Thrust Chamber

Figure 0. Firing of the Hybrid Rocket

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Executive Summary

Imagine you are a child in elementary school who is eagerly awaiting for your first rocket demonstration. Inspiring the youth of today is critical to the future of scientific ingenuity. Such is the desire of our client, Brant White, of the American Institute of Aeronautics and Astronautics (AIAA), Wisconsin section. Mr. White has requested a rocket to be built with the sole purpose of providing a demonstration, a spectacle of science, to a group of young aspiring scientists. Our group resolved this problem by minimizing the size of the rocket. We created a small, stationary hybrid rocket which would have a very small thrust output in order to be safely shown to children.

Problem Statement

Our client, Brant White, desires a compact, portable hybrid rocket engine capable of fitting within an envelope of the required dimensions of 20” x 15” x 7.5”. The client wishes for the engine to burn an acrylic solid fuel and the oxidizer to be gaseous oxygen. The reaction must be visible inside the combustion chamber for display purposes. We need to achieve a continuous firing duration of no less than four seconds (ideally seven) and produce one pound of thrust. The thrust chamber (i.e. the solid acrylic fuel rod) must be replaceable and be able to burn for the desired time interval without burning all the way through the outer surface of the acrylic tube. Due to this being a classroom demonstration we also have to create a blast shield in order to prevent projectiles, debris, and other dangerous substances from hurting or endangering the audience and operators.

Background Information and Research

Our first step in understanding how to design a hybrid rocket chamber was to research the chamber itself. We learned that the chamber acts as a vessel for the gas to flow through and as a solid fuel for the rocket. This means that the inner diameter will increase after each firing. This proposes a problem; If the inner diameter of the chamber becomes too large, the chamber could rupture causing hot, flaming gas to spew out of the chamber. To avoid this, we calculated the regression rate; the rate at which the inner diameter of the acrylic rod would increase. By determining regression rate, we could predict the number of completed runs it would take before we would need to replace the acrylic rod when its thickness was not safe enough to run another trial. (The calculations are shown below and go into more detail in the section labeled calculations.) Once we knew this rate, we could predict how long we can fire the rocket before we had to replace it.

The rest of our research and background information consisted of many intense calculations. We go into further detail about this in the section labeled “Calculations and Derivations.”

Specifications and Constraints

Since we are dealing with high pressures and flammable materials, there are many constraints to which our group must adhere in order to ensure functionality as well as safety. Besides the restrictions listed in the problem statement above, the specifications will be divided into two categories: specifications given directly from our client and assumed constraints which factor into the overall design of our rocket. These all were carefully considered when finalizing our design.

The client's requirement for the rocket to supply one pound of thrust gave us a starting point to base our calculations on; these calculations would determine parameters such as throat and bore diameter of the nozzle and acrylic chamber, respectively. Mr. White wishes for the rocket to fit within the envelope dimensions listed in the problem statement.. Moving onto the operation of the rocket, Mr. White requests that the rocket itself must be capable of firing multiple times without the need for a replacement fuel grain. On top of that, it is assumed that we shall provide a few replacement fuel grains in order for multiple demonstrations to take place without the client needing to manufacture more fuel grains. As for the thrust chamber, Mr. White asked for our design to be capable of achieving a minimum production of one pound of thrust. Finally, detachable blast shields must be capable of being hard-mounted onto our final design in order to ensure the safety of the students spectating the demonstration, as well as the demonstrator.

Transitioning to standard rocket constraints, flammable materials must be minimized. With this in mind, all components must use oxygen-safe materials with respect to their design pressure and temperature. We must take temperature and pressure of our system into consideration. Since the rocket will be used strictly for demonstrational purposes, the engine will be stationary. Oxygen gas shall be used as our oxidizer, and the reaction will take place within the acrylic tube.

Overall, many dictated and assumed design constraints restrict the overall creative ingenuity process into a concrete foundation which serves well to emphasize precise calculations and ensure a safe and successful rocket.

Brainstorming

Since the constraints, mentioned earlier in this report, restricted many aspects of how our rocket would be designed, the attention of the group was mainly focused on the creation of the blast shields. The blast shields were one of the few parts of the thrust chamber that we had complete control over integrating into the design. Our group brainstormed many ideas. Ideas ranged from encasing the entire thrust chamber in a box that would act as a blast shield to having separate shields on a stand right next to the chamber, to having the shield somehow built into the frame of the overall chamber. With the size constraint in mind, we quickly determined that having blast shields attached to the thrust chamber in some form would be the best option to minimize cost and maximize the efficiency of the blast shields if the acrylic tube were to explode during firing. With blast shields that were separate from the chamber, there was a greater chance of shrapnel flying around the blast shields. Another suggested idea was the construction of a hinged, blast shield wall. With just a hinged wall sitting in front of the blast shield, the wall could fall over in the event of an explosion. Many of the original design concepts we had for how the blast shields would be attached were promising. After further review of all design concepts, the design concept of blast shields being built into the frame made the most sense because this chamber had to be easily assembled and disassembled repeatedly.

Additionally, we debated over what material the blast shields should be made of. Due to the fact that one of the main points of the hybrid rocket engine is for demonstrational purposes, the material that we would choose for the blast shields had to be transparent. With just this taken into account, we could not make the blast shields out of sheet metal, concrete, aluminum or wood. Given the remaining materials we came up with from one of our brainstorming sessions, we narrowed down our choices to plexiglass, fiberglass, acrylic, Lexan, and glass. Considering the heat that the engine was going to give off while it is running, we could eliminate the possibilities of having blast shields made of vinyl-based plastic and glass.

Considering the amount of heat this engine was going to give off, blast shields made of a vinyl-based plastic could be at high risk of melting with how close they were going to be positioned next to the chamber. Glass blast shields would also not have been wise due to glass being able to hold heat for extended periods of time. We would not want someone to get burned cleaning up the engine after the demonstration. Glass, in the price range we would be considering, is also fragile and would not make a good material to protect an audience from something. Between our remaining options of plexiglass, fiberglass, and Lexan, we decided to go with plexiglass because we could get the amount we needed for the cheapest price possible.

A second design variable relating to the blast shields was the shape they would have in encasing the acrylic chamber. The shape we would decide on would factor in to help determine the shape of our end plates. Our original thought was a triangular design due to the fact that a triangle has three sides instead of a square that has four (Figure 1). With only three sides, we would limit the amount of material that we would have to use for the end plates and the blast shields. After further consideration and realization that there were components we had to make space for inside of the blast shields, we changed our design to square end plates and square blast shields. We had to fit the acrylic tube and the bolts that would hold the entire chamber together inside of the blast shields. Making a triangular blast shield case would require more precision and would complicate the measurements we would have to make when cutting the end plates during the fabrication stage of production.

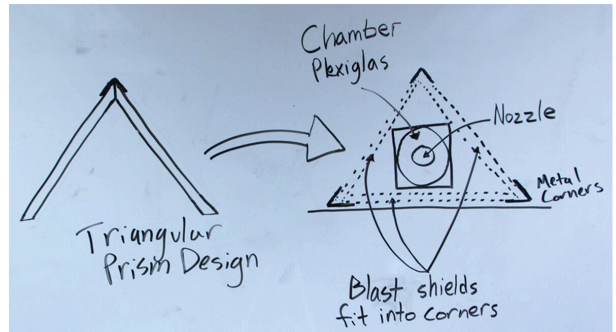


Figure 1. Sketch of a Beginning Concept of the Blast Shield Design. The above photo shows our idea of making the blast shields into a triangular shape.

Calculations and Derivations

Regression Rate of Acrylic Tube

$$r = aG_o^n x^m$$

Where: r is the Regression Rate in $\frac{Millimeters}{Second}$, X is the length of fuel grain in meters, a is the Regression Rate Coefficient, G_o is the Mass Flux in $\frac{grams}{Centimeter^2 \bullet Second}$, n is the Mixture Ratio between the fuel and the oxidizer. X^m was determined to have a value of 1, as the length of the fuel grain is not applicable to our design.

Derivation Used given $X^m = 1$:

$$\frac{dr}{dt} = a[\frac{m_o}{\pi r^2}]^n$$

Where: $G_o = \frac{m_o}{\pi r^2}$,

Explanation:

The regression equation gave us the rate at which the acrylic tube burned off due to its reaction with oxygen. It allows us to calculate the maximum run time of the rocket and allows us to operate the rocket safely by being able to predict when we need to replace the acrylic when it reaches an unsafe inner diameter.

Specific Impulse

$$Isp = \frac{F}{\dot{m}g_o}$$

Where: I_{sp} is the Specific Impulse, $\dot{m}$ is the Mass Flow Rate, and g_o is the acceleration due to gravity: $9.8\frac{m}{s^2}$

Explanation: I_{sp} is the

relationship between the thrust used to the weight of the propellants. It is the change in momentum created per unit propellent consumed through the system. The I_{sp} value was given to us. Through manipulation of the equation for I_{sp}, we can find the mass flow rate.

Area of Throat of Nozzle

$$A_t = \frac{q}{P_t}\sqrt{\frac{RT_t}{M_k}}$$

Where: A_t is the area of the throat of the nozzle in in^2, q is the flow rate in $\frac{meters^3}{Second}$, P_t is the gas pressure at the throat of the nozzle in $\frac{lbs}{in^2}$, T_t is the temperature of the gas at the throat of the nozzle in $Kelvin$, R is the ideal gas law constant: $0.0821\frac{L \bullet Atm}{Mol \bullet K}$ and M_k is the mass of the specific heat ratio in $grams$.

Exit Velocity of the Exhaust

$$C^* = P_c\left(\frac{A_t}{\dot{m}}\right)$$

Where: C^* is the exit velocity of the exhaust with given value of $C^* = 1750\frac{m}{s}$, P_c is the pressure of the chamber in PSI, A_t is the area of the throat of the nozzle in (m), $\dot{m}$ is the Mass Flow Rate in $\frac{Kg}{Second}$

Explanation: The equation allowed us to calculate the most important part of our rocket, the nozzle throat area. This essentially gave us the thrust that was required.

Mass Flow Rate

$$\dot{m} = \frac{F}{I_{sp}g_o}$$

Where: $\dot{m}$ is the Mass Flow Rate, I_{sp} is the Specific Impulse with a given value of 250 seconds, and g_o is the Acceleration Due to Gravity: $9.8\frac{m}{s^2}$.

Explanation: To find mass flow rate, we manipulated the I_{sp} equation and solved for mass flow rate.

Total Propellant Weight Flow Rate

$$\dot{w}_T = \frac{F}{\eta_{comb} \cdot I_{sp}}$$

Where: $\dot{w}_T$ is the Weight Flow Rate, F is required force in $\frac{Ibs}{Second}$, η_{comb} is the Average Combustion Efficiency of the Motor, and I_{sp} is the Ideal Specific Impulse of the propellants in $\frac{Ib \bullet Second}{Ib}$.

Approximate Fuel Weight Flow Rate

$$\dot{w}_f = \frac{\dot{w}_T}{MR+1}$$

Where: $\dot{w}_f$ is the Fuel Weight Flow Rate, $\dot{w}_T$ is the Weight Flow Rate, and MR is the Propellant Mixture Ratio in the Combustion Chamber,

Approximate Oxidizer Weight Flow Rate

$$\dot{W}_{ox} = \dot{w}_T - \dot{w}_f$$

Where: $\dot{w}_{ox}$ is the Oxidizer Weight Flow Rate, $\dot{w}_T$ is the Weight Flow Rate, $\dot{w}_f$ is the Fuel Weight Flow Rate.

Approximate Consumed Fuel Weight

$$w_f = \dot{w}_f \bullet t_b$$

Where: w_f is the Consumed Fuel Weight, $\dot{w}_f$ is the Fuel Weight Flow Rate, and t_b is the Total Burn Time in Seconds.

Approximate Consumed Oxidizer Weight

$$w_{ox} = \dot{W}_{ox} \bullet t_b$$

Where: w_{ox} is the Consumed Oxidizer Weight, $\dot{w}_{ox}$ is the Oxidizer Weight Flow Rate, t_b is the Total Burn Time in Seconds.

Total Required Fuel Weight

$$w_{f,T} = 100 \bullet \frac{w_f}{FC}$$

Where: $W_{f,T}$ is the Total Required Fuel Weight, w_f is the Consumed Fuel Weight, and FC is the Fuel Consumption Percentage, and was assigned a fixed percentage of 90%.

Total Required Oxidizer Weight

$$w_{ox,T} = 100 \bullet \frac{w_{ox}}{FC}$$

Where: $w_{ox,T}$ is the Total Oxidizer Weight, w_{ox} is the Consumed Oxidizer Weight, and FC is the Fuel Consumption Percentage, and was assigned a fixed percentage of 90%.

Individual Fuel Grain Weight

$$W_G = \frac{W_{f,T}}{N}$$

Where: W_G is the Individual Fuel Grain Weight, $W_{f,T}$ is Total Required Fuel Weight, and N Number of Fuel Grains.

Individual Grain Fuel Volume

$$V_G = \frac{W_G}{\rho_f}$$

Where: V_G is the Volume of the Individual Grain Fuel, W_G is the Weight of the Individual Fuel Grain, and ρ_f is the Weight Density of the Fuel.

Individual Grain Total Volume

$$V_{G,T} = \left[1 + \frac{PS}{100}\right] \cdot V_G$$

Where: $V_{G,T}$ is the Total Volume of the Individual Grain, PS is the Fuel Grain Port Sizing Parameter, and is approximately 10%, and V_G is the Volume of Individual Fuel Grain.

Individual Grain Diameter

$$D_G = \left[\frac{4 \cdot V_{G,T}}{LD \cdot \pi}\right]^{\frac{1}{3}}$$

Where: D_G is the Diameter of the Individual Grain, $V_{G,T}$ is the Total Volume of the Individual Grain, and LD is the Fuel Grain Length-To-Diameter Ratio.

Individual Grain Length

$$L_G = LD \bullet D_G$$

Where L_G is the Length of the Individual Grain, LD is the Fuel Grain Length-To-Diameter Ratio, and D_G is the Diameter of the Individual Grain.

Example Calculation

Length and Diameter of Acrylic Tube for a 70 Second Firing Time

$$\dot{w}_t = \frac{1 Ib_f}{0.95 \bullet 250 Sec} = 0.0042105263 \frac{Ib_f}{Sec}$$

$$\dot{w}_f = \frac{0.0042105263 \frac{Ib_f}{Sec}}{2.35+1} = 0.0012568735 \frac{Ib_f}{Sec}$$

Where $MR = 2.35$ where 2.35 is a given value.

$$\dot{w}_{ox} = 0.0042105263 \frac{Ib_f}{Sec} - 0.0012568735 \frac{Ib_f}{Sec} = 0.0029536528 \frac{Ib_f}{Sec}$$

$$w_f = 0.0012568735 \frac{Ib_f}{Sec} \bullet 70 Sec = 0.087981145 Ib_f$$

$$w_{ox} = 0.0029536528 \frac{Ib_f}{Sec} \bullet 70 Sec = 0.206755696 Ib_f$$

$$w_{f,T} = 100 \bullet \frac{0.087981145 Ib_f}{90}$$

Where $FC = 90\%$ and 90% is a given value.

$$w_{ox,T} = 100 \bullet \frac{0.206755696 Ib_f}{90} = 0.2297285511 Ib_f$$

Where $FC = 90\%$

$$w_G = \frac{0.0977568278Ib_f}{1\ Desired\ Fuel\ Grain} = 0.0977568278Ib_f$$

$$V_G = \frac{0.0977568278Ib_f}{74.289\frac{Ib_f}{ft^3}} = 0.0013158991ft^3$$

$$V_{G,T} = [1 + 0.1] \bullet 0.0013158991 = 0.001447889ft^3$$

Where $\frac{PS}{100} = 0.1$

$$D_G = \left[\frac{4 \bullet 0.001447489}{3\pi}\right] = 0.0850096142ft = 1.0201in$$

Where $LD = 3$

$$L_G = 3 \bullet 0.0850096142ft = 0.2550288426ft = 3.0603in$$

Preliminary Designs

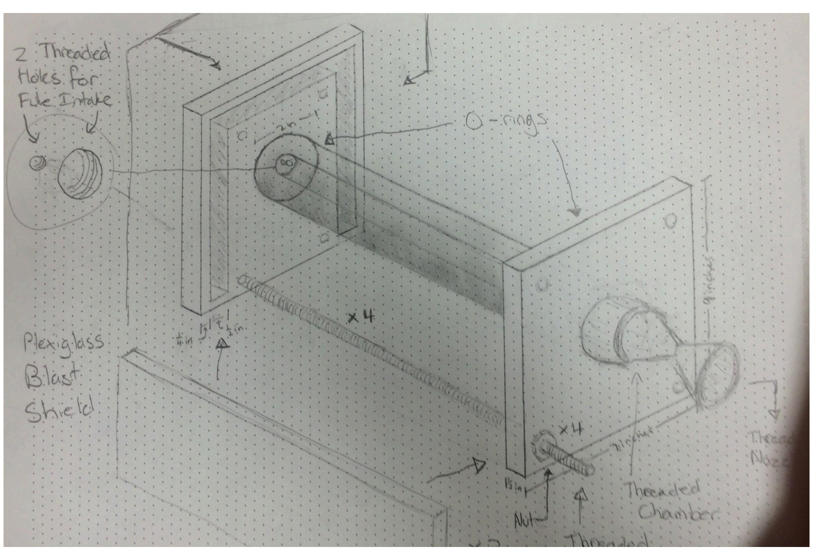


Figure 2. Sketch of Preliminary Assembled Design. This is one of the first sketches of our design fully assembled. It is not fully dimensioned or to scale.

After our brainstorming sessions, we integrated our ideas into one concise design. Our general design consisted of having two metal plates on either side of an acrylic tube surrounded by three blast shields held together by four threaded rods (Figure 2). The acrylic tube is transparent in order to see the reaction take place within the chamber. There is a metal tube welded onto the end of the second metal plate.. The tube is threaded on the inside. Our nozzle is threaded on the outside to screw into the welded on metal tube. The nozzle has a converging and diverging section. On the first metal plate, there are two holes to allow gas into the chamber: one for the oxygen, and one for the propane (Figure 3). The holes for the rods are threaded.

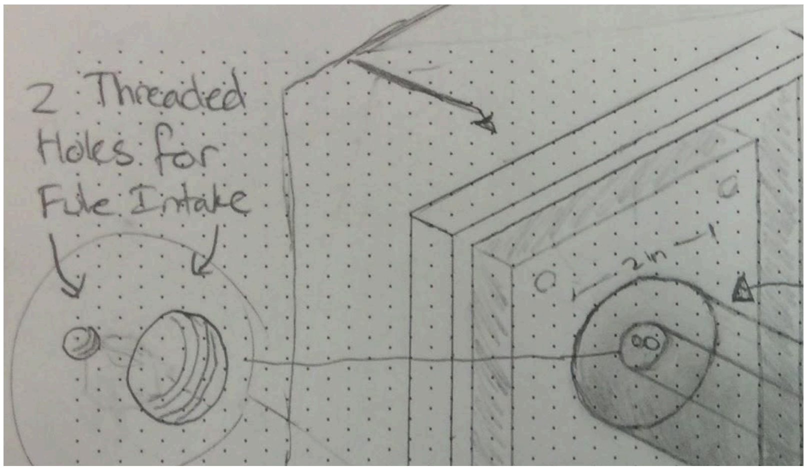


Figure 3. Exploded View of Figure 2. Our preliminary design consisted of having two threaded holes for the oxygen and the propane to flow through.

Complications with the Design

Many problems came about when developing our design. First of all, we originally ordered hot rolled, finished steel for the metal plates. Unbeknownst to us, this became a huge problem. Medium steel, like this, is extremely difficult to cut and fabricate. We stumbled upon this after we had ordered the steel and were about to fabricate it. After talking with members of the shop team, we realized our costly mistake. Then, we bought aluminum plates to use instead. Aluminum was much easier to work with and was sufficient in our design.

Figure 4. Close-up View of Back Metal Plate. In the top right corner, the CNC machine cut too far causing an unnecessary cut.

Another problem was discovered when fabricating the grooves for the blast shields to rest in. (Figures 4-5). The groves were not cut perfectly. In the top right corner of each of the metal plates, the machine cut too far leaving a cut into the side of the groove. The extra cut did not affect the functionality of the design. However, it makes the metal plate look sloppy and poorly fabricated. Given more time, a new plate would have been cut to make it more aesthetically pleasing.

Figure 5. Close-up View of Front Metal Plate. A close up view of the top right corner reveals an error in fabrication.

Even though the bolts were a basic part of our design, we ran into many problems sizing them correctly. When we first ordered our parts, we ordered extra long bolts thinking it would account for any change of length or miscalculation we had. Upon arrival, we learned that only the first inch of the bolts were threaded, and we overestimated the total length of the chamber. We initially thought it may be possible to cut and rethread the bolt where we needed it, but after further discussion with members from the shop team, it proved to be more trouble and take more time than it was worth. When we learned this, we recalculated the length of the chamber assembly and took a trip to Ace Hardware to purchase new bolts that would be sufficient in our design. We came back with four six inch bolts that were fully threaded just in case we overestimated the length again. When we put everything together, we realized we actually underestimated the overall length of the chamber. With eight useless bolts, we triple checked the actual length of threaded rod we needed and made sure we were correct. A final trip made to Ace Hardware gave us four feet of threaded rod and four lock nuts to secure our thrust chamber. The rods were cut into equal pieces using a drop saw and the burrs were sanded off. The lock nuts were secured to one end of each piece of rod.

In regards to the blast shields, two problems had to be dealt with. We initially ordered ¼ inch plexiglass, however, the grooves to hold the blast shields had been incorrectly dimensioned at ½ inch instead of ¼ inch. This problem arose through miscommunication. This problem was successfully resolved by using acrylic cement to glue two ¼ inch blast shields together. If we would have had time to redesign our project, we would remake the metal plates with the correct dimensions for the grooves in order to eliminate the need to glue two plexiglass blast shields together. Furthermore, during fabrication, the blast shields were cut a few millimeters too long. Because of this, when the thrust chamber was fully assembled, there was a small gap between the acrylic tube and the o-ring in the nozzle. This was a significant problem because the chamber needs to be airtight, as there can not be gas leaking out of the chamber. To remedy this problem, we sanded down the blast shields until they did not interfere with the o-ring and the acrylic tube.

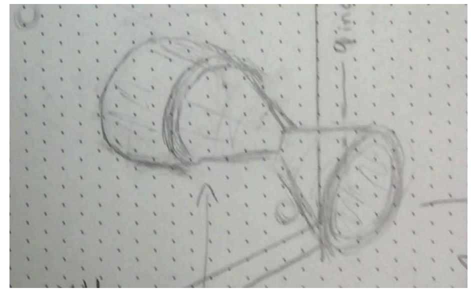


Figure 6. Preliminary Sketch of the Nozzle. Above is the first concept of the nozzle. It consists of one steel piece with converging and diverging cones.

The original design of the nozzle was not practical to fabricate which was a converging and diverging nozzle (Figure 6). Instead, we built a nozzle that the acrylic rod would sit in (Figure 7). The nozzle would go through the back metal plate to eliminate the need for threads. The end part of the nozzle (Figure 8) was originally designed to be 1.5 inches instead of 2 inches. However, because we did not have enough time, we only got the end diameter down to 2 inches. This caused the nozzle to have more weight. Ultimately, this did not affect the functionality.

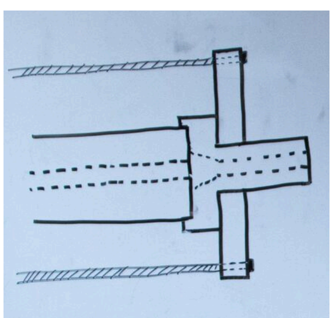
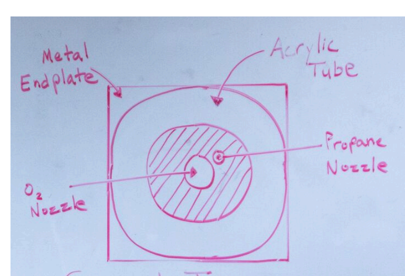


Figure 7. Sketch of the Final Design of the Nozzle.

Figure 8. Steel Nozzle. Above is a close up view of the nozzle showing where steel tube was cut down.



With the first metal plate, there were originally two holes for the gas to flow through: one for the oxygen and one for the propane (Figure 9). However, when we talked with the Packaging and Feeds team, who were responsible for the propane and oxygen, we realized there was not going to be enough space on our metal plate for both the oxygen line and propane line to fit into. Therefore, we redesigned our metal plate to have only one hole through which both gasses flow. An additional metal plate created by the ignition group was added in front of our metal plate (Figure 10). All of the fuel lines connect to this metal plate.

Figure 9. Preliminary Design of the Front Metal Plate. Above is a sketch on a whiteboard of the first design of how the fuel lines were to connected to our front metal plate.

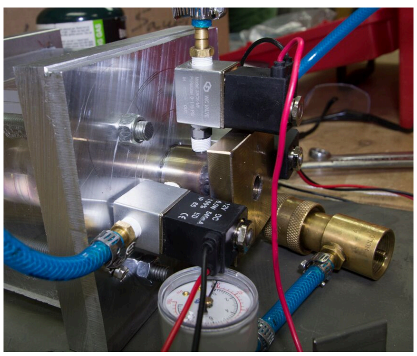


Figure 10. Assembled Design of the Back Plate. This picture shows the integration of the group's steel metal hooked up with all the fuel lines.

Evaluated Design and Fabrication

After consulting with our lab instructor and members of the COE shop, we eliminated errors and finalized our design. Our design is broken down into 6 main components: metal plates, threaded rods, o-rings, blast shields, an acrylic tube, and nozzle.

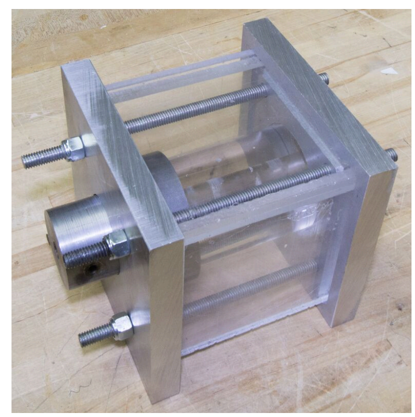


Figure 11. Fully Assembled Finished Design. Every component is integrated together into a sleek compact design.

In our design, we have two aluminum plates that hold the chamber together (Figure 11). The metal plates are six inch squares and ¾ inch thick. This allows enough room to house the acrylic tube, an o-ring, the blast shields, and the four holes for the threaded rods. In the first plate, we used a mill to counterbore a hole where the acrylic rod rests. In the counterbored hole, there is another cut in the metal by a CNC mill to make space for an o-ring. In the center of the counterbored hole is a smaller hole that goes through the entire plate, which was also cut using the mill. This hole is the entrance for the gas to flow through the acrylic tube. Around the counterbored hole is four holes drilled on a drill press to allow four threaded rods to run through the plates. (Figures 12-13) The holes are all placed equidistant from the center of the plate to apply even pressure. They were also placed far enough away from the acrylic rod that the reaction is still visible in the chamber. There are also three grooves CNC milled into the metal plate in order to hold the blast shield in place (Figures 12-13). There is no groove on the bottom of the plate because it is not necessary to have a blast shield beneath the chamber, since it will be affixed to a metal plate, which will prevent any shrapnel from escaping out the bottom in the event of an explosion. The second metal plate has two similar features to the first metal plate: the groove and the 4 holes for the threaded rods. (Figure 14) In the center of the plate is a hole cut using a hole saw to allow the nozzle to fit through (Figure 14). The two metal plates are heavy enough to hold the entire chamber in a stationary position while the rocket is firing.

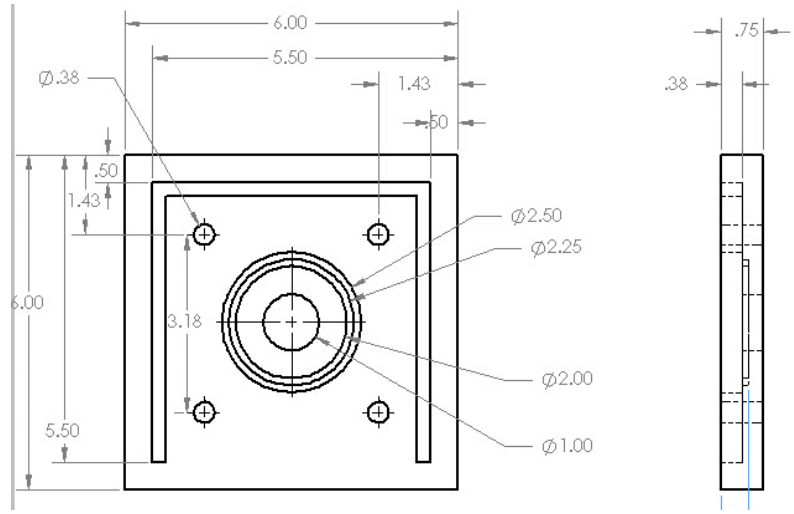


Figure 12. Drawing Sheet of the Front Metal Plate. Above is a drawing sheet of the front metal plate which was drawn and dimensioned using Solidworks

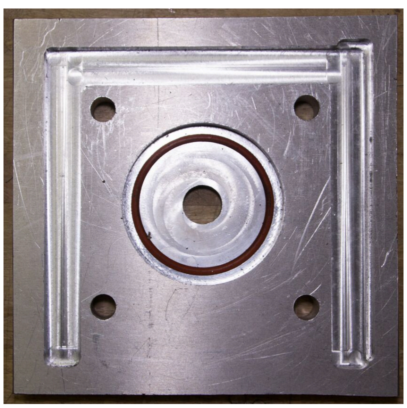


Figure 13. Front Metal Plate.

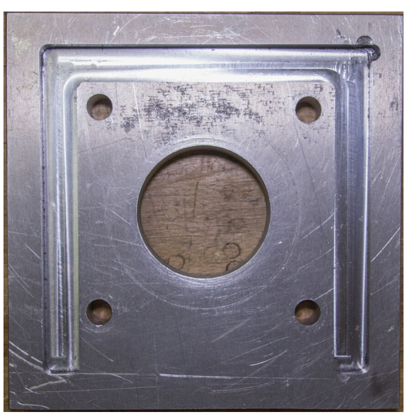


Figure 14. Back Metal Plate.

We also have four threaded steel rods in our design. Their purpose is to hold the entire thrust chamber together. They hold the acrylic rod, blast shields, and nozzle in place. The rods push the acrylic tube against the o-rings to create a sealed chamber (Figure 15).

Figure 15. Threaded Rods and Nuts.

Two o-rings, one set in the first metal plate and one set in the nozzle, provide an airtight seal around the acrylic chamber. Specific dimensions for the grooves for the o-rings were found in the Parker O-Ring Handbook (Parker Hannifin Corporation). These dimensions needed to be exact. If they were miscalculated, they would not give a good seal to the chamber, causing gas to leak out and become a potential safety hazard. Glands for the o-rings were machined to a very low tolerance to prevent this problem.

Figure 16. Plexiglass Blast Shields.

We used ½ inch thick plexiglass, made up of two ¼ inch layers, in the manufacture of our blast shields, which surround three sides of the chamber to prevent molten acrylic from injuring the audience and operators in the event of a catastrophic malfunction (Figure 16). The blast shields were cut using a vertical band saw.

Figure 17. Acrylic Tube.

The acrylic fuel grain was a key component in our design, serving as both the reaction chamber and the fuel source (Figure 17). Getting the correct dimensions for the tube along with the regression rate of the acrylic was critical and required extensive calculations, which are outlined in detail later on. The acrylic tube is 3 inches in diameter with a 0.5 inch bore through the center.

Our nozzle was machined from a three inch diameter steel rod. On the front of the nozzle, just like the first metal plate, there is a counterbored hole to house the acrylic rod and a gland to hold the o-ring (Figure 18). The counterbored hole was cut out using a lathe. The angled part of the nozzle was cut using a countersink on the lathe. Then, the end of the nozzle (Figure 19) was cut down to 2 inches to reduce its weight. Because the nozzle was steel, it was very labor intensive to manufacture. However, we feel as though this is a necessity due to the extreme conditions the nozzle would be subjected to. On the narrow end of the nozzle, we added a hole for a pressure sensor using a drill press. A small spotface hole was cut to make a flat surface for pressure sensor to rest on. Then, the hole was tapped to make threads for the pressure sensor to screw into.

Figure 18. Front View of the Nozzle. Above is a view of the nozzle looking down the throat of the nozzle. The o-ring can be seen along with the counterbored hole

Figure 19. Side View of the Nozzle. The smaller diameter of the nozzle can be seen along with the hole for the pressure sensor.

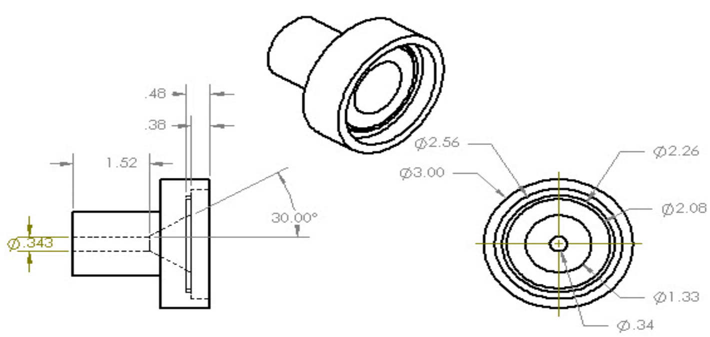


Figure 20. Drawing Sheet of the Nozzle. The drawing sheet was drawn and dimensioned in Solidworks.

Part Ordering and Cost Analysis

3" Round Cold Finished 1018 Steel	$38.67
3/8-16 x 9" Grade 5 Hex Cap Screw Zinc Plated	$14.96
2.5" X 1' Clear Cast Acrylic Rod	$65.39
3/4" 1045 Hot Rolled, Steel Plate-12"x12"	$81.51
226 Silicone O-Ring, 2" ID, 2-1/4" OD, 1/8" Width	$5.25
24"x24"x0.25" Thick Clear Plexiglass Sheet	$47.56
3/8-16 Grade 2 Finished Hex Nuts	$0.20
Scrap Aluminum from Shop	$50.00
Extra Bolts and Nuts Bought	$5.16
TOTAL:	**$308.70**

As you can see from our materials list, we more than doubled our originally set budget of approximately $150. There were several causes of this but it ultimately boils down to our lack of knowledge of the required materials for this project and miscommunication. We took it upon ourselves to figure out what materials we should use for each component of the thrust chamber and that is why we ordered what we did. We should have cross-referenced what we thought we needed with suggestions from the actual experts, our lab instructor Chip and Scott Munson. Another mistake we made was not consulting the workers inside of the fabrication lab until after we ordered all of our parts. We should have taken into consideration that they would also know more than us about working with some of these materials that we ordered. This would have saved us a lot of time, headache, and money.

Testing the Prototype

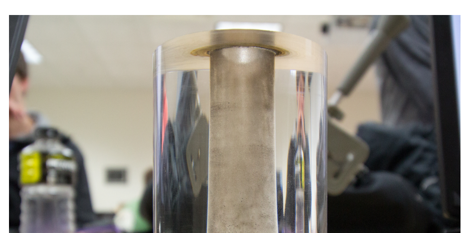
The first time we tested the rocket, the ignition team and control systems group were not finished with their designs. To account for this, we had to engineer a way to ignite the rocket a different way. We were able to find a spare car battery, which we used to manually control the valves Because the spark plug was not working either, we rolled up a napkin and inserted it into the end of the nozzle. The napkin made an effective makeshift fuse and successfully ignited the system. We started with a very low pressure stream of propane and slowly increased it until we had a controlled flame coming out of the nozzle. Then, we turned on the oxygen. The pressure of the oxygen was so high that when it ignited, it blew out the flame with an explosion. We continued to test the rocket three more times, each time resulting in an explosion.

Because we were not satisfied with our results, we continued testing three days later. This time, the control system had their computer program up and running, which allowed us to properly control the flow of oxygen and propane. We still did not have a functioning spark plug, so we continued testing with the makeshift fuse. We successfully opened the propane valve, allowing the acrylic to heat to the necessary temperature for ignition. Oxygen was introduced to the system, and the rocket fired according to our plans. A loud noise was heard as the combustion changed from propane to oxygen and acrylic, and a narrow, steady flame was produced by the nozzle. We consider this our first successful test, as we could see the reaction inside the chamber, and combustion was sustained until power was cut to the system. After six seconds, we unplugged the Arduino and stopped the rocket. Although our methodology may not have been conventional, we managed to have a successful test firing of the rocket.

Given the success of our most recent trial, we set out to achieve a longer sustained burn. We reset the apparatus and slightly increased our oxygen pressure. For this test, we allowed the rocket to fire for a total of 17 seconds, a whopping four times our minimum requirement, before manually shutting it down. We concluded from this that the rocket can safely be fired for the optimal 7 second period without melting the thrust chamber.

Conclusion

Looking back over our problem statement, we fulfilled all nine of our client's requirements for the thrust chamber of the hybrid rocket engine. We were able to design the chamber such that there was sufficient space for all of the other components to fit into the package. In testing its portability, we were easily able to carry the rocket out of the Engineering Centers Building. The design was not heavy or cumbersome. Thirdly, we designed our chamber with an acrylic tube. During our test, the acrylic ignited and allowed the rocket to fire. Next, while this was not part of our groups design, the other group did use oxygen as the oxidizer to run the rocket. To address the visibility requirement, we built our chamber with a clear acrylic tube and clear plexiglass blast shields. The reaction was clearly visible during all four of our tests. During our third test, we were able to get a continuous firing of around 17 seconds, which was more than four times the minimum duration. For the seventh requirement, we needed to have one pound of thrust. While we were not able to test the actual thrust from the rocket, from our calculations, our rocket should have produced more than one pound of thrust. The fuel grain is made of an easily replaceable acrylic tube, three extras of which we provided to our client. We designed the acrylic tube to be thick enough to perform several runs of the optimal firing



duration without melting through the chamber and destroying the system. Even after all of our testing, we still could have used the acrylic tube for more test runs (Figure 21). For the final requirement, we incorporated blast shields into the framework of our metal plates. Even though we were never faced with a catastrophic malfunction, we are confident that our blast shields would be sufficient to protect the audience and operators of the device.

Figure 21. Acrylic Tube After Testing. The above picture shows how the inside diameter of the acrylic regressed after testing.

Because our final design met every client need, we can say with confidence that the project was a success.

References

B. Tom (2015, October 22). National Aeronautics and Space Administration: General Thrust Equation - Space Flight Systems. (2nd ed.) [Online]. Available:https://spaceflightsystems.grc.nasa.gov/education/rocket/thrsteq.html

D.J. William (2001, January 1). Converging and Diverging Nozzle Applet (1st ed.) [Online]. Available: http://www.engapplets.vt.edu/fluids/CDnozzle/cdinfo.html

Greiner, B., Federick, R, "Results of Labscale Hybrid Rocket Motor Investigation," AIAA/ASME/SAE/ASEE 28th Joint Propulsion Conference & Exhibit, Nashville, TN, AIAA, Paper 92-3301, 1992.

H. Nancy (2015, May 5). National Aeronautics and Space Administration: Rocket Thrust Equation Glenn Research Center (1st ed.) [Online]. Available: https://www.grc.nasa.gov/www/K-12/airplane/rockth.html

Parker Hannifin Corporation. Parker O-Rings Handbook: 50th anniversary addition [Online]. Available: https://www.parker.com/literature/ORD%205700%20Parker_O-Ring_Handbook.pdf

Jerry M. Seitzman. " Rocket Propulsion: Thrust Coefficient, Characteristic Velocity and Ideal Nozzle Expansion" [Online]. Available: http://soliton.ae.gatech.edu/people/jseitzma/classes/ae4451/thrust_coefficient.pdf

R. Nakka. (2001, July 5). Solid Rocket Motor Theory--Thrust (1st ed.) [Online]. Available: http://www.nakka-rocketry.net/th_thrst.html