RocketLynx

Design and Construction of a Hybrid Rocket Propulsion System

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Professor Doug Gallagher
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Abstract

A hybrid rocket engine using nitrous oxide and acrylonitrile-butadiene-styrene (ABS) was developed by the Rocketlynx team. The team’s objective was to design, simulate, manufacture, and test a hybrid rocket engine that could produce 100 lbs. of force for 10 seconds. The first static test of the rocket engine occurred Saturday, April 3rd, 2021, and a second took place Friday April 30th, 2021, both times at the Air and Space Port in Watkins, Colorado. Test results illustrate that the rocket engine achieved 48 lbs of thrust for fractions of a second, multiple times. Critical testing procedure issues have been identified, namely controlling the nitrous oxide pressure and perfecting the ignition system. A major result of this research is the demonstrated viability of Rocketlynx hybrid rocket engine design.
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Nomenclature

**Oxidizer:**

$m_f$: Combined Mass Flow Rate of Oxidizer and Solid Fuel

**Combustion Chamber:**

$Re_D$: Reynolds Number of Diameter

$\rho$: Density of Fluid

$\nu$: Momentum Diffusivity

$D$: Diameter

$\mu$: Dynamic Viscosity of the Fluid

$f$: Friction Factor

$NU_D$: Nusselt Number

$Pr$: Prandtl Number

$h$: Convection Heat Transfer Coefficient

$R'_\text{gas}$: Apparent R-value of a Gas

$R'_\text{solids}$: Apparent R-value of a Solid

$Q'$: Heat of the System

$R'$: Apparent R-value

$T$: Temperature

$k$: Thermal Conductivity

$\varepsilon$: Effectiveness

$Re$: Reynolds Number

$r$: Radius

$C_d$: injector discharge coefficient
Introduction

1.1 Project Overview

Rocketlynx is a senior design team at CU Denver that is in its third year of developing hybrid rocket engines. A hybrid rocket engine has a solid fuel grain and a liquid or gaseous oxidizer. There is a renewed interest for hybrid propulsion in the aerospace industry, mainly due to lower toxicity oxidizers, the safer design, and advances in additive manufacturing. Nitrous oxide was chosen as the oxidizer because of its self-pressurizing capabilities, high accessibility, and extensive documentation of its properties. The thermoplastic acrylonitrile-butadiene-styrene (ABS) was chosen as the solid fuel due to recent research identifying its viability for hybrid rocket engines, as well as the potential to utilize additive manufacturing with ABS. A hybrid rocket engine design was chosen over solid and liquid rockets due to its relatively high level of safety and simple design, which allows for simpler manufacturing. Last semester the team completed the majority of the design and simulation work for a third iteration of a hybrid rocket engine. This semester, the team has been focused on finalizing designs, manufacturing, and developing the data acquisition subsystem. The team has primarily worked in two sub-teams this semester, manufacturing and avionics. Once the construction, assembly, and programming of all the subsystems was completed, a first static hot fire was conducted. Redesigns took place following a success and failure analysis. With the redesigns in place and an updated hybrid engine and testing system prepared, a second static hot fire test occurred. Finally, the team
analyzed data collected from the second test, did another success and failure analysis, and then made recommendations moving forward.

**Chapter 1: SubSystems Overview and Project Management**

**Oxidizer Subsystem**

The oxidizer subsystem is fully manufactured and has been through a cold flow test and two hot testing phases. The oxidizer system performed as expected in the cold flow test yielding the correct mass flow rate and good atomization of the nitrous. The oxidizer system behaved similarly for both hot tests however there were some slight over pressurization issues during the second test that will be discussed later on. All of the components of the oxidizer system survived every testing phase retaining their structural integrity and can still be used in later iterations of the motor if needed. The only changes that needed to be made to the system after each test were replacing the PTFE O-rings sealing the injector and oxidizer cap in addition to replacing the teflon tape on the threads of the transitional manifold where it connects to the feed system.

**Combustion Chamber Subsystem**

The combustion subsystem is almost ready for a full test. The designs have been finalized and focus has shifted to fabrication and testing procedures. Particular care has been given to the combustion chamber housing since the first year's team lacked proper sealing, resulting in the rupturing of the aluminum combustion chamber. Calculations concerning the heat transfer and pressure have been updated and reexamined to avoid this issue.
Nozzle Subsystem

A slight redesign occurred concerning the nozzle. Part of the nozzle was revised to fit the top of the nozzle within the phenolic liner, as to improve the flow of the hot exhaust gas. All that remains to be done is to assemble the nozzle’s two o-rings.

1.2 Manufacturing Overview

A key objective of this semester was to utilize the designs to manufacture a working hybrid propulsion system. This means we need to manufacture an oxidizer subsystem, feed subsystem, nozzle, solid fuel grain, phenolic liner, combustion chamber, clamping system, and testing system. The team has already manufactured all of these parts and have completed two hot tests with them. However some parts such as the nozzle, fuel grain, phenolic liner, and clamping system were damaged in the first test and had to be manufactured again for the second hot test.

1.3 Avionics Overview

The avionic components will perform two primary functions. They will control the servo motors, safely controlling the operation of the rocket engine. Additionally, they will allow for the acquisition of various data that will be gathered and analyzed from the tests. There are four major components of the avionics system. The first is the servos and sensors, which comprises the pressure transducers, thermocouples, and the load cell. Next is the microcontrollers and the wiring. Another key item avionics addresses is the power system, namely the battery. Finally, the last key component is the human interface, which
describes the software and mechanical tools used to control and analyze the engine’s test performance.

**1.4 Budget**

The total budget for this project was $2,700. The total expenditures so far is at $2,687.59. The remaining balance to date is $12.41.

*Table 1: Rocketlynx Budget*

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<td>Nozzle O-Rings</td>
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Chapter 2: Oxidizer Subsystem

2.1 Oxidizer System

The Oxidizer system’s design has not changed this semester. There is still an oxidizer cap that houses the injector and is inserted into one end of the combustion chamber and has a transitional manifold bolted to it to join the oxidizer and feed system.

2.2 Oxidizer Cap

The oxidizer cap is inserted into one end of the combustion chamber in the final motor assembly. The oxidizer cap is sealed to the combustion chamber using PTFE O-rings seated in properly sized square grooves creating a piston and cylinder seal as shown in Figure 2.2. The oxidizer cap also houses the injector which is sealed to the oxidizer cap using PTFE O-rings seated on the injector creating a face seal with the oxidizer cap. Lastly the oxidizer cap is bolted to the transitional manifold using 8 3/8” UNC tapped holes. When the transitional manifold is bolted on, it creates a face seal with the top O-ring on the injector, and clamps the injector inside of the oxidizer cap. The oxidizer cap has now been through two hot tests taking no damage and retaining all of its structural integrity allowing it to be used in a future iteration of the motor.
2.3 Injector

The injector will be inserted into the oxidiser cap located at one end of the combustion chamber and then it will be sealed using the transitional manifold. The injector will be sealed to the oxidiser cap using PTFE O-rings seated in properly sized square grooves creating a face seal to the oxidiser cap. The top of the injector will then sit flush with the top of the oxidiser cap, and the transitional manifold will connect the three elements with 8 ⅜” bolts connecting to the 8 ⅜” UNC tapped holes on the oxidiser cap creating another face seal. The transitional manifold will provide the nitrous oxide to the injector. Then the injector will atomize the nitrous oxide into the combustion chamber.
2.4 Transitional Manifold

The transitional manifold joins the feed system to the oxidizer system. It features 8 \( \frac{3}{8} \)" holes to attach it to the oxidizer cap. The neck of the manifold is tapped for \( \frac{1}{2} \)" Male NPT in order to attach it to the feed system as shown in Figure 2.4.
2.5 Oxidizer Feed System

The oxidizer feed system has remained mostly unchanged from the previous report. The primary change that was made was a shift away from a pressure differential based control system towards a temperature based control system. This new control system uses a thermocouple which is mounted on the combustion chamber in order to modulate the flow of the oxidizer into the system. This decision was made because the integrity of the combustion chamber is more important than the mass flow rate of the oxidizer. It was also
found that with the injector being the primary restriction in the oxidizer system, the mass flow rate would likely remain constant throughout the duration of the test fire. The revised, temperature based control system has also been simplified in its logical systems as well, instead of using a control system, the system uses different temperature ranges to identify the status of the combustion chamber and modulate the servo position accordingly. The system has 3 ranges, a sustained safe range, a safe burst range, and a dangerous range. In the safe range, the valve will be delivering 100% mass flow of oxidizer to the combustion chamber, in the safe burst range, the valve allows for between 50% and 75% of the mass flow rate, and in the dangerous range, the valve closes completely in order to prevent catastrophic failure of the combustion chamber. The two pressure transducers will still be integrated into the feed system and will be used for data acquisition, this data can be used to determine the losses in the feed system and allow for further optimizations of the feed system in the future. The systems safety valve also underwent minor modifications, instead of using a microcontroller, this system will be driven by a single servo controller, this ensures that we have manual control over the oxidizer at all times and removes potential failure points. An updated system diagram of the feed system can be observed in figure 2.5 below.
While one of the goals of the data acquisition is to determine the actual losses through the feed system, some calculations were performed to estimate the total losses of the feed system. With these values, the feed system is able to be more optimized for better, more efficient flow. Minor loss coefficients and total head losses were calculated using the Hooper 2K method to provide accurate results. This led to the sum of minor losses being equal to 4.57 and the total head loss being equal to 1.4 ft.

**Figure 2.5: System Diagram of Feed System**
3.1 Corrections to the Heat Transfer Calculations and Heat Transfer to Thermocouples

The heat transfer calculations that were initially performed were flawed. These calculations were based upon an internal temperature that was incorrect. The temperature that was initially used was 2850 K, which was noticeably higher than seemed probable. This value was actually the temperature that would have been used for nanoscale heat transfer. This would be a temperature that would be used should one attempt to work out the transfer of energy and heat on the nano scales. Therefore since this project needs values that are useful for macro scale heat transfer calculations, the majority of the previous work had to be redone to become useful and significant. A major change that was made in this process was one that shaped the direction of the research, calculations, and results. Instead of attempting to calculate the maximum temperature that the combustion process could produce, it was decided that it would be wiser to just determine the maximum temperature that we wanted to test. After deciding upon a goal temperature, the rest of the calculations were fairly easy to adjust and receive new results for since the majority of the calculations were performed using Microsoft Excel. Once a reasonable temperature was used as the input, many of the strange and shocking results of the previous calculations were resolved. With the new values, the combustion chamber is definitely within a safe range in regards to the pressure and thermal loads that it will have to endure for the duration of the testing. Even when nearing our maximum temperature, the combustion chamber will be able to
withstand the pressure loads and maintain a safety factor greater than 2.5. When performing these analyses and comparisons between the loads and the strengths of the combustion chamber, the analysis assumes that the aluminum chamber is at the maximum temperature that will be tested. Since the testing will only last for 10 seconds, the combustion chamber material will not reach the temperatures that are being used for the strength properties in the calculations and the analysis. This means that since the chamber is safe with these assumptions and precautions, it will be even safer during the actual testing. Recognizing and correcting the incorrect temperature assumptions and subsequent calculations has proven the safety of the combustion chamber of the engine.

The thermocouples will be attached to the exterior of the combustion chamber in order to measure the interior combustion temperature. In order for this to work, there had to be additional heat transfer calculations performed to make the collected data useful. Calculations were performed at 4 different internal temperatures to determine the temperature on the outer surface of the combustion chamber where the thermocouples will be taking their readings. This was done so that at these benchmark temperatures, there could be an output so we roughly know how hot the engine is burning during the test. This will be used not only as a way to collect data from the test but also as a part of our shut off plan. Should the temperature of the interior surface of the combustion chamber exceed 773 K, one of the ball valves will be closed so the combustion process will be stopped. This is for the safety of the team primarily, should the combustion chamber heat up much more than that, the risks of a violent failure increase significantly. This plan will protect the team members during the testing as well as protect the combustion chamber itself should we
want to attempt another test at some point later. In order to accomplish this goal, the heat transfer coefficient had to be calculated, which involved finding the Reynold's number, friction factor, and the Nusselt number. The heat transfer coefficient was then used to find the heat transfer through the combustion chamber walls so the outer surface temperature could be calculated.

\[ Re_D = \frac{\rho v D}{\mu} \]  

\[ f = \frac{1}{[1.84 \log\left(\frac{6.9}{Re_D} + \left(\frac{D}{3.7}\right)^{1.11}\right)]} \]  

\[ NU_D = \frac{L_n(Re-1000)Pr}{1+12.7^*\left(\frac{L_n}{\pi}(Pr_2^\frac{3}{2}-1)\right)} \]  

\[ h = \frac{NU_D^*k}{D} \]  

\[ R_{gas}' = \frac{1}{2\pi \tau h} \]  

\[ R_{solids}' = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k} \]  

\[ Q' = \frac{\Delta T}{\Sigma R'} \]  

These equations ultimately led to the realization that since the combustion chamber walls are relatively thick, the external temperature changes are very small. This is simultaneously a good and bad revelation. On the one hand, this means that the combustion chamber is a lot safer than if there were a large variance in the external temperature as the combustion process heats up. On the other hand, it makes the data collection a lot more difficult. Since there is such a small variance between the cold external temperature and the hot external temperature, there could be additional difficulties in having accurate data.
collection, and it could make our failsafe measures more difficult as well. At an internal surface temperature of 473 K, the external surface temperature will be 283.17 K, this is for our low burn temperature. Whereas at the upper limit of our internal temperature of 773 K, the external surface temperature will be 283.44 K. Having such a small range of temperatures for the thermocouples to read may make our data analysis difficult after the test.

Through the successful second test of the engine, it was found that the total generated thrust was significantly lower than our initial goal of 100 lbs of thrust. This could be caused, in part, by a number of environmental conditions that were improperly accounted for and overlooked, but it is also very likely that there were some improper calculations performed in regards to the theoretical thrust profile. The true oxidizer to fuel ratio was different than that which was used in the calculations for the thrust profile. This is mostly caused by the environmental conditions surrounding the oxidizer tank on the day of testing. The oxidizer was excited by a higher environmental temperature on the day of the second test, which meant that the oxidizer was being supplied at a higher pressure than it was designed for which caused the combustion process to burn more of the oxidizer than the calculations initially planned for. For future tests, the calculations need to be adjusted for the real pressure of the oxidizer tank as well as with the corresponding oxidizer to fuel ratio. Most of the calculations themselves appear to still be correct but the data that was used in the calculations was not entirely representative of the testing conditions that were present during the second test. This was largely overlooked because on the day of the first test, the environmental conditions were ideal for the testing and as such the thrust
calculations were not needing adjustment. That test ended with a violent failure so we won’t know if the calculations were actually correct for those conditions. Moving forward, unless something like an ice bath is used to keep the oxidizer tank cooled, the calculations for the thrust need to be adjusted for the correct environmental temperature and pressure within the oxidizer tank.

When it comes to the calculations pertaining to the heat transfer into the combustion chamber housing, those calculations performed should still be correct and had been performed with a great degree of accuracy for both tests. Improvements to be undertaken would be to refine the Excel spreadsheet used to perform the calculation to be a better use of the capabilities of Excel. In the current state, the heat transfer calculations are very time consuming and involve a great deal of hand calculation in order to get the correct variable values to perform the desired heat transfer calculations with accuracy. This could be refined by making the spreadsheet to include the published variables and the values found through linear interpolation. If the spreadsheet is made to include those values in addition to the heat transfer calculations themselves, it would greatly increase the speed of the calculations as well as reduce the capabilities for human error in the calculations by reducing much of the work needed to generate the correct values.

The combustion chamber itself worked as intended and survived a critical failure as well as multiple tests with combustion. The collected data from the successful tests prove that the temperature and thus the pressure within the combustion chamber were lower than anticipated, but with the calculations already performed with the very large safety factors on the combustion chamber housing, the chamber itself does not need any further
adjustment for a project with the goal of 100 lbs of thrust. Should a higher thrust goal be set, then the combustion chamber should be reevaluated for safety at the higher pressures and temperatures anticipated for those conditions. The calculations performed for the combustion chamber housing itself are also fairly easy to adjust and perform should loading conditions change. When it comes to the combustion chamber housing itself, it is exactly the way that this team wants it to be, functional and safe to use for multiple tests.

3.2 Attaching the Thermocouples to the Housing

There are many ways to attach the thermocouple to the housing, where a total of six different methods were common. The first is using cyanoacrylate (super glue) due to its ease of application that hardens quickly, easily removable, and its availability. However, super glue is not made to withstand high temperatures and will tend to evaporate. Additionally, cyanoacrylate is a good insulator and can suppress temperature values. The second option is using UV cure epoxy, which is good for long-term use, cures in 10 seconds, able to attach to metals, and does not require heating to cure. However, UV cure epoxy requires a UV light source, and will be difficult to remove without damaging the thermocouple. The third option is using Epoxy air-cured, which is also good for long-term use, and can be attached to metals. On the other hand, a proper cure can take hours, and can damage the thermocouple when removed.

The fourth option is a high-temperature solder, which is a great option for long term use and can be accurate enough to stick to small components. Nonetheless, a high-temperature solder can affect solder joint alloy composition, is expensive, and requires soldering skills. The fifth option is using Kapton tape, which is easy to attach and
remove without damaging the thermocouple, low cost, and allows for accurate placement of the thermocouple. However, Kapton tape can be unstable and lift when heated. Yet, Kapton tape can act as a thermal insulator and will affect the reading of the thermocouple. The sixth option is using Aluminum foil tape, which is also easy to attach and remove without damaging the thermocouple, low cost, stable for long term use, and is accurate enough to attach to small components. The only issue with using Aluminum foil tape is that it is not transparent, thus the exact position of the thermocouple will not be known.

Considering all the options, it was decided that Aluminum foil tape would be a great attachment method due to its thermal conductivity and ease of attachment. The thermocouple will be attached to the external surface of the housing chamber using Aluminum Foil Tape. Moreover, the reading of the thermocouple on the surface of the combustion chamber will be used to calculate the temperature inside the chamber using the thermal properties of the Aluminum 6061-T6 pipe and phenolic liner. Moreover, Kapton tape will be used to tape over the Aluminum tape to insulate it from the surroundings to ensure a more accurate reading on the surface, and to improve adhesion.

3.3 O-ring Seals

The oxidizer cap and nozzle are sealed to the combustion chamber using ¼” PTFE O-rings with an inner diameter of 2.5”. The O-ring material was chosen to be PTFE since it has the highest operating temperature range out of all the available O-ring materials. PTFE O-rings are more firm than traditional rubber O-rings and for this reason the O-rings will have to be resized during their mounting process. This means that in order to get the
O-rings into their groove they need to be stretched out and then once they are in the groove they need to be shrunk back down to their original size. To do this the O-rings will be soaked in hot water and then stretched by being pushed down a conical shape. The O-rings will then be placed in the groove and shrunk back down to size using a band clamp. These O-rings will be seated in square grooves cut into the nozzle and oxidizer cap. These grooves were sized appropriately using the Parker O-rings handbook. Due to the heat generated during each test the O-rings plastically deform and take on the square geometry of the groove they are seated in. Even though the O-rings are now square and not round they do still create a strong enough seal for more tests to be performed. For this reason multiple tests can be performed on the same day without having to disassemble the motor and replace the O-rings. However the O-rings were replaced after the first test in order to eliminate points of failure for the second test. Going forward the O-rings should be replaced after each testing phase. PTFE is a thermoplastic and thermoplastics become brittle if they are exposed to high temperatures over a long period of time. Therefore several tests can be performed in the same day without replacing the O-rings since they still retain the proper modulus of elasticity but if the same O-rings are exposed to high temperatures over a long period of time, for example several different testing phases, their modulus of elasticity will drop causing them to become brittle and allowing for failure. It is probable that a set of O-rings could survive several testing phases but at some point they will become brittle and allow for failure which could be extremely dangerous. Therefore in the pursuit of safe and successful tests the O-rings must be replaced after each testing phase.
3.4 Clamping System

The oxidizer system and nozzle are attached to the combustion chamber using a clamping system. This system is composed of 2 end plates which go over the top of the oxidizer system and nozzle and then are held together by 4 ¾" all-thread rods. The end plate that goes over the oxidizer system actually sits on top of the transitional manifold and bolts to the oxidizer cap adding reinforcement to the manifold and centering the plate over the motor assembly. The end plate that goes over the nozzle has a hole through the center so as not to restrict any flow through the nozzle. Although this clamping system will not be easy to implement into an airframe it will securely hold the motor assembly together for testing and allow for easy and quick disassembly for troubleshooting purposes. The clamping system also adds a level of safety when testing since it helps contain any possible projectiles in the event of an explosion; during the first hot test the clamping system did just that.

During the first hot test that was performed the nozzle was blown apart and shot out of the combustion chamber along with some phenolic liner. If there hadn't been an endplate over the nozzle end of the combustion chamber the nozzle pieces, phenolic liner pieces, and probably the entire fuel grain would have been launched high up into the air and had the possibility of traveling enough distance to reach members of the team and fire department seated 200 feet away from the motor. However since there was a clamping system implemented the fuel grain and majority of the phenolic liner were contained in the combustion chamber. The pieces of graphite from the nozzle and some phenolic liner pieces
were blown out of the combustion chamber but were kept from going high up into the air by the end plate and were dispersed horizontally at the top of the motor traveling less than 50 feet from the motor. Some very small pieces of graphite and phenolic liner were able to make it through the hole in the end plate and did land close to the team and fire department but these pieces were small enough and light enough to not cause any damage to anyone or pose any threats to our safety.

Looking forward as more iterations of this motor are made and it is implemented into an airframe the clamping system should still be used to add safety and easy assembly. However the clamping system will need to be modified to be implemented into an airframe seeing as it is currently too bulky to be fitted into one. One possible solution would be to make the end plates out of thicker high grade aluminum to reduce weight along with manufacturing them as a circle instead of a square to allow for more clearance. The all-thread rods could be sized down from \( \frac{3}{4}'' \) to \( \frac{1}{2}'' \) or smaller and then more rods could be used to still retain the same amount of strength in the connecting rods while allowing for more clearance and an overall slimmer profile.

### 3.5 Ignition System

The ignition system has had a design change from making the DAQ system much simpler. The initial design was going to use an arduino to trigger a relay which would complete a circuit with a battery. This was changed to a manual switch design using a key switch and a button in-line with the igniter itself. This is a much more robust ignition system and reduces the points of ignition failure due to its simplicity. A few tests were run on the igniters to see what is required to light the fuel. Test #1 was with no pyrogen or fuel
sample. The igniter activated with just a simple AA battery. Test #2 was with pyrogen. The igniter had enough energy to ignite the pyrogen and created a bright flame that lasted about one second. Test #3 was with pyrogen and a fuel sample. The pyrogen was lit but did not light the fuel. However there were indicators that the fuel began to melt. The consensus was there was not enough pressure created by the pyrogen because it was exposed to the open air; this also caused most of the energy to dissipate into the air instead of heating the fuel. During the actual static fire the conditions the fuel will be under will be vastly different. The fuel will be completely encased in aluminum, the pressure can only escape through a small nozzle, and there will be a constant stream of oxidizer flowing across the pyrogen keeping the flame lit. The only way to test the igniter completely is during the static fire.

Figure 3.5: Ignition System Test Using Pyrogen and Fuel Sample
Chapter 4: Test Stand and Data Acquisition

4.1 Test Stand Design and Force Data Acquisition

The test stand has gone through numerous design changes to accommodate several different testing methods. After exploring several different designs and testing orientations the first test stand iteration was built at the end of the 2019/2020 school year. This iteration was built to accommodate a vertical testing orientation. Due to this, the load cell will be mounted horizontally allowing the rocket engine to be bolted directly to it. The load cell will be wired to an AI-1000 single channel conditioner; this is due to the load cell signal output not being large enough to be picked up by a microcontroller. The conditioner will amplify the signal to a readable voltage as well as reduce noise in the signal itself. Calibration of the load cell will be completed when it is mounted to the testing stand. This is to reduce any complications with the calibration process. The engine will be mounted onto the load cell, then a 100lb weight will be rested on top of the mount as well. This is due to the signal conditioner needing a max load applied in order to calibrate the sensitivity.

4.2 Thermocouple Data Acquisition

A K-type thermocouple will be used to measure the temperature inside the combustion chamber. The thermocouple will be connected to a Teensy microcontroller using an amplifier. It was decided to use the MAX6675 micro controller. The MAX6675 amplifier was chosen due to its built in cold junction compensation function and has a temperature reading range from 0 °C to 1025 °C. The MAX6675 does a direct digital conversion of a K-type thermocouple signal and outputs the data in a 12 bit resolution.
(0.25 °C). In addition, the MAX6675 has an accuracy of 8 LSBs which equates to around ±2°C. However, the MAX6675 has an error of ±3°C from the cold junction compensation, which means that the MAX6675 when combined with the K-type thermocouple has a total accuracy of around ±5°C.

A data acquisition test was conducted with the thermocouple using an Arduino Uno microcontroller. The results were compared to readings from a Digital Thermometer with an accuracy of ±1°C and a K-type Dual Digital Fahrenheit LED Display Thermometer. The test was conducted at three different temperatures; room temperature, cold water, and hot water. The microcontroller gathered data from the thermocouple for a time frame of six seconds at an interval of 0.2 seconds for each test, where the collected data was averaged. The microcontroller showed readings in both Fahrenheit and Celsius, a copy of the code used can be seen in Appendix.B.

The data collected at room temperature showed an average temperature of 25.51 °C equal to 77.91 °F that can be seen in Table 4.2.1 below. Compared to a reading from the Dual Digital Fahrenheit LED Display Thermometer at 77 °F.

Table 4.2.1: Room Temperature Test

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
<th>Time (s)</th>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.75</td>
<td>78.35</td>
<td>3.2</td>
<td>25.75</td>
<td>78.35</td>
</tr>
<tr>
<td>0.2</td>
<td>25.5</td>
<td>77.9</td>
<td>3.4</td>
<td>25.25</td>
<td>77.45</td>
</tr>
<tr>
<td>0.4</td>
<td>25</td>
<td>77</td>
<td>3.6</td>
<td>25.5</td>
<td>77.9</td>
</tr>
<tr>
<td>0.6</td>
<td>25.75</td>
<td>78.35</td>
<td>3.8</td>
<td>25</td>
<td>77</td>
</tr>
<tr>
<td>0.8</td>
<td>25.5</td>
<td>77.9</td>
<td>4</td>
<td>26</td>
<td>78.8</td>
</tr>
</tbody>
</table>
The data collected in cold water showed an average temperature of 4.16 °C and 39.49 °F that can be seen in Table.4.2.2 below. Compared to a reading from the Dual Digital Fahrenheit LED Display Thermometer at 34.9 °F and readings from the digital thermometer at 1.5 °C and 34.7 °F.

**Table.4.2.2: Cold Water Test**

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
</tr>
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<tr>
<td>0</td>
<td>3.75</td>
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<td>0.2</td>
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<td>39.2</td>
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<td>4.5</td>
<td>40.1</td>
<td>0.6</td>
<td>4</td>
<td>39.2</td>
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<td>0.6</td>
<td>4.5</td>
<td>40.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average:

\[
\text{Temperature (°C)} = 25.51 \\
\text{Temperature (°F)} = 77.91
\]
The data collected in hot water showed an average temperature of 92.90 °C and 199.21 °F that can be seen in Table 4.2.3 below. Compared to a reading from the Dual Digital Fahrenheit LED Display Thermometer at 195 °F and readings from the digital thermometer at 91.2 °C and 196.2 °F.

**Table 4.2.3: Hot Water Test**

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>93.25</td>
<td>199.85</td>
<td>3.2</td>
<td>92.5</td>
<td>198.5</td>
</tr>
<tr>
<td>0.2</td>
<td>93.5</td>
<td>200.3</td>
<td>3.4</td>
<td>92.25</td>
<td>198.05</td>
</tr>
<tr>
<td>0.4</td>
<td>93</td>
<td>199.4</td>
<td>3.6</td>
<td>92.5</td>
<td>198.5</td>
</tr>
</tbody>
</table>


<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>92.75</td>
<td>198.95</td>
<td>3.8</td>
<td>92.5</td>
<td>198.5</td>
</tr>
<tr>
<td>0.8</td>
<td>93.25</td>
<td>199.85</td>
<td>4</td>
<td>92.75</td>
<td>198.95</td>
</tr>
<tr>
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<td>93.25</td>
<td>199.85</td>
<td>4.2</td>
<td>93</td>
<td>199.4</td>
</tr>
<tr>
<td>1.2</td>
<td>93.5</td>
<td>200.3</td>
<td>4.4</td>
<td>93</td>
<td>199.4</td>
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<tr>
<td>1.4</td>
<td>92.75</td>
<td>198.95</td>
<td>4.6</td>
<td>93</td>
<td>199.4</td>
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<td>93</td>
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<td>199.85</td>
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<td>198.95</td>
<td>5.2</td>
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<td>199.85</td>
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<td>93</td>
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<td>5.6</td>
<td>92.25</td>
<td>198.05</td>
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<td>92.5</td>
<td>198.5</td>
<td>5.8</td>
<td>93</td>
<td>199.4</td>
</tr>
<tr>
<td>2.8</td>
<td>93</td>
<td>199.4</td>
<td>6</td>
<td>92.5</td>
<td>198.5</td>
</tr>
<tr>
<td>3</td>
<td>92.75</td>
<td>198.95</td>
<td><strong>Average</strong></td>
<td>92.90</td>
<td>199.21</td>
</tr>
</tbody>
</table>

Overall, when comparing the temperature collected from all three devices, the temperature differences between them are lower than 5 °C. Hence, a successful test of the thermocouple. In other words, when recording data during the final testing of the hybrid rocket engine, the thermocouple will be able to successfully record data with an accuracy of ±5 °C. Additionally, it was found that the microcontroller will only be able to take a reading every 0.2 seconds, otherwise it will fail and record a constant temperature.
4.3 Pressure Transducer Data Acquisition

Two pressure transducers were integrated into the oxidizer feed system piping, the pressure transducers chosen for this application were IIL 1000 PSI pressure transducers. These were chosen because they are rated to well above the oxidizer pressure, are inexpensive, and they are capable of measuring pressures down to a temperature of -20C. Both pressure transducers were tested and calibrated during the cold firing test up to a pressure of 750 PSI. The data acquired from the pressure transducers showed an average loss of approximately 58 PSI, this can be compared against the loss calculations performed in order to test the accuracy of our calculations and observe the real world losses produced in the feed system.
Chapter 5: Avionics

5.1 Avionics Module

The avionics module’s primary function is to house the electronics and data control elements of the rocket motor. In its current iteration this includes a battery, microcontrollers, an analog-to-digital converter, buck converters, with external ports to run wires to/from the DAQ devices and the hot-fire control box. Since the current iteration of the avionics module was designed solely to fulfill the needs of a hot-fire test of the motor, multiple design options were considered, but ultimately one was chosen that was most adaptable to the future needs of the project.

Initially, producing a simple rectangular box with internal mounting systems for each electronic element being used was considered. Although this could have satisfied the requirements of the hot-fire test, it would not be adaptable into a version that could eventually be integrated within a full airframe. That future consideration became the driving factor behind the geometry and organization of the current avionics module design. The module has an outer diameter of 6” and an overall length of 20”, which was needed to house all electronic components. The entire module is held together by four ¾” threaded rods and eight ¾” hex nuts that are tightened against the end caps. Internally, custom mounting plates have been made for each electronic component so that these components are secure, and each plate is mounted within the module in a vertical orientation. The plates are positioned centrally within the module by using the threaded rods as guides for each plate. Each plate is held in place along the threaded rods by #6 O-rings that prevent the plate from moving in the vertical direction. Enough space has been left between the
outer casing, which has an internal diameter of 5.75", and the electronic plates so that wires can be run from element to element within the module. The end caps also have ports at their center so that wires can be run to/from the rocket motor DAQ elements and the hot-fire control box. In addition, a test fire stand has been designed and created so that the module can sit stably in a vertical orientation on the ground next to the rocket motor during the hot-fire test. See figure 7.3.1 below for the current assembly of the avionics module with and without the test fire stand.

Figure 5.1.1: (a) Avionics Module Assembly with Test Stand (b) Avionics Module Assembly without Test Stand
Additive manufacturing was the main process for creating the avionics module due to the benefits of rapid prototyping, quick design iterations, the ability to design and manufacture unique geometries, and the ease of production. The Prusa i3 MK3 was used for creating these parts, and these printers are located in the Electronics and Maintenance Laboratory in North Classroom. These printers use both PLA and PETG feedstock, and this allowed for the creation of parts in a timely and cost effective manner. The benefit to using these printers is the method of rapid prototyping where prototypes were manufactured using a low infill density ranging from 5-10%, and a slightly higher resolution (layer height) of 0.3 mm. This allowed for prototypes to be created using as little filament as possible, in as short of time possible, while maintaining the integrity of each part for test fitting. Final iterations of these prototypes were then printed at a range of infill densities which were specific to their application in the module. A 0.2 mm resolution was used for all parts which enhanced the quality of the final parts. Some of these parts had to be reprinted due to poor bed adhesion which caused the first print to fail, or due to warping from the print bed which caused misshapen parts. Other parts needed to be reprinted due to modifications of the design after they were test-fitted to the module. In order to combat the warping and bed adhesion issues, Dimafix was applied to the print beds prior to printing. Each final iteration was tested in the module prior to final assembly to ensure the final iterations were sufficient. Table 5.1 below exemplifies the properties and specifications used for each part’s final iteration. The total amount of filament used for these final iterations is as follows: PLA was 229.7 m; PETG was 92.68 m. Figure 5.1.2 is of the test stand mid print. This shows the infill density of 20% with a gyroid infill pattern. Gyroid infill was used for manufacturing
all parts due to it’s high shear strength and low weight. This means parts were overall much more resistant to bending stresses and each part required less filament to produce.

Table 5.1: Avionics Module Parts List

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Quantity</th>
<th>Resolution [mm]</th>
<th>Filament type</th>
<th>Support Needed</th>
<th>Infill [%]</th>
<th>Infill Pattern</th>
<th>Filament Used Per Part [m]</th>
<th>Total Filament Used [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EndCap</td>
<td>2</td>
<td>0.2</td>
<td>PETG</td>
<td>No</td>
<td>25</td>
<td>Gyroid</td>
<td>46.34</td>
<td>92.68</td>
</tr>
<tr>
<td>Test Stand</td>
<td>1</td>
<td>0.2</td>
<td>PLA</td>
<td>No</td>
<td>20</td>
<td>Gyroid</td>
<td>135.65</td>
<td>135.65</td>
</tr>
<tr>
<td>Al1000 Plate</td>
<td>1</td>
<td>0.2</td>
<td>PLA</td>
<td>No</td>
<td>25</td>
<td>Gyroid</td>
<td>16.21</td>
<td>16.21</td>
</tr>
<tr>
<td>Battery Bottom</td>
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<td>0.2</td>
<td>PLA</td>
<td>No</td>
<td>25</td>
<td>Gyroid</td>
<td>15.72</td>
<td>15.72</td>
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<tr>
<td>Battery Top</td>
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<td>0.2</td>
<td>PLA</td>
<td>No</td>
<td>25</td>
<td>Gyroid</td>
<td>14.54</td>
<td>14.54</td>
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<tr>
<td>Battery Vertical</td>
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<td>0.2</td>
<td>PLA</td>
<td>Yes</td>
<td>25</td>
<td>Gyroid</td>
<td>18.09</td>
<td>18.09</td>
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<td>Rasp Pi Plate</td>
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<td>Teensy Plate</td>
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<td>Yes</td>
<td>25</td>
<td>Gyroid</td>
<td>15.99</td>
<td>15.99</td>
</tr>
</tbody>
</table>
Figure 5.1.2: Test Stand Mid Print

Given that the current iteration of the avionics module will not be subjected to any significant forces, materials were chosen that would allow for quick prototyping and ease of production. All internal component plates and the test fire stand were made of PLA, whereas the end caps were made of PETG, with a clear acrylic outer casing. PETG was chosen for the external end caps, as it provides better thermal properties as well as higher impact and chemical resistance when compared to PLA (Redwood, Schöffer, Garret, & Fadell 2018). The internal component plates were made out of PLA, as they will not be subject to
significant external forces or conditions. The difference between internal and external component materials also allowed the team to observe the difference in additive manufacturing qualities of PLA and PETG filaments. The outer casing’s material was chosen to allow the team to monitor the internal components during the assembly of the module and throughout the hot-fire test setup to ensure electronic components are wired and connected properly.

As highlighted earlier, the avionics module’s current design was pursued with the future of the project in mind. It’s current geometry and layout allows for it to be adapted into an airframe, which is slated as a goal for future iterations of the team. Some future considerations of the avionics module will include mechanical design considerations for significant forces experienced within the rocket airframe, space consolidation for electronic components/power supply elements, inclusion of additional components such as altimeters/accelerometers and vehicle stage separation charges, and the overall weight which will affect the center of gravity of the rocket. The current iteration provides a solid foundation for future adaptations and gives the team a good idea of what design choices can be carried into the future iterations of the module. This includes test phases of a larger rocket motor, as well as, the final construction of a fully functioning rocket.
Chapter 6: Manufacturing

6.1 Oxidizer Cap

The oxidizer cap was manufactured out of aluminum round stock using a lathe. The inner geometry of the cap that houses the injector was machined first. Next the outer diameter of the top of the cap was machined and then the workpiece was flipped 180 degrees in the lathe’s chuck. Then the sloped inner portion of the cap that would be in the combustion chamber was machined out. Lastly the outer diameter of the cap that would be inserted into the combustion chamber was machined and the grooves for the O-rings were cut into it. Then the workpiece was taken out of the lathe and setup in the mill and the 8 holes for the ⅜” oxidizer cap bolts were drilled out and tapped for UNC.

Figure 6.1: Oxidizer Cap
6.2 Injector

The Injector was manufactured out of aluminum round stock using a lathe. The outside geometry of the injector that sits in the oxidizer cap was machined first. Next was the center drill so that the smaller diameter of the injector could be drilled all the way through. After the center drill and the smaller diameter were added, the larger inner diameter of the injector was drilled. To finish the part, the stock that was holding the injector in the lathe was removed and then a burr remover was used to soften the edges of the piece.

Figure 6.2: Injector
6.3 Transitional Manifold

The transitional manifold was manufactured out of aluminum round stock using a lathe. The outer geometry of the transitional manifold was machined first. After the outer diameter of the transitional manifold was machined, we wrote a program in the lathe to add the ½” NPT threads that will connect the feed system to the transitional manifold. To finish the part, the stock that was holding the transitional manifold in the lathe was removed and the part was brought to the mill to have the 8 holes center drilled and then drilled with a ⅜” bit. Then a burr remover was used to soften the edges of the piece.

*Figure 6.3: Transitional Manifold*
6.4 Feed System

The parts that needed to be manufactured for the feed system were two ½” NPT pipes with ⅛” NPT taps for the pressure transducers. These pipes were made by ordering the correct length ½” NPT pipes and then adding the ⅛” NPT tap to them. This was done by drilling and tapping a 1 inch long ½” piece of steel round stock to ⅛” NPT. Once this was done the piece was tig welded to the side of the ½” NPT pipe and a ¼” hole was drilled in the center of the pipe where the piece had been welded. This gave us two ⅛” NPT taps for our pressure transducers that could withstand higher pressures.

Additionally, a mounting system was designed for the ball valve with an adapter that attaches it to the servo motor. It was decided to design a two part mounting system and a one part adapter. The design was manufactured using additive manufacturing methods by 3D printing the design. A picture of a prototype printed in PLA filament can be seen in Figure 6.4, and engineering drawings of the design can be found in Appendix A. The prototype was tested to ensure it will be able to open and close the ball valve, which was achieved. The design will be mounted together using brass heat inserts and M4x25mm screws. At the same time, the adapter will be attached to the servo motor using servo horns, and to the ball valve using Nylon locking nuts. Moreover, it was decided to print the two part mounting system using a Fused Deposition Modeling (FDM) printer with PETG as the filament, with print setting of 25% infill and 0.2 mm resolution. However, it was decided to use a metal printer for the adapter to ensure it is robust and able to withstand the forces applied to it. The adapter will be printed using a Selective Laser Melting printer with Aluminum 6061 as the metal powder.
6.5 Nozzle

Most high power hybrid rocket nozzles are made from graphite, because it can be machined to close tolerance, it has a low thermal conductivity, the material has excellent heat conductor, great resistance to thermal shock, and has a high corrosion resistance properties.

Figure 6.4: Ball Valve and Servo Motor Mounting

Figure 6.5.1: Manufacturing Nozzle with a Trak’s Lathe
The nozzle shown in Figure 6.5.1, was made from a graphite stock. Graphite is made from ceramic, which is soft, abrasive, and brittle in nature. Hence, processing the nozzle from it required time, technical know-how, right feed and speed system technique during machining to avoid chipping, rapture and breakage.

**Table 6.5: Machining process for the Nozzle**

<table>
<thead>
<tr>
<th>Section</th>
<th>Machine/Tool</th>
<th>References/ Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal length</td>
<td>Bandsaw</td>
<td>Initial length cut</td>
</tr>
<tr>
<td>External O-rings size</td>
<td>Lathe, pathing Tool</td>
<td>Slower RPM</td>
</tr>
<tr>
<td>Center hole</td>
<td>Center Drill</td>
<td>Prior to drilling actual hole</td>
</tr>
<tr>
<td>Outer Diameter Throat hole</td>
<td>11/32 drill bit</td>
<td>Introduce the throat hole</td>
</tr>
<tr>
<td>Throat hole</td>
<td>35/64 drill bit</td>
<td>Introducing the nominal throat OD.</td>
</tr>
<tr>
<td>Diverging angle at 45°</td>
<td>⅛ carbide tip</td>
<td>Introduce first face angle</td>
</tr>
<tr>
<td>Converging angle at 15°</td>
<td>⅛ carbide tip</td>
<td>Introduce second face angle</td>
</tr>
<tr>
<td>Actual OD</td>
<td>Facing tool</td>
<td>Specific diameter</td>
</tr>
<tr>
<td>Smooth finish</td>
<td>Slower RPM and sanding</td>
<td>Sanding machine, hand surface polish</td>
</tr>
<tr>
<td>Actual nozzle length</td>
<td>Lathe, parting tool</td>
<td>Cut stock piece to specific nozzle length</td>
</tr>
</tbody>
</table>
Table 8.5, shows the process used to machine a 3 inch diameter graphite with a 1.88 inches in length stock piece with a Trak’s lathe. The initial length of the graphite was cut using a bandsaw which was slightly longer than the actual length to give room for excess graphite to hold the material in the chuck safely while turning, parting the grooves, and also being able for facing each ends of the piece to provide adequate clearance during the machining process.

Since the process of machining the graphite was messy, dusty and can be toxic, the following proper safety precautions were taken into consideration; the handling was done using latex gloves to prevent cross contamination throughout the shop. The use of eye protection safety goggles was imperative for general machine purposes. Another important safety precaution taken was the use of a mask and or respirator to prevent the inhalation of any graphite particles. Finally, because graphite sticks to almost anything, a vacuum was positioned close enough to suck-up dust and also to contain any chipping particles from getting inside the lathe’s motor in order to avoid any unforeseen electrical discharges because graphite particles easily conduct electricity. Due to the brittle nature of the graphite, a 330 RMP was used throughout the machining process to prevent chipping and unwanted cracks and also to produce a smooth finish.

The rod was secured in the chuck of the lathe with one faced end turned until the O-rings grooves were done. The grooves must be deep so that the rings fit securely enough to slide into the aluminum motor tube. The O-rings are an important part of the graphite machining because the rings need to form a seal between the nozzle and the combustion
chamber tube. A center drill bit was used to mark the center of the nozzle with the help of a pilot hole. The diverging face angle of 45 degrees was machined using a boring bar and compound angle set to make that cavity. The process used to cut the converging angle of the graphite was identical to the process of cutting the divergent end side of the stock. It was a good idea to use 4 pieces of metal sheet to fit in between the chuck grip and the rod to prevent indentation, chipping and cracking since graphite is brittle and fragile as shown in Figure 6.5.2.

![Machined Graphite Nozzle to Specification](image)

*Figure 6.5.2: Machined Graphite Nozzle to Specification*

The nozzle failed massively during the first test, which led to it being disintegrated because there were Nitrous oxide gases escaping throughout the system that led to over pressurizing. This in turn, caused the phenolic liner and the solid fuel to be ejected upwards against the retention plates by crashing the graphite into pieces and smoke. Since then, the nozzle has been redesigned by changing the diameter from 3.00 inches to 2.75 inches to accommodate the phenolic liner to protect the O-ring sealings and the retention plate that
were at a higher risk of failure due to over pressurizing and the temperatures created by combustion gases from the Nitrous oxide and the solid fuel.

### 6.6 Fuel Grain

**Table 6.6.1: ABS required Dimension**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>16</td>
<td>2.55</td>
<td>0.593</td>
</tr>
</tbody>
</table>

**Table 6.6.2: ABS machining process**

<table>
<thead>
<tr>
<th>Section</th>
<th>Machine/ Tool</th>
<th>References/ Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Length</td>
<td>Bandsaw</td>
<td>Cut initial length</td>
</tr>
<tr>
<td>Center hole</td>
<td>Vectrax Mill, Center Drill</td>
<td>Prior to drilling actual hole</td>
</tr>
<tr>
<td>Front face side Diameter</td>
<td>Vectrax Mill,16/32 drill bit</td>
<td>Introduce the first half diameter</td>
</tr>
<tr>
<td>End face side Diameter</td>
<td>Same as front face side diameter</td>
<td>Same process</td>
</tr>
<tr>
<td>Actual Diameter</td>
<td>Inner Diameter</td>
<td>Vectrax Mill, 19/32 drill bit</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Actual outer Diameter</td>
<td>Lathe, Turning tool</td>
<td>Shaving of the excess from stock</td>
</tr>
<tr>
<td>Actual length</td>
<td>Vectrax Mill, milling bit</td>
<td>Milled to actual length</td>
</tr>
</tbody>
</table>

Table 6.6.1 shows the required final dimension for the solid fuel and Table 6.6.2 was used as a reference for the machining operation of the ABS rod.

![Bandsaw cutting ABS Rod to be machined](image)

**Figure 6.6.1: Bandsaw cutting ABS Rod to be machined**

A bandsaw was used to cut the ABS material of length 17 inches from a stock of 3 feet because it is a fairly good machine for cutting plastics without splitting the stock. Also, the saw allows versatile application for straight continuous cut and the heat usually generated by the saw is proportionally dissipated due to the long saw blade as shown in Figure 6.6.1.
For the most part, ABS is not as dangerous to work with since the particulates created have low weight and velocity, their impact resistance is less of a concern during turning, cutting, shaving, and milling. Hence regular safety goggles worked fine during the machining operation. When drilling holes in ABS plastic, an appropriate method for such material is crucial in order to avoid defects, danger of breakages, tearing up, overheating and any dimensional deviations to the inner hole. Such machining operations deserves a lot of time, and attention must be paid to heat buildup, size deviations due to inner expansion as a result of excess heating from drilling, so slower RPM was used. This expansion process can also lead to compressive stress inside the rod, high level of warping, cracks, fractures, dimensional errors and bursting open of the ABS stock.

A pre-drilling diameter was selected for initial drilling for the center of the rod to be punched, then, pilot drilled with a 3 mm drill bit after that a bilateral drilling was introduced using 16/32 inch drill bits starting from one side which meet in the midway of the ABS rod. The bilateral drilling process can cause unfavorable deviations in the diameter.
of the hole size inside the rod as each face drilling meets. Therefore the same drilling
process was repeated for the opposite end of the rod to obtain a uniform size from both
ends. Finally, the hole size was further expanded by using a standard jobber drill bit of
19/32 to drill the required inner diameter of 0.5938 inches into the ABS rod.

Clearly, adjustment had to be made by rotating the Vectrax mill to a horizontal axis
in order to drill the inner diameter hole through the ABS plastic, since the required final
length of 16 inches of the material was too long to fit into the mill vertically. Because of the
adjustment made to the mill, additional support material and mounting fixtures had to be
used to secure and clamp the ABS material down firmly enough to avoid movement,
internal deflection, vibration and deformation while drilling the holes through and milling
off excess material as shown in Figure 6.6.2. 1/2 inch excess ABS was left on both ends,
since it was necessary to accommodate the internal hole to be chamfered to make room
for the internal hole to be plugged at each chucked end of the lathe during machining to
achieve accurate dimension within tolerance and also to avoid chipping. Another difficulty
encountered was the length of the jobber drill bits, which was not long enough to drill the
inner diameter even up to halfway of the ABS rod, therefore, an extension rod was welded
to the 19/32 drill bit to drill the required length of hole.
Although, coolants are not typically necessary for thermoplastics machining operations, in our case water-soluble coolants was necessary during the drilling process using the mill to prevent burning and gumming-up inside of the rod due to excess heat generated, especially, when the depth of the inner diameter is more than that of itself. Furthermore, peck drilling techniques (i.e. that is frequent pull out of the drill bits from the rod) in conjunction with the coolant were used to reduce heat and to aid in the removal of particulate since the drilling hole length is deep.

In Figure 6.6.3, the ABS rod is placed on a lathe machine to turn. The turning process of the ABS was to reduce the ABS material from 3 inch diameter to 2.55 inches outer diameter by shaving off excess material of the rod to obtain the desired shape and length.

6.7 Phenolic Liner

The phenolic liner that was ordered already was the correct diameter and thickness so all that needed to be done was to cut it to the right length. This was done using a horizontal band saw.
6.8 Clamping System

The clamping system consists of 2 different end plates and 4 sections of \( \frac{3}{4}'' \) UNC all-thread rod. The all-thread rod was ordered in two 10 foot sections and both sections were cut in half to yield 4 sections of all-thread rod. Both end plates were machined out of \( \frac{1}{4}'' \) plate steel using a mill. The end plate that goes over the oxidizer assembly featured 8 more holes than the other end plate but the manufacturing process was very similar for both plates. The plates were cut to the correct size using the vertical band saw and then placed in the mill. Using the mill’s pocket feature with an end mill tool the holes in each plate were machined out.

6.9 Test Stand

This year it was decided that we would test the motor in the vertical position opposed to last year's strategy of testing the motor in the horizontal position. Because of this the test stand had to be altered but not scrapped. The original test stand was made out of 1” square tube steel and resembled a 3’x9” rectangle. To make this test stand fit our needs we welded two 2’ sections of square tube steel to each side to increase stability. Then the tube steel at the load cells mounting point was notched out on the bottom to ensure that the mounting bolt heads for the load cell would not stick out and the test stand could sit flat on the ground. Then the 4 6mm bolt holes for the load cell were drilled in that location.
6.10 Test Stand Adapter Plate

In order to attach the motor assembly to the load cell we used an adapter plate. The adapter plate bolted to the motor’s clamping system using the ¾” all-thread rod and then bolted to the end of the load cell that was not already attached to the test stand. The adapter plate was made from a ¼” steel plate by cutting several sections of the plate to the correct size and then mig welding them together in the proper orientation. Two gussets were added to the end of the plate that would attach to the load cell for added rigidity. During the welding process we encountered a lot of warping issues, fortunately we were able to bend back most of the warped parts and widen some holes in order to make the
adapter plate fit correctly. However if we were to repeat this process it would be smarter to create a jig to weld the adapter plate in so as to counteract any warping.

Figure 6.10: Test Stand Adapter Plate
Chapter 7: Test Plans

The team plans to obtain experimental data on the performance of the rocket engine through a series of static fire tests using the test stand the team has built. A cold flow test is planned to be conducted within the next week to analyze the functioning of the oxidizer subsystem. Shortly following the cold flow test, a hot fire test will take place, allowing the whole engine to be analyzed.

7.1 Cold Flow Test

A cold flow test is a key first test to ensure the rocket engine is ready to move on to a hot fire test. It examines how the oxidizer subsystem performs by testing the oxidizer subsystem without connecting the combustion chamber and nozzle. Specifically, it gives experimental data on the oxidizer, feed system, avionics, and the injector. There are several tangible objectives of the cold flow test. The first objective is to obtain an experimental value for the mass flow rate. This will be done by weighing the nitrous oxide tank before and after the test, as well as timing the test. Further, the test has a goal of allowing the team to identify the experimental value of the injector discharge coefficient, $C_d$. Additionally, the test will ensure the feed system’s servo motors and ball valves function correctly while under such high pressures. Finally, this test will allow the team to verify the avionics and the entire data acquisition system is well calibrated and overall working correctly. This will be a proof of concept for the software, hardware, and sensors involved in collecting data that are so crucial to this operation of understanding the performance of the hybrid rocket engine.
7.2 First Hot Fire Test

A hot fire test examines the performance of the entire rocket engine, with all of the subsystems involved. This test has the objective of analyzing the functioning of every component of the engine. The primary result obtained from the hot fire test is the thrust curve. This curve describes the thrust of the engine as a function of time. Additionally, the sensors will allow data to be collected that describes the combustion chamber pressure over time as well. This thrust curve is the most important data point for the test. It will verify whether the experimental values for the burn time, thrust peak and thrust curve, and the combustion chamber pressure resemble the theoretical values. Specifically, the success criteria entail a burn time of about 10 seconds, a thrust peak of 100 lbs of force, and a peak chamber pressure of 400 psi.

The first hot test was performed Saturday April 3rd at the Air and Space Port in Watkins, Colorado under the supervision of the Watkins Fire Department. The rocket motor was set up in the center of a large open parking lot and the Rocketlynx team and fire department stood 200 feet away from the motor. The weather on the day of testing was sunny and windy with temperatures around 40 degrees fahrenheit keeping the nitrous tank at a pressure of 750 psi. At the start of the test there was ignition and then an orange flame at least a foot long could be seen, in this flame there were at least four clear mach diamonds that could be observed as shown in figure 7.2.1(a). However after about one second the nozzle exploded producing a black cloud of graphite bits as shown in figure 7.2.1(b). The team then waited about 15 minutes before approaching the motor to assess the damage.
Originally it was planned to use pyrodex pellets to ignite the motor. However a few days prior to the first hot test there were concerns about whether the pyrodex pellets burned hot enough and long enough to ignite the nitrous and ABS. For this reason the team decided to use a C6-0 solid fuel Estes rocket motor as means of ignition. The Estes rocket motor was embedded into the fuel grain right by the injector. This was done by drilling a hole the size of the Estes rocket motor in the oxidizer cap end of the fuel grain just to the side of the fuel grain port. The Estes rocket motor was then placed into the hole and glued in place. The end result allowed for nitrous to flow through the port right to the side of the Estes rocket motor which can be observed in figure 7.2.2. The intention was for the Estes rocket motor to be pointing at the ABS to increase the chances of lighting it while also having room for nitrous to flow in and mix with the ABS during ignition. Since we were definitely able to achieve ignition this proved to be a smart decision.
In the first second of the launch at least 4 clear mach diamonds could be seen in the flame coming from the motor. This means that we achieved supersonic flow through our nozzle and the supersonic exhaust was slightly over-expanded. That means the static pressure of the exhaust coming out of the nozzle was less than the static pressure of the ambient air. This is not surprising to see at lower altitudes since the static pressure at low altitudes is relatively high. If this motor were implemented into an airframe and launched upwards as it climbs in altitude the static pressure of the ambient air would drop and eventually be equal to the static pressure of the exhaust exiting the nozzle which is ideal.
After one second there was an explosion of a black cloud at the nozzle end of the motor as seen in figure 7.2.4(a). This black cloud was actually small particles of graphite and phenolic liner being blown out of the combustion chamber. The largest pieces of graphite and phenolic liner we were able to find after the test were still no larger than 1” the biggest piece of graphite that was recovered is shown in figure 7.2.4(b).
Once the motor was disassembled we found no trace of the nozzle in the combustion chamber and the fuel grain had slid right up to the end plate at the nozzle end of the combustion chamber. In addition it was found that the phenolic liner had detached from the fuel grain and slid up the fuel grain towards the nozzle about a foot as seen in figure 7.2.5(a). This is why some phenolic liner pieces were blown out of the combustion chamber and the phenolic liner on the nozzle side of the fuel grain was cracked and breaking apart signaling that pieces had already been broken off of this end of the liner and ejected out of the combustion chamber. This cracked end of the phenolic liner is shown in figure 7.2.5(b). The side of the fuel grain facing the nozzle was very black with soot from the combustion and particles of graphite from the nozzle as shown in figure 7.2.5(c).
Figure 7.2.5: (a) Phenolic liner slid a foot up fuel grain  (b) Cracked phenolic liner on nozzle end  (c) Scared up fuel grain at nozzle end
There are two reasons for the explosion of the nozzle, the first being the nozzle’s design. The nozzle was designed and manufactured with a ¼” lip on the very end of it that butted up to the end of the combustion chamber. When the motor was fully assembled this lip was compressed between the end of the combustion chamber and the end plate of the clamping system. Upon ignition the entire motor assembly experiences very high pressures very quickly and wants to expand putting more pressure on the lip of the nozzle. This much pressure being exerted on a ¼” ring of graphite could cause it to crack and from there be blown out by the pressure inside the combustion chamber. This issue was corrected in the next iteration of the motor by removing the lip on the nozzle and installing it completely in the combustion chamber. The other reason for the nozzle’s explosion is the fuel grain sliding forward in the combustion chamber and smashing into it. The fuel grain is held in place in the combustion chamber by being glued to the phenolic liner which runs the entire length of the combustion chamber therefore fixing it in place. However since the phenolic line was found slid a foot or more up the fuel grain it is clear that the glue used to fix the two together failed. When the glue failed not only did the fuel grain slide forward but the phenolic liner cracked apart on one end allowing it to be blown out of the combustion chamber and slide forward as well. The glue that was used was silicon based and not meant to handle the high temperatures inside the combustion chamber. This issue was corrected by using a high heat application resin based glue called Cyanoacrylate in the next iteration of the motor.

7.3 Second Hot Fire Test
The second hot fire test happened on April 30th, 2021. With the new nozzle design and the improved glue for the fuel, this test was expected to go much longer. The data acquisition system became much more robust, we are able to connect and disconnect the battery and have the system record everything without being corrupted. We were able to do 9 attempts to ignite the rocket. The first attempt was an ignition failure, the C6-0 motor did not ignite due to either user error or due to a dud motor. Due to the dud motor we had to rely on Pyrodex pellets to ignite the engine. The timing on the Pyrodex was the biggest challenge that was faced while igniting the engine. Early ignition would make the pellets pop like a firecracker and shoot smoke out the top before the nitrous could decompose, late ignition meant the nitrous would push the pellets out the nozzle before they could ignite.

During the tests, the team noticed the nitrous tank was overpressurized 200 psi than what the injector was designed for. This caused a substantial increase in oxidizer mass flow through the combustion chamber. This caused the exit flame to be completely transparent apart from a few particles that were likely from the phenolic liner. Due to this anomaly, attempts 2 - 4 were actually successful ignitions, but without the knowledge of having a transparent flame the nitrous was promptly cut off. Attempts 4 - 7 were spent getting the ignition timing correct, and attempts 8 and 9 were successful 10 second burns.

Attempt 8 was a full throttle test, meaning the valve was to be fully open for the entire test. In the figure below it is apparent that the combustion was very lean leaving no visible combustion gases.
The theories the teams have are as follows: The over pressurized tank increased the O/F ratio so much that the burn was no longer in the efficient range we aimed for, thus the amount of fuel being burned was so little to the amount of oxidizer being supplied. Or the other theory is that due to the first igniter not properly igniting it became an obstruction in the port and shielded a portion of the fuel to the oxidizer further increasing the O/F ratio. Luckily these things can be dealt with in future tests fairly easily now. The results of this test can be seen below.
There is a clear correlation between the pressure through the feed system and thrust being generated. What was surprising to the team was the amount of effect the pressure has over
the burn profile of the solid fuel; a circular port is supposed to increase in thrust as the port grows but the pressure drop began to override that behaviour. This is most likely due to the length of the tests, if the burn were to continue for a more extended time while we had a constant pressure the thrust would have most likely started increasing.

For the next test the team wanted to experiment with the throttling capabilities. Once the engine was ignited the valve was opened and closed a couple of times to see if it stays running and see how it affected the thrust profile. The results can be seen below.

*Figure #: Attempt 9 Thrust Profile*
7.4 Areas of Concern

The thermocouples must be calibrated correctly to the ambient temperature to identify what temperature corresponds to a dangerous level of heat on the surface of the combustion chamber. This will require the temperature during the test to be monitored, ensuring the environmental temperature remains in the predicted range. An environmental temperature that is dangerous for the oxidizer, thermocouples, or any other component of the engine will cause the testing to be delayed and rescheduled.

A challenge last year’s team faced was igniting the solid fuel grain. An analysis of the problem concluded that the ignitor was unable to achieve enough heat to be effective in burning the HTPB. While trials have been conducted with the ABS solid fuel, demonstrating the team’s ignitor’s ability to burn the ABS, igniting the solid fuel grain remains a challenge.
due to the issue of timing. There are multiple approaches to ignition that are being considered, such as having the ignition occur various seconds prior to turning the valve, or simultaneous with opening the valve. The team will have to monitor the test of whether or not a successful ignition had taken place, as to minimize the amount of oxidizer wasted. The team plans to have replacement ignitors on hand and different timing planned if ignition fails. Analyzing the merits of different timings of ignition may be an item that is pursued with additional rounds of testing.

Another issue the team is keeping in mind is the composition of the nitrous oxide that is being used. The current nitrous oxide bottle is from an automotive fuel company. Automotive grade nitrous has hydrogen sulfide mixed in to give it a rotten egg smell, as a safety feature. This sort of nitrous oxide will likely serve the team’s testing purposes, but the team is open to switching to a more pure form of nitrous oxide. Depending on the performance of the nitrous, the automotive nitrous may be switched out for medical nitrous, which is 99.0% pure. Again, this is an area that will be analyzed post testing and may be pursued in future static tests.
Chapter 8: Design Modifications

8.1 Design Modifications

8.1.1 Transitional Manifold

Initially, there were suspicions that the manifold would fail and break during testing. However, after two iterations of testing the manifold stayed intact and worked as it should. The manifold had exceeded expectation and did not require any sealing, where eight holes for the bolts were enough to seal the transition from the feed system to the injector. In addition, the manifold remained in pristine condition after testing allowing it to be used for testing again if needed. It is not suggested to redesign or modify, since the manifold's design is purely based on the shape of the injector and feed system. If the injector or feed system was modified, then a redesign might be required. However, some modifications that could be considered include fillets or chamfers around the edges. In addition, a thicker manifold at the bottom, as in deeper holes for the bolts, could be useful and ensure a tougher manifold.

8.1.2 Servo Mounts

The servo mount design showed a promising result. The servo mount was able to work during testing with no failure during two testing iterations. When prototyping the servo mounts it was considered well designed with no noticeable issues. However, when connected to the servo controller during the first test iteration it was noticed that the connection between the servo motor and ball valve was slightly loose. In an effort to reduce slack some padding was added beneath the ball valve that helped achieve a more secure connection. Prior to the second test iteration the servo mounts excluding the adapter were
reprinted with reduced height to attempt a tighter connection. Although the slack was reduced by lowering the height, the connection was still slightly loose, and padding was still required beneath the ball valve to ensure a firm connection. Moreover, the hole sizes for the servo mounts were adjusted. Where four of the holes in the top plates were made larger to allow the screws to pass through smoothly. Additionally, two holes were made larger to allow brass heat insert to be added to the top plate. A modified engineering drawing can be found in Appendix A for the servo mounts that were used during the second test iteration.

For future consideration it is suggested prototyping the servo mount with multiple heights to find the height that ensures a tight connection. Otherwise, if the problem persisted a redesign of the base should be considered. Other than that, it is also suggested to reduce the size of the servo mounts, where the current design uses two thick support beams. It is suggested to consider reducing the thickness of the beams or using one support instead. Additionally, using metal printing for all parts can be beneficial where the mount will be able to withstand larger forces and will have a longer lifespan. On the other hand, the servo mount adapter worked perfectly with no noticeable issue where it is not suggested to redesign the metal printed part.

8.1.3 Feed System

The feed system performed successfully in both hot fire tests. This means that it worked at 750 PSI (as well as an overpressure of 900 PSI) with no system leaks and successfully delivered oxidizer to the combustion chamber. However, the feed system should be refined and redesigned for future iterations. The primary points of improvement are manual flow modulation precision, a fully automated firing system, and system
modularity and packaging capability. Manual flow modulation precision was poor; this was primarily as a result of large ball valves being used in the feed system, because the ball valves were oversized for our desired mass flow rate, throttling and modulating the flow of oxidizer was very difficult, this resulted in an "on" and "off" type behavior instead of a more linear response. As such I recommend a smaller valve is used, as well as an alternative valve type such as a butterfly valve, as this will provide a more linear throttling curve. Improving this will allow for thrust to be modulated accurately in the future. An automated control system should also be incorporated, this was roughly developed using a 3 stage temperature control system, but in the future this should be made a full control system with a feedback loop and continuous modulation of the oxidiser, this can also be further developed to incorporate predetermined thrust profiles using throttling of the control valve, a fully optimized version of this system should make manual flow modulation unnecessary. Lastly, feed system packaging should be modified in order to be better suited for use in a scale rocket fuselage, this could be done using AN nitrous lines and fittings as they are flexible and modular making them much more adaptable to a full rocket test in the future.

8.1.4 Injector

The injector performed very closely to how it was expected through the cold test and through the two hot tests. The desired mass flow rate that the injector was supposed to produce was 0.67 lb/s. During the cold flow test it was calculated to have a mass flow rate of about 0.3 lb/s. This result was expected due to the drop in pressure over time during the test. During the First hot test, no data was acquired but the rocket engine produced an
orange flame with mach diamonds which was a desired result. During the second test, the Nos tank was over pressurized and the flame produced was clear. This was not a desired result but with the over pressurized system there was a higher mass flow rate and therefore, the clear flame was expected.

The injector survived all three testing days and is still in great shape. It is recommended to reuse the injector in future years as it produced a mass flow rate that was very close to the desired mass flow rate. However, some assumptions could have been incorrect when calculating the orifices for the injector resulting in a slightly lower mass flow rate. If closer precision to the mass flow rate is desired for the system in future tests, it is recommended to recalculate both orifice diameters of the injector. It is not recommended to redesign the injector type as the conical spray and simple design proved effective in the tests.

8.1.5 Solid Fuel

After two testing iterations, the team has successfully demonstrated that ABS plastic as a solid fuel is a serious contender in terms of hybrid rocket engine. ABS plastic was used as the solid core of fuel that allows the Nitrous oxide to be pressurized through it. The NOX is usually in vaporized or gaseous form that covers the surface area of the ABS port, hence, the Solid fuel in the presence of the oxidizer can be ignited, thereby generating thrust propulsion. The heated ABS material starts to rapidly degrade through the formation of free radicals which occur through chemical decomposition of the material under the influence of the ignitor, which produces yellowish with blue edge flames along with acrid or rubbery odor.
Figure 8.1.4: Fuel Grain from Test 1

For the first test, the result was not perfect because the nozzle disintegrated and formed a big boom of flames and smoke, because the phenolic liner and the ABS rod ejected upwards against the retention plate after the glue became undone between the two components and also due to the system being over pressurized crashing the nozzle and cracking away some part of the Phenolic liner as seen in figure 8.1.5. Although, the team completed the first test fire with combustion from the ABS solid fuel grain, which was significant compared to HTPB used by Rocket Lynx II, the combustion was not stable enough to reach the estimated time of static flight and unable to collect any thrust data proposed as shown in Figure 8.1.4. Test 1 also showed that combustion occurs at the port surface area of the ABS from the burning gases which produced flames and charred surface inside and at the ends of the plastic material.

Moreover, the result of the second series of testing was very good, and that data were collected from the result. This demonstrated that the ABS solid fuel core could be
ignited and that assured the team that the combustion component assembly performed as initially proposed. The burning of Nitrous Oxide produced a combustion of the inner surface area of the tubular ABS rod and the combustion was a self-sustaining process because the system produced sufficient energy and thrust of 48 pound force during second static test run 4 even after the ignition source was removed.

Moving forward, we believe that the following near-term activities should be considered; first, it is important that more grain cross section profiles other than the tubular port be cast, 3-D print and or manufacture to create a more desired burn profile. 3-D printing of the ABS was not implemented during this project because of the length of solid fuel the team chose, which was too long to print. Henceforth, since a nice burn time was achieved during the second test, the team recommends that the fuel length be cut in half for easy machining or 3-D printing. The advantages of additive manufacturing may include the potential to form or design more complex port grain structures and the ability to profile different port geometries, such as spiral, cross, star, rod, and tube fuel ports. Facts have proven that their centrifugal flow pattern can significantly improve the regression rate and combustion efficiency of the fuel. Therefore, the modification of the ABS fuel grain port profile is crucial to achieving maximum thrust proposed in this project for the next design testing. This idea is important because it will be desirable for different stages of the burn to have different thrust curves. For this project, the tubular ports were chosen which needs to be a high thrust to fire the static test as progressively as possible.
Finally, the composition of the three main properties of Acrylonitrile Butadiene Styrene can vary greatly depending on the formation of the material and other factors or determinants of the burn characteristics such additives that can either inhibit or aid in the combustion process be looked into.

8.1.6 Phenolic Liner

The thin layer of phenolic liner is to provide a secure fitting for the solid fuel and protect the combustion chamber from intense thermal expansion. Throughout the team’s design, we proposed to use a thicker phenolic material as a combustion chamber insulation, but we were not certain as to how much thickness and what grade type of the material is enough for proper insulation. A series of firing tests were performed to determine the thermal properties and a more accurate thickness of the tube needed for the chamber.

Figure 8.1.5: Phenolic Tube from Test 1

After gathering more data from the first test to the second series of the testing it was shown in Figure 8.1.5 that if all components are properly in place and things being equal,
the type and the thickness of the phenolic tube with a lower density, higher specific heat making a favorable material to use for future testing design.

8.1.7 Data Acquisition

The data acquisition system began as a complex multi-computer system which consisted of 4 sensors (pressure, temperature, and load) feeding data to two microcontrollers which would relay data to an onboard computer, which would then save and send that data to an offsite computer using an ethernet cable. This excessive complexity resulted in a failure in the data acquisition system during the first hot fire test. This system was then revised for the second hot fire test, this revision removed both the onboard computer and offsite computer, leaving the two teensy microcontrollers to log data for the four onboard sensors. The teensys were programmed to save data continuously, meaning if the system lost power, data would be saved to the point of power loss and begin where it left off once power was regained. This revision and simplification resulted in successful data acquisition for the second hot fire test. However, this system and its simplicity did have some shortcomings. The primary areas for improvement are the addition of a live data stream to the rocket motor operators and a redundant data logging system. A live data stream would allow for rocket operators to see crucial rocket data such as combustion chamber temperatures or pressures in real time and make changes accordingly, this adds a safety net to prevent potential failures and ensure the rocket is operating correctly. This could be added using either a laptop with a preprogrammed UI, or an analog control panel with gauges for each sensor. A redundant data log would ensure that the system always has a data backup in the case that data is lost or corrupted, fire tests are valuable and rare
chances to accrue valuable data which is imperative for future rocket iterations, as such, it
is very important that there are multiple data logs to prevent data loss.

Chapter 9: Path Forward

The team is busy finalizing preparations for the cold flow and hot fire static tests
that are coming up shortly. Once the hot fire test is completed, the data from the sensors
and the condition of the rocket engine post test will be analyzed. The data will provide
guidance to redesigns to further improve the engine. The team would like to complete a
second set of cold flow and hot fire tests, time permitting. A second test would assist
identifying any outliers in the data set and allow for further iterations of improvements of
the design and testing procedure.

Additionally, the team needs to consider how to best make use of its remaining funds
in the budget. Some will need to be spent on replacement oxidizer and a fuel grain for a
second round of testing. Another portion of the budget will be allocated for the
procurement of materials for next year’s team, to give them a financial cushion as they
expand upon the project. Initially, there were suspicions that the manifold would fail and
break during testing. However, after two iterations of testing the manifold stayed intact and
worked as it should.
References


Appendix A: Engineering Drawings

Ball Valve and Servo Motor Mounting (Adapter part):
Ball Valve and Servo Motor Mounting (base part first iteration):
Ball Valve and Servo Motor Mounting (top part first iteration):
Ball Valve and Servo Motor Mounting (base part second iteration):
Ball Valve and Servo Motor Mounting (top part first iteration):

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University of Colorado Denver

Dimensions are in millimeters
Default Tolerances:

±1

±0.05

±0.01

Angles ±2

Drawn By: Almohamad Saleh

Date: 12/2
Avionics Module Engineering Drawings:

University of Colorado Denver

Dimensions are inches and degrees

Avionics Module
All 000 Plota

Drawn by: Yecheon Kim
Scale: 1:2 | Date: 03/03/2021
Appendix B: Arduino Code

Arduino Code (Thermocouple Test):

#include "max6675.h" // max6675.h

int soPin = 10; // SO pin
int csPin = 9; // CS pin
int sckPin = 8; // SCK pin

MAX6675 rocketlynx(sckPin, csPin, soPin); // instance object of the MAX6675

void setup() {
  Serial.begin(9600); // initialize serial monitor with 9600 baud
}

void loop() {
  // Display Temperature Readings on the serial monitor
  Serial.print("C = ");
  Serial.print(rocketlynx.readCelsius());
  Serial.print(" F = ");
  Serial.println(rocketlynx.readFahrenheit());
  delay(200);
}
Excerpt of the Rocket Lynx Gantt Chart