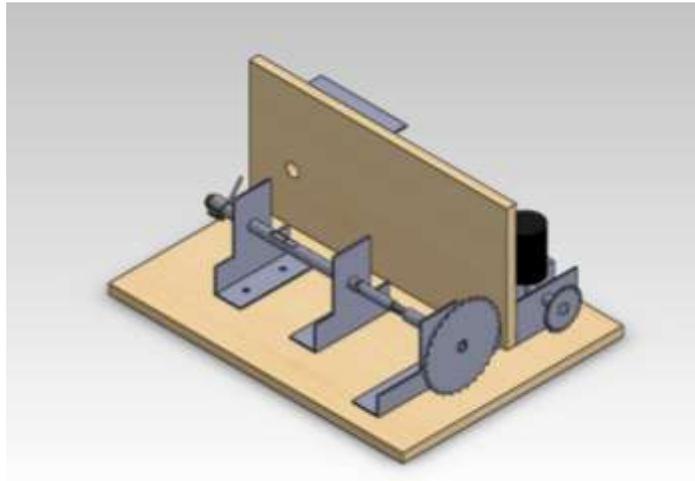


Figure 38. Modified Design.

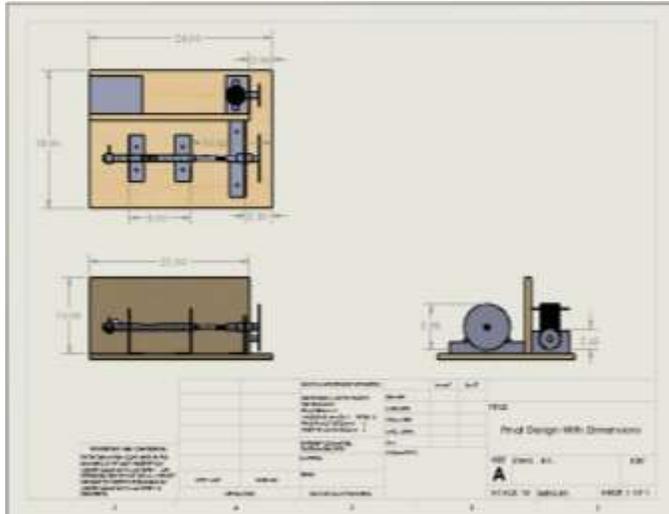


Figure 39. Modified design drawing.

2. Budget Comparison

To build Lyman's filament extruder, the price would have been high. When all the parts that were in his design were appraised, the final amount of the Lyman filament extruder came to \$560.16. When the filament extruder that was used for this project was priced, it was reduced to \$42.38, less than 1/10th of the price.



Figure 40. Assembled extruder.

3. The Circuit Diagram

The design of the filament extruder was significantly different from Lyman's extruder. This called for a new circuit design to connect the band heater to a PID controller. The controller that was selected was an Omega CN 800. This controller had 11 different ports with the 4th and 5th designated to the thermocouple. The figure below explains how the PID controller was wired to the AC source, band heater, and thermocouple. The thermocouple was a type K (chromel – alumel) thermocouple which is the most commonly used due to its ability to read temperatures from -200 °C to 1350 °C. The PID controller used the thermocouple to read the current temperature of the nozzle and send a signal to the band heater. If the PID temperature is set to 135 °C, then the band heater turns on until the temperature of 135 °C is reached and then it shuts off.

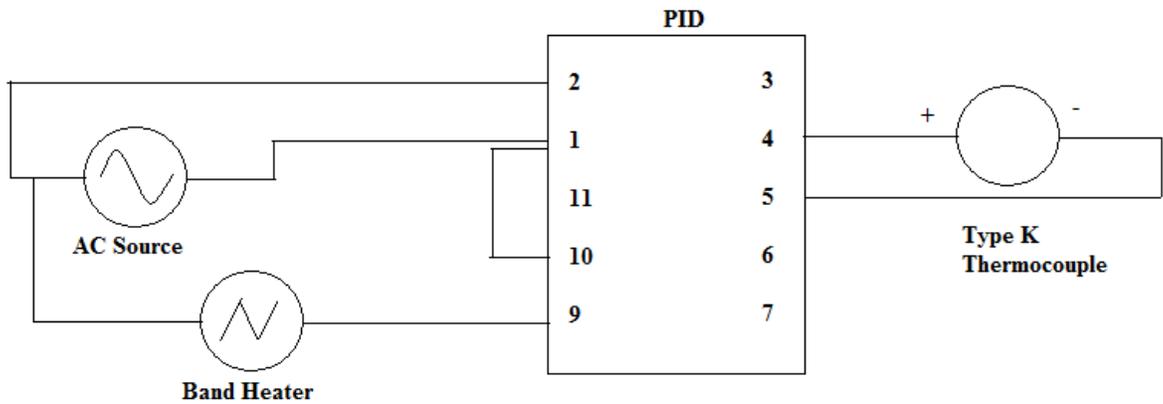


Figure 41. PID circuit design.

A circuit needed to be designed from the band heater, and the windshield wiper motor. This was a much simpler circuit to create. A voltmeter was connected to the motor and then plugged in to the 12 volt DC source. When the circuit was installed, the user was able to select the desired input voltage (up to 12 volts). As the voltage increased, the RPM (rotations per minute) would increase also.

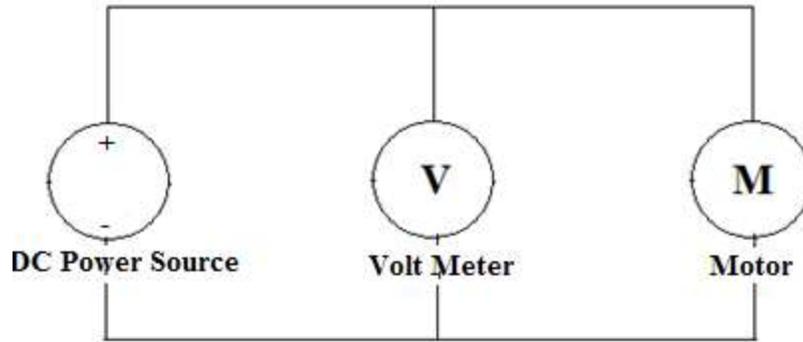


Figure 42. Motor circuit design.

B. The Procedure

When operating the filament extruder a procedure must be followed to ensure safety for the user. The overall goal of this filament extruder was to transform the shape of the ABS from small chips to a 3mm in diameter filament. Once this transformation of the shape has occurred, the material was then ready to be experimented with in the 3D printer.

1. Pre-Set-Up

Before using the filament extruder the type K thermocouple and wire from the temperature monitor needed to be held to the pipe as close to the nozzle as possible. The easiest method to hold the wires to the pipe was to use a hose clamp. Once the wires were secure, the power supply needed to be installed to the windshield wiper motor. The positive terminal from the power supply needed to be wired to the positive terminal of the motor. The same was needed for the negative terminals. Once everything was installed, the preheating began. The PID controller was then set to approximately 150 degrees Celsius. Then after waiting for the temperature monitor to read that the temperature reached 100 degree Celsius, the time to extrude began.

2. Procedure

Once the extruder was ready, the voltage was then slowly increased from 0 to 12 volts to allow the auger to begin turning. Once the temperature was above 100 degrees and the auger bit was turning, the plastic was inserted through the opening that was cut on the top of the pipe. The material was inserted in small increments to allow the material to heat up

gradually. The material did take some time to heat up enough to become soft enough to exit the nozzle. However, after waiting a few minutes the material slowly began to exit the port of the nozzle. Once the material began to exit the nozzle faster, all that was left to do was guide the new filament out of the nozzle and let gravity pull the filament along.



Figure43. Extruder top view.

3. Clean Up

After the desired amount of filament is extruded, cleaning the nozzle was necessary. Once the extruder was used, an hour was needed to allow the apparatus to cool. As the cooling process proceeds, the material that was extruded hardens. The only method to successfully clean the nozzle and pipe was to disassemble the apparatus. Once the bolts were removed from the pipe brackets, the nozzle was removed from the pipe. Then the pipe was drilled with a 5/8th bit to remove the unwanted material. Similarly the nozzle was drilled out with a 3/16 bit to unplug the port. Once the pipe and nozzle was unplugged, the system was placed back together which completed the cleaning process.



Figure 44. Extruder pipe plugged.



Figure 45. Extruder pipe plugged close.



Figure 46. Nozzle plugged.

C. Preparing The Plastic/Aluminum

Once the filament extruder was working correctly and gave adequate results, the next step was to extrude with an ABS/Al mixture instead of pure ABS. The process of mixing ABS plastic with aluminum nanoparticles required patience. Before aluminum was added, the plastic needed to be dissolved in acetone to the correct amount. After the ABS acetone mixture was concluded, different amounts of aluminum nanoparticle were added to different samples to give an assortment of ABS/Al ratios. Then these samples were prepared for the extruding process.

1. Selecting Acetone ABS Mixture

Before aluminum nanoparticles could be added to the ABS, the plastic would need to be softened. Acetone provided a safe way to soften the plastic so the metal could evenly distribute through the ABS. To soften the plastic with acetone, the percentage ratio of acetone to ABS was experimentally found. As seen in the following figures, too little acetone used to dissolve the plastic resulted in the shape of the plastic not changing. Likewise, when too much acetone was used, too much time was required in the dissolving process.



Figure 47. ABS dissolving 5%.

The first attempt to understand the acetone to ABS ratio was to take 30.48 cm (12 in) of 3 mm (0.1181 in) in diameter ABS plastic and dissolve it with 5, 10, 15, 20, and 25 ml of acetone. The aluminum could not be mixed in with the ABS until it was softened enough by the acetone. The first step in this experiment was to take 30.48 cm (12 in) of

ABS filament (that was ready to be used in the 3D printer) and cut into pieces small enough to fit inside a small 50 ml beaker. Then 5 ml of acetone was measured and poured in the beaker with the ABS. The beaker was placed in a fume hood to help the dissolve and soften the plastic sooner. It was left overnight and by morning it had not dissolved nearly enough to be ready to combined aluminum nanoparticles with it. The picture above was taken after the dissolving process was complete.



Figure 48. ABS dissolving 10%.

Since 5 ml of acetone was not enough to successfully dissolve the ABS, the next step was to increase the amount of acetone. Therefore, the same procedure was done with the ABS, only this time 10 ml of acetone was used. The amount of ABS was left the same, at 30.48 cm (12 in), and it was then dissolved with 10 ml of acetone. The acetone was left to dissolve with the ABS overnight. The figure above shows that 10 ml of acetone still was not enough to soften the plastic, or change its shape for that matter.



Figure 49. ABS dissolving 15%.

After the experiment with 5 and 10 ml did not work, 15 ml of acetone was used for this experiment. The same amount of ABS was used, and as a result the plastic changed shape significantly more than when 10 ml was used. However, the figure above shows that this was not enough to mix the metal with.



Figure 50. ABS dissolving 20%.

The next step in increasing the amount of acetone was to use 20 ml. The end result was shown in the figure above. The original shape of the ABS plastic was still visible, so further experiments were conducted with more acetone.



Figure 51. ABS dissolving 25%.

The fifth and final experiment that was done with the 30.48 cm (12 in) of ABS plastic used 25 ml of acetone. This amount of acetone almost completely dissolved the plastic

and was the best results obtained so far. The results were close to what was desired. However, it was clear that to be certain a larger number of experiments was needed.

For the next series of tests, the same procedure was used, only this time 76.2 cm (30 in) of ABS was used instead of 30.48 cm (12 in). The acetone was used in much larger amounts, starting at 5 ml ranging to 75, all using 76.2 cm (30 in) of plastic. The reason the amount of plastic was increased was that if one of the experiments was ready to be mixed with aluminum, there needed to be enough to test in the filament extruder first. The following table shows the trials and outcomes of all the experiments that were conducted with both 30.48 cm (12 in) of ABS (shown above) and 76.2 cm (30 in).

Table I. Different Experiments with the ABS/Al Mixture

Test #	Length of ABS (cm)	Length of ABS (in)	Amount of Acetone (ml)	Results from the mixture
1	30.48	12	5	Did not change the shape of the plastic filament
2	30.48	12	10	Did not change the shape of the plastic filament
3	30.48	12	15	Did not change the shape of the plastic filament
4	30.48	12	20	Started to change the shape of the filament, but not enough
5	30.48	12	25	Started to change the shape of the filament, but not enough
6	76.2	30	5	Did not change the shape of the plastic filament
7	76.2	30	10	Did not change the shape of the plastic filament
8	76.2	30	15	Did not change the shape of the plastic filament
9	76.2	30	20	Did not change the shape of the plastic filament
10	76.2	30	25	Did not change the shape of the plastic filament
11	76.2	30	30	Started to change the shape of the filament, but not enough
12	76.2	30	40	Started to change the shape of the filament, but not enough
13	76.2	30	50	Changed the shape of the plastic filament
14	76.2	30	60	Changed the shape of the plastic filament
15	76.2	30	70	Changed the shape of the plastic filament but took too much time
16	76.2	30	75	Changed the shape of the plastic filament but took too much time

After all 16 of the experiments concluded, the 76.2 cm (30 in) of ABS plastics dissolved with 50 ml of acetone was selected to experiment with further. This mixture, before the aluminum nanoparticles were added, was tested in the filament extruder. After a few attempts of extruding the new mixture, a successful filament was extruded that looked similar to the plastic before it was dissolved. When all of these experiments were complete, the time to add aluminum nanoparticles came.

2. The Procedure Of Weighing Aluminum

There was not a guarantee that the filament extruder would work once the aluminum was added to the ABS/acetone mixture. Also, if it successfully extruded with metal, it was uncertain if it would 3D print. The solution to these problems was to make different concentrations of aluminum in the mixture. This lead to conducting experiments with

ABS/Al in percentages of 15%, 10%, 5%, and 1% in an attempt to discover how the metal would affect the extruding process. Since the goal of this project was to be able to 3D print with ABS and 10% of aluminum combine, that was the first concentration attempted. To calculate 10% aluminum the following equation was used.

$$M_{Al} = 10\%M_{ABS} \quad (10)$$

In that equation M_{Al} was the mass of the aluminum, and M_{ABS} was the mass of the ABS plastic. To begin this procedure, the first step was to weigh a 76.2 cm (30 in) piece of ABS filament as seen in the figure below.



Figure 52. ABS mass.

To weigh 76.2 cm (30 in) of ABS and the aluminum nanoparticle, a balance made by Denver Instruments was used. For this particular experiment, the weight of 30 inches of ABS plastic was 1.9894 grams. Once this was found, 10% of this was roughly 0.1989 grams.



Figure 53. Aluminum mass.

3. Procedure Of The ABS/Aluminum

Once the desired percentage of aluminum nanoparticle is weighed and set aside, the mixture of 76.2 cm (30 in) is dissolved by 50 ml of acetone. After approximately 12 hours, the acetone was almost dissolved, but the plastic was still in liquid form. At that point, it was finally time to add the nanoparticle to this mixture. After mixing the aluminum to the liquid plastic, the solution was stirred with a spatula. After the aluminum was mixed with the solution, then it was placed in the hood until it hardened. The image below was the ABS/Al/acetone mixture before it hardened.



Figure 54. ABS/Al dissolving.

Once the mixture dissolved, it formed a solid piece of plastic/aluminum. It was removed from the beaker and, using scissors, it was cut into pieces small enough to fit into the hopper of the filament extruder. Once the ABS/Al was in the form of small chips, it was ready to be used in the filament extruder.

RESULTS AND DISCUSSION

A. The ABS/Al Processing

Once the ABS/aluminum was combined together and extruded, it was ready to be printed in the 3D printer. This section will discuss what was modified with the ABS/Al filament in attempt to successfully print a rocket grain.

1. The Extruded Material

When the filament extruder finished producing this mixture of ABS and aluminum, the goal was to use it in the 3D printer to print a rocket grain. The amount of aluminum that was used in the overall material was roughly 10% of the ABS weight. However, the filament extruder didn't always produce a ABS/Al mixture that was able to be inserted into the head of the 3D printer. The filaments that were produced often would have sections that were smooth with burs in it every few inches. These burs would cause a problem with the new filament that was loaded into the 3D printer head. The port in the head of the 3D printer had the clearance to allow the 1.75 mm ABS filament through it to print. When the bur from the new filament reached the head, it would stop instantly. The motor that would pull the filament from the top of the head to the nozzle would continue to turn, but would only dig up the sides of the new filament.



Figure 55. Filament exiting the extruder.

The next step was to get the Makerbot™ to 3D print the new material, and the only way to do this was to eliminate the burs on the filament. The best solution to fixing the bur problem was to take a piece of 600 grit ultra-fine sandpaper and carefully sand off the bur. Once all the burs were off the filament, the 10% aluminum material was successfully inserted into the head of the 3D printer. However, it did not 3D print.

2. Experimentation with the Percentage of Al in the ABS

When the 10% aluminum/ABS concentration did not work, the first step taken towards getting the 3D printer to print was to try different concentrations of aluminum in the ABS. Due to adding the aluminum to the ABS, the viscosity of this material no longer has the same softening point, or viscosity as it did without the aluminum. One way to see how the amount of aluminum affects the melting point or viscosity is to change the percentage of aluminum. Therefore, the same experiment was conducted; with except instead of 10% aluminum, 15%, 5%, and 1% was used.

When the experiment was conducted with 15%, the results were not as good as the 10% material. This concentration was very brittle, and had a significantly higher amount of burs in the filament. After it was extruded and the burs were sanded down, it was tested in the 3D printer. The material went into the head of the 3D printer and conveyed down to the nozzle, where it began to melt. However, it didn't melt enough to allow any of the material out of the nozzle when it was printing. Once the procedure of printing was stopped, the 3D printer would not release the filament. The material hardened and plugged the entire head of the 3D printer.

When the 5% was used, the results were better than the 15%. This material extruded with less burs than other experiments. This filament was also the least brittle. However, when it was placed into the 3D printer, the results were no different than they were in previous experiments. The ABS/aluminum material reached the nozzle but did not print. When the procedure failed, just as before, material hardened in the head of the 3D printer.

When 1% was used, it was found to have advantages, and a few surprising disadvantages. This reduced concentration extruded a filament with few burs, yet it wasn't as flexible as the 5% filament. When the material was inserted into the head of the

3D printer, it reached the nozzle but did not print. The important part that was noted when experimenting with this material is it did not plug the head of the MakerBot™.

3. Difficulties With The Results

After the experimentation with the concentration of aluminum failed to produce any results, it was observed that there were other areas assisting to the failure. The problems that were seen were the temperature and the feedrate. The feedrate was displayed in the program Replicator G™, before the G-code was generated a dialog box appeared asking the user about the temperature and feedrate. The temperature and feedrate affect the 3D printing process in different ways. The temperature affects the viscosity of the material that is being printed whereas the feedrate affect doesn't affect the physical attributes of the material, only increases or decreases the process.

B. Adjusting The 3D Printer

Experimenting with the concentration of aluminum in the ABS plastic was not enough to achieve a 3D printed object. The next step in attempt to successfully print a rocket grain is to make adjustments with the 3D printer itself. However, before making any adjustments to the settings on the Makerbot™ (temperature, feedrate, feedrate speed, etc.), a basic understanding of how to unload the normal ABS filament and load the new ABS/Al filament will need to be explained. Also how to change temperature and feedrate as well as cleaning the head of the 3D printer will all need to be covered.

1. How To Use New Filaments In The Makerbot™

Before the new material can be 3D printed in the Makerbot™, the ABS filament that is already in the head of the printer needs to be released and the new material that is undergoing experimentation needs to be inserted in its place. Once the ABS filament was exchanged for the new ABS/Al filament, the experiments in 3D printing the new filament were started. However, there were filaments that would not insert into the 3D printer. In those occasions, often the easiest solution was to sand off the burs on the sides of the filament. After these tasks were completed, the Makerbot™ was ready to make its first attempt in 3D printing with the new ABS/Al material that was extruded. For more detailed information on what steps were taken to remove the old filament and replace it with the new one, please refer to the appendix section.

2. How To Clean The Head Of The Makerbot™

Throughout experimenting with different filaments that had different concentrations of aluminum, some of the filaments did not unload from the head of the Makerbot. When this occurred, the only way to remove the filament plugged in the head was to disassemble the head and drill the material out. For additional information on disassembling the head of the Makerbot™, please refer to the appendix. The suggested reasoning as to why the head was plugging was due to the melting point changing. The melting point of ABS was approximately 105 degrees Celsius. When the aluminum nanoparticles were added to the plastic, the melting point must have increased to the point where the current temperature of the 3D printer's nozzle was not hot enough to soften the material. Two suggested ways to prevent the material from clogging the nozzle was to increase the port size in the nozzle, or to increase the maximum heat the 3D printer distributed.



Figure 56. New material being 3D printed.

3. Port Sizes Vs. Speed Vs. Temperatures

The next area to examine was the port sizes, the speed rates, and temperatures of the 3D printer. This led to conducting several experiments. These experiments were intended to increase the heat of the nozzle, increase the port size of the nozzle, and reduce the feed rate of the 3D printer. The port size, speed rate, and temperature were changed, to see how it would affect the new material as it was 3D printed. In the first experiment, nothing was changed. The temperature was set to 220 degrees Celsius as default, the feed rate was 50 millimeters per second, and the original size of the port in the nozzle was 0.007 of an inch. The first step taken in attempt to get the 3D printer to print was to increase the size of the port in the nozzle. The initial size of the port was extremely small, approximately 0.005 of an inch, and plugged easily. Using a jeweler's drill, the port in the nozzle was increased from 0.007 to 0.014 of an inch. The experiment was conducted with the ABS/Al filament, and it failed. Using the drill again, the port was increased to 0.0156 (roughly 1/64th) of an inch. The experiment resulted in the nozzle plugging again. Finally, the nozzle was increased to 0.0313 (1/32nd) of an inch. This plugged the nozzle also. In fear of making the port size too large, it was decided to experiment with the temperature. Two different trials were set with the temperatures being 230, and 250 degrees Celsius. When the temperature was set to 230, ABS/Al came out of the port in small conglomerates. At a temperature of 250, the material exited the material faster, however not enough to print with consistency. After observing the printer in operation, it was decided to experiment with the feed rate next. The feed rate was taken from 50 mm/sec and reduced to 25 mm/sec. Then it was reduced again to 5 mm/sec. Each time the feed rate was reduced, the Makerbot™ printed with more consistency. The following table summarizes each experiment.

Table II. Different Experiments Conducted When 3D Printing ABS/Al

Attempt #	Nozzle Port Size (inches)	Temperature (Celsius)	Feed Rate (mm/sec)	Out Come	Reason
1	0.007	220	50	wouldn't print	plugged the printer nozzle
2	0.014	220	50	wouldn't print	plugged the printer nozzle
3	0.0156	220	50	wouldn't print	plugged the printer nozzle
4	0.0313	220	50	wouldn't print	plugged the printer nozzle
5	0.0313	230	50	would print	plastic/aluminum came out in very small increments
6	0.0313	250	50	would print	plastic/aluminum came out, needed slower feedrate
7	0.0313	250	25	would print	plastic/aluminum came out, still needed slower feedrate
8	0.0313	250	5	would print	plastic/aluminum came out in large conglomerate not consistent

4. Results From The 3D Printer

On the final experiment, the Makerbot™ produced a small conglomerate. It was unable to produce a rocket grain made of the new ABS/Al material, however enough was produced to be analyzed. The results obtained were not what were hoped for. The goal was to 3D print a new rocket grain that was 10% aluminum. Since a small conglomerate is not a rocket grain, changing the temperature and feedrate was not enough. Aside from the melting point of ABS/Al being higher than ABS, the viscosity must have changed as well.

C. SEM Analysis

SEM (Scanning Electron Microscopy) is a type of microscope that produces images of a material by scanning it with a focused beam of electron instead of light. This was

developed in the early 1950's when scanning electron microscopes had developed new areas of study in medical and physical science communities. The SEM has many advantages over traditional microscopes. The SEM can examine a larger depth of field, has a higher resolution rate, and has more control over the level of magnification. SEM was used in the research conducted to analyze the materials that were 3D printed. These materials included plain ABS, ABS that was extruded by the filament extruder, extruded ABS mixed with aluminum nanoparticles, and ABS mixed with aluminum nanoparticle that were 3D printed. This was done to examine the aluminum in the ABS, and to see how well it was disbursed through the material.

1. SEM Before The Filament Was 3D Printed

SEM was done on the filament before it was 3D printed in the 3D printer at different stages. The first stage was SEM with plain ABS before it was extruded, the second was ABS after it was extruded, and the last two stages were the ABS/Al after they were extruded. The results of SEM on the plain ABS before it was extruded can be seen below.

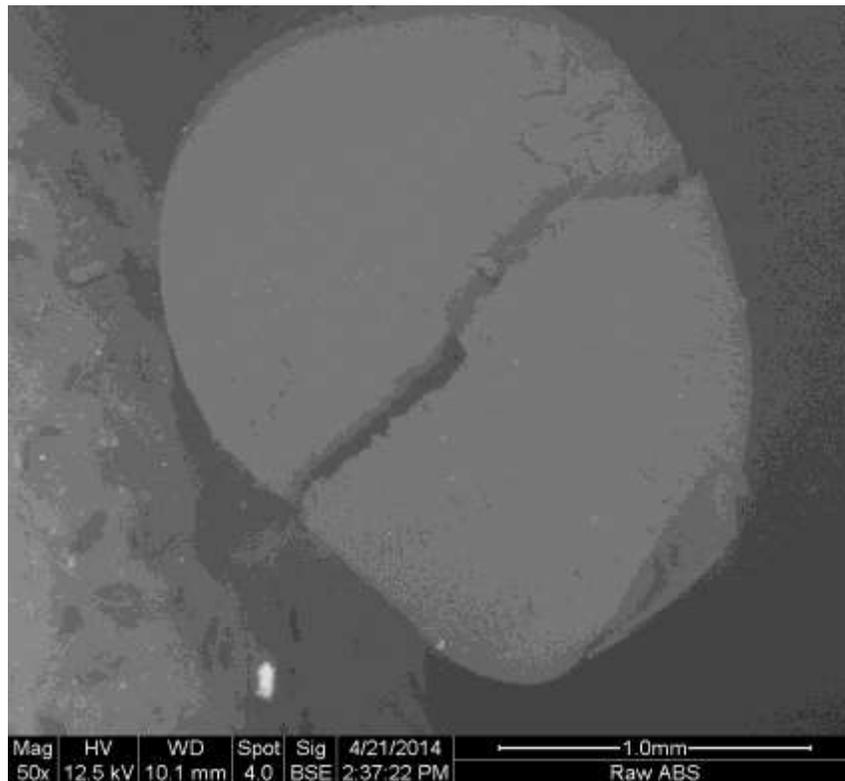


Figure 57. Raw ABS before extrusion.

Above is a SEM picture of pure ABS filament. This filament was taken from the spool of ABS that was manufactured by Makerbot Industries™. In the image above, the impurities (the white dots) are minimal. This image was used for a baseline since it is what is used to 3D print with. The SEM images that follow were compared to the SEM of ABS to see how the changes that were made (extrusion, adding aluminum, etc.) affected the ABS material structure.



Figure 58. ABS extruded without metal.

This image above is an SEM picture of ABS that was extruded without aluminum nano fiber mixed with it. The ABS is dissolved with acetone. Then after it was dissolved, it was extruded in the filament extruder that was built. The filament that was extruded was then placed in the SEM. This SEM picture was taken to show the purity of raw ABS that was extruded. This picture was compared to the SEM picture of ABS before it was extruded, and there weren't any significant differences. This shows that dissolving ABS in acetone and processing it through the filament extruder does not change the purity of the ABS. Since there is not a visible difference between the raw ABS and extruded ABS SEM images, when the aluminum is mixed in later the SEM will show what affects the aluminum is making on the material.

After the aluminum nanoparticles were weighed to equal 5% mass of the ABS, these two materials were mixed together and dissolved as explained in the previous chapter. Then they were viewed in the SEM. When the ABS and aluminum was placed together, they were prepared differently before being scanned in the SEM. The figure below shows the ABS/Al mix in the SEM after the material was polished. To polish a material to use in the SEM, the material must be polished and sanded first. This procedure can be viewed in the appendix.

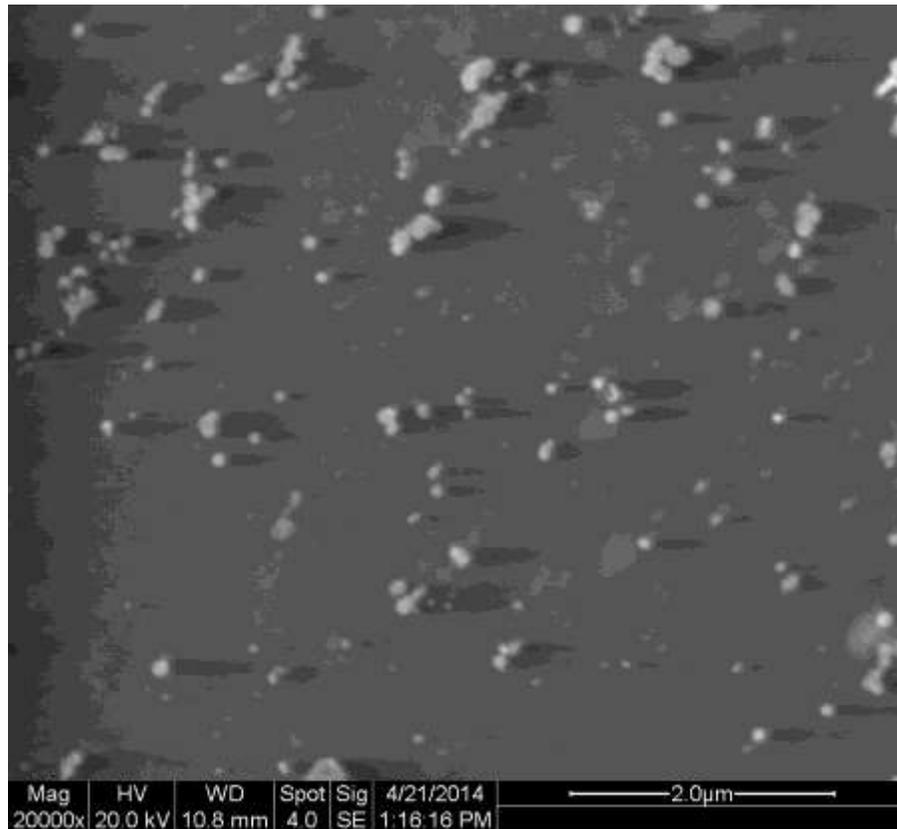


Figure 59. SEM polished.

This image shows that the aluminum was evenly distributed throughout the ABS. The aluminum does form into several groups, but the groups are even throughout the plastic. For this ABS/Al material to work correctly as a hybrid rocket grain, the aluminum must be evenly distributed, or else a grain would be 3D printed and an unbalance in aluminum would cause some stops with more aluminum to burn slower in the rocket. This would

also cause holes to form in the grain while it undergoes combustion in the rocket, producing undesired results.

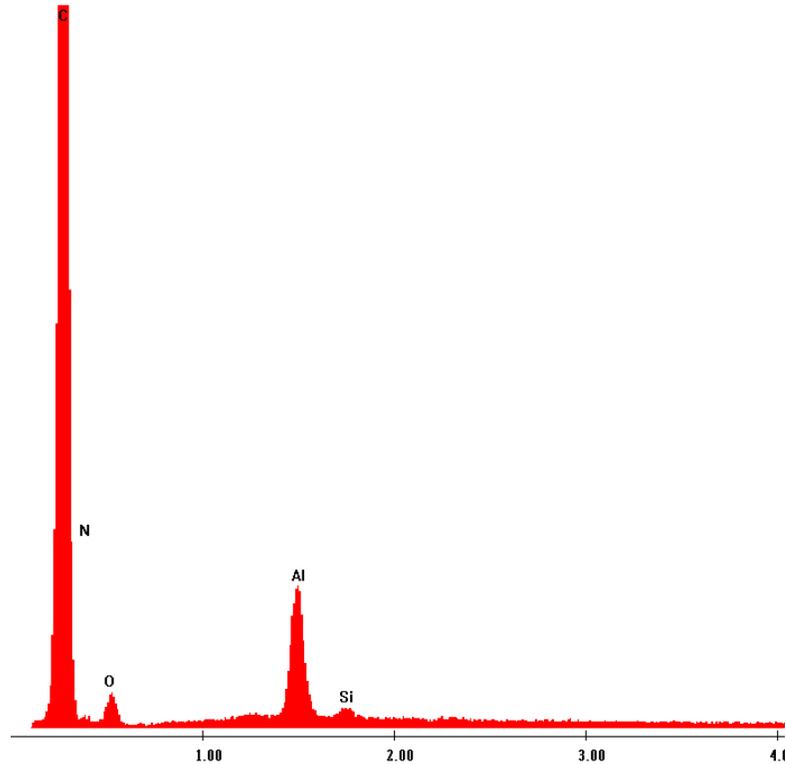


Figure 60. SEM Chemical analysis results with metal.

After the ABS/Al material was extruded, it was analyzed in the SEM. The Figure 60 (above) was obtained before the material went to the 3D printer. When the material was undergoing the SEM, a chemical analysis was conducted to understand further what elements were present. This was done to see how much aluminum remained in the material after it was extruded. As seen in the figure above, aluminum was still in the material and did not burn out through the extruding process.

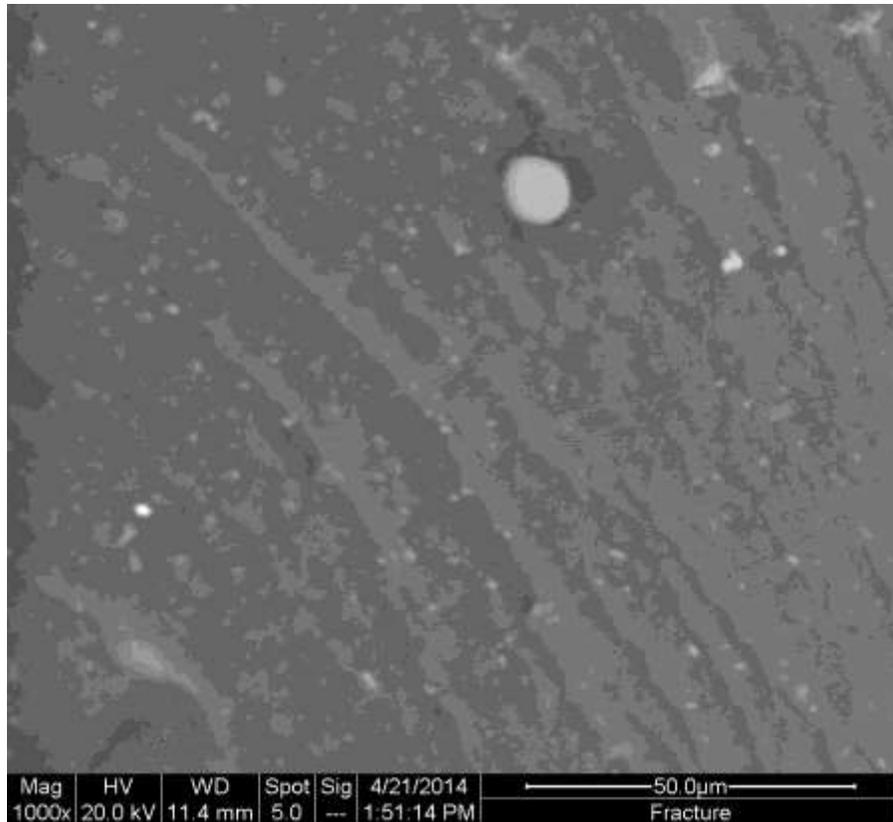


Figure 61. SEM fractured.

After taking one SEM picture of the ABS/Al material when it was polished, another set of SEM pictures were taken immediately after the material was fractured. A small piece of ABS/Al filament was set in a container of liquid nitrogen. Then it was quickly taken out and broke in half. The bigger half of the material was placed in the SEM broken side facing upward. This was helpful in giving an image of the aluminum dispersed through the plastic without sanding. It also shows how when the aluminum was dissolved in the ABS, it is distributed in different amounts. This image supports the SEM polished image shown before. Both show that the aluminum does not group together in one section of the ABS.

2. SEM After The Filament Was 3D Printed

After the ABS/Al material was extruded in the filament extruder it was 3D printed. The small amount that was printed was taken to the SEM to see if the spatial distribution of aluminum was comparable to the results before it was 3D printed.

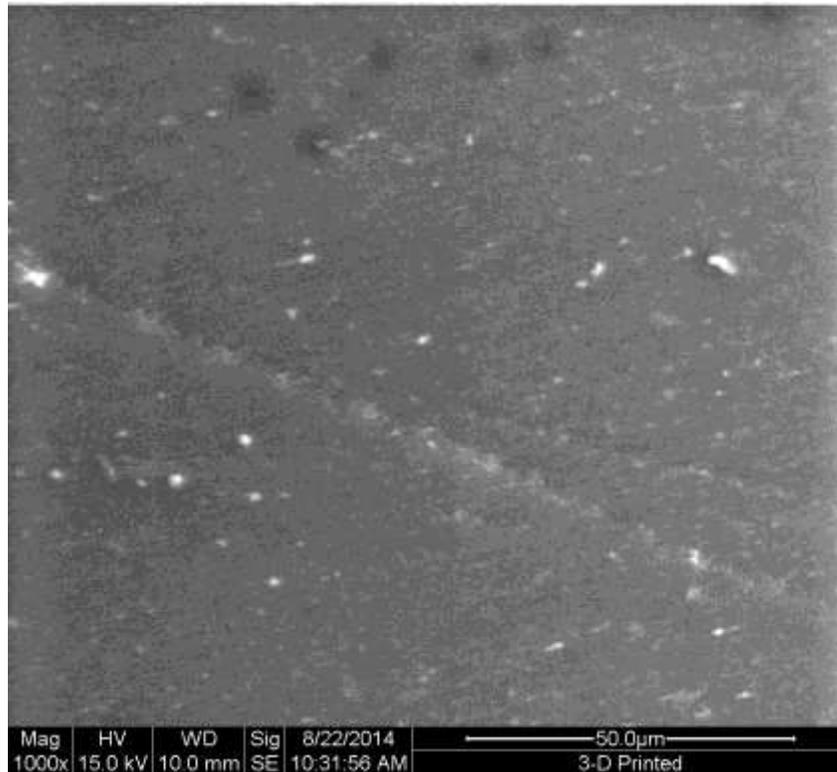


Figure 62. SEM after 3D printed.

As seen in the figure above, the aluminum is distributed evenly as it did before it was 3D printed. This SEM figure shows that 3D printing will not unbalance the aluminum distribution. This ABS/Al material would produce a rocket grain that undergoes the combustion process evenly without burning one part of the grain faster than others.

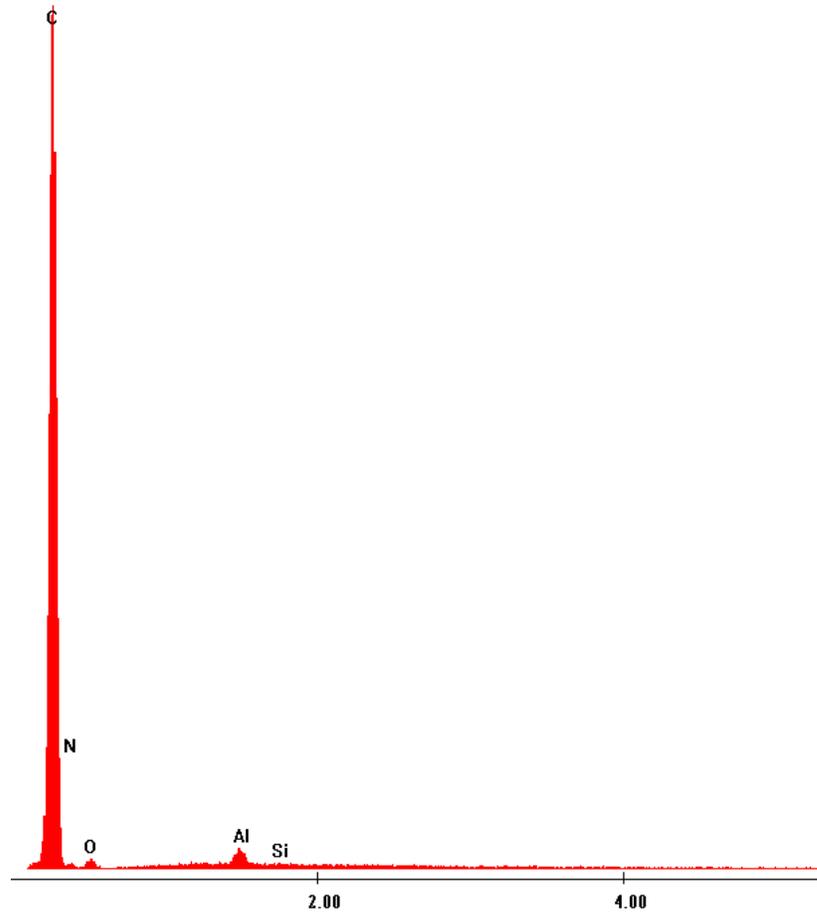


Figure 63. SEM chemical analysis results after 3D printed.

In figure 63 the chemical analysis of the material after it was 3D printed. This material was mostly ABS, but it consisted of 1% aluminum nanoparticles. The amount of aluminum in this material was 0.44 percent weight. The molecular weight of ABS can vary. The reason the weight varies is due to the composition of ABS varying from different manufactures. The chemical analysis result was conducted only show that there still in aluminum in the material after it was 3D printed.

Table III. Semi Quantitative Analysis

Element	Polished Composite 5% Al		Polished 3D Composite 1% Al	
	Atomic %	Weight %	Atomic %	Weight %
C	89.11	92.09	93.24	94.79
N	3.81	3.38	3.54	3.08
O	4.05	3.14	2.17	1.65
Al	2.82	1.3	0.98	0.44
Si	0.21	0.09	0.08	0.03
Total	100	100	100	100

This table is the semi quantitative analysis that was done on the material before and after it was 3D printed. This shows approximately how much of a particular element is in each ABS/Al mixture. As stated before, the polished composite had 5% aluminum mixed in with the ABS, and after it was extruded, the quantitative analysis showed that there was only 2.82% remaining. It is uncertain as to why there is less than 5% of aluminum in semi quantitative analysis. This percentage is atomic percent which gives the percentage of one kind of atom relative to the total number of atoms. Likewise, when the polished composite was 3D printed and underwent a quantitative analysis, the material initially had 1% aluminum, but was left with 0.98% remaining. This was a better result than with the 5%. This analysis is subject to error however. It only gives a quantitative amount on a small section of the matter from the top layer. In order to get an accurate amount of how much aluminum is in the material, the quantitative analysis would need to be conducted at several points along the material.

SUMMARY AND CONCLUSIONS

Theory of hybrid rocket motor operation provided the foundation of this research project. Hybrid rocket engines operate with a solid fuel and a liquid oxidizer. The hybrid rocket was then compared to both, the liquid and solid rockets to show the advantages it possessed.

Selecting the material for fuel for the hybrid rocket was where the research in this project began. HTPB was a popular choice for the solid fuel due to its high thrust rates, but paraffin wax also has received attention due to it being easier to mold. In this project, ABS was chosen since it was the material that was primarily used for 3D printing. With the ability to 3D print fuel for the hybrid rocket, different designs for the combustion chamber can be designed. A spiral pattern in the combustion chamber was created in an attempt to increase the efficiency of the rockets thrust.

When HTPB was compared to ABS, HTPB would outperform by a small margin. It is easier to 3D print ABS, as compared to HTPB which involves casting. It was researched to see if adding a small amount of metal to the ABS would increase the thrust it produced. Since the aluminum burns hotter than plastic, it was believed that this would give an increased regression rate, which would in turn exert higher thrust.

Mixing aluminum and ABS together was the next step in obtaining this new rocket fuel. After several experiment with different ABS/Acetone mixtures, 30 inches of ABS was taken and dissolved in 50 ml of acetone. Once the acetone softened the ABS, the Aluminum was added and mixed. After this mixture became a solid again, it was cut into small pieces and placed into a beaker.

Since the mixed material was no longer in the form of a 0.75 diameter filament, the material needed to be extruded into that shape. Since the new material was in pieces, a filament extruder was built to transform the materials shape back to a filament. Some of the parts to make the filament extruder were a band heater, a PID controller, a windshield wiper motor, and a nozzle. Once the extruder was operational, the new ABS/Al material was extruded into a shape that could be 3D printed.

Once the new ABS/Al material was extruded, it was then examined under the SEM to evaluate the distribution of the aluminum. As result, the SEM showed the aluminum was evenly distributed throughout the plastic. If the aluminum grouped in one area of the plastic, the material would not combust evenly when launched in the rocket.

The process of 3D printing the ABS/Al material was trial and error. In each experiment either the diameter of the nozzle, the temperature of the nozzle, or the feed rate was changed in attempt to receive a successful print. On the eighth attempt of 3D printing this new material, with the temperature increased to 250 °C, the feed rate reduced to 5 mm/sec, and the nozzle drilled to 0.0313 inches, a small conglomerate was produced. This small piece was taken to the SEM for further analysis. The SEM showed the aluminum was still evenly distributed.

FUTURE WORK

The most obvious work that is needed for this project is the new ABS/Al material needs to successfully print a grain for the rocket. To this date, the 3D printer was able to print a small conglomerate that was analyzed in the SEM. To get the 3D printer to make a full size rocket grain the 3D printer will need additional experiments done on the feed rate, temperature, and nozzle size.

Another area that still is in need of research is the SEM figures of the new material. Currently, there are only SEM pictures on the top layer of the new material. At some point, the material should be cut into halves and additional SEM pictures should be taken. This would give additional information of the distribution of nanoparticles on a three dimensional level.

The last section of this research that is still needed is the viscosity. When the aluminum nanoparticles were added to the ABS, the viscosity changed. Because the viscosity of aluminum is much higher than the viscosity of ABS, it is logical that the viscosity of this new material increased. The best place to start with this is to find a viscosity curve as a function of particle loading for ABS. The final key would be to find a polymer scientist that could take some of the new material that and generate a new viscosity curve.

If a new spiraled grain was successfully design and 3D printed using the new ABS/Al material, then the last part of this project would be to fire one in the hybrid rocket. If that happened the amount of thrust and length of time would determine if 3D printing grains with metal is worth more research. To graph a regression rate of this material and compare it to other materials that have been commonly used for rocket grain would explain overall how well the new material works.

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APPENDIX A

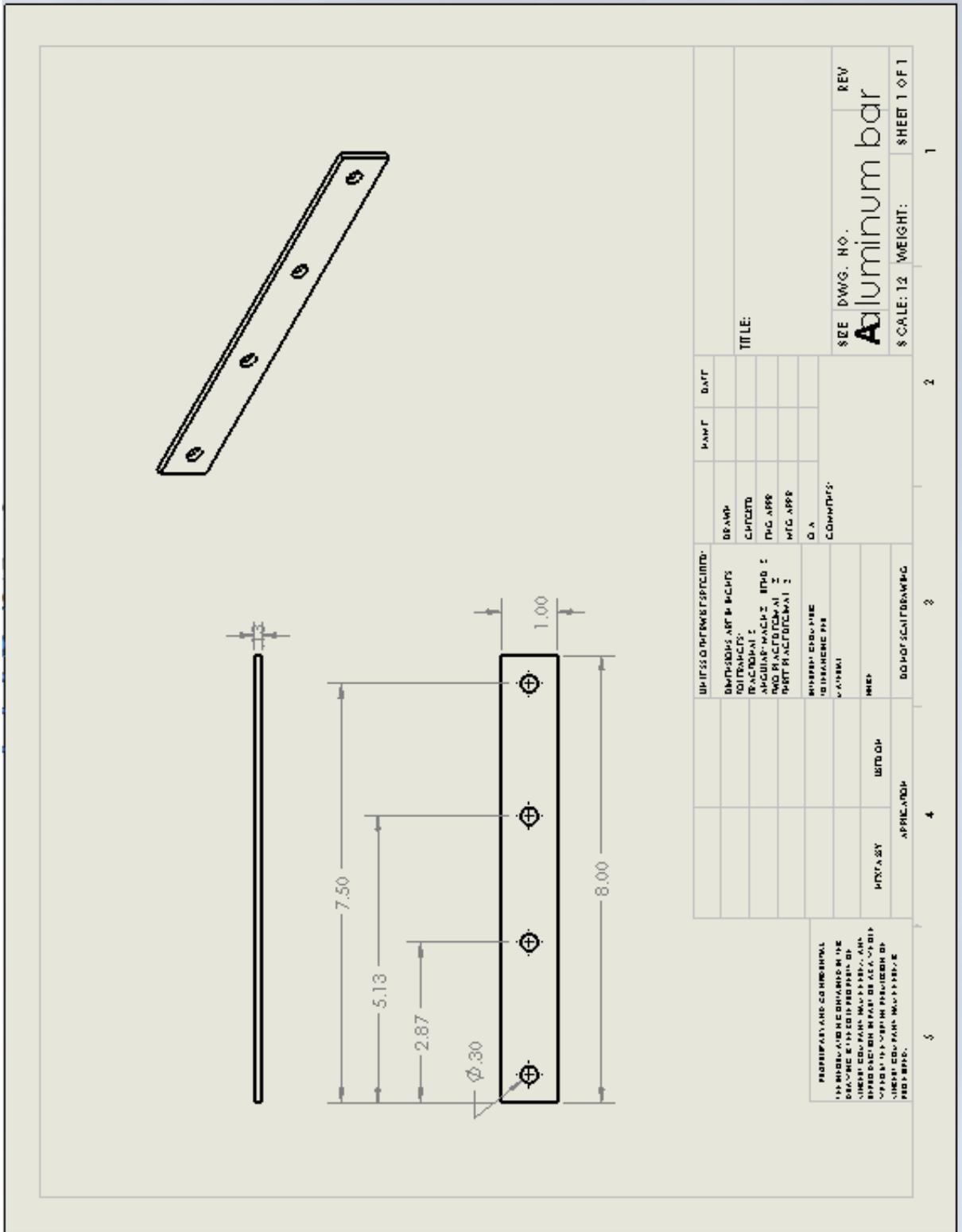


Figure A-2. Aluminum bar drawing.

APPENDIX B

Testing section

To test the hybrid rocket a series of tasks must be done beforehand to ensure safety to those who are testing.

- Create a grain for the rocket in Solidworks™
- Make the grain 2” in diameter and 6” long
- Create a hole in the grain and if possible make the hole rotating shape
- Disassemble the rocket stabilizer plate by loosening the bolts and take the newly printed grain and plate it between the top and bottom supports
- Place a new O-ring in the O-ring groove on the top and bottom of the grain.
- Tighten the bolts back in the rocket and take the rocket to the test pad
- Set up a table to keep the computer and run an extension cord to the computer
- Take a AC to DC power source and test to see if it is producing 12 volts
- Run alligator clips from the power source to the DAQ and hook the DAQ up to the computer thru a USB cable
- Hook the DAQ to the pressure transducer
- Place the igniter in the igniter port
- Hook the welding hose from the oxygen tank to the quick connect on the rocket
- Turn the regulator off, then slowly open the oxygen tank
- Then open the regulator till the valve reads 100 PSI
- Start LABVIEW on the computer
- Get the camera's in place
- Turn the oxygen on, and light the rocket

APPENDIX C

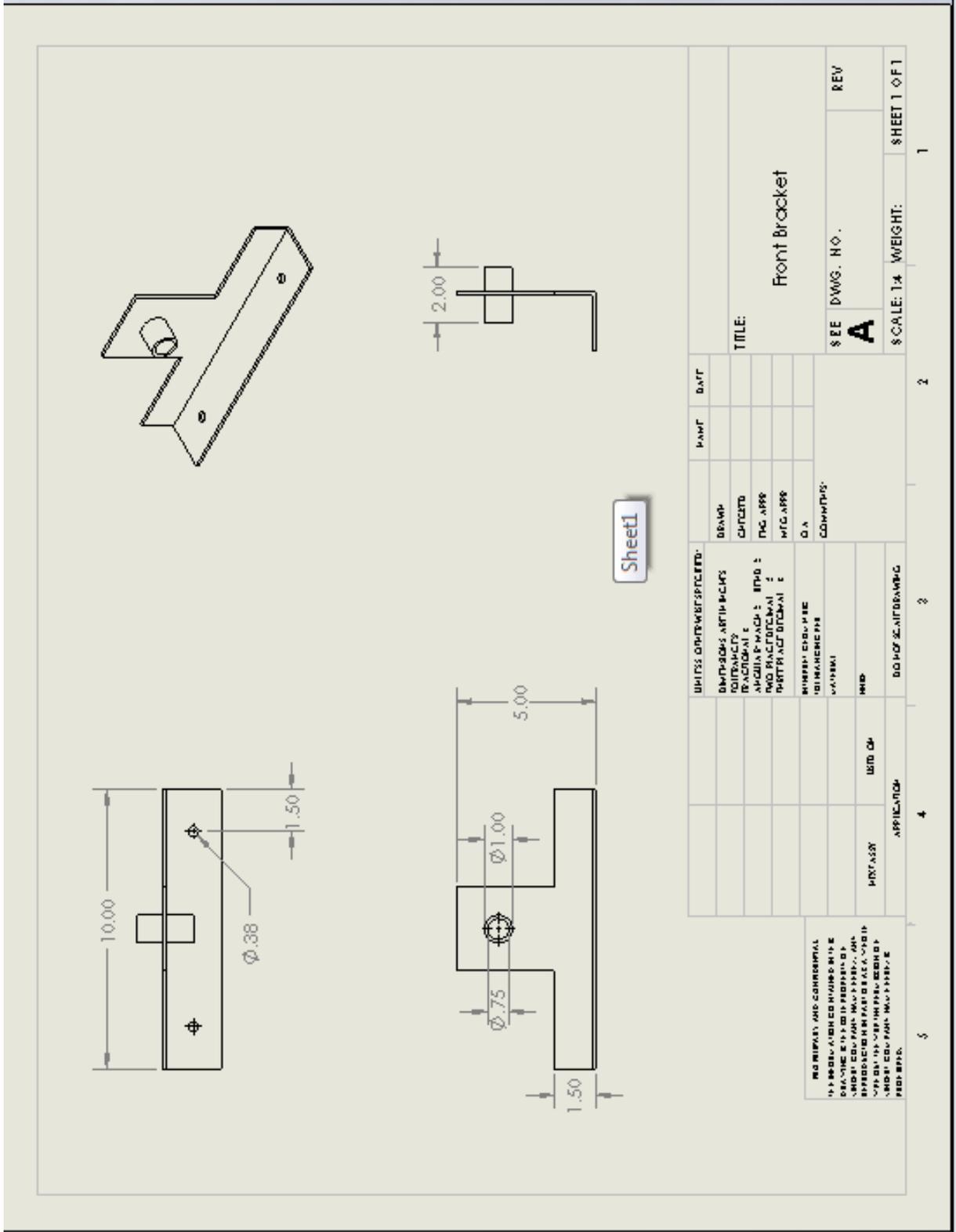


Figure C-1. Big bracket drawing.

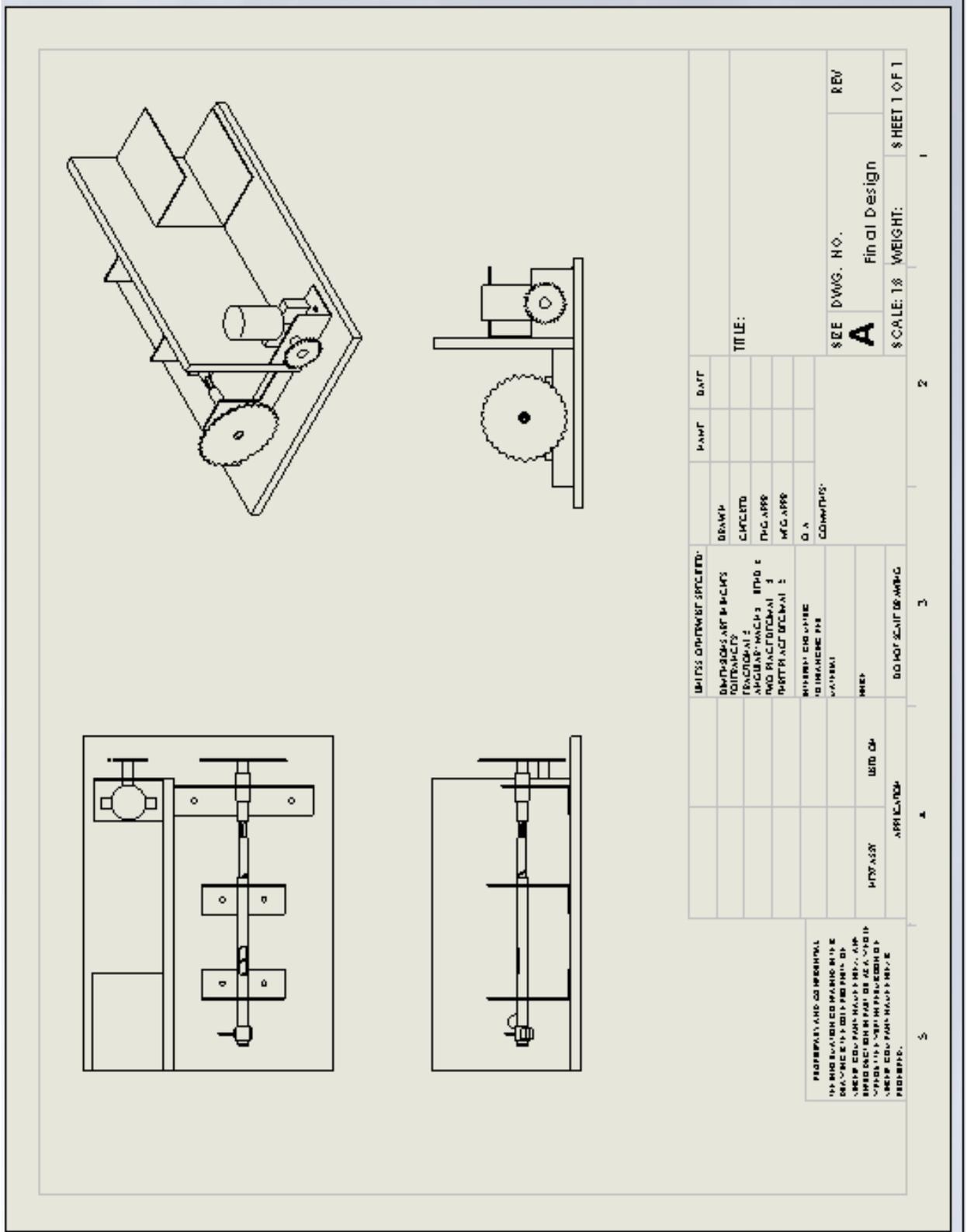
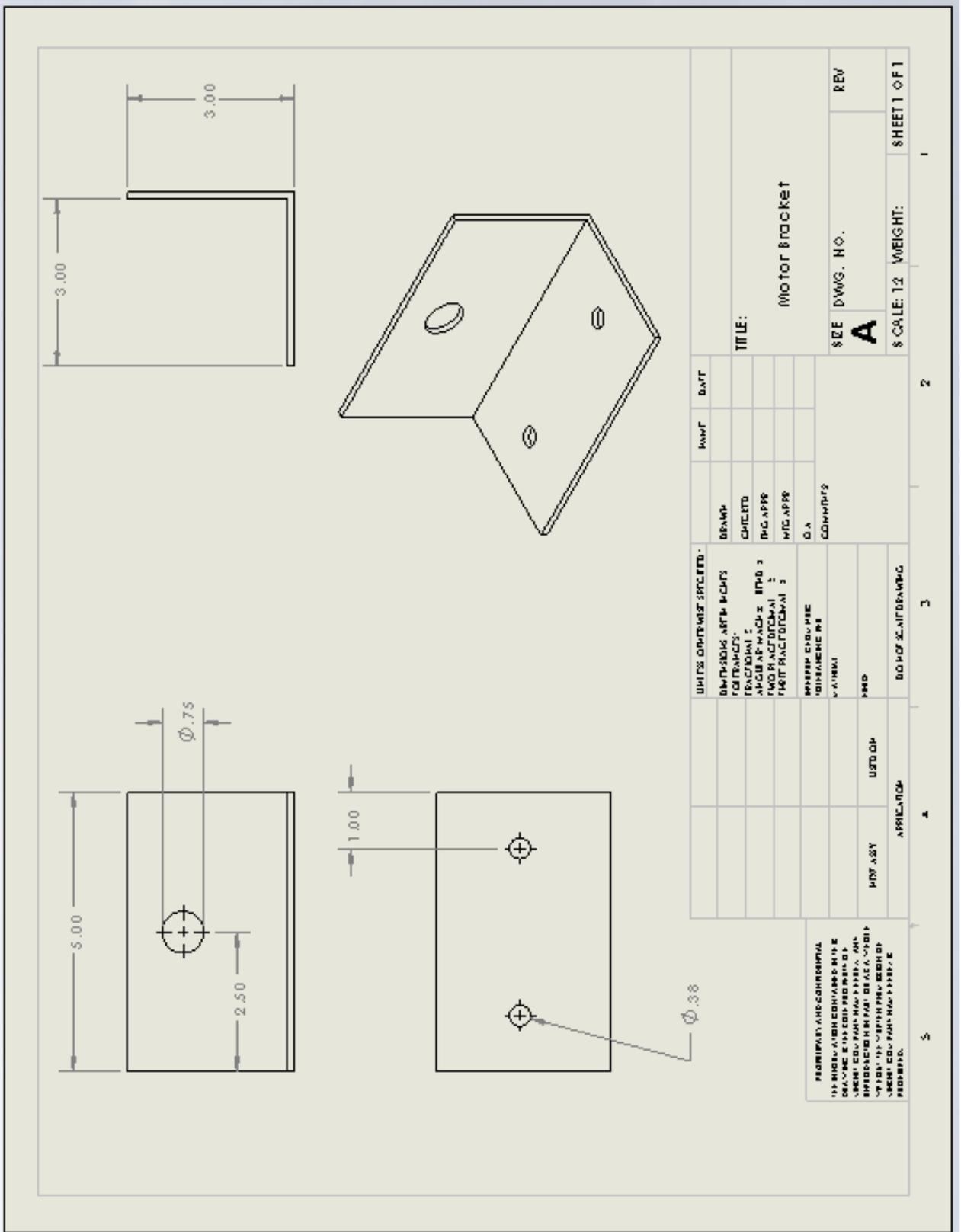


Figure C-2. Final design drawing.



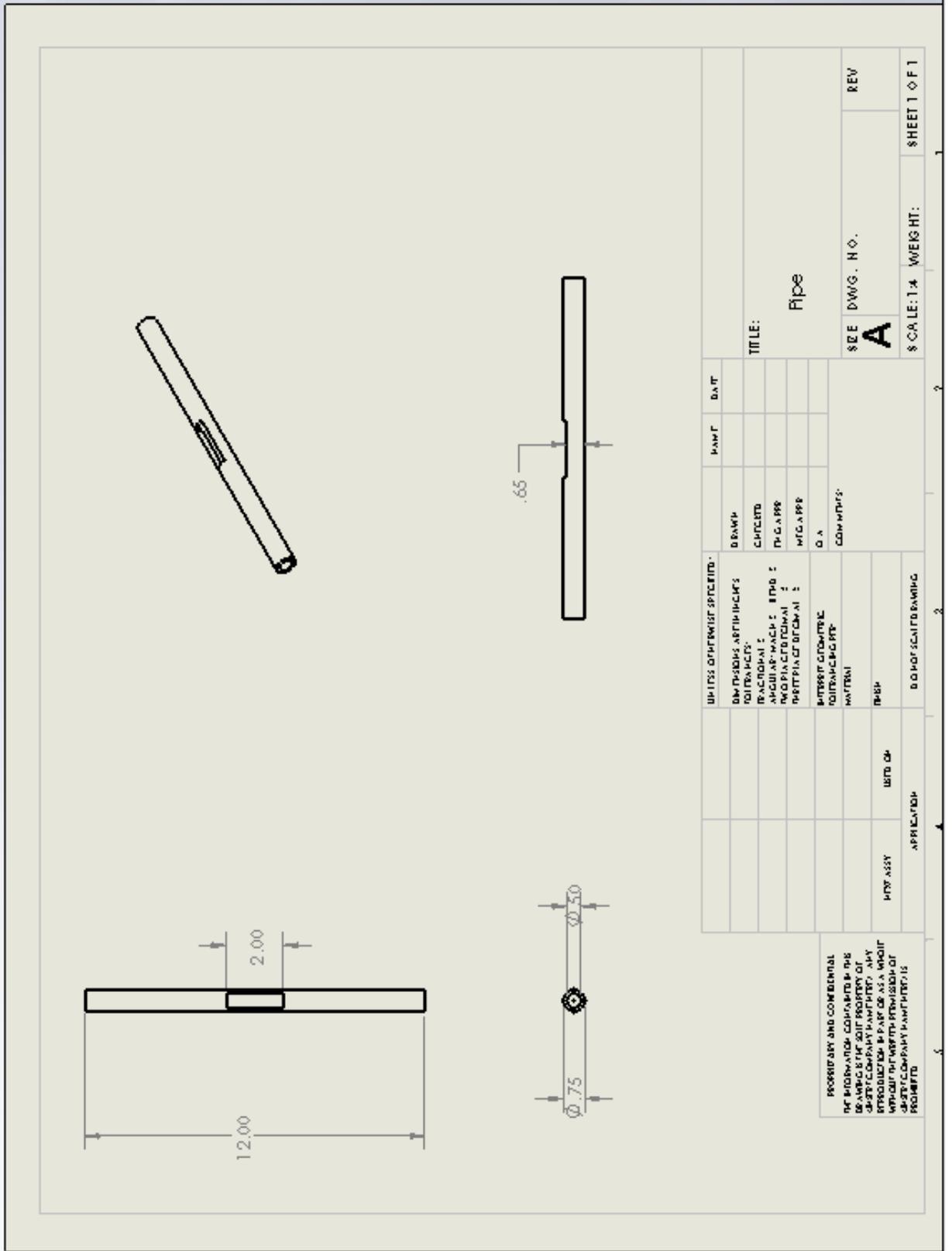


Figure C-6. Pipe drawing.

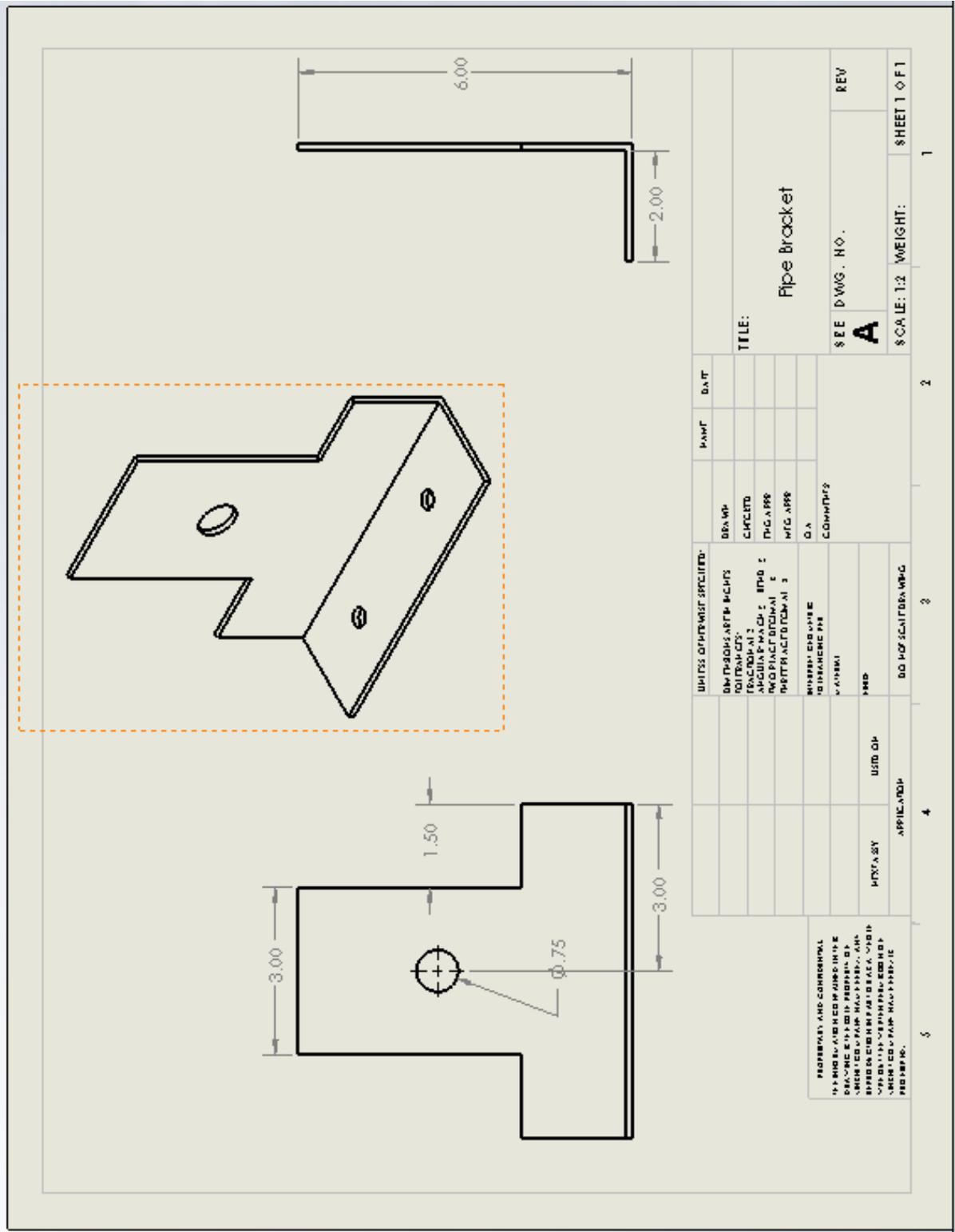


Figure C-7. Side-bracket drawing.

APPENDIX D

Following the initial design, a list of prices was compiled to determine what the price would be to reconstruct the Lyman Filament Extruder. Most of the parts that are mentioned in Lyman’s design were obtainable at Home Depot, Grainger, Newegg, or McMaster Car. However, when the price were determined and totaled, the final dollar amount came to \$560.16. In efforts to lower the final cost, the machine was examined carefully and the 53 parts that made Lyman’s extruder were reduced to a more basic design. This new design of the extruder contained 11 parts (not including the nuts and bolt). All 11 of these parts were redesigned, based on Lyman’s design, and fabricated. As result, with the electrical engineering department providing the 12 volt supply and the PID (proportional integral derivative) controller, the total amount of money spent on this project was \$42.38.

Part #	Item	Price	Location	Other Info	website
1	Wood Frame Base	20.21	Home Depot	can be	
2	Wood Electric Pannel	20.21	Home Depot	bought in a	http://www.homedepot.com/p/1-2-in-x-24-in-x-24-in-Pine-Plywood-Project-Panel-4-Pack-1502010/20344149#specifications
3	Wood Fan Mount	20.21	Home Depot	four pack	
5	Motor Bracket	10.11	metalsdepot	3/8 not 1/8	http://www.metalsdepot.com/catalog_cart_view.php?msg=
6	Hopper Base	10.11	metalsdepot	need of	
7	Large Sprocket	26.05	McMaster		http://www.mcmaster.com/#roller-chain-sprockets/=odjcf1
8	Small Sprocket	16.59	Grainger		http://www.grainger.com/Grainger/TSUBAKI-Sprocket-6L776?Pid=search
9	Bumper Feet	15.32	Grainger		http://www.grainger.com/Grainger/3M-Self-Adhesive-Bumper-1AYD3?Pid=search
10	Nozzle Brass	31.45	Grainger	Need to be	Machined
11	Black Iron Coupling	2.16	Grainger		https://www.grainger.com/Grainger/Coupling-5P552?Pid=search
12	Band Heater	30.3	Grainger		https://www.grainger.com/Grainger/TEMPCO-Band-Heater-2VYC8?Pid=search
13	1/4" Bolts	5.63	Grainger		https://www.grainger.com/Grainger/Hex-Bolt-Refill-1Y98?Pid=search
14	Pipe Floor Flange 1/2"	16.88	McMaster	3 1/2 not 3	http://www.mcmaster.com/#steel-pipe-flanges/=odkjat
15	Filament Guide	10.13	Grainger	Need to be	https://www.grainger.com/Grainger/Flat-Stock-2EYV6?Pid=search
16	Heat Bearer Insulator		Grainger	3 1/2 not 3	https://www.grainger.com/Grainger/Rod-Stock-2AHH6?Pid=search
17	Washers (1/4)	14.8	Grainger		https://www.grainger.com/Grainger/MASTER-PRODUCTS-Flat-Washer-6PE76?Pid=search
18	Nylock Nuts (1/4)	26.25	Grainger		https://www.grainger.com/Grainger/MICRO-PLASTICS-Hex-Nut-2GU97?Pid=search
19	Steel Bearing Plate	18.04	Grainger		https://www.grainger.com/Grainger/MICRO-PLASTICS-Hex-Nut-2GU97?Pid=search
20	Hopper Base	same as part 6			
21	1/2 Pipe Nipple	7.06	Grainger		https://www.grainger.com/Grainger/Pipe-Nipple-1VGR4?Pid=search
22	Nuts	same as part 18			
23	Nuts Nylock (M4)	3.18	Grainger		https://www.grainger.com/Grainger/Hex-Nut-1KYG2?Pid=search
24	Washers (M4)	3.23	Grainger		https://www.grainger.com/Grainger/Flat-Washer-6EY55?Pid=search
25	Bicycle Chain	14.24	Amazon		http://www.amazon.com/Bike-Gear-Chain-2-Inch-8-Inch/dp/B004044QVQ
26	Hopper	3D print			
27	Set Screws	8.7	Grainger		https://www.grainger.com/Grainger/Socket-Set-Screw-6FE38?Pid=search
28	Large Sprocket Adapter				
29	Cap Screw				
30	Small Sprocket Adapter				
31	Cap Screw	3.58			
32	Washer (3mm)	1.76	McMaster		
33	Wipster Motor	65.8	Grainger		http://www.grainger.com/Grainger/DAYTON-Universal-ACDC-Motor-2M033
34	Bolt (1/4)	8.35	McMaster		http://www.mcmaster.com/#standard-cap-screws/=odmcp4
35	Colair	19.43	Grainger		http://www.grainger.com/Grainger/RULAND-MANUFACTURING-Shaft-Collar-2AME2
36	Thrust Bearing				
37	Aluminum Flat Bar	same as part 15			
38	Brass Bushing				
39	Auger Drill Bit	25.97	Home Depot	not sure ab	http://www.homedepot.com/p/Irwin-Speedbor-5-8-in-High-Speed-Steel-Ship-Auger-Bit-3
40	Bolt (1/4)	16.17	McMaster		http://www.mcmaster.com/#standard-cap-screws/=odmd2v
41	PID Temperature Contoller	32.99	Newegg		http://www.newegg.com/Product/Product.aspx?Item=95IA0U00AC2074&nm_mc=KNC-Goo
42	Power Supply	24	Ebay		
43	Solid State Relay	15.95	Ebay		
44	Thermocouple	5.31	Amazon		http://www.tcdirect.com/deptprod.asp?deptid=180
45	Voltage Regulator				
47	Kapton Tape				
48	Switches				
49	Screws #4				
50	Screws #8				
51	Phenolic Washers		5 Grainger		
53	Fan	4.99	Newegg		http://www.newegg.com/Product/Product.aspx?Item=N82E16835119049&nm_mc=KNC-Goc

Figure D-1. Budget.

APPENDIX F

How To Use New Filaments In The Makerbot™

Before the new material can be 3D printed in the Makerbot™, the ABS filament that it is already in the head of the printer needs to be released and the new material that is undergoing experimentation needs to be inserted in its place. To unload the pure ABS filament, turn the 3D printer on (the switch is on the back right hand side). Once that is done, on the display screen select 'Utilities' then select 'Filament Options' then 'Unload Filament' (it says right filament and left filament chose the side that is applicable). Once all this is complete the motor in the head of the 3D printer that moves the filament through the head reverses and releases the filament. Then select 'Load Filament' and carefully place the new ABS/Al filament in the head of the 3D printer. Once the motor starts to pull the filament into the head, wait until the filament is pulled through the head and is exiting through the nozzle.

APPENDIX G

How To Clean The Head Of The Makerbot™

Throughout experimenting with different filaments that have different concentrations of aluminum, some of the filaments did not unload from the head of the Makerbot™. When this occurred, the only way to remove the filament plugged in the head was to disassemble the head and drill the material out. To disassemble the head of the Makerbot™, the first step is to remove the bolts that hold the fan and the heat sink to the step motor with an Allen wrench. Once the fan and heat sink are removed, take a 1/8th drill bit and place it in the hole next to the step motor. Once the drill bit is in the hole, gently turn it clockwise. Do this until the drill bit clears the entire section where the filament goes. After that, reassemble the fan and heat sink with the bolt. To make certain the head has been cleaned, try loading a normal ABS filament in the head. If that works, then the head of the Makerbot™ has been cleaned.