Rocket Propulsion Capstone
Final Report

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Fall 2023-Spring 2024

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DISCLAIMER

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EXECUTIVE SUMMARY

This project's mission is to design and develop an experimental rocket propulsion system for a high-power Level Two rocket. To achieve this, the team will develop a unique Ammonium Perchlorate Composite Propellant (APCP) formula to propel the rocket to its maximum potential altitude. The rocket is intended to achieve a maximum thrust of 5120 Newton seconds of impulse and is aimed at reaching peak performance for a single-stage L class rocket.

To ensure the success of this project, the team has coordinated a series of critical steps. The first is to conduct at least two small-scale motor tests using 38 mm and 54 mm motors to refine the propulsion formula and ensure its safety and reliability. These preliminary tests will serve as essential checkpoints in the development process in order to fine-tune the rocket's performance characteristics. To gather comprehensive data on the rocket's performance, the team has built a specialized test stand. By collaborating with an electrical engineering team, this stand will allow for calculations of thrust curves, impulse, and burn rates for the experimental motors. These metrics will provide insights into the performance and efficiency of the rocket’s propulsion system.

One of the core components of this project involves designing and building a motor casing capable of withstanding the high pressures that the rocket motor will experience. This casing is critical to the rocket's safety and successful launch for the final 75 mm motor. The team has developed a MATLAB code which can calculate design components such as motor casing thickness, allowable stress, and allowable pressures depending on material strength and motor casing dimensions. The team will ensure the final design of the motor casing can handle the demands of the high pressures, temperatures, and forces of the motor without compromising safety.

A device which is called a “test strand burner” is also designed and built for the testing of different propellant formulas. This is a pressure vessel which allows the team to burn small strands of the propellant formula and receive data on the pressures and temperatures during the propellants burn. From this data, the team can analyze the burn rate and thrust curve in software's such as RockSim and BurnSim to evaluate the formula. This increases the efficiency of the iteration process while the team is determining the best propellant formula. The formula which performs the best in the rocket simulations by achieving the highest altitude is then used in casting 54 mm motors to ensure the formula's scalability.

Once 54 mm motors have been successfully tested using the unique propellant formula, the team will begin testing 75 mm motors of the unique formulas. The team will first launch a rocket using the 54 mm motor to determine the performance and ensure the formula functions safely inside the rocket. After this launch, the team will continue testing 75 mm motors until successful. Using the thrust curve data from the successful 75 mm testing, the team will simulate the launch of this motor in the NAU rocket body to accurately determine the performance. Once this has been completed the capstone requirements have been achieved, however an optional final 75 mm motor launch is allowed is time allows.

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1 Background

Northern Arizona University's Rocket Club has been growing quickly in recent years. Because of this, the expense for launching rockets has exponentially increased as the launches and members continue to increase. In addition to this, many members seek a future in aerospace, and being able to learn how solid rocketry works is a vital skill for this field. Knowing how to formulate, cast, test, and show results is an important step in knowing how to design solid rocket propulsion.

1.1 Project Description

The team's goal for this project is to construct a high-power level 2 rocket propulsion system (level 2 rockets have an impulse range of 640.01N-s to 5120.00N-s) and test stand to collect thrust and impulse data on the rocket motors they build. Their primary objectives include the formulation and development of an Ammonium Perchlorate Composite Propellant (APCP). APCP is a solid propellant that utilizes ammonium perchlorate as an oxidizer and a metal such as aluminum as fuel. To ensure the safety and efficacy of the propulsion system, a dedicated rocket test stand has been designed and constructed. Through collaboration with an Electrical Engineering team responsible for the electrical system connected to a load cell on the test stand, the test stand will gain the capability to collect force data allowing for the team to understand the thrust curves and burn rates. These metrics are important as they will show how the motor will perform during a launch.

The team has been given a budget of $2,000 by GORE and $500 for the electronic components to complete these tasks. Additionally, the fundraising has currently surpassed $1,000 raised. This will allow the team to make purchases that need to arrive more quickly than the order process will allow and do a more thorough analysis and design for each component of the rocket. The team is scheduled to conduct at least two small-scale motor tests of diameters 38 mm and 54 mm to refine and validate their propellant formula design. During the development of the propellant formula, the team will also be designing a custom motor casing to be built for the final 76 mm motor. This 76 mm motor is the final goal, with a targeted scheduled launch in March 2024.

This project's research and final products will allow future students at NAU (Northern Arizona University) to have a distinct path to develop their own propellant formulas and motor grains. Also, the creation of the motor test stand through this project will be a fundamental tool for future students to test the motors they create.

1.2 Deliverables

The major deliverables for the first semester of the course include three presentations, two reports, two rounds of prototyping, a website, and a final CAD. Prototyping will allow the team to refine the propellant formula and ensure the test stand design is functional. Relative deadlines for these can be seen in the course schedule below, Table 1.

Table 1. Capstone 1 Schedule

Week Number	Deliverable Due	Week Number	Deliverable Due
1		9	Website Check
2	Team Charter	10	Analytical Analysis Memo
3		11	Presentation 3 Prototype 1
4	Presentation 1	12	
5		13	Report 2
6		14	Final CAD Final BOM
7	Presentation 2	15	Prototype 2
8	Report 1	16	Website Check

Our client deliverables include a functioning test stand by the end of April 2024. Subscale testing of the rocket propellent by the end of December 2023. Midscale testing of the rocket propellent must be completed by roughly mid-semester of spring 2024. Full-scale testing of the rocket motor, including nozzle and casing, must be completed during March 2024. The client has stipulated that the rocket must use solid fuel and ammonium percolate oxidizer since this is cheaper than liquid rocket fuel and meets the safety constraints of the client's rocketry association.

1.3 Success Metrics

1.3.1 Test Stand Success Metrics

The test stand's success hinges on several key components. First, it must be capable of effectively accommodating a variety of motor sizes. Specifically, it should securely support motors of various diameters and from 7 inches to 36 inches in height. Second, the test stand's performance relies on its ability to accurately capture data such as the force input over time of the motor in Newtons. The load cell must also be carefully calibrated to the 500 kg maximum which the load cell allows. Lastly, the structural integrity of the test stand is vital. It must be able to withstand the maximum stress forces with a safety factor of at least 1.5, ensuring its continued functionality for future generations of students.

To ensure that the test stand design is successful, a structural analysis must be done to each of the designs to make sure that the structure can withstand 5120 Newton seconds of impulse (the limit for a L-class motor). Additionally, for future years of NAU students to use this test stand, a factor of safety must be incorporated to ensure it can last for many years ahead. Finally, the material chosen must also be carefully considered to account for the heating process which will occur during testing. The team must analyze the melting temperatures of the chosen material and determine that heat from the exhaust fumes does not exceed this amount.

Through the integration of the final test stand design into Ansys Mechanical static structural analysis, the team determined that the maximum stress on the structure will be 381.7 psi for the chosen design. This analysis will be presented later in this paper; however, it is mentioned now as the maximum stress calculations are a key component to ensuring the final product is a success. Consequently, the base plate must be designed to withstand most of the stress of the structure and capable of withstanding this maximum stress while maintaining a sufficient safety margin.

1.3.2 Nozzle Success Metrics

The goal of the nozzle is to convert the chamber pressure into thrust by safely directing the exhaust gas out of one end of the motor, taking advantage of Newton’s third law of motion. Experimentally, the amount of impulse that the propulsion system creates will be a metric of comparison between nozzle shapes. The impulse that the propulsion system must not exceed is 5120 newton-seconds. The nozzle will be designed to achieve an impulse close to 5120 N-s without exceeding that value. Impulse is calculated by integrating thrust force, F, over time (see the following equation) [14].

$$I_t = \int_0^t F \, dt$$

Another useful measurement for determining the relative success of the rocket nozzles is thrust-to-weight ratio. It is an important metric because its value is useful in determining the rocket’s stability and speed as it leaves the launch rail, which is important to know for safety reasons. Thrust-to-weight ratio may also be used to determine the maximum acceleration possible, which will allow the team to better understand the altitude that the rocket may reach with any propulsion system configuration. According to simulations performed in Rocksim, a high-end level 2 motor ranges from 15,000 to 16,000 ft in altitude (when loaded into the carbon fiber rocket that our capstone team will be flying. Trust-to-weight ratio is calculated in accordance with the following formula:

$$\text{Thrust-to-weight} = \frac{F}{w_0}$$

Here, variable F represents the thrust force, and w_0 represents the total weight of the rocket (can be specific to the propulsion system if all non-propulsive weight is neglected).

1.3.3 Propellant

In order for the propellent to be considered successful the rocket must reach the altitude goals mentioned in section 2.2. This goal depends on various factors in the project as such it cannot be used to assess the success of solely the propellant. To measure the success of the propellant the team will run various tests of the different formulation using the test stand we built. The goal of these tests is to improve the impulse and thrust that the propellant produces as we iterate the design. The calculation to obtain this data will be done with the tools the electrical engineering team puts together for the test stand. Overall success of the propellant will be judged by how it improves over multiple rounds of testing.

1.3.4 Motor Casing

The propellant mass fraction (ζ) represents the ratio of the useful propellant mass (m_p) to the initial mass of the propulsion system (m_0). Initial mass, m_0, consists of the non-propulsive hardware (motor casing, O-rings, nozzle, etc.) and the useful propellant mass. The propulsion mass fraction indicates the quality of the propulsion system design. Higher values are desirable because this indicates that the bulk of the propulsion system weight is propellant. The formula is shown below. M_f represents the final mass of the propulsion system after burning the propellant. [11].

$$\zeta = \frac{m_p}{m_0} = \frac{m_0 - m_f}{m_0}$$

2 REQUIREMENTS

Throughout this chapter, a comprehensive discussion of all project requirements will be presented. These requirements are based on the specific demands of the client, Dr. Carson Pete, as well as the needs of the NAU Rocket Club. Also, the team will discuss the engineering requirements of the project determined by the team through an analysis of design constraints necessary to achieve the desired project objectives. Finally, the team will provide a visual representation of these requirements in the form of a House of Quality, illustrating the relation between customer requirements and engineering characteristics.

2.1 Customer Requirements (CRs)

For any engineering project, it is imperative that key customer requirements are well defined. In this project, there are multiple requirements that must be strictly followed to succeed in the project and satisfy our clients and potential end users. These customer requirements are listed below with appropriate explanations.

Sturdy Test Stand-

CR1: Develop a rocket motor test stand which can precisely record the motors' downward force for motors of sizes 38 to 75 millimeters.

Functionality-

CR2: Optimize and test a unique ammonium perchlorate propellant formula.

CR3: Design and develop a 75 mm motor casing and bulkhead to fit inside the NAU Rocket Club's carbon-fiber rocket body.
CR4: Design and develop an optimized, tested nozzle for the final 75 mm level 2, M-class motor.
CR5: If the rocket does not reach an altitude of 30,000 feet during launch, define the class type motor and size required to reach 30,000 feet.
Optimize the 75 mm motor to reach peak altitude during launch, preferably reaching a minimum of 15,000 feet.

Saleable-

CR6: Build multiple 38-, 54- and 75-mm motors to be tested on the rocket motor test stand.

- To save resources and room in our budget, our rocket design must be able to be scaled in standard motor sizes. These sizes range from 29 mm-75 mm. Our testing will comprise mostly of 38 mm until an appropriate propellant mixture is found.

Timely Completion-

CR7: Assemble a full 75 mm motor to be placed inside the carbon fiber rocket body to be successfully launched by the end of April 2024

- Because this project has a strict time to be completed by (Early March), we must ensure that our research, development, and testing is done by this time frame. By this time, we need our full-scale 76 mm motor done and tested to ensure the Rocket Club can use it in their rocket.

Low Cost-

CR8: Must stay within the budget of $2000 provided by GORE and the additional fundraiser money.

- We need to make sure that our project fits well inside of our given budget of $2000. With fundraising, we can increase our range by another $350, but the replication of these steps must be done within a budget-friendly manner. Because the results of this project will be used by future capstones and the NAU Rocket Club, it is important to keep the budget in-line with theirs.

Comply with Tripoli Rocketry Association Standards-

CR9: Must incorporate safety standards such as distance from motors or rockets when testing and have an in-depth safety checklist written and followed for each test and launch.

- Complying with the major rocketry association is beyond important to making sure our team is safe and responsible when working with dangerous chemicals like the ones we will be using. The Tripoli Rocketry Association has laid out strict safety standards that we must comply with.

2.2 Engineering Requirements (ERs)

The following engineering requirements are critical to defining and directing the project. Many of these requirements come from our client's requirements or from the Tripoli requirements.

Test Stand:

ER1A: Must be lightweight for carrying to testing locations (< 60 lbs).
ER1B: Must accommodate motor sizes ranging from 38 to 75 millimeters diameter and 10 to 30 inches height.
ER1C: Must be capable of securely mounting and testing the motors.

- Safety is important to our client. This applies to various areas of the project, for the test stand this means it must contain the testing of the rocket motors and be strong enough to use multiple times. The maximum impulse of a level two rocket motor is 5120N*s. So, the test stand must be able to perform under that loading and not sustain any permanent deformation.

ER1D: Must include necessary instrumentation for data collection during testing, such as thrust (up to 287.8 lbf), temperature (up to 500 degrees F) and pressure sensors (up to 1500 psi).

Propellant Formula

ER2A: Must be optimized to have the highest thrust and impulse output, as close to 287.8 lbf and 5120 Newton seconds as possible.

- Reach Minimum Altitude- During the final launch, the rocket must reach an altitude of 10 km, roughly 32,000 ft.

ER2B: Final formula must be tested in grain sizes of 54- and 75-mm motors to ensure the safety and reliability of the formula.

- Meet Minimum Thrust-to-Weight Ratio set by Tripoli- Another component of maintaining the safety standards set by Tripoli is ensuring we meet the minimum thrust-to-weight ratio. This means that the rocket must have 5N of thrust for every 1N of weight of a 5:1N/N ratio [26]. Means. To meet this requirement, the team will have to perform simulations to obtain thrust and calculate the density of propellent to account for the fuel's weight. We plan to apply a factor of safety to account for the fact that the simulated thrust is larger than the actual thrust will be due to idealizations in the simulation. This is a one-sided constraint as a thrust-to-weight ratio higher than 5:1 is still within the standard.

Motor Casing and Bulkheads

ER3A: 75 mm motor casing outer diameter must be within tolerance ± 0.1mm of 0.1mm less than inner diameter of the rocket body to ensure a snug fit with the rocket body and prevent vibrations or components from moving during launch.

- The rocket motor must fit inside of the provided NAU Rocket Club rocket. The rocket they have provided for us has a max internal diameter of 75 mm, so the propellent and casing must fit within the 75 millimeters of the rocket. It may be slightly smaller but should be close to 75 mm in diameter since the client requested a motor of that size.

ER3B: The bulkheads must be made for 54- and 75-mm motors and incorporate at least two O-Rings and 1 snap-ring to ensure stability within the motor casing during launch
ER3C: Design the 75 mm motor casing to withstand 1500 psi with a factor of safety of 1.5 (for a total pressure rating of 2250 psi).

- Of the major safety concerns the final one is that the casing that we design must be made of a non-Ferrous and ductile material [26]. This requirement is because ferrous metals can cause sparks which would create uncontrolled burning or ignition. The material must be ductile so that if the casing explodes it does not create projectiles. This is another binary constraint that will affect our material selection.

Nozzle

ER4A: Design nozzle to optimize rockets thrust based on computational fluid dynamics principles.
ER4B: Test nozzle design using the test 54 mm motors and their thrust curves using the same propellant formula for each trial.

Launch

ER5: Complete Final Launch by March 2024- The launch sites only allow launches on specific days and times. Additionally, the NAU Rocket Club only goes to some of these launches. The final launch needs to take place for the Club to see so we must align our schedule to launch with them. This is a binary constraint, but we can also measure it in months. We must be ready to test 3 months into the new year.

2.3 House of Quality (QFD)

The full QFD can be seen in appendix A. The customer requirements (CR) and engineering requirements (ER) have been explained above in sections 2.1 and 2.2 respectively. This QFD uses a 0,3,6,9 scale. On this scale 0 represents an inverse relationship, a 3 represents a neutral or no relationship, a 6 represents a slight relationship, and a 9 represents a strong relationship between the two requirements. This can be seen in the figure below where the correlation between CR and ER is shown.

		Technical Requirements						
Customer Needs	Customer Weights	Reach minimum altitude	Stay within Budget for the Project	Dimensions meet constraints of rocket size	Stand withstands impulse of rocket testing	Meet Minimum Thrust to Weight Ratio Set by Tripoli	Complete final launch by march 2024	Non-Ferrous Ductile Casing
Functionality	4	9	3	6	9	3	3	3
Low Cost	4	0	9	3	0	6	3	0
Scalable	3	3	3	9	6	6	3	3
Sturdy Test Stand	4	3	3	6	9	3	3	3
Comply with Tripoli Rocketry Association safety standards	5	3	3	6	6	9	3	9
Timely Completion	3	3	3	3	3	3	9	3

Figure 1. QFD, CR and ER Correlation

In appendix A, the results of the QFD show that the most important technical requirement is that the test stand withstands the impulse, 5120 N*s of rocket testing. The test stand is critical for the team to iterate the propellant and meet the other engineering requirements. Additionally, if the test stand could not withstand the impulse, it would be incredibly unsafe.

3 Research Within Your Design Space

3.1 Benchmarking

3.1.1 Test Stand Benchmarking

Benchmarking is a critical step in evaluating and comparing different test stand designs for rocket motors. This process allows the team to make an informed decision about how to design a unique test stand for this project's individual needs. The team did a thorough analysis of three state-of-the-art test stand designs which include the Aerocon Systems Horizontal/Vertical Test Stand, the FUTEK Rocket Engine Trust Measurement Stand, and Richard Nakka's STS-5000 Static Test Stand.

To begin, the Aerocon Systems Horizontal/Vertical Test Stand [1], shown in figure 2, offers several advantages including the flexibility of accommodating various ring sizes for different diameter motors. Its affordability, priced at approximately $600 with all the necessary clamps, makes it accessible for smaller projects. However, it has some drawbacks, primarily related to its material composition. The aluminum body's low melting temperature is not ideal for applications involving rocket motor testing, as the body may not be able to withstand the high temperatures from the motor's exhaust during testing. Furthermore, the absence of impulse measurement integrated into the stand design necessitates additional tools and equipment, potentially adding complexity to the testing process.

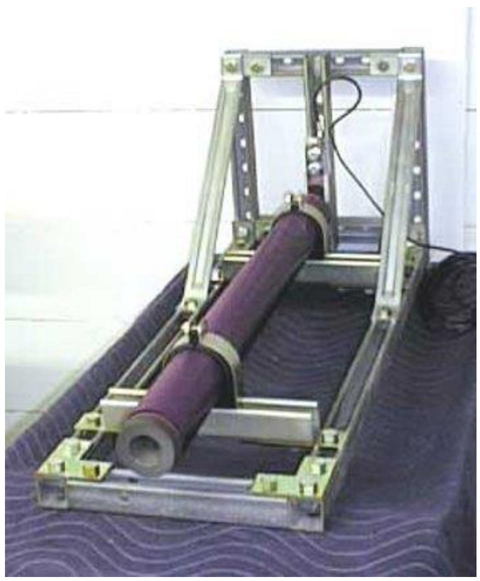


Figure 2. Aerocon Systems Horizontal/Vertical Test Stand [1]

In comparison, the FUTEK Rocket Engine Thrust Measurement Stand [2] shown in figure 3 has a much sturdier construction, being made from steel and formed sheet metal. It offers multi-axis sensors, load cells, and wireless capabilities, ensuring safe and accurate measurements. However, there are challenges associated with this choice. The requirement for a work order to purchase and the long lead times could pose logistical hurdles for projects with tight schedules or budgets. Additionally, the cost of a single load cell, approximately $6,000, can quickly escalate when multiple load cells are needed. Purchasing just one of these load cells surpasses the project's budget.

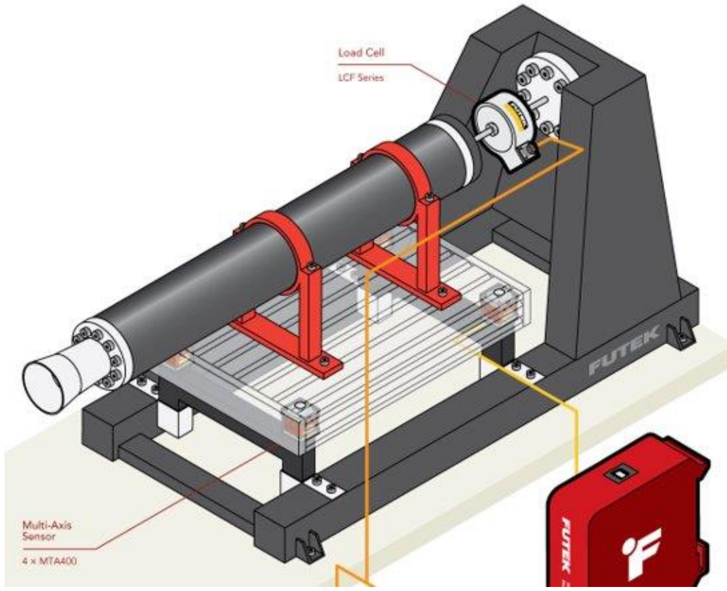


Figure 3. FUTEK Rocket Engine Thrust Measurement Stand [2]

Finally, Richard Nakka's STS-5000 Static Test Stand for Rocket Motors [3] shown in figure 4 has its advantages, such as the vertical orientation, which allows for a realistic positioning during testing. This design stands out for its cost-effectiveness and simplicity; however, it also presents limitations. Unlike commercial test stands, this design is not available for purchase. The team would need to source the parts separately and construct the stand themselves, which can be time-consuming and may demand specialized knowledge. The design is also described as improvised, raising doubts about its ability to handle the forces generated during rocket motor tests effectively.

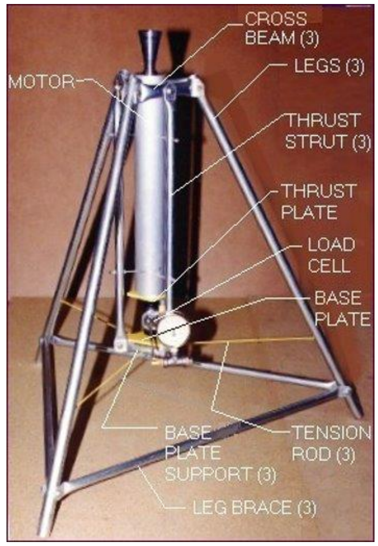


Figure 4. Richard Nakka's STS-5000 Static Test Stand [3]

In addition to these pros and cons, sub-system level benchmarking should also consider factors like safety features, data acquisition and analysis capabilities, ease of assembly and disassembly, compatibility with different motor types, and scalability for future testing needs. The choice of a test stand design should be informed by a thorough evaluation of these factors, ensuring that it aligns with the project's goals, constraints, and requirements. Ultimately, the decision should balance performance, cost, and feasibility, and the unique demands of the specific rocket motor testing project.

3.1.2 Propellant Benchmarking

The first benchmark that the team looked at for the propellent was the AeroTech RMS 75/1280 Motor [4]. This motor follows the safety standards set by the manufacturer, but it is unclear if these standards comply with the Tripoli standards. This motor meets the size requirements. Unfortunately, this motor is not affordable as it costs around 500 dollars, and a new one must be purchased for each launch.

Figure 5. AeroTech RMS 75/1280 Motor [4]

The second benchmark the team looked at was the Aerotech High-Power M1350W-P 75 mm shown below [5]. This motor complies with all the Tripoli standards. However, it requires a level 3 certation to purchase and launch, no one in the NAU Rocket Club has this certification Mutch like the fist motor we looked at, this motor fulfils the size requirement but is out of budget with a cost of $800.

Figure 6. Aerotech High-Power M1350W-P 75 mm Motor [5]

The final benchmark that the team looked at was the Aerotech High-Power L875DM-PS 75 mm [6]. This motor follows the Tripoli standards and only requires a level 2 certification, which some club members have. This motor also meets the size requirements and costs $800. This is expensive, considering this must be replaced every time the rocket launches. This motor also requires the club to buy additional tools if they want to make any adjustments.

Figure 7. Aerotech High-Power L875DM-PS 75 mm Motor [6]

3.2 Literature Review

3.2.1 Shannon Comstock: A Focus on Motor Casing and Safety

[7]

"Design and analysis of composite rocket motor casing"

This scholarly article compares different materials for rocket motor casings, specifically Carbon Fibers and Epoxy. It provides valuable formulas for the calculation of material properties, which is essential for determining the structural integrity of the rocket motor casing.

This reference is highly relevant to our project as it assists in selecting the appropriate material for the motor casing, considering factors such as strength and weight.

[8]
"Design and structural analysis of solid rocket motor casing hardware used in aerospace applications"

This scholarly article focuses on the structural analysis of rocket motor casing hardware. It provides equations for calculating the required thickness of the motor casing to ensure its integrity during operation. Additionally, it analyzes rocket design to determine the factor of safety. This reference is crucial in helping us design a rocket motor casing that can withstand the high pressures and forces generated during testing.

[9]
"Nondestructive Testing of High-Strength Steel Rocket Motor Cases"

This scholarly article explores nondestructive testing methods for high-strength steel rocket motor cases. It delves into the detection and analysis of crack propagations in motor cases, which is essential for ensuring their structural soundness. The techniques discussed in this reference can be valuable in our project to assess the condition of rocket motor cases after testing and determine whether they can be reused.

[10]
"Shigley's Mechanical Engineering Design"

This textbook provides a comprehensive resource for mechanical engineering design. It includes formulas for calculating stresses in pressurized cylinders, which is directly applicable to our project in determining the structural integrity of rocket motor casings under pressure. The book serves as a valuable reference for mechanical design aspects.

[11]
"Mechanics of Materials"

This textbook covers the analysis of materials, making it a valuable resource for understanding the properties and behavior of different materials under various loads. It assists in the selection of materials based on the calculated forces, ensuring that the chosen materials can withstand the stresses generated during rocket motor testing.

[12]
NASA's "Rocket Laboratory Safety and Design Manual"

This online source discusses safety procedures before test flights in rocket laboratories. It provides essential guidelines for ensuring the safety of personnel and the environment. It also discusses health hazards related to chemicals commonly used in rocket assemblies and propellants, which is crucial for risk assessment in our project.

[13]
"Rocket Safety Plan Template for Recreational Use or for Academic and Outreach Classes"

This online source offers a safety checklist that can be adapted for our specific testing procedures. It outlines the necessary roles and responsibilities of team members during a test flight, ensuring that safety protocols are in place. This reference is instrumental in developing a comprehensive safety plan for our rocket testing project.

[14]
"An approach to selection of material and manufacturing processes for rocket motor cases using weighted performance index"

This scholarly journal provides a new method for determining the best material and manufacturing process for the motor casing. This describes a process they have formulated called "Weighted Performance Index" where the material options are weighted against one another based on the importance of the design requirements. This allows the team to choose the best material for the motor casing while learning about the manufacturing process.

[15] "Solid Propellant Burning Rate from Strand Burner Pressure Measurement"

This scholarly journal provides an approach to analyzing the data received from the test strand burner to obtain a more accurate thrust curve and burn rate. This article provides the process the authors take to get these results, such as the equations used and their models. This will allow the team to follow their steps after receiving the data from the strand burner.

[16] "Development of strand burner for solid propellant burning rate studies"

This journal describes a student's method for designing a strand burner which requires a lower pressure than the normal strand burner. The student uses nitrogen gas to fill the strand burner which alters the burn of the propellant and lowers the internal pressure. This process and description of designing a strand burner allows the team to have a clear idea of the design requirements when building the strand burner.

3.2.2 Andrew King: A Focus on Nozzle Design/Manufacture
[17]

G.P. Sutton and O. Biblarz, "Rocket Propulsion Elements"

Rocket Propulsion Elements is an all-encompassing book that helps with most aspects of this project. When it comes to nozzle design, the textbook provides performance values, correction factors, phenomena and losses, boundary layers, and multiphase flow. This textbook also includes equations for variable trust, which is relevant to this project.

[18]

R.C. Hibbeler, “Fluid Mechanics”

R.C. Hibbeler’s, *Fluid Mechanics* discusses compressible flow in depth. More specifically, it discusses the characteristics of supersonic flow through converging and diverging nozzles. Converging and diverging nozzles are extremely prevalent in aerospace applications and are the design choice of nozzle for this project. The next topic that this source discusses is shockwave propagation through a compressible fluid, and how they travel through nozzles.

[19]

“Fundamentals of Engineering Thermodynamics”

Fundamentals of Engineering Thermodynamics can help in the Nozzle Design process in many ways. The first being the fact that it provides equations to help determine basic properties such as pressure and temperature. It provides info on determining the heat capacity ratio and important condition used in the nozzle's diverging portion design. It allows for a better understanding of the motion of gas through nozzles.

[20]

“An Introduction to Aerospace Propulsion”

This textbook source covers aerospace propulsion thermodynamic cycles, which is helpful in determining performance. The section pertaining to rocket propulsion covers an extremely wide range of general equations that will help with design and performance. Another helpful chapter of the book, *Solid Propellant Rocket Engines*, does a great job explaining how solid propellant works and how it affects the rest of the motor assembly design.

[21]

“Gas Dynamics and Thermodynamics of Solid-Propellant Rockets”

This textbook contains many equations for many aspects of rocket propulsion. There are explanations of compression shocks and shock waves, method of characteristics in the one-dimensional problem of gas dynamics, and many more explanations of fluids behavior in rocket nozzles. Correction factors are explained, which will aid in accounting for errors in our project.

[22]

“Short Nozzles Design for Real Gas Supersonic Flow Using the Method of Characteristics”

This source is a scholarly article pertaining to method of characteristics (MOC). It explains the process of using MOC to develop an axisymmetric nozzle of the shortest possible length. Minimizing the length of nozzles is important in the efficiency of the propulsion system

due to the lower mass. This article also discusses how modeling with MOC changes for ideal vs. real gases.

[23]

"Design and optimization of aerospike nozzle using CFD"

This scholarly article explains how to design an aerospike nozzle using computational fluid dynamics (CFD) software (such as Ansys). Although it is catered towards the aerospike design, this source provides information of using CFD software that can be applied to other designs. This source also describes how MOC can be used with CFD to optimize nozzle design.

[24]

"Effects of Nozzle Throat and Combustion Chamber Design Variables on Divergent Portion of the Nozzle"

This source is a scholarly article that explains the importance of the materials chosen for nozzles. It shows how finite element analysis (FEA) may be used to determine the strength and safety of the design. It also goes into detain on how the conditions of the combustion chamber and converging portion of the nozzle affect the geometry of the diverging portion of the nozzle.

[25]

"Short Index of Propulsion Slides"

This is an online source from the National Aeronautics and Space Administration (NASA). It contains a wide variety of information pertaining to this capstone. It will help for the design of rocket nozzles because it has general info and animations explaining thrust equations and atmospheric conditions. And thermodynamics.

[26]

"NASA Technical Reports Server (NTRS)"

This is an online source from NASA. It provides equations for atmospheric conditions of pressure and temperature at variable altitudes. This will be a great source for nozzle design because the ambient air pressure conditions such as pressure greatly affect nozzle performance. The team can use this info to optimize the design for either Flagstaff or Phoenix elevation.

[27]

"Dynamic characteristic modeling and simulation of an aerospike-shaped pintle nozzle for variable thrust of a solid rocket motor"

This is a scholarly article which describes the process of designing a variable thrust aerospike nozzle for a solid propellant rocket. This is relevant to the project because it goes into more detail about the Prandl-Meyer functions, which is something that I need to use. They perform ground tests on the nozzle, so their research in this aspect will be helpful to consider.

[28]

"Supersonic Several Bells Design of Minimum Length Nozzle Contours for More Altitudes Level Adaptations"

This scholarly article goes into detail about creating a program to numerically solve the geometry of a dual-bell nozzle. Although I am not creating a dual-bell design, this resource still allows for me to better understand the Prandtl-Meyer function and how to design with MOC. It also presents a few ways to validate results given by MOC programs. This can be done either numerically or through hand calculations.

[29]

"Development of Improved Throat Inserts for Ablative Rocket Engines"

This is a NASA Technical Note which goes into detail about the effectiveness of seventy-five different throat inserts in nine different nozzle designs. This source provides insight on how ablative cooling works and allows for a better-informed design for this project's rocket nozzle.

3.2.3 Grace Morris: A Focus on Propellent Design and Safety

[27]

"Interactive General Chemistry"

This textbook covers basic chemistry concepts. This will be helpful when thinking about the propellent composition. The section on combustions and compounds will be the most helpful since they are most applicable to the project. However, all the sections of the book are important since a solid foundation in chemistry will be required to develop the propellent formula.

[28]

"Experimental Composite Propellant"

This textbook goes in-depth about the prosses of creating solid propellant and all the components that must be considered. Additionally, the book contains a list of recommended minimum safety standards to implement when creating propellant. This textbook also came recommended to the team by some propellant making mentors we connected with.

[29]

“Review on Typical Ingredients for Ammonium Perchloride Biased Solid Propellant”

This scholarly article discusses some of the common ingredients used in solid rocket propellent. The primary takes away for this paper is the solid propellant made of binder, metal fuel, oxidizer, and additives. The binder, metal fuel, and oxidizer are set, the only thing that can be changed is the additives and ratios.

[30]

“Additive Manufacturing of Ammonium Perchlorate Composite Propellant with High Solids Loadings”

This scholarly paper goes over a procedure for additive manufacturing of rocket propellent and how this procedure affects burn rate. Additionally, they discuss how voids within the propellent negatively affect burn rate.

[31]

“Size and Shape of Ammonium Perchlorate and their Influence on Properties of Composite Propellant”

This scholarly article covers the experimental set up they used when creating and testing the different composite propellants. This informs the team as to who we might go about testing and creating our propellant.

[32]

“Tripoli Rocketry Association Safety Code”

This website is the official safety code from Tripoli. The main sections we need to focus on are section 7, which talks about general range operation rules. Including the rocket’s constructions and stability. We also need to focus on section 10, which talks about motor limitations.

[33]

“APCP Solid Propulsion Development”

This details how students at Penn State built their rocket test stand and rocket propulsion system. Since this is also an engineering capstone project it gives us a good marker of what can be done for the project and how to start accomplishing it.

[34]

“Thermodynamic Investigation of Conventional and Alternative Rocket Fuels for Aerospace Propulsion”

This is a scholarly article which goes into detail about how different propellant mixtures influence coefficient of thrust, characteristic velocity, specific impulse, and many other performance parameters. One of the key takeaways is that for high thrust, instead of high velocity, propellants with a large molecular mass are preferred.

[35]

“Tensile Behaviors of Thermal Aged HTPB Propellant at Low Temperatures Under Dynamic Loading”

This is a scholarly article which contains tensile stress-strain curves for HTPB. This article will be a useful reference for the material properties of the binder that the team is using since it considers many different loading conditions.

[36]

“Solid Propellants: AP/HTPB Composite Propellants”

This online resource discusses all components of solid rocket fuel. However, the sections on additives and burn properties will be most useful as other resources have already discussed the other components. This informs the team farther about additives to consider buying and why.

3.2.4 Remington Dasher: A Focus on Propellent Formulation and Test Stands

[37]

“Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics (Volume 185)”

This textbook goes into key Ammonium Perchlorate decomposition details. The authors depict pure Ammonium Perchlorate decompositions along with different mixture results. This data gives us a baseline for what mixtures exist and how they decompose.

[38]

“Fundamentals of Aerodynamics, Sixth Edition”

For any object that passes through a fluid, it is important to understand the effects acting on that body. In this textbook, fundamental concepts and equations are given for objects passing through air, which is what we are working with when it comes to rocketry.

[39]

“Ammonium Perchlorate Composite Basics”

In this scholarly article, fundamental equations are defined for the combustion of the rocket. It also shows different grain geometries and their associated burn curves. We can use these equations along with the grain geometry types/dimensions to calculate our burn rates. It is important to know these factors so we can numerically ensure our modeling programs are reaching the correct values.

[40]

“Combustion of Solid Propellants”

In this scholarly article, the author gives multiple important chemical properties of relevant rocket chemicals. Such chemicals include Ammonium Perchlorate, Atomized Aluminum, resins, and binders. Being able to deduce the right propellant and additives for our formula is key to succeeding in the project, so this source should be an important reference.

[41]

“Ammonium Perchlorate as an Effective Additive for Enhancing the Combustion and Propulsion Performance of Al/CuO Nanothermites”

For the last scholarly article, different Ammonium Perchlorate composites are tested and plotted to visually see their decompositions. It is important for us to know at what percentage ammonium perchlorate performs the best, so we know how to optimize our own propellant mix. Using this source will allow us to dial this in in the cheapest way possible without having to waste our material on something that has already been tested.

[42]

“APCP Solid Propulsion Development”

For this online resource, the author gives very important information on test stand design and how to cater it to what forces will be experienced. The source then describes how to be safe around testing and secure the stand in place. Their example was much larger than ours, but it is important to keep similarity between the two regardless.

[43]

“Solid Rocket Boosters”

In this online source, we see the space shuttle Solid Rocket Boosters (SRB) chemical composition. Obviously, this is on a much larger scale than what we are going to test, however, analyzing other solid rocket formulas and cross-referencing with other formulations can help us tremendously when it comes to mixing our own specialized batch.

[44]

"Aluminum 6061-T6; 6061-T651 Data Sheet"

This source allocates the important material properties of aluminum. This is important because the casing must be designed to accommodate an aluminum casing to ensure the strength to weight ratio is as ideal as possible. These values are what will be used to make sure the casing is adequate.

[45]

"Thermal analysis on solid rocket motor casing"

With this source, the major takeaway is the casing Factor of Safety. There are many standards that we need to adhere to. Unfortunately, Tripoli does not have Factors of Safety in their safety guidelines, so this source makes up for that. This source shows that the Factor of Safety that we need to model around is 1.5.

[46]

"Design and Structural Analysis of Solid Rocket Motor Casing Hardware used in Aerospace Applications"

This source defines the Maximum Expected Operating Pressure and its value that should be than 150 kilograms per cubic centimeter shall be allowed for rocket motor casings. An analysis will be done with our casing around this metric.

3.3 Mathematical Modeling

3.3.1 Motor Casing – Shannon Comstock

In the motor sub-assembly design, understanding the criteria for the motor casing's thickness is one of the first variables which should be calculated to begin the design process. While there are multiple ways for determining the best casing thickness", the scholarly article presented previously "Design and structural analysis of solid rocket motor casing hardware used in aerospace applications" [8] describes and efficient way of calculating this value through the following equation:

$$t = \frac{P * D * Mismatch\ Factor}{biaxial\ gain * 2 * (SE - 0.6P)}$$

Here, "P" represents the pressure in pounds per square inch, and "D" is the inner diameter of the casing. The "Mismatch Factor" and "biaxial gain" are factoring that account for variations and uncertainties. The allowable strength "S" is calculated as the ultimate tensile strength (U.T.S) divided by the factor of safety (F.S), and the weld efficiency "E" is desired to be 90%. For ASME standards, the biaxial gain value = 1.1 and the mismatch factor = 1.15. Therefore, we need to find the pressure, inner diameter, and ultimate strength of the chosen material to complete this calculation.

Pressure "P" is determined by the equation:

$$P = B(K_n)^{\frac{1}{1-n}}$$

In this equation, "B" is a constant specific to the propellant being used, and "n" corresponds to the pressure or burning rate exponent as defined in the burn rate equation.

As of right now, the team is working on determining the best material to use for the motor casing which is why the completed calculations could not be made for this section yet. However, once the material is determined based on affordability and strength, the team can come back to these calculations to easily complete them and find the required motor casing thickness.

These equations and considerations are crucial for determining the appropriate thickness of the motor casing, ensuring that it can withstand the internal pressure generated during rocket motor testing. Proper calculations are essential to guarantee the structural integrity of the casing.

3.3.2 Rocksim / Nozzle MOC - Andrew King

A great program for determining the performance of the team’s propulsion subsystem is Rocksim. It is a simulation software that provides values related to rocket performance such as maximum altitude, velocity, acceleration, flight time, stability margin and many more. This program was helpful as a starting point to the project because it was used to identify how much total impulse and average thrust sour motor must have. It provides a general benchmark of performance that we should strive to match in our design.

Rocksim allows for the fine tuning of a variety of environmental properties such as wind speed range, altitude, relative humidity, temperature, cloud coverage, etc. (Figure 8). It also allows for the fine tuning of rocket properties such as geometry and weight. It displays a model of the rocket and indicates where the center of gravity and center of pressure are located. The distance and order that these points are on the rocket determines the stability margin. See Figure 9 for reference.

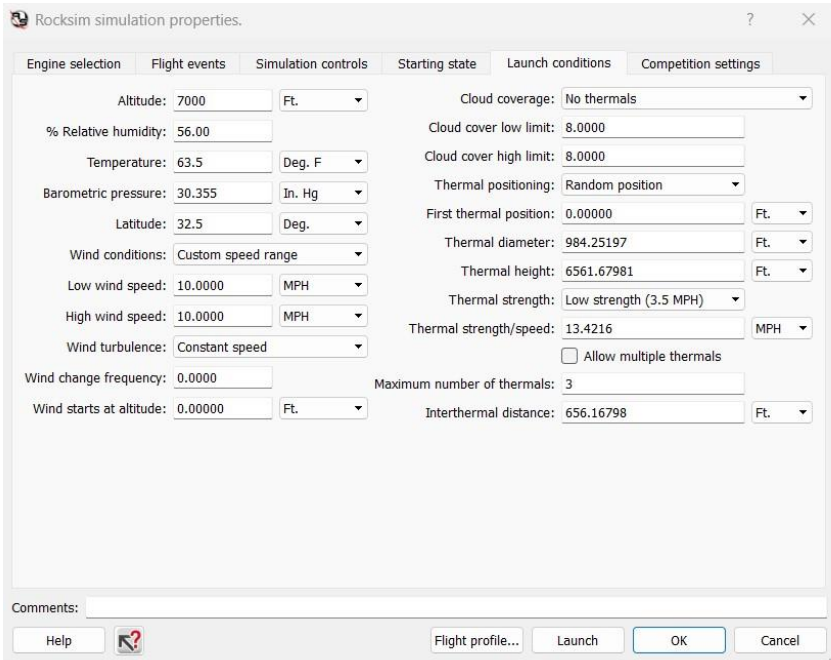


Figure 8: Rocksim Simulation Properties

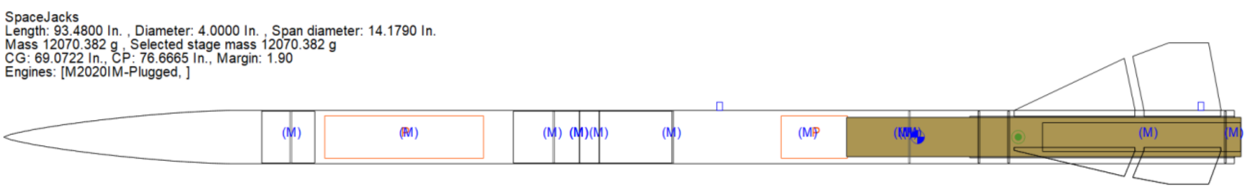


Figure 9: Rocksim Software Display Model. It shows the location of various centers of mass and the overall center of pressure of the rocket.

As we progress through the design of the propellant formula, its characteristics may be loaded into Rocksim as a custom motor. This is a required step for launching at the Tripoli Rocket Association Site in Wickenburg but will also be a helpful step to take to ensure that we are on the right track to reaching the altitude goals. As shown in figure 10, the team may produce graphs that show important performance parameters. We can use these graphs to compare how different propellants affect speed, velocity, acceleration, etc.

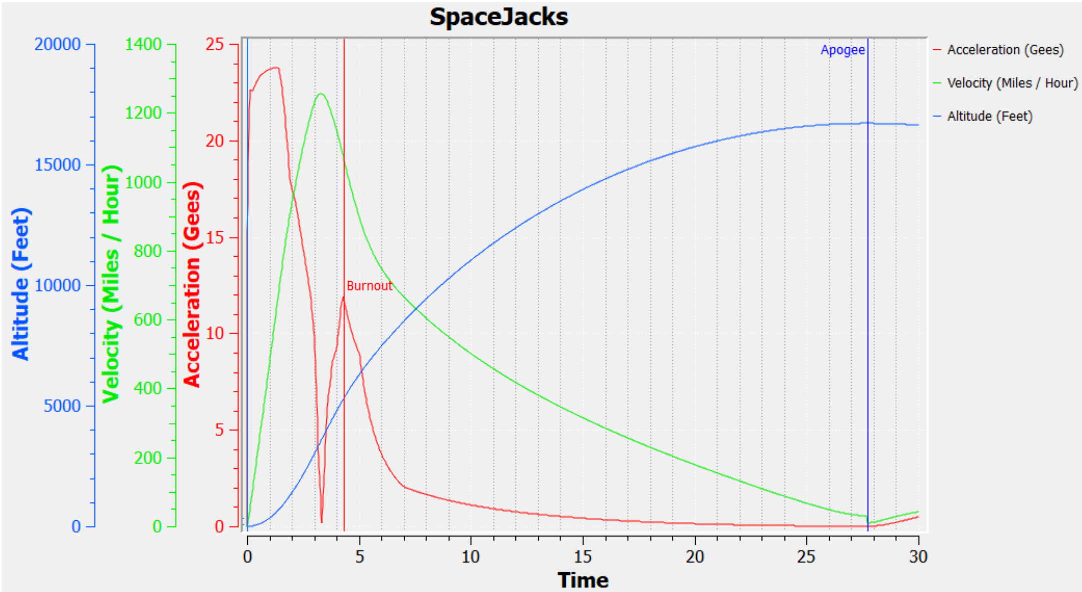


Figure 10: Rocksim Graph

Another program that will be helpful with mathematical modeling is MATLAB. MATLAB will be used to generate the diverging nozzle geometry with the method of characteristics. MOC utilizes Prandtl-Meyer expansion equations to generate the nozzle contour. There are many programs that do this available on the MATLAB website. Having an MOC program is extremely helpful because if there are changes to the propellant formula or number of grains, the throat diameter and heat capacity ratio parameters can be quickly changed to produce an entirely new curve. See figure 11 for a representation of what the program outputs.

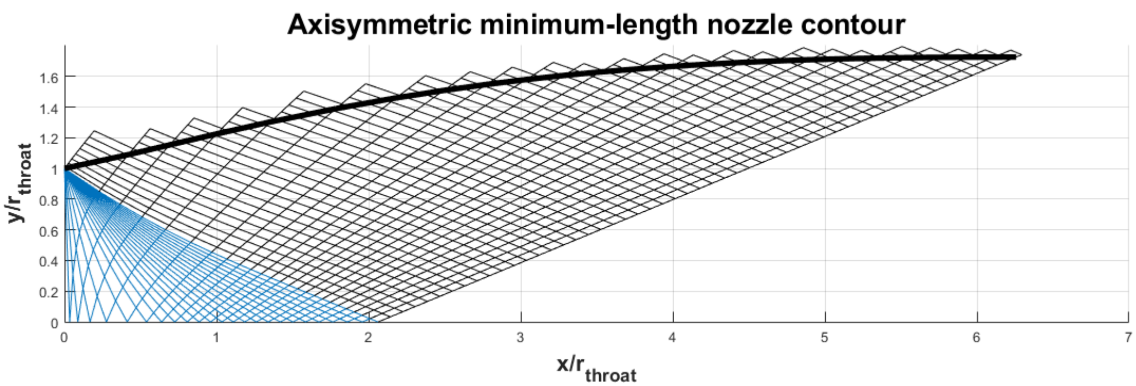


Figure 11: MOC Nozzle Contour

The importance of utilizing Prandtl-Meyer and MOC for generating the nozzle contour is because otherwise there may be unwanted shockwave interactions. Such interactions are not intended and may destroy the nozzle, and subsequently, the rest of the propulsion system.

The points generated by the MOC program may be exported to CAD software such as SolidWorks, where they can be connected by a spline and swept along the central axis to generate the complete nozzle shape. This model can then be imported to CFD software such as Ansys, which can validate the design by simulating supersonic fluid flow through the nozzle.

3.3.3 Propellant - Grace Morris

When determining the propellant grain geometry and formulation the team will run many simulations prior to testing, since testing is expensive, and the budget is limited. The primary engineering tool we will use for this is Burnsim. Burnsim creates simulated thrust curve data biased on the propellent grain geometry and the propellant formula.

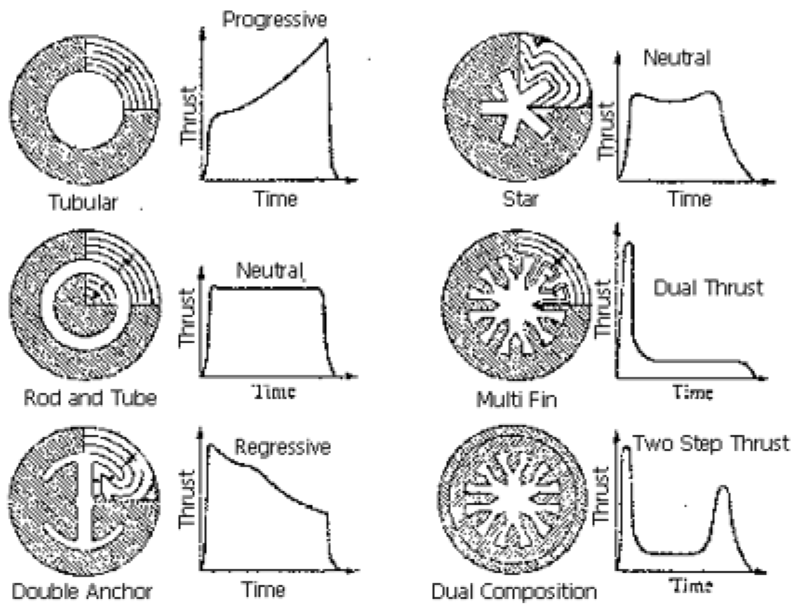


Figure 12. Grain Geometry and Thrust curves [Nakka Rocketry]

As seen in the above figure, figure 12, grain geometry has a huge impact on the thrust that the rocket produces and how this thrusts changes over time. This is mainly because as the motor burns, the surface area changes depending on the initial grain shape. This changing surface area affects the burn rate. The changing burn rate affects the thrust and the way the rocket performs.

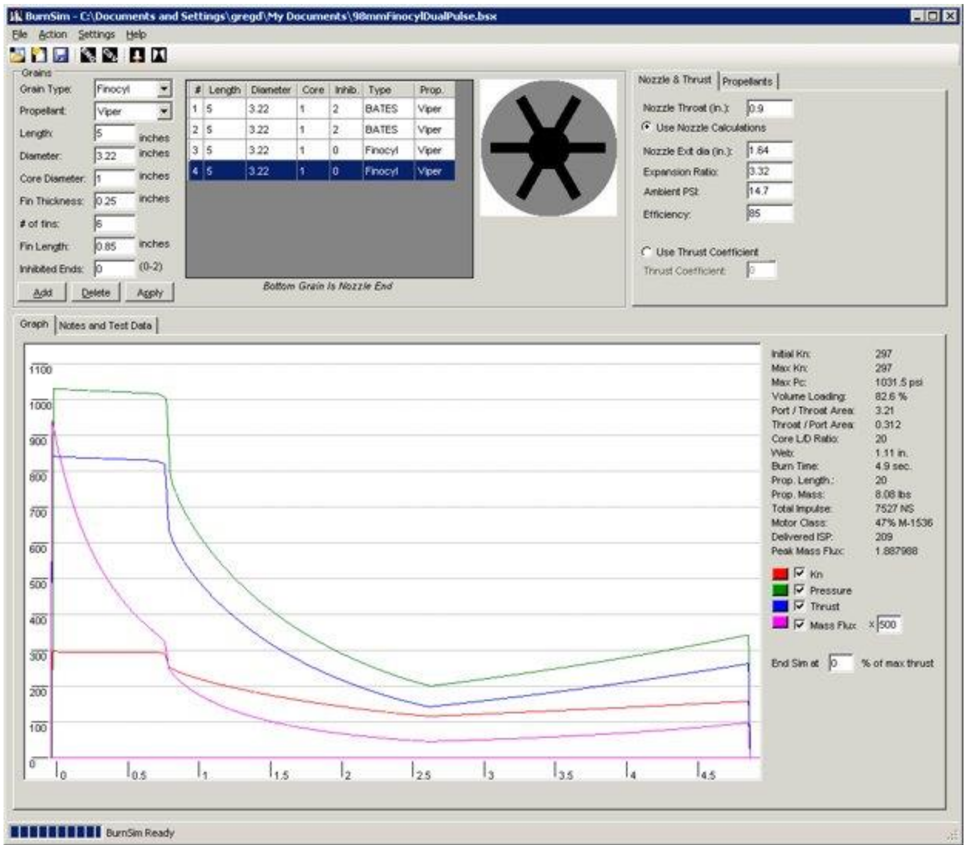


Figure 13. Example of BurnSim Thrust Curve

The above figure, figure 13, shows how BurnSim generates various helpful graphs, including the thrust curve and the pressure curve for the grain geometry. As can be seen in the upper right of figure 13, BurnSim allows us to input propellant formula data and nozzle dimensions. In the upper left all the inputs for grain geometry can be seen.

All this information will help us evaluate our propellant formulation. It will also allow us to determine the grain geometry we should use to help us reach the altitude goals with the burn time of our specific formula once we have selected it. BurnSim's primary is to ensure the team that the propellant formula is safe to test. After testing all BurnSim results will be verified and modified biased on tests and true burn equation coefficients.

3.3.4 Burn Rate - Remington Dasher

Burn rate is pivotal in the requirement of altitude. A slow burn rate may only get the projectile to a few thousand feet, but a longer burn rate can allow for a much higher altitude. A slower burn rate may not offer enough force to overcome the local gravity, so we need to make sure that the burn rate is fast enough to keep the rocket straight and on course, but slow enough to maintain this thrust to get to the required altitude. A key and extremely important equation to keep in mind is listed below.

$$r = aP_c^n$$

This equation is imperative to the success of the motor and thus the project. Here, we have the variable "r" which is the burning rate of the solid propellant [39]. This burning rate is defined as the linear consumption rate normal to the burning surface. This factor can range anywhere from 0.1-2 inches per second [39]. The rate is mostly influenced by the combustion pressure (P_c). We know the casing pressure from our earlier analysis.

Many of these calculations are experimental based which is why it is so important for us to be able to test our different designs. Different simulations can give us close results, but until we do test, we will not have an exact idea on how these geometries and formulations act in the real world. As these equations get more complicated with different grain sizes and complex geometries which means a numerical solver like MATLAB can help us greatly. It is important to be able to compare our real data to the simulations to validate our work and the model we use to get our data. The plan for this simulation is casting our propellant in-line with the data that was used to find the burn rate analytically. We would then use the test stand to time the burn and make sure that the analyical calculation is appropriate with the experimental rate.

4 Design Concepts

4.1 Functional Decomposition

4.1.1 Propulsion System Functional Models

The black box model shown in the figure below depicts the rocket's propulsion system. This model allowed the team to track the main inputs and outputs of the system. The main inputs being the motor itself, chemical energy, and e-matches. All of these are required components to launch the rocket. This model also helps us understand the kind of signals we should expect from the system so that we know it is working. Primally, we expect to hear noise and feel heat. Additionally, when constructing the test stand, we should plan to measure the other expected outputs, thrust and impulse.

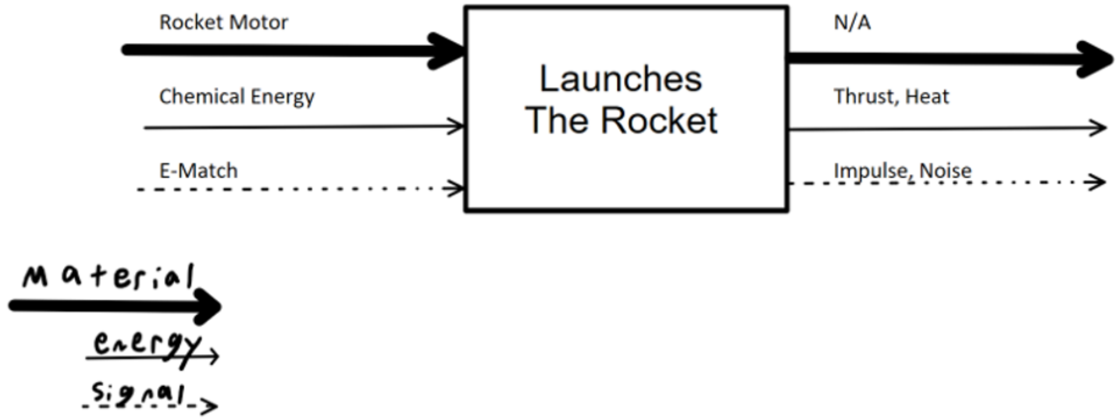


Figure 14. Black Box Model for Rocket Propulsion System

To develop a better understanding of the motor the team created the functional flow model seen below. This model shows us how the motor will interact with the system and the processes the motor will undergo. One of the things of note is that the motor needs to be firmly secured since substantial amounts of various types of energy are moving through the system. The other main thing this model brought to our attention was that the motor needs to carry a significant amount of chemical energy for the rocket to lift off.

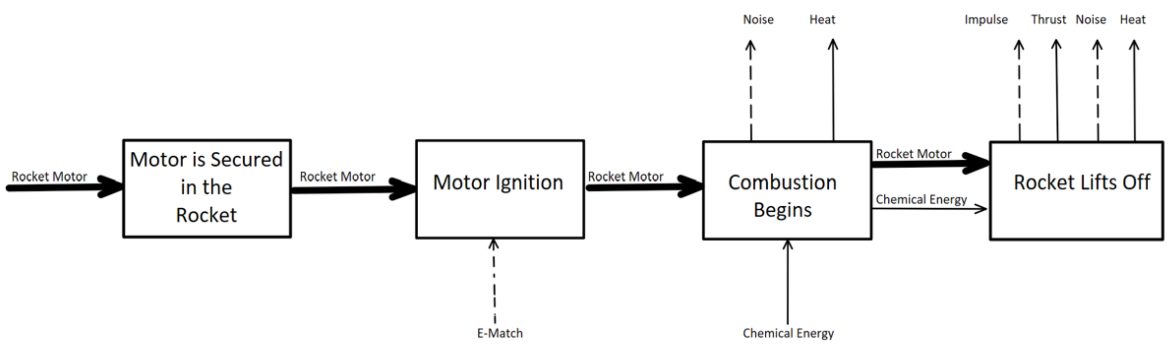


Figure 15. Functional Flow Model for Rocket Motor

Both of these models help the team to identify key points we need to consider as we progress through the project. This makes these models critical to consider as we move into the design phase.

4.1.2 Test Stand Functional Models

The black box model and flowchart for the rocket test stand represent a systematic approach to understanding the inputs, processes, and outputs of the test stand system. In this model shown in figure 16, the inputs include a stable structure, rocket motor, load cell, and a data collection interface. Additionally, figure 18 shows the correlation key between arrow thickness and the processes characteristics for reference. The primary goal or task of the motor test stand is to collect thrust and impulse data from the rocket motor. The output of the black box model includes a stable structure, micro deformations in the load cell, and thrust impulse data.

The flowchart shown in figure 17 further details the sequence of events within the system. It begins with the input of the motor, which is locked into the test stand. As the motor ignites and applies thrust, it generates a force, which causes the load cell to deform, leading to micro deformations in the load cell. The load cell's electrical signals and data are collected and transferred to the data collection interface, where impulse and thrust analysis take place.

This black box model and flowchart are crucial for the project for several reasons. Firstly, they provide a clear visual representation of the entire testing process, ensuring that all necessary components and steps are accounted for. This is essential for the project's success, as any oversight or omission could compromise the quality of data collected and the safety of the testing process. Secondly, it emphasizes the importance of having a stable structure, as this is the foundation on which the entire test process relies. Lastly, it highlights the significance of collecting and analyzing data accurately, as this data is central to understanding the performance of the rocket motor. In summary, the black box model and flowchart serve as a valuable blueprint for the project, ensuring that the testing process is well-structured, efficient, and reliable.

Figure 16. Black Box Model for Test Stand

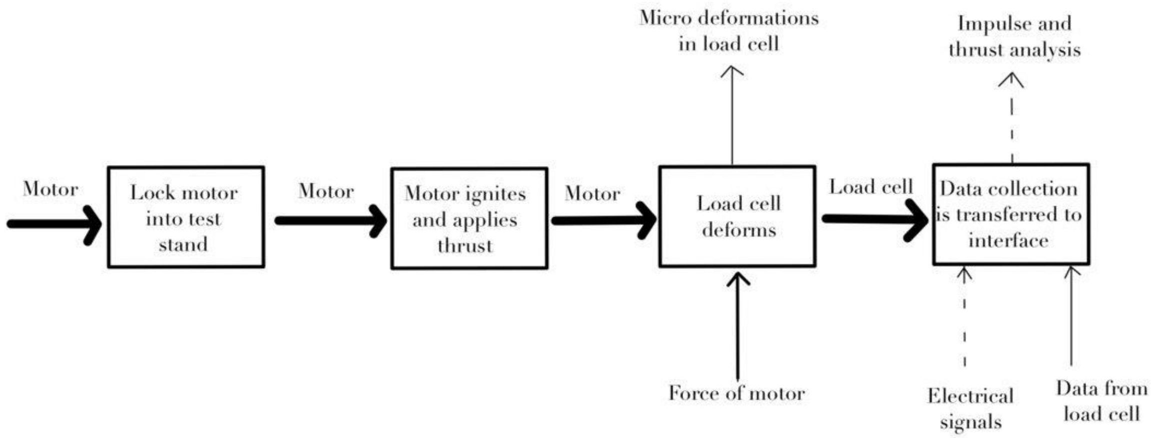


Figure 17. Functional Flow Model for Test Stand

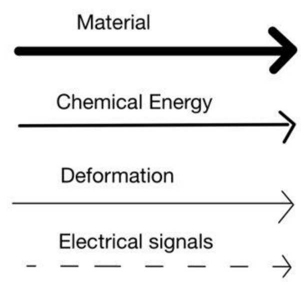


Figure 18. Model Correlation Key

4.2 Concept Generation

4.2.2 Test Stand Concept Generation

First Vertical Test Stand Design:

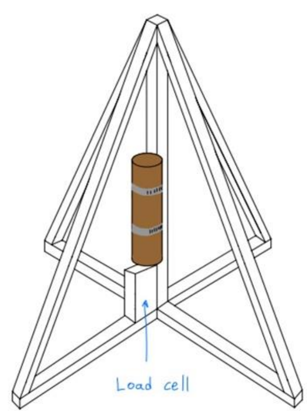
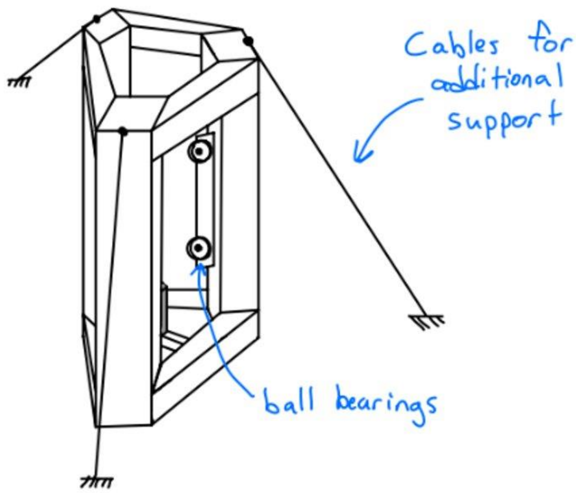


Figure 19. Vertical Test Stand 1

The first vertical test stand design shown in figure 19 is a pyramidal design that may be manufactured with materials that the team already owns. Unfortunately, there is a major flow in this design which makes it a safety hazard. Due to the converging extrusion above the rocket motor, burning hot exhaust will impact the test stand structure and likely compromise its structural integrity.

It is possible that the team could change the orientation of the motor or add an exhaust deflection plate to make this design safer, but that would complicate the design further than our other design options. It does require less material than other test stands but is not worth the safety risk that it poses.

Second Vertical Test Stand Design:



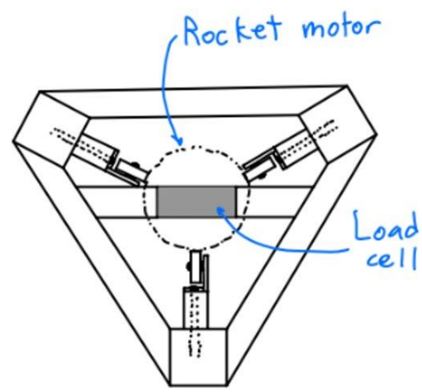


Figure 20. Isometric View of Vertical Test Stand 2 Figure 21. Top View

The second vertical test stand design is shown in figures 2 and 21. This design secures the motor in place with 6 different ball bearings. The ball bearing supports will be attached to adjustable brackets so it can secure different motor sizes. An additional support system is the cables attached to the top of the test stand frame. These cables attach to the ground surrounding the test stand, providing stability against forces that want to tip the stand over.

The stand is designed to minimize the amount of material necessary. The triangular cross-section saves more material than a square cross-section frame. A downside to this design is that it requires multiple extrusion sizes, which may complicate our orders. We may be required to buy additional hardware or order parts from multiple websites, increasing shipping costs.

Third Vertical Test Stand Design:

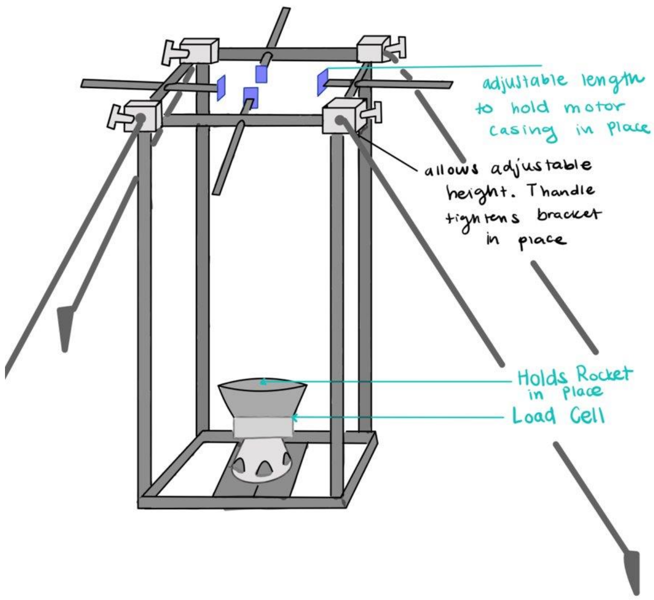


Figure 22. Vertical Test Stand 3

The third vertical test stand design concept shown in figure 22 offers several advantages, the most critical being secure load cell attachment, effective force distribution and multiple attachment points to the motor. Along with these design features, it also includes low friction contact points, adjustability for various motor sizes, ease of construction, and structural stability. However, there are also some disadvantages, such as the need to account for gravity in calculations and the requirement to design a specialized load cell holder.

The initial design parameters and constraints are aligned with project requirements: secure the load cell attachment ensuring accuracy and safety, adjustability accommodates different motor sizes, simplicity aids efficiency, and structural stability is essential for withstanding testing forces. Nevertheless, addressing gravity effects and designing the load cell holder are crucial aspects to consider within the project's timeline and budget.

First Horizonal Test Stand Design:

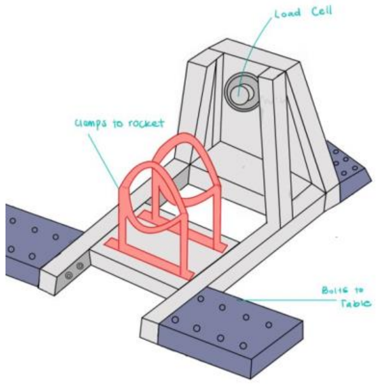


Figure 23. Horizontal Test Stand 1

The first horizontal test stand design concept shown in figure 23 incorporates several key features for stability and universality. It uses mounting blocks to ensure the stand's stability, allows for negligible gravity during tests due to horizontal mounting, and simplifies the setup by directly mounting the load cell to the back plate. Additionally, it accommodates rocket motors of various diameters which is crucial for the projects' goals of building many sized motors during testing. However, the drawbacks of this design include potential friction between clamps and the rocket motor, substantial forces on the plate and supports, and a requirement for a specific motor body height. These initial design parameters and constraints must be carefully considered to optimize the concept for reliable rocket motor testing.

The initial design parameters and constraints of this concept highlight the importance of stability, load cell placement, and versatility for different motor diameters. However, the need to address issues like friction and structural strength is evident. The constraints involve height requirements and the potential for high forces, indicating the necessity for careful engineering to ensure safety and accuracy during rocket motor testing.

Second Horizonal Test Stand Design:

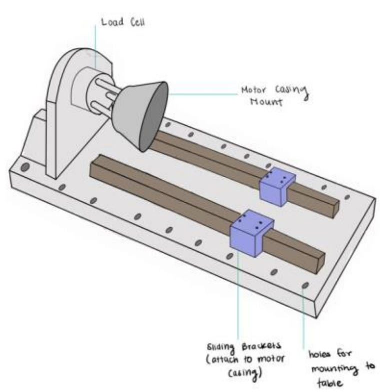


Figure 24. Horizontal Test Stand 2

The second horizontal test stand design shown in figure 24 has several notable advantages, including the absence of significant friction due to the rail slides and negligible gravitational effects due to the horizontal mounting. These features greatly assist in the designs' requirements as they contribute to accurate and reliable testing results. It is a relatively straightforward and cost-efficient design, making it accessible for various projects. However, there are certain disadvantages that also come with this design. The design's minimal contact with the motor may limit its ability to securely hold the motor in place, causing an increase in potential safety hazards. Additionally, the test stand may exhibit high-stress points due to all exhaust forces placed on the back wall, increasing the risk of structural failure.

Regarding the initial design parameters and constraints, this concept prioritizes simplicity and cost-effectiveness. By minimizing friction and gravitational influences, the design can take more accurate data during testing which the other designs cannot do without altering the data after testing. However, the trade-off is that this design has limited contact with the motor, potentially affecting the reliability of the data if the motor is to deviate for its fixed axis. While this design benefits from its simplicity, the lack of connection to the motor body may lead to high-stress points in the design, which need to be carefully considered and engineered to ensure structural integrity and safety. Ultimately, this design concept represents a balance between achieving the necessary precision and minimizing costs and complexity.

Third Horizonal Test Stand Design:

The third horizontal test stand design is shown in Figure 25. It is a sturdy design that utilizes materials that the team already owns (aluminum extrusion). The motor is secured by hose clamps to a linear bearing along the central extrusion. The load cell is secured against a thick baseplate. The stand is secured via bolts into a sturdy surface. The bolts will be strong enough to account for the shear of a level two rocket motor.

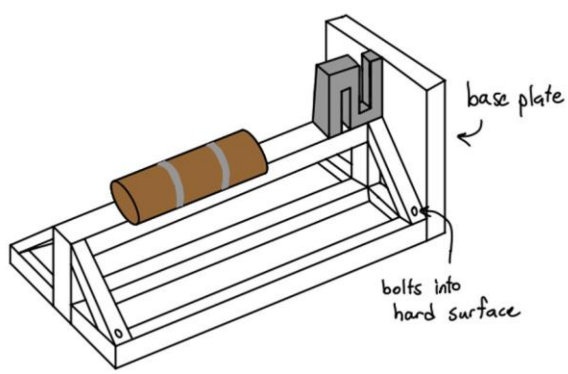


Figure 25. Horizontal Test Stand 3

Rocket Propellant Formulation Design:

All propellant formulations were generated by looking at benchmarking against common formulas, such as cherry limeade. Additionally, throughout this generation we ensured that all percentages fell within the ranges found in the scholarly articles and textbooks form section 3.2.3.

Table 2. Propellant Formula 1, 70% AP

Percent By Weight	**Component**
70%	Ammonium Perchlorate
15%	Aluminum Powder
14%	Binder
1%	Additives

The first variation of the propellant formula has 70% ammonium perchlorate (AP) and 15% aluminum powder (Al). During the current round of concept generations and evaluation the team held the amount of binder and additives constant. Additives will be explored later in the project once some testing has occurred.

Table 3. Propellant Formula 2, 65% AP

Percent By Weight	**Component**
65%	Ammonium Perchlorate
20%	Aluminum Powder
14%	Binder
1%	Additives

The second variation of the propellant has 65% AP and 20% Al. As stated above the binder and additives are held constant. This allows the team to explore the relationship between AP, oxidizer, and Al, fuel, while doing the first round of concept generation for the formula.

Table 4. Propellant Formula 3, 60% AP

Percent By Weight	**Component**
60%	Ammonium Perchlorate
25%	Aluminum Powder
14%	Binder
1%	Additives

The final variation of the propellant has 60% AP and 25% Al. These percentages are on the fringes of the acceptable range for the Al, fuel. Due to this the team expects this formula to burn quickly. This fast burn rate may be helpful; however, it does have the potential to hinder the rocket Performance.

Propellant Grain Geometry Design:

In this design formulation stage, we are taking a deeper look into different grain geometries that can be seen in solid rocket motors. Some geometries offer longer burning times and less thrust while others prioritize a quick burn with low burning times. All this analysis is shown below. All this analysis was done with MIT's "Cherry Limeade" propellant to give us a baseline on our numbers.

Grain Geometry Concept 1: Uniform Concentric BATES

#	Length	Diameter	Core	Inhib.	Type	Prop.
1	2.75	2.557	0.75	0	BATES	Cherry Limeaid
2	2.75	2.557	0.75	0	BATES	Cherry Limeaid
3	2.75	2.557	0.75	0	BATES	Cherry Limeaid
4	2.75	2.557	0.75	0	BATES	Cherry Limeaid
5	2.75	2.557	0.75	0	BATES	Cherry Limeaid

Figure 26. Concept 1: Uniform Concentric BATES Geometry [BurnSim]

For the first grain geometry features the same grain type as all the other grains in the test with all the same core diameter. This design makes it easy to cast many grains at once and only has us buying a single mandrel to form to. This would be the most cost-effective method, but we need performance and not only cost-savings.

#	Length	Diameter	Core	Inhib.	Type	Prop.
1	2	2.557	0.75	0	Finocyl	Cherry Limeaid
2	4	2.557	0.875	0	BATES	Cherry Limeaid
3	2	2.557	0.75	0	Finocyl	Cherry Limeaid
4	4	2.557	0.875	0	BATES	Cherry Limeaid
5	2	2.557	0.875	0	BATES	Cherry Limeaid

Figure 27. Concept 2: Different Grain Geometry [BurnSim]

In this grain geometry concept, we attempted to piece together two different types of grain geometries, three BATES style and two "Finocyl" style geometries. The idea here was to make grain geometries that move into ideal burning rates for different geometries. The expected effect of this geometry style is to progressively use grain styles that burn at higher rates as the web progresses.

#	Length	Diameter	Core	Inhib.	Type	Prop.
1	6	2.557	0.9	0	BATES	Cherry Limeaid
2	4	2.557	0.85	0	BATES	Cherry Limeaid
3	2	2.557	0.8	0	BATES	Cherry Limeaid
4	2	2.557	0.75	0	BATES	Cherry Limeaid

Figure 28. Concept 3: Non-Uniform Concentric BATES Grain Geometry [BurnSim]

For the last grain geometry concept, we took the first two concepts and combined the major factors. From the first generation, we used the same grain geometry type to reduce cost and casting time. From the second generation, we used the aspect of working around increasing burn rates and areas. We did this by increasing the core diameter progressively as the burn rate increases. We can then run each of these simulations and see which one we should choose.

4.3 Selection Criterion

4.3.2 Test Stand Engineering Calculations

First Vertical Test Stand Design:

For the first vertical test stand design, a basic statics analysis was performed to determine the stability of the test stand in two different scenarios. The first scenario, Case A, assumes that the motor is perfectly vertical, in line with the test stand. Case B is a worst-case scenario which assumes that the motor is ten degrees from vertical. See figure 29 for the statics drawings.

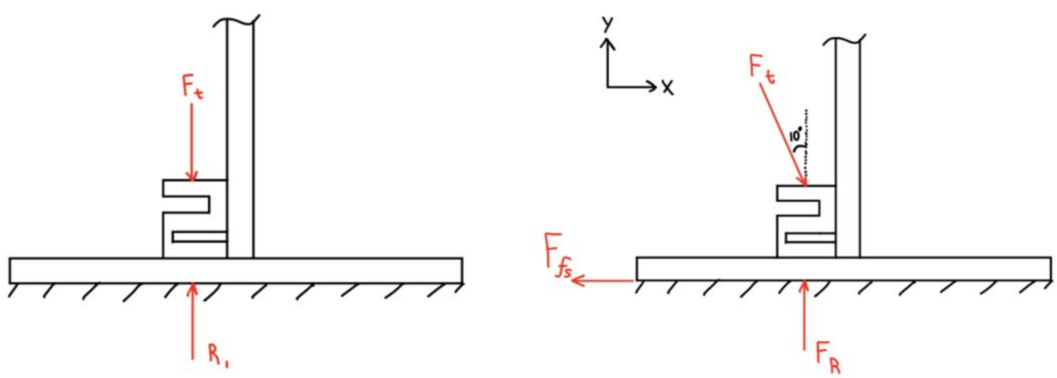


Figure 29. Case A (left) and Case B (right), Vertical Stand 1

The equations to solve for the forces are as follows:

$$I = F_t * t$$

$$F_t = \frac{I}{t}$$

$F_x = F_t * \cos(\theta)$

$F_{fs} = F_R * \mu$

It was assumed that the impulse, (I) is 5120 newton seconds, burn time (t) is 4 seconds, gravitational acceleration (g) is 9.80665m/s^2, and the coefficient of friction (μ) is 0.56. The values are shown in table 5.

Table 5. Vertical Stand 1 Reaction Forces

Force	Case A	Case B
F_t	1280.00 N	1280.00 N
F_R	1280.00 N	1260.55 N
F_x	-	222.27 N
F_{fs}	-	-222.27 N

The conclusion drawn from the data is that if the motor is mounted incorrectly at 10 degrees from vertical, the coefficient of friction between the frame and ground must be greater than 0.1763. The coarse soul at the test site will most likely keep the motor from slipping because of this.

Second Vertical Test Stand Design:

The second vertical test stand utilized all the same equations and assumptions as the first vertical test stand (excluding friction forces). The focus of this analysis was to determine the tension forces present in the supporting cables. The same cases were used (case A is if the motor is mounded perfectly vertical, and case B assumes that the motor is mounted incorrectly, 10 degrees from vertical) (see figure 30).

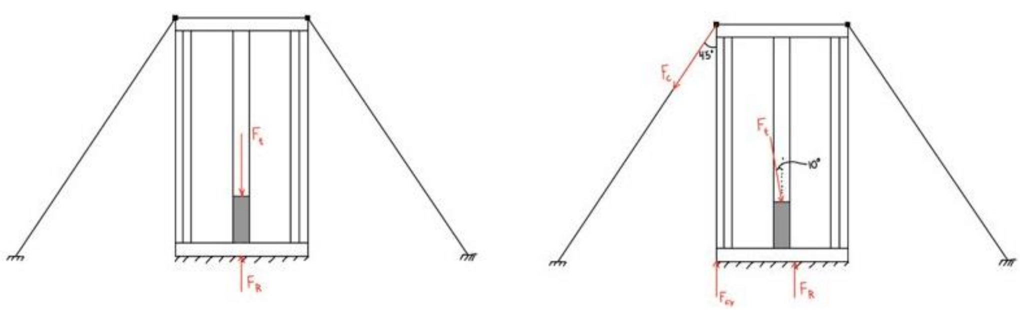


Figure 30. Case A (left), Case B (right), Vertical Stand 2

The results of the calculations are summarized below in table 6:

Table 6. Vertical Stand 2 Reaction Forces

Force	Case A	Case B
F_t	1280.00 N	1280.00 N
F_R	1280.00 N	1260.55 N
F_c	-	314.34 N
F_x	-	222.27 N

According to the calculations, the tension forces experienced in the cable is 314.337 newtons of force. If the team used steel cables, they would be more than strong enough to support the test stand. The biggest point of failure would be where the cable stakes into the ground.

Third Vertical Test Stand Design:

For the third vertical test stand design, the team did a static structural analysis using Ansys Mechanical and Ansys Space Claim to determine the maximum stresses the structure would experience. In figure 31, the result of the analysis shows the distribution of stresses, the highest stresses being red and the lowest being blue.

The engineering calculations for this test stand design play a crucial role in ensuring its structural integrity and safety during rocket motor testing. The maximum force applied to the load cell, equivalent to 5120 N·s of impulse or 287.8 lbf of thrust, is applied to the load cell as it would occur during testing. When this force is applied in the -Y direction to the load cell, the largest stress encountered is calculated to be 381.7 psi. To ensure safety of the structure, the plate and load cell must be reinforced to support this stress while incorporating a factor of safety (F.O.S.) to account for uncertainties and potential variations. Assuming a factor of safety of 1.5, the design must be tailored to withstand a stress of 572.6 psi.

A beneficial feature of this design is that the thrust forces, once applied, will quickly dissipate into the ground after passing through the plate. This design feature minimizes the transmission of these forces to the rest of the structure, reducing the likelihood of structural failures and enhancing overall safety. By allowing the ground to absorb and dissipate the thrust forces, the design mitigates modes of failure that could impact the entire test stand. This approach optimizes the efficiency of the test stand while ensuring that the structural elements primarily affected are adequately reinforced, emphasizing the importance of thorough engineering calculations in creating a reliable and safe testing platform for rocket motors.

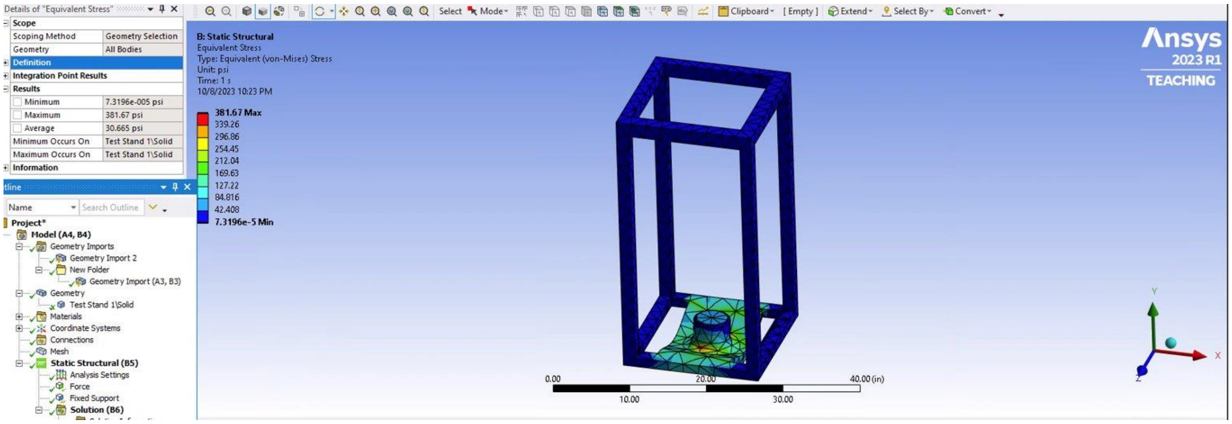


Figure 31. Ansys for Vertical Test Stand 3

This analysis shows the maximum stresses of the structure and how the connection between the load cell and the base plate would be the most likely location for failure. The small red spot between the load cell and the base plate shows this maximum stress, indicating that the design of the connection piece needs to be designed to not deform under this loading. The green section on the rest of the base plate shows that this would experience stresses but not as much as the location directly around the load cell. The rest of the structure is blue, indicating that there is little or no stress in those members.

First Horizontal Test Stand Design:

The engineering calculations provided for this test stand design shown in figure 32 highlight a crucial point regarding the structural integrity of this design. The stress is highest at point B, which means member EB needs to be significantly reinforced to ensure that this beam will not fail, especially during testing. Reinforcing this member could be difficult as it would require a plate of steel which would need to intersect at 90 degrees with member EC. This would then likely need to be welded together and would overall be very difficult to build compared to the other designs. From the static analysis shown in Figure 33, it is found that the maximum stress the design would experience is 409.8 lbf. To ensure that the design can handle loads and variations while maintaining a safety margin, a factor of safety of 1.5 is incorporated. By multiplying the maximum stress of 409.8 lbf by this factor, we get 614.7 lbf, much higher than the horizontal design concepts to follow.

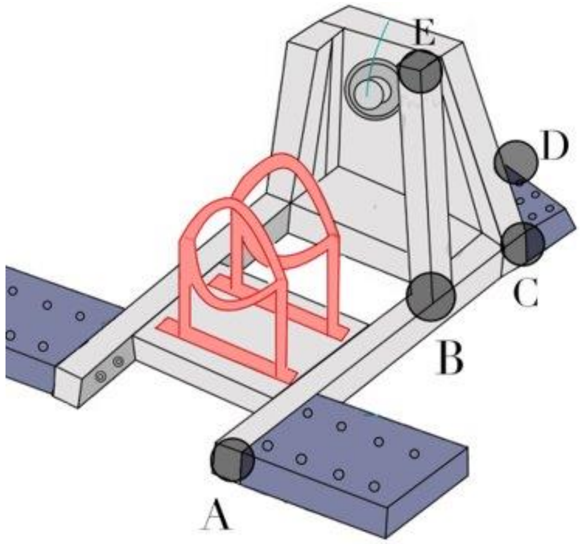


Figure 32. Critical Points for Horizontal Test Stand 1

$$Impulse = 5120\ N * s = (5120\ N * s)\left(\frac{1}{4\ s}\right)\left(\frac{0.224808943 lbf}{N}\right) = 287.76\ lbf\ (Thrust)$$

Where 4 seconds is the approximate burn time

$+ \sum M_D = 0$

$(R_1)(18in) - (F_{Thrust})(9in) - (F_{Thrust})(4in) = 0$

$(R_1)(18in) - (287.8lbf)(9in) - (287.8lbf)(4in) = 0$

$R_1 = 204.9lbf$

$+ \sum F_y = -204.9lbf + R_{Dy} = 0$

$R_{Dy} = 204.9lbf$

$+ \ \sum F_x = 204.9lbf - R_{Dy} = 0$

$R_{Dx} = 287.8lbf$

$+ \sum M_B = 0$

$-(287.8lbf)(9in) - (287.8lbf)(4in) + M_D + (204.9lbf)(18in) = 0$

$M_D = 53.2\ lbf * in$

$-R_{Ay} + R_{Dy} + F_B = 0$

$-R_{Ay} + 204.9lbf + 2 - 4.9lbf = 0$

$R_{Ay} = 409.8lbf$

Figure 33. Stress Calculations for Horizontal Test Stand 1

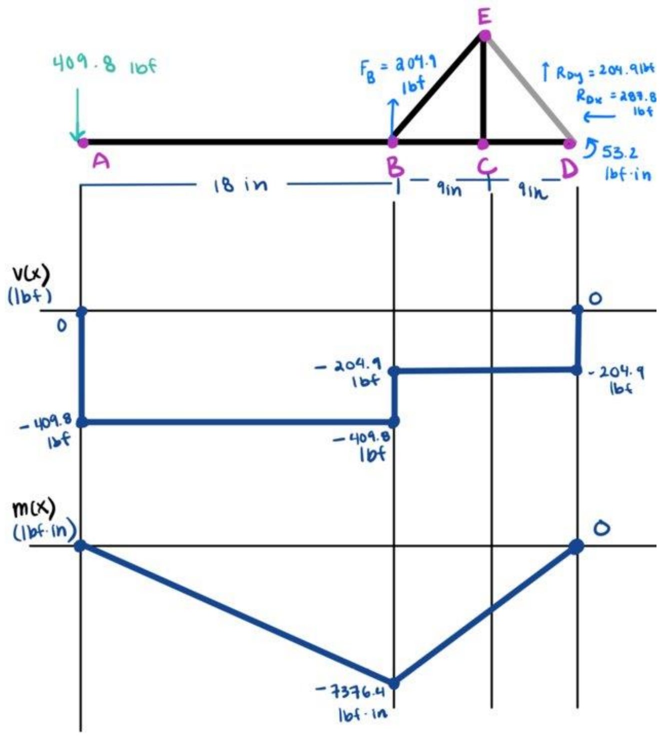


Figure 34. Shear and Bending Moment Diagrams for Horizontal Test Stand 1

Second Horizontal Test Stand Design:

The engineering calculations for this test stand design shown in Figure 35 involve a comprehensive analysis of the forces applied to the motor casing mount. Applying a force of 287.8 pounds-force in the negative X-direction to the mount raises concerns regarding the maximum stress. The calculated force max of 488.5 psi is a significant factor, suggesting that the design would necessitate multiple steel plates to support the back wall. The risk of failure and the likelihood of fatigue and deformation become more apparent under such high stress conditions.

To address these concerns, a factor of safety (F.O.S) of 1.5 is incorporated. Multiplying the initial stress by the F.O.S, the back plate must now be designed to withstand 732.8 psi. This additional engineering consideration highlights the importance of robust structural design and materials selection to ensure the test stand's integrity and safety, especially when subjected to high forces during rocket motor testing.

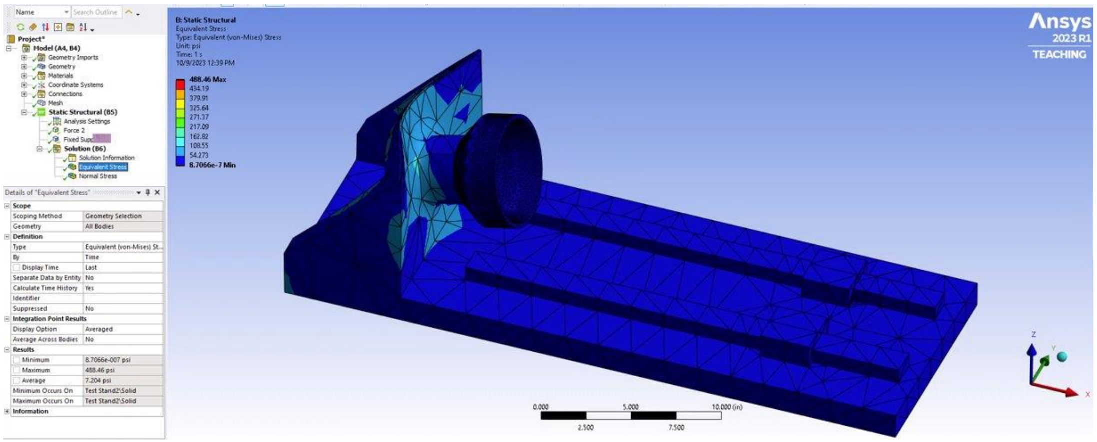


Figure 35. Ansys for Horizontal Test Stand 2

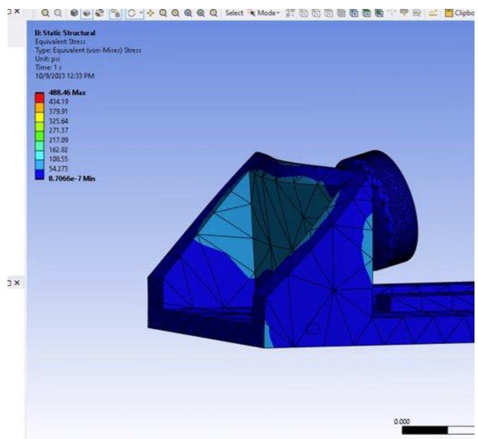
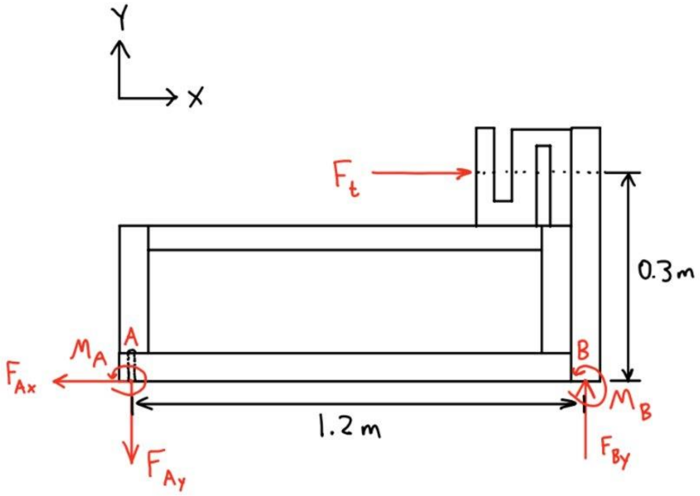


Figure 36. Close-Up of Figure 35.

Third Horizontal Test Stand Design:

For the third horizontal test stand, a basic static analysis was performed to determine the magnitude of forces experienced by the design. To begin the process, a total impulse of 5120 newton seconds, and burn time of 4 seconds was assumed. Multiplying these two values together reveals the average thrust force. The reaction forces and equations can be observed in Figure 37.



$$I = F_t * t$$

$$F_t = \frac{I}{t}$$

$$\sum M = 0$$

$$\sum F_x = 0$$

$$\sum F_y = 0$$

Figure 37. Free Body Diagram and Equations for Horizontal Test Stand 3 Analysis

Results are summarized in table 6:

Table 6. Horizontal Test Stand 3 Reaction Forces

Force	Force (N)
F_t	1280
F_{Ax}	-1280
F_{Ay}	-320
F_{By}	320

Calculations reveal that point A is a critical point in securing the test stand. Due to moment forces, there is a vertical force pulling the test stand upwards at point A. In addition, all the horizontal force caused by thrust is translated to this point. Therefore, the team must be careful in choosing strong enough bolts. There will be a large amount of shear in those bolts.

Rocket Propellant Formulation Design:

The propellent formula has two important quantities to consider the exhaust velocity and the specific impulse. The equation for both values is shown in the two figures below and are strongly related to the altitude the rocket can reach. However, the team uses ProPep 3 to do the analysis quickly. ProPep 3 also includes many other values that will be helpful when designing the nozzle and casing. Unfortunately, like any simulation ProPep 3 makes many idealized assumptions so the velocities, temperatures, and impulses it produces are not accurate to the actual values. So, some testing will still have to be done.

$$c^* = \sqrt{\frac{R'/M \quad T_o}{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}}$$

Figure 38. Exhaust Velocity Equation [31]

$$I_{sp} = \frac{1}{g}\sqrt{2\,T_o\left(\frac{R'}{M}\right)\left(\frac{k}{k-1}\right)\left[1-\left(\frac{P_e}{P_o}\right)^{\frac{k-1}{k}}\right]}$$

Figure 39. Specific Impulse Equation [31]

Figure 40 below shows the ProPep 3 results for the first formula, 70% AP. The exhaust velocity for this formula is roughly 5190 ft/s.

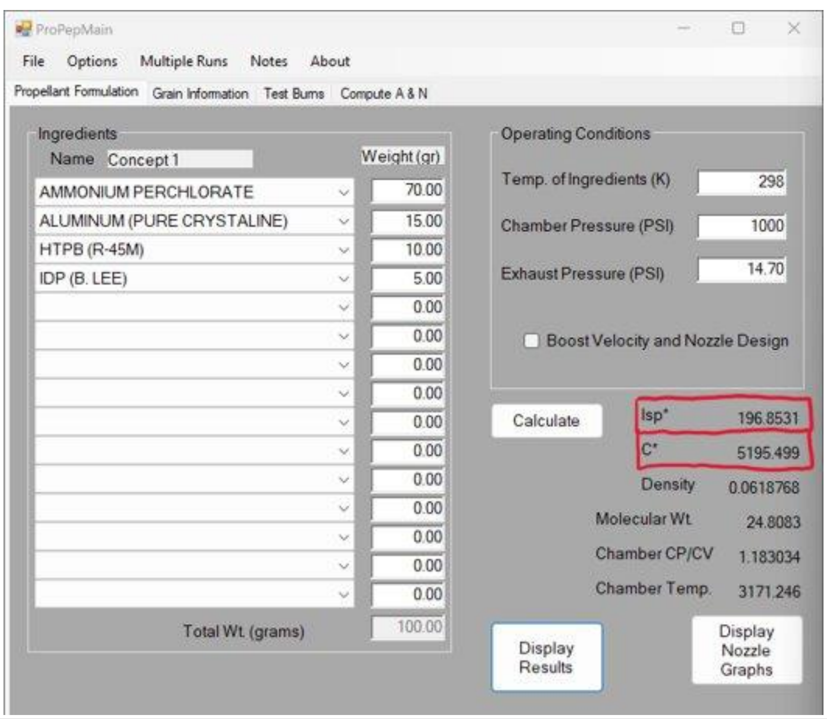


Figure 40. ProPep Results for Formula 1

Figure 41 below shows the ProPep 3 results for the second formula, 65% AP. The exhaust velocity for this formula is roughly 5230 ft/s.

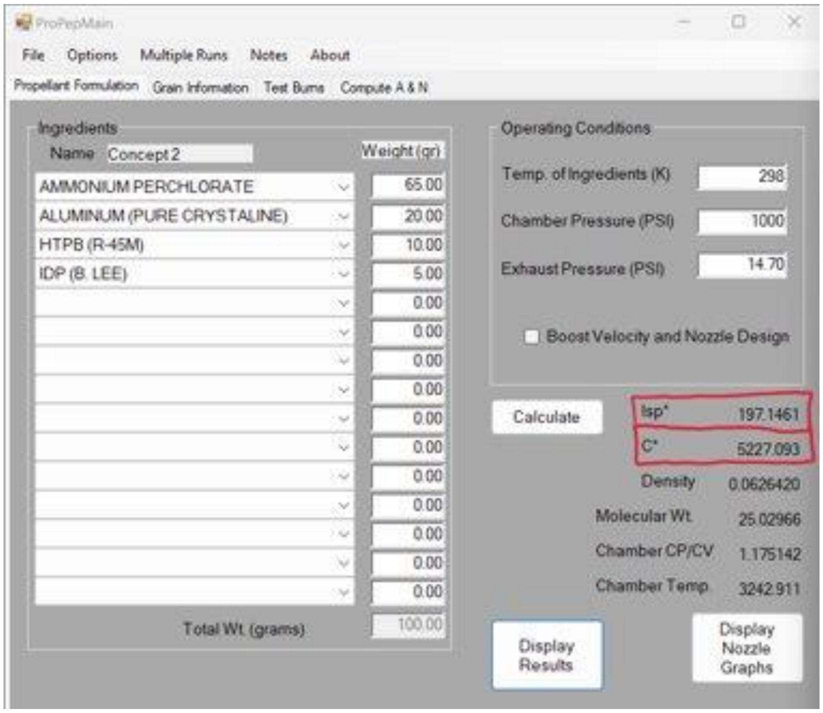


Figure 41. ProPep Results for Formula 2

Figure 42, below, shows the ProPep 3 results for the third formula, 60% AP. The exhaust velocity for this formula is roughly 5080 ft/s.

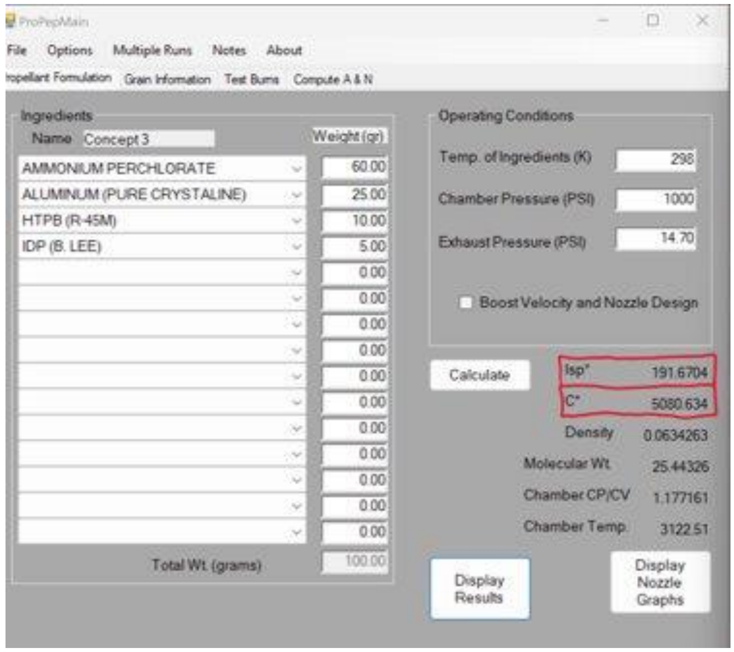


Figure 42. ProPep Results for Formula 3

These results show us that 65% AP has the highest impulse and velocities, while 70% AP has the second highest. The 60% AP formula has a significant drop in these properties. Full results for all these concepts are shown in 7.2 appendix B. in the same order as they are listed here.

Propellant Grain Geometry Design:

For the propellant grain geometry concept selection process, BurnSim was used to generate important metrics like casing pressure, burn time, total impulse, and total propellant mass. Each of these metrics are important in their own way and a brief description will be given for each.

- Casing Pressure: The pressure inside the casing is a very important metric to keep in mind and design around. Too much pressure can cause the gases to leak which reduces the efficiency of the motor and can also cause the casing itself to fail. This would be an expensive error which means we need to do everything in our power to make sure this does not happen.
- Burn Time: We need to make sure that out propellant burns long enough to get us to the maximum altitude possible, but at the same time, it needs to be fast enough to where it is still able to overcome the gravitational potential that is being acted on the body. This is where propellant length and geometry comes into play, but not as important as the total burn time.

- Total Impulse: This metric is important, not only because of our requirements, but also because it defines our average thrust per burn time. BATES style grain geometry is commonly uniform in its thrust curve, so simply dividing the total impulse by the burn time can give us our average thrust which is something we have to consider when it comes to rocket height and performance.
- Propellant Mass: The mass of the propellant is key to achieving a high altitude. If our propellant is too heavy, the propellant will try much harder to get the higher weight off the ground which will use up energy that could be used to get our rocket further up. This means that the least number of grains and the less dense the formula is ideal.

From BurnSim, we were given this data from each of the three concept variants. These are tabulated in tables below.

Table 7. Concept 1 Results

Concept 1: Properties	Concept 1: Results
Max Casing Pressure (psi)	1791
Burn Time (s)	3.41
Total Impulse (Ns)	5387
Propellant Mass (lbf)	3.92

Table 8. Concept 2 Results

Concept 2: Properties	Concept 2: Results
Max Casing Pressure (psi)	2209.9
Burn Time (s)	3.23
Total Impulse (Ns)	5007
Propellant Mass (lbf)	3.637

Table 9. Concept 3 Results

Concept 3: Properties	Concept 3: Results
Max Casing Pressure (psi)	1724.9
Burn Time (s)	4.02
Total Impulse (Ns)	5344
Propellant Mass (lbf)	3.882

4.4 Concept Selection

4.4.1 Test Stand Concept Selection

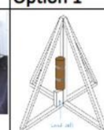
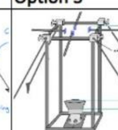
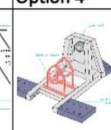
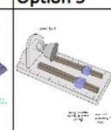
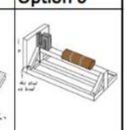
		DATUM	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Criteria	Weight							
Reach minimum altitude	2		0	0	0	0	0	0
Stay within Budget for the Project	2		+++	++	+	-	-	0
Dimensions meet constraints of rocket size	3	D	---	++	+++	--	0	+++
Stand withstands impulse of rocket testing	2	A	--	+	++	+++	++	+
Meet Minimum Thrust to Weight Ratio Set by Tripoli	3	T	0	0	0	0	0	0
Complete final launch by march 2024	2	U	0	0	0	0	0	0
Non-Ferrous, Ductile Casings	3	M	0	0	0	0	0	0
+			6	12	15	6	4	11
0		17	4	4	4	4	5	4
-			13	0	0	8	2	0
TOTAL		0	-7	12	15	-2	2	11

Figure 43. Pugh Chart of Test Stands

By creating a Pugh chart of the test stand design concepts, the team analyzed the concepts based on the engineering calculations within the concept selection phase to determine the best design for the project. By comparing the designs to the datum, chosen to be the Aerocon Systems Horizontal/Vertical Test Stand, a score was given for each of the designs based on the project requirements. These requirements were then weighed on the importance of these in relation to the test stand.

Through this process, it is determined that option three performed the best in comparison to all other test stand designs. This is due mainly to the very high rating for “dimensions meet the constraints of the rocket size” and “withstands impulse of rocket testing” along with the single positive rating for “stay within budget of the project”. Since this design performed the best in the analysis and concept selection, the team has chosen this design to move forward with for the project.

Below, a first iteration CAD model shown in figures 44 and 45 as well as an engineering drawing shown in figure 46 is presented. This model shows how the test stand will allow for a variety of heights and diameters of motor bodies, making it a very versatile design.

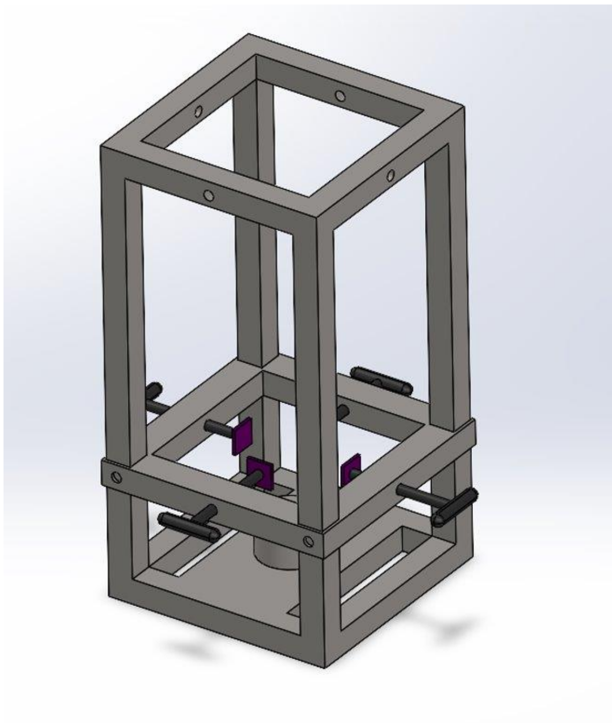


Figure 44. View 1 of Final Test Stand

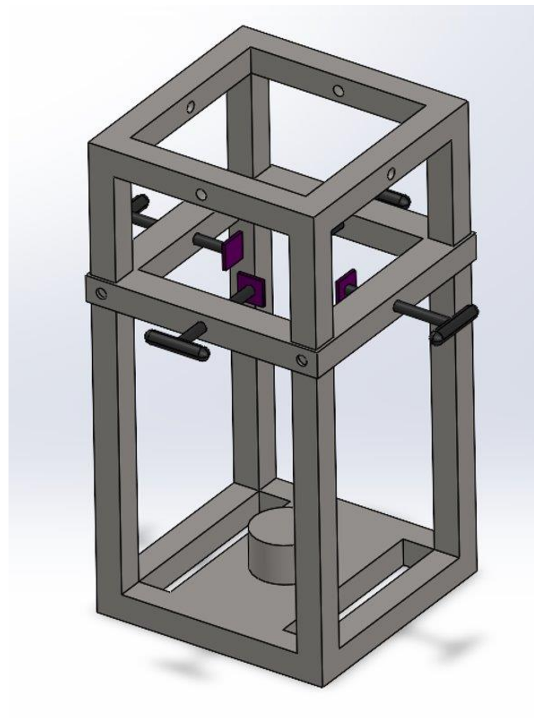


Figure 45. View 2 of Final Test Stand

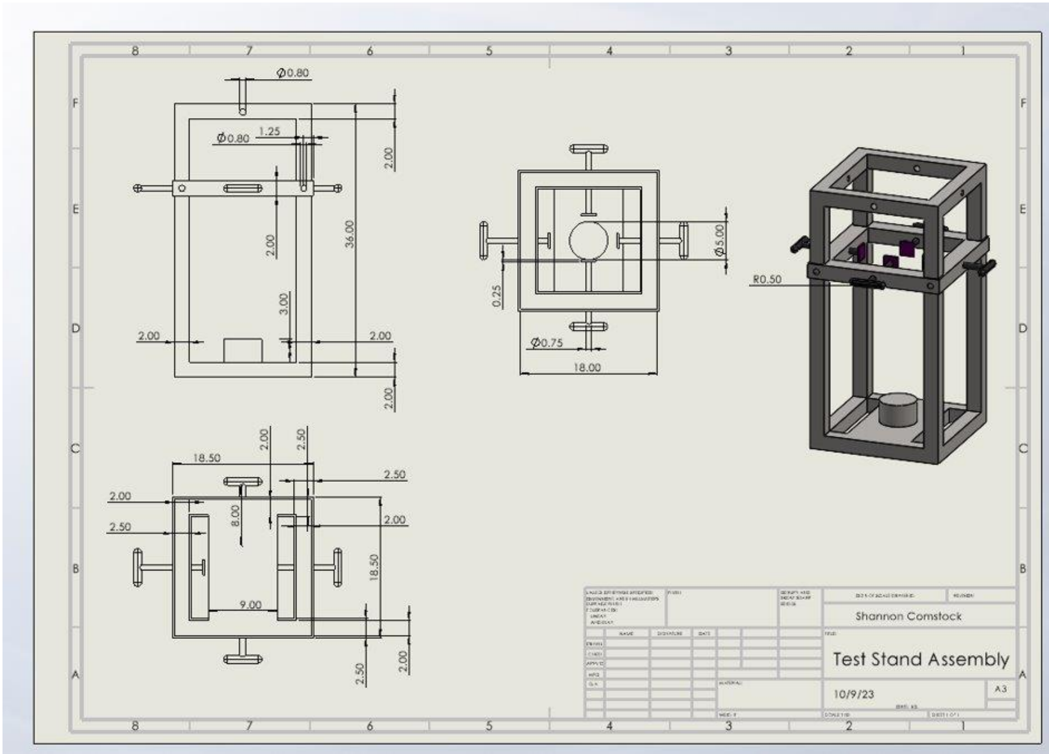


Figure 46. Drawing of Final Test Stand

4.4.2 Propellent Formulation Concept Selection

Criteria	Weight	DATUM	Option 1	Option 2	Option 3
		73% AP	70% AP	65% AP	60% AP
Reach minimum altitude	3		+	++	-
Stay within Budget for the Project	2	D	+	+	++
Dimensions meet constraints of rocket size	3	A	0	0	0
Stand withstands impulse of rocket testing	1	T	-	--	+
Meet Minimum Thrust to Weight Ratio Set by Tripoli	3	U	-	-	--
Complete final launch by march 2024	2	M	0	0	0
Non-Ferrous, Ductile Casings	3		0	0	0
+			5	8	5
0		17	3	3	3
-			4	5	9
TOTAL		0	1	3	-4

Figure 47. Pugh Chart for Propellent Formulas

The datum for Pugh chart in the above figure was set by averaging the benchmarking we used. As can been seen above the 65% AP formula is the best. The next step is to get this formula checked by one of the mentors who has experience with solid propellent. After that we plan to begin looking into purchasing chemicals, propellent mixing, and additives.

4.4.3 Propellent Grain Geometry Concept Selection

		Option 1	Option 2	Option 3	Option 4
Criteria	Weight	Competition Motor	Uniform Concentric	Variying Geometries	Non-Uniform Concentric
Reach minimum altitude	3		+	-	+
Stay within Budget for the Project	2		+	-	--
Dimensions meet constraints of rocket size	3	D	+	+	+
Stand withstands impulse of rocket testing	1	A	-	+	0
Meet Minimum Thrust to Weight Ratio Set by Tripoli	3	T	+	-	++
Complete final launch by march 2024	2	U	-	-	+
Non-Ferrous, Ductile Casings	3	M	0	0	0
+			12	7	14
0		17	1	1	2
-			3	9	4
TOTAL		0	9	-2	10

Figure 48. Pugh Chart for Grain Geometries

For the datum, we used a standard competition motor that has been used by the Rocket Club in the past and has offered decent results. The three concept variants are tested against this datum. We can see that the third concept variant is the winner. We can see that this wins in the Pugh chart and it also has superior data in the design selection criterion tables. A full BurnSim simulation can be shown for each variant in Appendix C. A final CAD drawing is shown below based on the Pugh chart selection.

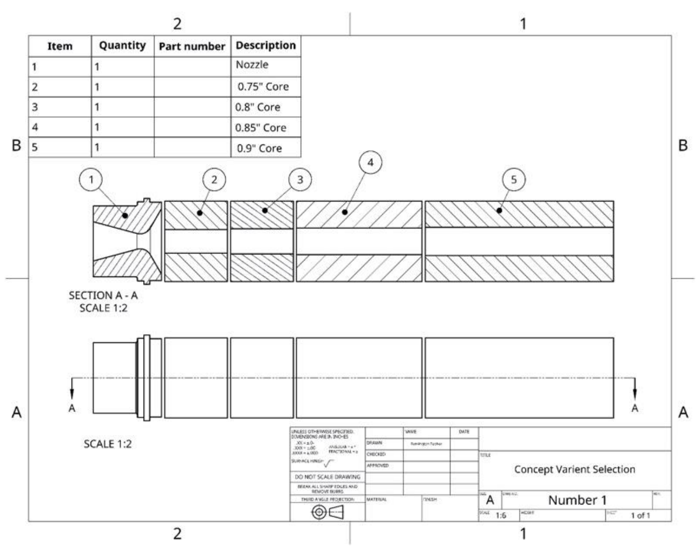


Figure 49. Drawing of Grain Geometries

5 Schedule & Budget

5.1 Schedule

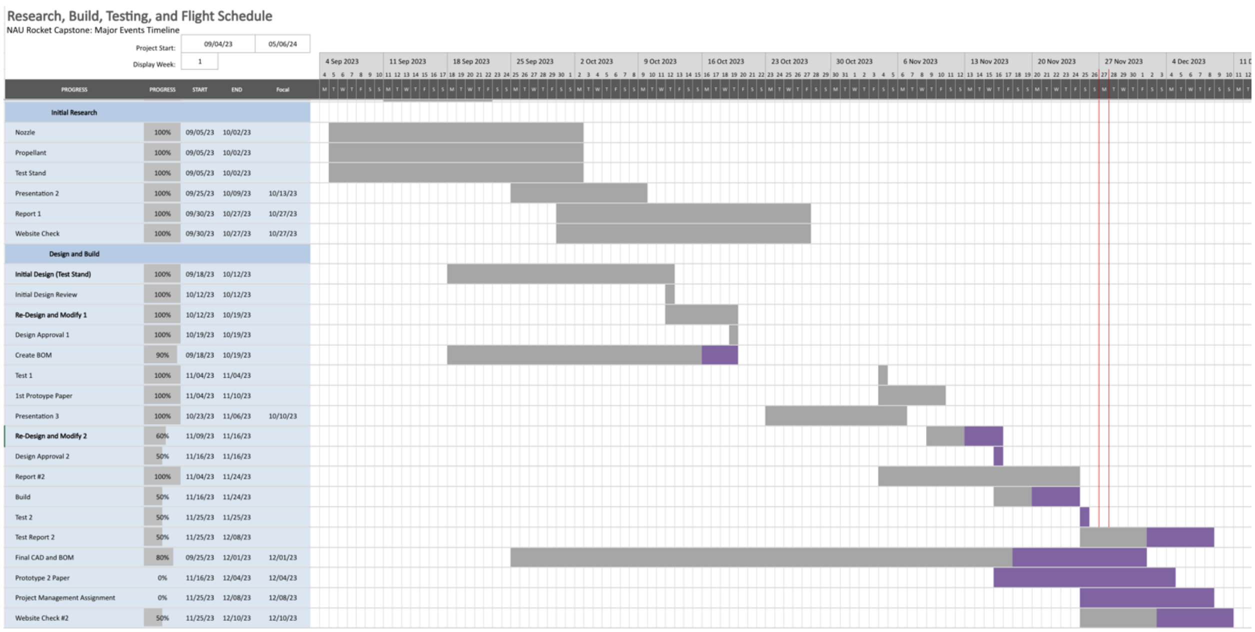


Figure 50. Fall Schedule Gantt Chart

The Gantt chart shown in figure 50 shows the current semester's schedule and the progress made. The grey areas indicate the completion of the tasks while the purple areas indicate the uncompleted tasks. The team has currently completed one launch of a 54 mm motor using our own propellant formula and plan to launch one more 75 mm motor this weekend in Phoenix.

Additionally, the delivery of the chemicals to begin mixing propellant took much longer than expected. Something the team did not account for was that at this time of year, many universities are purchasing chemicals to build rockets for competitions, causing certain chemicals to sell out very quickly. Some chemicals were very difficult to find and took a lot longer to be delivered than anticipated. The team is still on track for having all the customer requirements met by characterizing the propellant in Rocksim using the data from the 75 mm motor testing and hopefully having a successful 75 mm motor launch.

5.2 Budget

Budget Items	Percent of Budget	Dollar Amount	Notes	Funding total	4200
75mm Final Rocket Motor	15.00%	630		Gore Fund	2000
38mm Test Rocket Motor	15.00%	630		GoFundMe	1000
Test Rocket Motors	15.00%	630		EE Team	500
Nozzle	17.00%	714	Primarily funded through undergraduate research	Undergraduate	700
Casing	8.00%	336			
Test Stand	7.00%	294			
Test Stand Electronics	18.00%	756	Primarily funded thorugh EE team funds		
Miscellaneous	5.00%	210			
Total	100.00%	4200			

Figure 51. The Project Budget with Final Expense Total

In figure 51, above, the full budget is shown. The team has fundraised $1000, which gives the team money to put towards the strand burner. Additionally, the test stand cost slightly more money than expected, so the extra spending from the test stand will be covered with some of the new fundraising money. For a more detailed view, see appendix E. The Team will continue to fundraise to pay for a stand mixer needed for propellant mixing.

5.3 Bill of Materials (BOM)

The major element of the project that the team is defining for the Bill of Materials is the test stand. Our test stand has been in development since the beginning of the project, and it is finally at a point where the final CAD and Bill of Materials is completed. The test stand allows us to test our full propellant design with our casing created. The test stand is for when we have full motors to test inside our created casing. The current Bill of Materials is shown below as Figure 52.

SUBSECTION	ITEM NO.	PART	DESCRIPTION
TEST STAND	1	1/4" Washer	Load Distribution
	2	1/4"-20 1/2" Bolt	Solar Shack Extrusion Connection
	3	1/4"-20 5/8" Bolt	8020 Extrusion Connection
	4	4040 Lite Extrusion	Vertical
	5	1/2"-13 All Thread (36in)	Aligns Motor in Holder
	6	10' 2x2x1/8 Angle Iron	Brackets
	7	5/16" Eye Bolt	Support Cable Connection
	8	1/4-20 T-Nuts	Slides into Extrusion to Secure
	9	Steel Plate	Secures Load Cell
	10	Knobs	Easy to turn Motor Aligners
	11	Solar Shack Extrusion	Horizontal Pieces of Stand
	12	Load Cell	Measures Thrust Data
	13	2"x1/8" Flat Bar	Stock for Motor Alignment Threads
	14	5" Aluminum Round	Stock for Motor Holder
	15	M6x12mm Flat Heat Bolts	Securing the Load Cell to Baseplate

STRAND BURNER	19	Pressure Vessel	Holds Pressure from Strand Burn
	20	3000 PSI Pressure Transducer	Digitally Reads Internal Pressure
	21	3/4in NPT Plug	Seals Pressure and Holds Transducer
	22	3/4in NPT Nipple	Connects Two Female Threads
	23	3/4in NPT Steel Tee	Connects Ball Valve and Release to Main Body
	24	3/4in NPT Cross	Connects Vessel to Transducer/Tee to Main Body
	25	3000 PSI Emergency Release	Ensures Pressure Remains in Safe Operating Range
	26	3000 PSI Ball Valve	Releases Internal Pressure After Burn
	27	1/2in Steel Tube	Brings Strand to Middle of Vessel
	28	JB Weld	Holds Tube to top Plug
	29	K-Type Braided Thermocouple	Measures Thermal Data Digitally
	30	3/4in Steel Round Stock	Stock for Strand Holding Platform
	31	3/4in NPT x 1/4in NPT Adapter	Used to Ensure no Air Leaks
	32	Vessel Clamps	Secures the Vessel to Some 2x4's
	33		
CASING	34	3in 0.125 Thick Aluminum Tube	Metallic Casing for Holding Pressure
	35	Internal Retaining's Rings	Secure Forward Bulkhead and Nozzle in Casing
	36	Dash 230 O-Rings	Seals Gas from Exiting Side of Casing
	37	Dash 229 O-Rings	Seals Gas from Exiting Side of Liner
	38	3in Aluminum Round	Used to Make the Forward Bulkhead
	39		
	40		
	41		
NOZZLE	42	Is molded Graphite Rod 1" dia.	Used as an Insert for Max Temperatures

	43	Mini Lathe	For Turning the Phenolic and Graphite
	44	Phenolic Sheet	For The Body of The Nozzle
	45	Hysol 9462	For Securing Graphite Insert to Nozzle Body
	46	Mini-Lathe Drill Chuck	Secures Center Drill and Drill Bits
	47	Center Bits	For Centering a Pilot Hole on Lathe
	48	RTV	For Securing Phenolic
	49	High Temperature JB Weld	Securing Graphite into Nozzle
	50		
	51		
PROPELLANT	52	Ammonium Perchlorate (90u) /1lb	One Part of the Bimodal Oxidizer
	53	Ammonium Perchlorate (400u) /1lb	Second Part of the Bimodal Oxidizer
	54	Atomized Aluminum /1lb	Fuel for the APCP Propellant
	55	Lamp Black /1lb	Pigmented Black Powder
	56	R45 HTPB /1gal	Binder and Emulsifier
	57	DOA /0.5gal	Plasticizer
	58	MDI	Room Temperature Curative
	59	Silicone Oil	Emulsifier and Surfactant
	60	Spatulas	For Reusable Mixing
	61	Glass Mixing Cups	For Reusable Mixing
	62	Popsicle Sticks	For Disposable Mixing and Weighing
	63	Two Part Silicone Mold Mix	For Casting Propellant Strands
	64	Mold Release Spray	For Ease of Removing Propellant Strands
	65	Mineral Spirits	Way of Cleaning Tools and Footwear
	66	7/16in Vented Alignment Cap (38mm)	Grain Casting Hardware
	67	7/16in Non-Vented Cap (38mm)	Grain Casting Hardware
	68	5/8in Vented Alignment Cap (54mm)	Grain Casting Hardware
	69	5/8in Non-Vented Alignment Cap (54mm)	Grain Casting Hardware
	70	7/8in Vented Alignment Cap (75mm)	Grain Casting Hardware
	71	7/8 Non-Vented Alignment Cap (75mm)	Grain Casting Hardware
	72	7/16in Mandrel	Grain Casting Hardware
	73	5/8in Mandrel	Grain Casting Hardware
	74	7/8 Mandrel	Grain Casting Hardware
	75	38mm Liner and Casting Tubes	Grain Casting Hardware
	76	54mm Liner and Casting Tubes	Grain Casting Hardware
	77	75mm Liner and Casting Tubes	Grain Casting Hardware
	78	Respirators	Ensuring Mixing is Safe

	79	Nitrile Gloves	Ensuring Mixing is Safe
	80	Tier	Dampens Table Vibrations
	81	Wood Sheet	Casting Tabletop
	82	Acrylic Sheet	Vacuum Chamber Lid
	83	Sealant	Vacuum Chamber Lid
	84	Stand Mixer	Mixing Large Amounts of Propellant at Once

Figure 52. Bill of Materials

The test stand features two different types of supports, 8020 Brand 4040 Lite Extrusion and recycled extrusion from the “Solar Shack”. This decision was made to reduce costs and recycle efficiently. T-Nuts are used to secure the extrusions together which are threaded to ¼"-20 bolts. The different lengths of bolts correspond to which extrusion is being connected to what. 0.5” bolts are being connected to the “Solar Shack” extrusion and the 0.625” (5/8”) bolts are being connected to the 4040 extrusions. The base plate is a 10 mm thick plate of aluminum given to the team by professor Dr. Jennifer Wade. The base plate had to be drilled and surfaced, but the result allowed for increased stability and ensured safety when handling.

The team created the brackets for the extrusions and all-thread brackets. The extrusion brackets allowed the team to manufacture 90-degree brackets much cheaper than we would have had to buy them for. The all-thread brackets allow us to use a threading to secure the motor. The parts not pictured are stability wires that are connected to stakes hammered in the ground. These increase safety as well of the motor is installed unevenly or not level. Ideally, these cables would never carry any significant loads. Additionally, the manufactured bill of materials is shown in appendix 12.7.

Total Overall Parts	315
Total Number of Unique Parts	75
Number of Parts Received	75
Percentage Manufactured by time	**96.41%**
Percentage Manufactured by part	**95.51%**
Percentage Purchased	**100.00%**
Percentage On-hand	**100.00%**
Parts We Need More Of	0
Parts Yet to Be Used	0

TOTAL COST ($)	$2,668.84

6 Design Validation & Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

6.1.1 FMEA- Test Stand

Product Name: Motor Test Stand		Development Team: Shannon Comstock, Remy Dasher, Andrew King, Grace Morris				Page No of			
System Name: Motor Testing						FMEA Number			
Subsystem Name: Thrust and Impulse Analysis						Date 11/1/2023			
Component Name:	Test Stand								
Part # and Functions	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Severity (S)**	**Potential Causes and Mechanisms of Failure**	**Occurance (O)**	**Current Design Controls Test**	**Detection (D)**	**RPN**	**Recommended Action**
Top Brackets	Temperature Deformation	Top extrusion bars and brackets will loosen due to expansion from motor exhaust heat, decreasing the structural interity over time	3	Motor exhaust reaches high temperature	4	Maintenance requirement to tighten all bolts	2	24	None
	Thermal Fatigue from the expansion and contraction from the exhaust heat on the brackets	Crack propogations can cause brackets to fail, decreasing the structural integrity	4	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	3	24	None
Bottom Brackets	Force Deformation	The brackets warp causing the structural integrity to decrease.	2	Impact loading from thrust force	2	Designed to withstand max loading	3	12	None
Top Extrusion Bars	Temperature Deformation	The aluminum extrusion warps from heat exposure, causing structure to deform and potentially effect grip on motor	6	Motor exhaust reaches high temperature	5	Coat/ cover the parts exposed to heat with thermal sheilding	4	120	Simulate thermal analysis of these components and detemrine if design needs to be altered
	Thermal Fatigue from the expansion and contraction from the exhaust heat	The aluminum extrusion fractures/ fails, causing motor to lack support in its fixed position	3	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	3	18	None
Bottom Extrusion Bars	Force Deformation	Instability in motor mounting during testing may cause motor to become disloged and become a projectile	9	Impact loacing from thrust force	4	Designed to withstand max loading	5	180	Simulate structural analysis of these components and determine if design needs to be altered
Bolts	Force deformation (Shearing)	Bolts shear during testing, potentially causing bracket to be unsupported	4	Impact loacing from thrust force	5	Designed to withstand max loading	4	80	None
	Force Deformation (Normal Stress)	Bolts buckle from compressive stress causing lack in structural integrity	4	Impact loacing from thrust force	5	Designed to withstand max loading	3	60	None
	Temperature Deformation	Bolts come loose from the structure, causing instability, potentially lack of support for motor	4	Motor exhaust reaches high temperature	2	Maintenance requirement to tighten all bolts	2	16	None
	Thermal Fatigue from the expansion and contraction from the exhaust heat	Bolts crack during tesing, decreasing structural integrity	2	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	2	8	None
T-Nuts	Force Deformation (Normal Stress)	Loosens from bolts, compromising the strength of the brackets hold on the extrusion	2	Impact loacing from thrust force	1	Maintenance requirement to tighten all bolts	2	4	None

Figure 53. FMEA for Test Stand

Through the process of defining potential points of failure in the test stand design, the team has identified issues which may cause deformation or failure of the system which need to be addressed. The most important failure modes which were most probable include the top extrusion bars deforming due to temperature fluctuations, while the bottom bars face the risk of deformation under external forces. To address these concerns, practical mitigation strategies are being considered. One approach involves the application of a thermal shield or coating to the top extrusion bar, providing a protective layer against temperature-induced deformation. Additionally, the team is exploring various methods for connecting the load cell plate to the extrusion bar to minimize the risk of force-related deformation.

To assess potential risks for the design of the test stand, the team is applying Ansys static structural and thermal simulations. This analytical approach allows us to evaluate the structural integrity and thermal resilience of the system under different conditions. In parallel, a comprehensive testing procedure has been developed to validate the simulations and identify any real-world issues. This involves conducting tests on the test stand, where motors will be burned to simulate operational conditions. The assessment includes a thorough check for deformations in the systems components and an inspection of bolts to ensure they remain securely fastened.

6.1.2 FMEA- Nozzle

Product Name	NAU Rocket Club Capstone	Development Team: Shannon Comstock, Remington Dasher, Andrew King, Grace Morris				Page No of			
System Name	Carbon Rocket					FMEA Number			
Subsystem Name	Propulsion Subsystem					Date: 11/3/2023			
Component Name	75mm Rocket Nozzle								
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
graphite insert for throat	Overpressurization of motor casing - Ductile Fracture	Explosion of motor casing, mounting points of nozzle are sheared off	10	Cross-sectional area of throat is too small	3	Measure precise throat diameter with micrometers	1	30	Pay special attention during design process, and ensure the insert has been machined to the correct diameter
	Throat area experiences extreme erosion	Decreased thrust performance	5	High temp. exhaust, abrasive granules present in exhaust gas	4	Simulations, and small scale experimental burn	3	60	Pick isotropic graphite, pick low-temperature propellant.
	Mechanical vailure via crack propogation	Fracturing of graphite insert, rapid decrease in thrust	8	Thermal expansion	2	Ensure proper fitting, and FEA simulations	3	48	Choose temperature resistant graphite, and consider adding insulation to reduce thermal expansion. Ensure the diameter is the same as the height of the insert
	Insert is ejected out of nozzle due to force of exhaust gas	The insert becomes a high-velocity projectile and the rest of the propulsion assembly may fail	10	If the step-down that holds the insert in place is too weak	1	Perform FEA on parts to ensure required strenth	2	20	geometry, precicely machine graphite for a press-fit, Heat up metal nozzle during press fit.

Figure 54. Major Element of FMEA for Nozzle Design

In this failure mode analysis, several worst-case scenarios for the nozzle sub-assembly were considered. The first part considered is the graphite throat insert. The purpose of this component is to reduce damage from the hot exhaust gases through a property known as ablative cooling. It is possible for this part to crack apart either due to thermal expansion or be ejected from the nozzle due to high chamber pressure. Both cases are dangerous to spectators of the rocket launch and can cause a catastrophic failure of the entire propulsion system. To mitigate these issues, extensive calculations/simulations will be done and ensure high-quality iso-molded graphite is used along with proper insulation.

Next is the copper converging-diverging nozzle part. This part can experience mechanical failure due to flow separation in the supersonic region of the nozzle and overheating from the exhaust gases. Failure of this part would also be catastrophic but can be avoided by ensuring that it has been machined properly (inside surface is smooth), material has high thermal conductivity (reduces buildup of heat on the inside surface of the nozzle), and simulation in ANSYS Fluid.

The last part considered in this FMEA analysis are the O-rings. If there are factory defects causing abnormalities in the material, or the O-ring grooves are not correctly fitted, the effects are dangerous. An improper fit will allow hot gases to escape through the motor/nozzle fitting. These hot gases will quickly heat up parts that are not designed to be subjected to those conditions, which may result in a catastrophic failure of the propulsion system.

6.1.3 FMEA- Propellant

In order to ensure that the propellant design is safe the team performed an FMEA analysis. This analysis considered the propellant grains, the liners, the casting tubes, and the E-matches. Failures with the liners, casting tubes, and the E-matches would only occur if there is a manufacturer error, so there is not much mitigation the team can do aside from rough quality checks. The primary failure concerns of this component occur with the propellant grain. The most concerning of the FMEA results, which are shown in figure 55 below, is that the propellant grain would experience force deformation.

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Propellant Grain	Force Deformation	Propellant falls out of rocket either before or during combustion depending on severity, this leads to unsafe conditions for spectators and decreased altitude performance	9	Incorrect propellant formulation; Propellant is not fully cured	4	Hardness checks	2	72	Two or more team members should look over the grains prior to launch
	Accelerated Burn Rate	Pressure builds and the rocket explodes, or the fuel burns too fast and decreases altitude performance	10	Propellent contains voids due to errors in manufacturing processes	3	Density checks	2	60	Include a shake table in manufacture to reduce size and occurrence of voids
	Decelerated Burn Rate	Minimum thrust-to-weight ration is not meet and rocket can not lift off	7	Incorrect propellant formula	7	Iterative formula testing and analysis	1	49	Double check final iterations with a mentor prior to launch

Figure 55. FMEA of the Propellant with Focus on the Most Important Failure Modes

If the propellant grain deformed it is possible for some propellant to be ejected from the rocket without combusting or for this unignited propellant to block the nozzle exit. If this happens it would be dangerous for spectators and could greatly increase the casing pressure. If the nozzle was blocked, then the pressure increase would be beyond the maximum pressure the casing is designed for. In order to avoid this the team will perform a shear analysis to ensure the propellent will cure with a high enough strength so that there is no propellant shearing off. Other failure modes are discussed in appendix D, which contains the rest of FMEA.

6.1.4 FMEA- Casing

The motor casing must be reusable and safe within its operation. A ductile and non-ferrous casing material must be chosen to mitigate the risks associated with a high-pressure vessel. This is why a Failure Modes Effect Analysis (FMEA) was conducted to determine where the major failure point could occur in this part of the project. The major analysis done here was the casing itself, the bulkhead that keeps the pressure inside the casing, as well as the nozzle which is where the escaped gasses flow which in turn provides the required thrust to move the rocket. The major FMEA topic is given below as Figure 56.

Product Name	NAU Rocket Capstone	Development Team: Shannon Comstock, Remington Dasher, Andrew King, Grace Morris							
System Name									
Subsystem Name									
Component Name	Motor Casing								
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Aluminum Casing	Casing rupture	Explosive decompression caused by rapid gas fluxuation	10	Voids in propellant grains, inconsistant aluminum rounds, incorrect milling	5	Grain analysis, Aluminum checks	4	200	Assign 1-2 teammembers to analyze each grain for voids, make sure during milling that aluminum is sound

Figure 56. Major Element of FMEA For Casing Design

The major element with the casing is a rupture. A rupture would not only destroy the casing but would also hurt the test stand and create an unsafe situation around the testing site. The primary cause of this rupture would be either inconsistent manufacturing of the aluminum tube or incorrect machining of the casing after arrival. The major mitigation to this issue is making sure that upon arrival, the aluminum tube is within specifications around the circumference of the tube as well as making sure that the machining is consistent and accurate for our calculations. A full view of the

6.2 Initial Prototyping

6.2.1 Physical Prototyping

The physical prototype that we had created involves the entirety of the test stand. With countless hours working on the design, analysis, and construction of stand, the test stand is at a point where just the load cell and motor mount must be mounted. Once the electrical engineering team is done with the programming and testing, the test stand will be operational. The major question that was meant to be answered was if this stand would be our final design. From the analysis done, the stand passes all major safety requirements as well as being variable for multiple different sizes of motors. The motor holder even has capability for 96 mm motors. This consideration was made for future Rocket Club members who may gain Level 3 Certifications to be able to test on larger structural loadings.

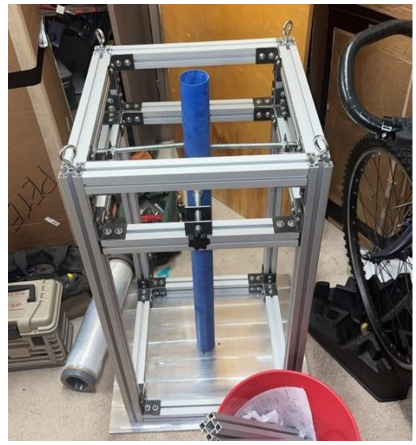


Figure 57. View 1 of Final Test Stand Figure 58. View 2 of Final Test Stand

In the Figures above, the test stand is holding a blue tube which acts as what our motor would look like inside the test stand. The all-threads grip well, but this will be analyzed later in the report. All that is left is to secure the load cell and the motor holder and the test stand will be ready to use and give us accurate data about the burn rates and thrust characteristics.

6.2.2 Virtual Prototyping

The team must ensure that testing the propellent formulation would be safe prior to testing. In order to that the team created virtual prototypes of the propellent in ProPep 3 and BurnSim, these were then compared the known burn curves for cherry limeade, MIT's solid rocket formula. This comparison will inform the team if the propellant behaves in ways that would be concerning during testing.

The virtual prototype starts with running the formula through ProPep 3. The results of this are shown in figure 59. This result shows that the exhaust exit velocity, C* is within a reasonable value, this was confirmed with Joshua Becker who has been kind enough to mentor and assist the team.

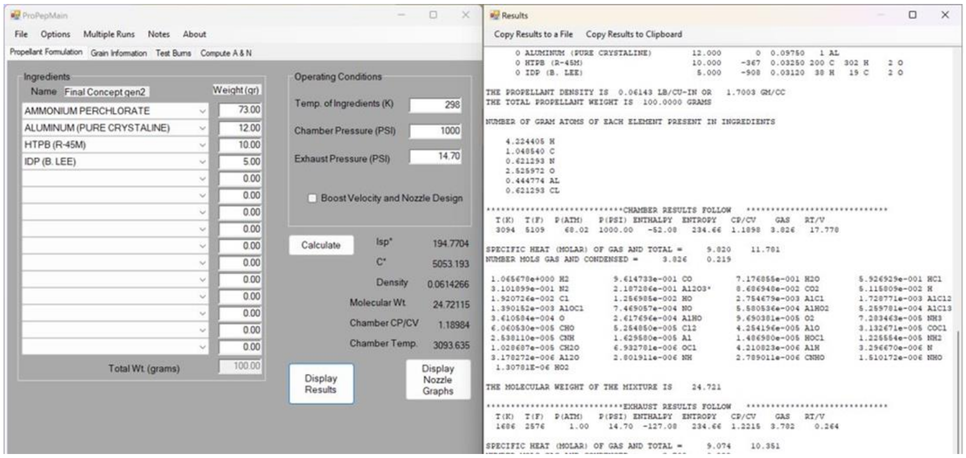


Figure 59. ProPep 3 Results for the Team’s Formula

The second stage of the virtual prototype is to run this formula thought BurnSim and compare that to BurnSim results for cherry limeade. The BurnSim results for the team's formula is shown in figure 60. As can be seen on the thrust curve there are no strange drop offs or spikes. The BurnSim results for cherry limeade are shown in figure 61. The cherry limeade results have a very similar shape, the only difference being that cherry limeade burns for longer with a lower mass flux than the team's formulation. The differences between the two formulations are not enough to warrant any safety concerns which would prevent physical testing. Based on these results the team is safe to move to strand testing of the propellent once all chemicals have been ordered.

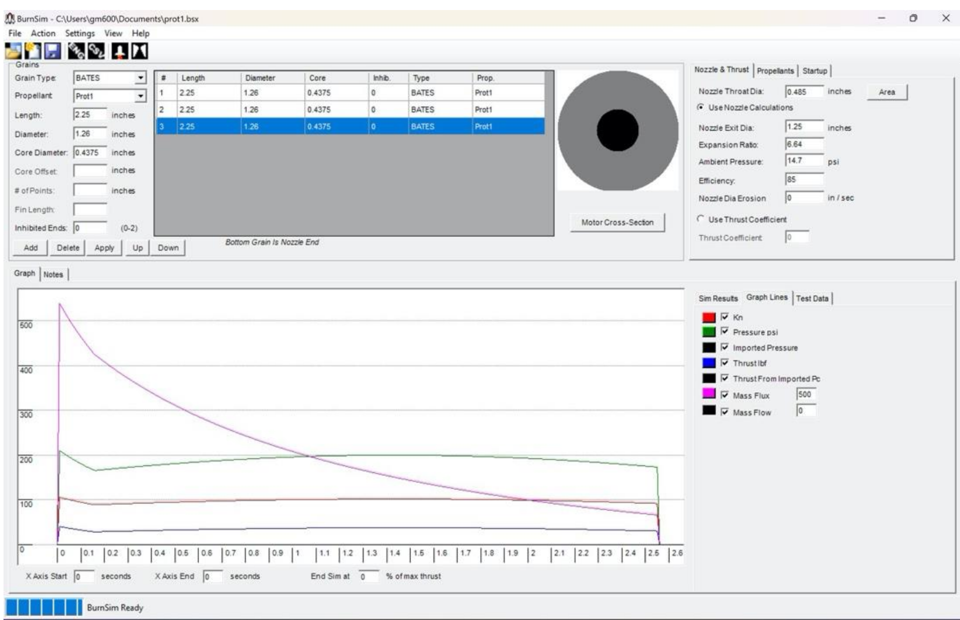


Figure 60. BurnSim Thrust Curve for the Team’s Formula

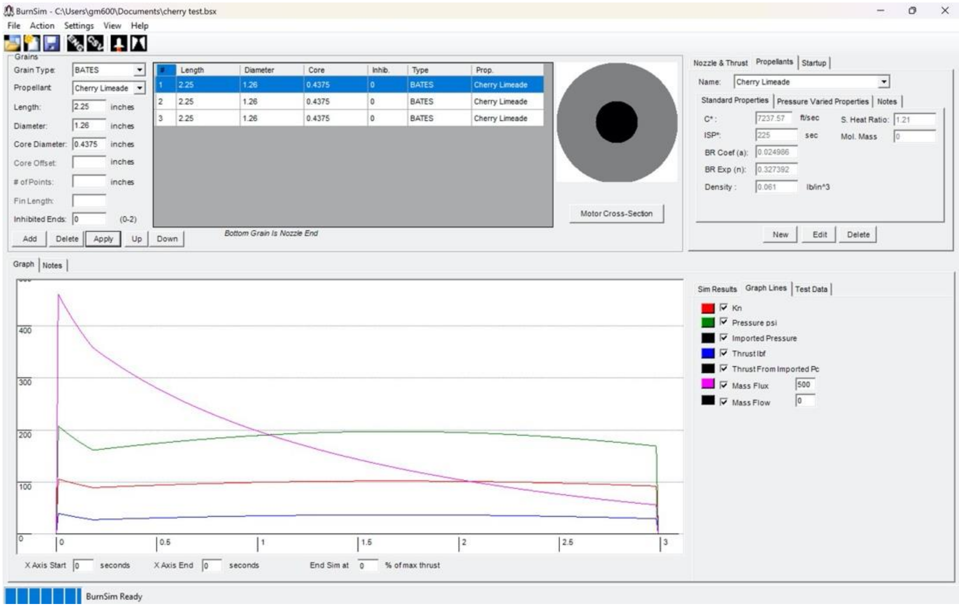


Figure 61. BurnSim Thrust Curve for MIT’s Formula

6.3 Other Engineering Calculations

6.3.1 Test Stand Calculations

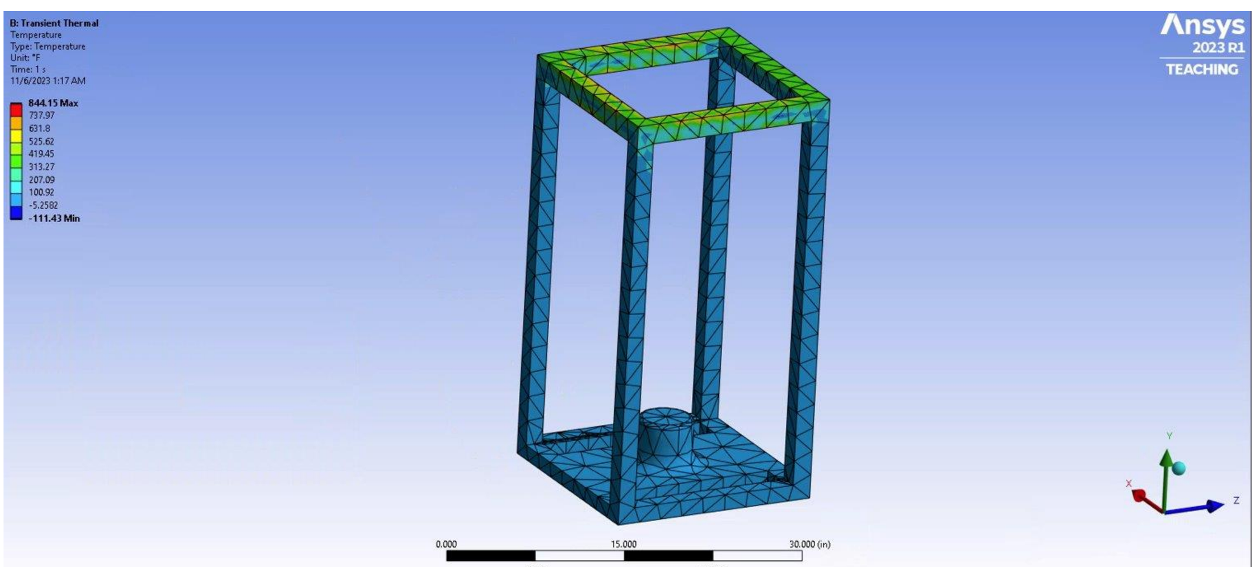


Figure 62. Ansys Thermal Analysis

In order to analyze if the materials of the structure will deform, the team used Ansys to do a thermal analysis of the system. By applying a direct heat flux of 230 x 10^4 W/m^2, which is the approximate heat output of the motors exhaust, a maximum temperature of 844.15 degrees Fahrenheit is applied onto the aluminum extrusion. This raises concern as aluminum begins to exhibit warping at temperatures exceeding 400 degrees Fahrenheit. To mitigate the risk of potential damage, a recommended course of action involves wrapping the aluminum extrusion in thermal shielding, thereby providing a protective layer to counteract the adverse effects of elevated temperatures.

Considering the contrasting thermal properties of aluminum and steel, where steel can withstand higher temperatures before warping (up to 1500 degrees Fahrenheit), the steel brackets and bolts do not raise concern for the heat it will experience. By proactively implementing thermal shielding around the aluminum extrusion, the team aims to prevent any thermal fatigue and ensure that it operates within the safe temperature limits.

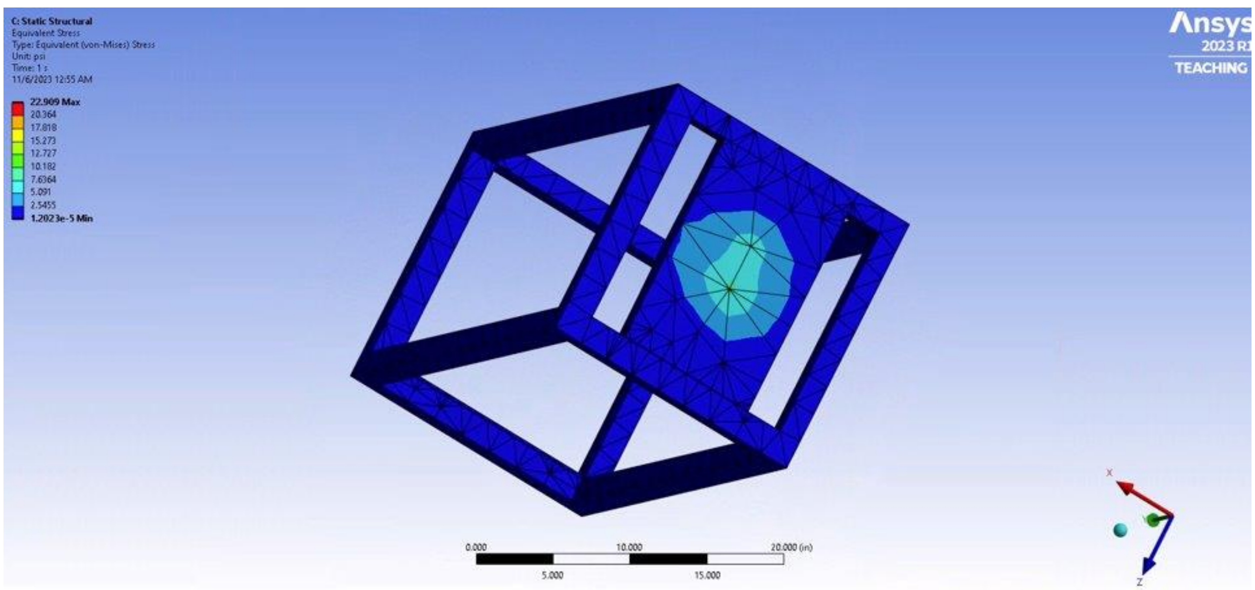


Figure 63. Ansys Static Structural Bending Stress Analysis

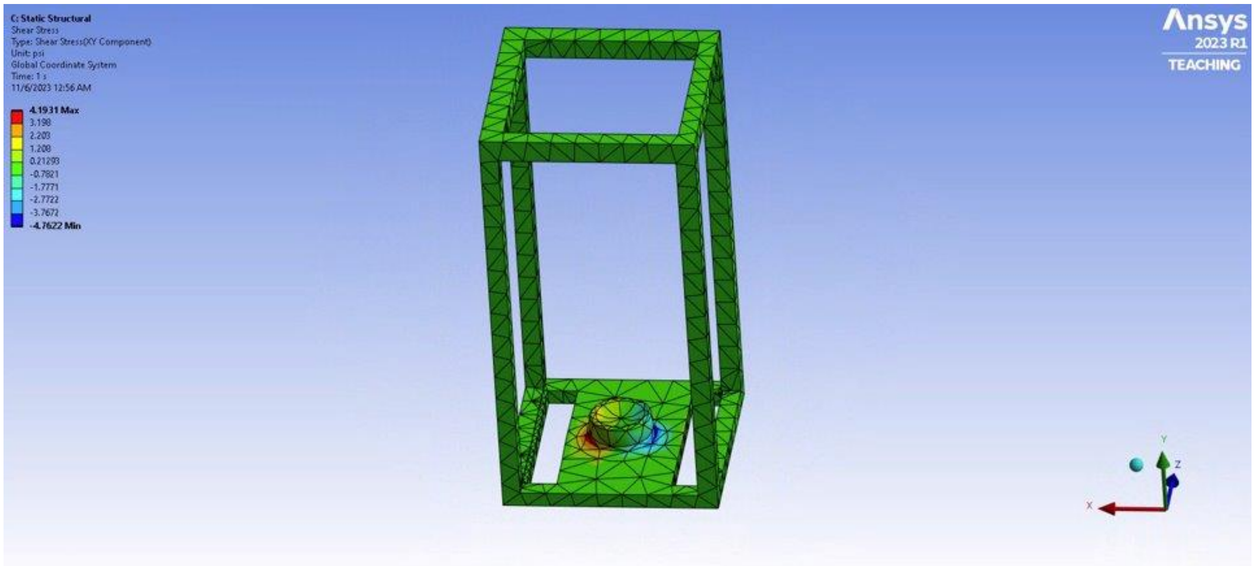


Figure 64. Ansys Static Structural Shear Stress Analysis

A static structural analysis was then redone in Ansys, spotlighting other aspects not previously discussed. The equivalent, Von Misses, stress is first presented in figure 63, showing the underside of the base plate and the distribution of forces on it. From this analysis, the team found that the forces stay very localized to the location of the load cell, preventing the other structure members from experiencing stress. This analysis allows the team to understand that the maximum stress the plate will experience is 22.9 psi and that the plate will be the only member which needs to be designed to withstand this force.

A shear stress analysis is then presented in figure 64, showcasing how the location directly around the load cell experiences the most shear stress. However, this shear stress is still quite small at a maximum of 4.19 psi on the baseplate, left of the load cell. Also, due to the loading period for each test being about 4 seconds, the fatigue on the material is low. From these results, the team determined that a steel plate will be strong enough to not deform or fatigue during loading due to such a small loading and loading period.

6.3.2 Nozzle Calculations

The calculations performed in section 3.3.2 were directed towards calculating the contour of the diverging portion of the nozzle. In addition to those calculations, a MATLAB script was programmed to better understand the performance characteristics of the design. It is based on example 3-2 of *Sutton & Biblarz Rocket Propulsion Elements, 9th Edition* [14]. First ideal thrust, F, and ideal specific impulse, I_s, are calculated. Then, cross-sectional area, A, local velocity, v, specific volume, V, absolute temperature, T, and local Mach number, M_0, are plotted with respect to pressure along the nozzle length.

First effective exhaust velocity is calculated (Equation 1). This variable is represented by v_2 and describes the average velocity of the exhaust gas at the nozzle exit. Equation 3 is true under the assumptions that the chamber cross-section is large compared to the nozzle throat, and the flow is isentropic and adiabatic. Typically, the subscript, 3, denotes conditions outside of the nozzle, or ambient conditions. In this case we set the exit pressure, p_2, equal to ambient pressure, p_3. Because of this, the exit pressure is set to atmospheric pressure at sea level (0.1013MPa).

$$v_2 = \sqrt{\frac{2k}{k-1} R T_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{(k-1)}{k}} \right]} \qquad \text{(Eqn. 1)}$$

The heat capacity ratio, k, is difficult to solve mathematically, so this value will be found via software such as ProPep, Burnsim, or NASA's Chemical Equilibrium Applications (CEA). The utilization of software in determining heat capacity ratio is especially useful because the propellant formulation will be constantly changing throughout the design process. The propellant formulation directly impacts the properties of its combusted gas.

For ideal expansion, v_2 is equal to the effective exhaust velocity, c. With this information, specific impulse may be calculated (Equation 2). Then, with the mass flow rate (found via change in mass over time) the ideal thrust is calculated (equation 3).

$$I_s = \frac{c}{g_0} \qquad \text{(Eqn. 2)}$$

$$F = \dot{m} c \qquad \text{(Eqn. 3)}$$

Next the values that are plotted against pressure are calculated. To simplify the process, equations are written in terms of p_y, which represents the variable pressure (ranging from chamber pressure to atmospheric pressure). The subscript, y, implies that the variable is a function of the changing pressure along the length of the nozzle and is a vector quantity. The equations to solve for specific volume, temperature, velocity, cross-sectional area, and Mach number are shown below in equations 4 through 5. Temperature, cross-sectional area, and Mach number are shown in equations 6 through 8.

$$V_1 = \frac{R T_1}{p_1} \qquad \text{(Eqn. 4)}$$

$$V_y = V_1 \left(\frac{p_1}{p_y}\right)^{(1-k)} \qquad \text{(Eqn. 5)}$$

$$T_y = T_1 \left(\frac{p_y}{p_1}\right)^{\frac{(k-1)}{k}} \qquad \text{(Eqn. 6)}$$

$$A_y = \dot{m}\frac{V_y}{v_y} \qquad \text{(Eqn. 7)}$$

$$M_y = \frac{V_y}{\sqrt{kRT_y}} \qquad \text{(Eqn. 8)}$$

v_2 = ideal rocket exhaust velocity

V = specific volume

k = heat capacity ratio

R = gas constant

T_1 = chamber temperature

p_1 = chamber pressure

p_2 = exit pressure

c = effective exhaust velocity

g_0 = gravitational acceleration

F = ideal thrust

$\dot{m}$ = mass flow rate

M = Mach number

With the equations stated above, the following plots were generated:

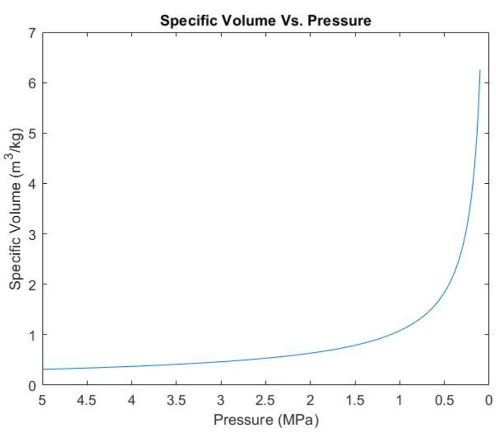


Figure 65: Specific Volume Vs. Pressure

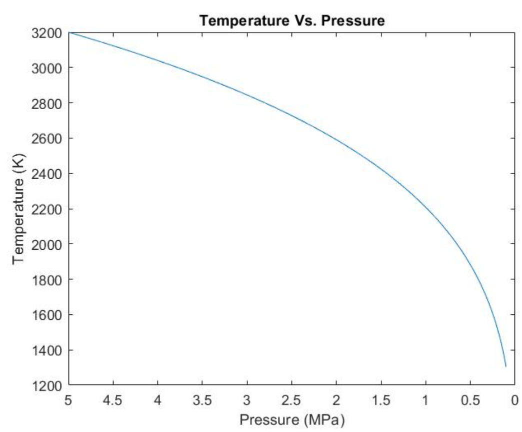


Figure 66: Temperature Vs. Pressure

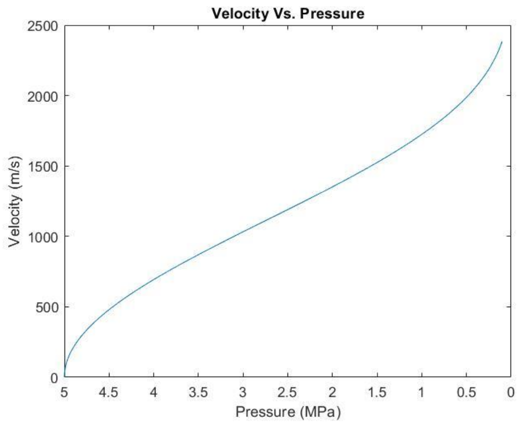


Figure 67: Velocity Vs. Pressure

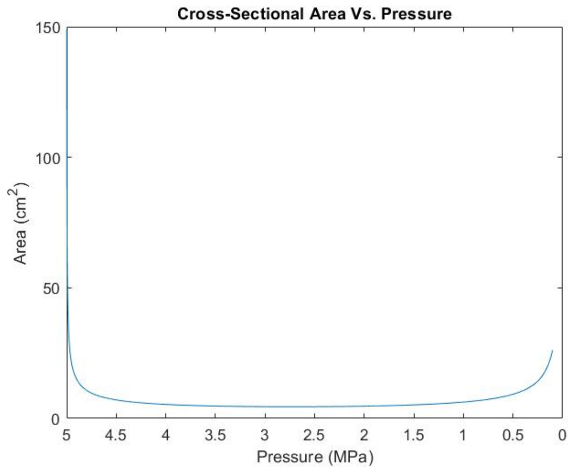


Figure 68: Cross-Sectional Area Vs. Pressure

6.3.3 Propellant Calculations

As discussed in section 6.1.3 a shear stress analysis must be done, in order to ensure the propellant does not shear off during launch. A simple drawing of the grain geometry is provided below, figure 69, for reference throughout this section.

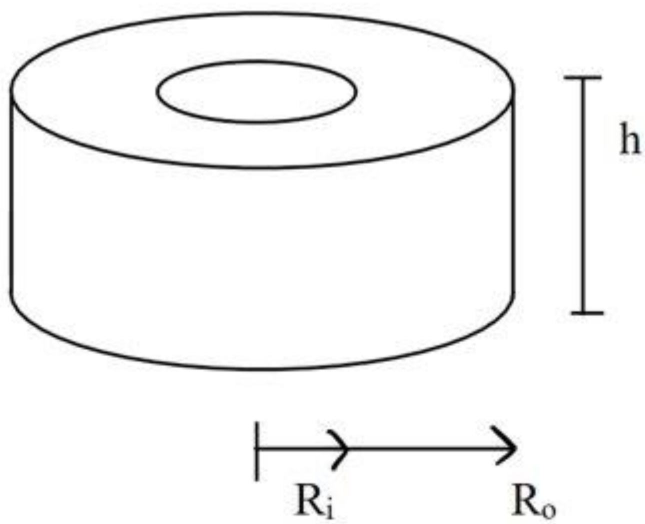


Figure 69. Propellant Grain Geometry

The maximum force will be applied to the inner radius of the grain, so the max shear stress will be calculated at this location. The shear and bending moment diagrams in figure 70 were drawn biased on a conceptual understanding of the general shear and bending behavior.

Beginning with the general equation for shear stress, equation 9, an equation for maximum shear stress can be obtained by substituting in the area and force at the location of maximum shear stress, equation 10. In order to solve the team plugged in the values in table 10 which will give results for a 35 mm motor. The team chose to perform the analysis for a 35 mm motor since that is where testing will begin, however this same analysis must be done for all motor sizes the team plans to test.

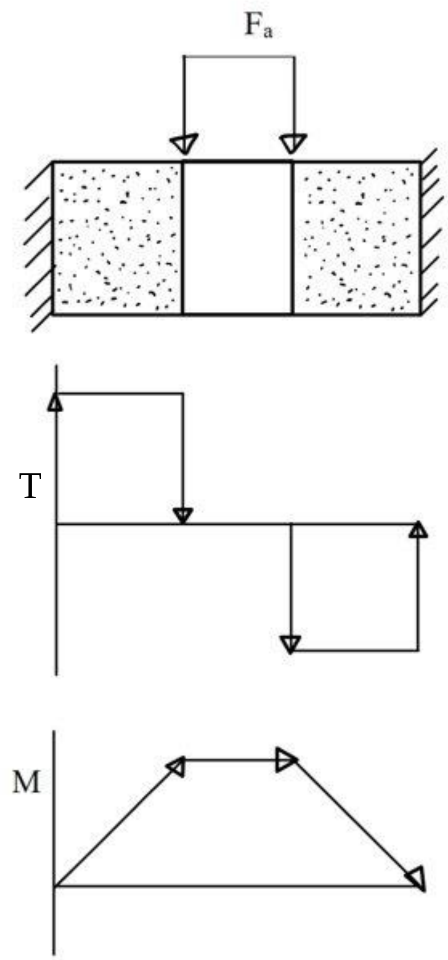


Figure 70. Shown Top to Bottom; Cross Section, Shear Diagram, Bending Moment Diagram for Propellant Grain

$$T = \frac{F}{A} \quad \text{(Eqn. 9)}$$

$$T_{max} = \frac{F_a}{h \cdot R_i} \cdot 0.75 \cdot \pi \quad \text{(Eqn. 10)}$$

Table 10. Physical Properties for a 35 mm Motor

Variable	Value
Ri	7/16 in
h	4.5 in
Fa	280 lbf

Using equation 10 and the values in table 10 T_{max} is found to be just under 0.25 MPa. Research on the binder shows that the max tensile strength is roughly 1.5 MPa, although it can be higher under certain conditions [35]. Assuming the shear strength is half that of the tensile strength, the max tensile strength is 0.75 MPa. This means that the actual stress the grain would experience is significantly less than the maximum stress that the propellent would be able to handle.

6.3.4 Motor Casing Calculations

The casing is a pivotal part of the project. It must be designed to withstand multiple cycles of 76 mm motors. The reusability of the casing ensures that costs remain low, and the club can spend more on chemicals rather than fabricating a whole new case. The casing must also be made from ductile and non-ferrous materials to ensure safety. The common casing material for rocketry is aluminum based on its ductile behavior as well as its strength-to-weight ratio. Because 76 mm is just twenty-one thousandths of an inch off from a 3 in OD tube, a 3 in 6061 Aluminum tube with a 0.125 in thickness will be chosen and used to evaluate the maximum pressures that can be experienced by the vessel.

6.3.4.1 Casing Hoop Stress

Hoop stresses are stresses acting on the circumference of the vessel. The calculations for these stresses depend on the thickness ratio of the vessel. If this ratio is greater than ten, the vessel can be evaluated as a thick-walled vessel. This calculation is done below.

$$\frac{r}{t} \geq 10 \qquad \text{(Eqn. 11)}$$

$$\frac{\left(\frac{(3in - 2 \cdot 0.125in)}{2}\right)}{0.125} \geq 10 \;\Rightarrow\; 11 \geq 10 \qquad \text{(Eqn. 12)}$$

This vessel behaves as a thick-walled vessel, so the following equation (Equation 13) will be the equation for a thick-walled vessel's hoop stress [10].

$$\sigma_t = \frac{r_i^2 p_i}{r_o^2 - r_i^2}\left(1 + \frac{r_o^2}{r_i^2}\right) \qquad \text{(Eqn. 13)}$$

Stress is known by determining the materials yield strength and applying a common factor of safety used with solid rocketry, the factor of safety being 1.5 [45]. The yield strength of

6061 T6 aluminum is 40 kpsi [44]. With the applied factor of safety, this brings the yield strength to 26.6 kpsi. Everything else is known besides the pressure. Solving for pressure would result in the max amount of pressure that the vessel can experience.

6.3.4.2 Casing Axial Stress

Since it is known that the vessel behaves as a thick-walled cylinder, the axial stress equation (Equation 14) can be defined.

$$\sigma_l = \frac{p_i r_i^2}{r_o^2 - r_i^2} \qquad \text{(Eqn. 14)}$$

In the same manner as with the hoop stress, the equation can be rearranged for pressure to check how much pressure is allowed for the end caps of the motor.

6.3.4.3 Results and Selection

Table 11: Results of Allowable Casing Pressures

	Max Allowable Pressure [psi]
Hoop Stress	2314.465
Axial Stress	4848.485

The pressures experienced within the casing shall not exceed 150 kilogram-force per square centimeter [46]. In pounds per square inch, this is 2133.5 pounds per square inch. This means that this casing design is appropriate. Ideally, the casing shall not exceed 1000 pounds per square inch, so the design passes all the safety factors associated with casing manufacturing.

Future Testing Potential

6.4.1 Future Testing for Test Stand

Before testing any propulsion system on the stand, the measurement devices must be calibrated and individually tested to ensure their accuracy. Calibration curves will be created, which allows the team to minimize any existing systematic error within the device. The calibration curve is generated by collecting data from our sensors and plotting them against a measurement device with known accuracy. The slope of the calibration curve is then used to correct the data output by our devices.

The other element that must be analyzed is motor support. The current design features four all-thread screws that press into the motor. This may hold the motor too well and not allow the motor to move enough to get accurate data, or the threads could secure the motor poorly. This means that the motor could get dislodged and create a major safety hazard, or the structure could experience damage with offset loading. A potential solution to this problem is using extrusion which is more rigid than the all-thread screws. This would require more parts but would minimize some important safety concerns.

6.4.2 Future Testing for Motor and Propellent

Prior to testing and iterating the propellent formula the team must build the testing equipment. The propellants and motors will be tested on the test stand discussed in section 6.4.1 and in a strand burner. A strand burner is a small pressure vessel that collects pressure and temperature data. This will allow the team to generate burn rate equations for all propellants witches are tested with this device. So, the next step is to create the strand burner then test propellants. Once the propellant formula is fully tested, including additives, the team will begin testing full motors, including nozzles on the test stand.

7 Final Hardware

7.1 Final Physical Design

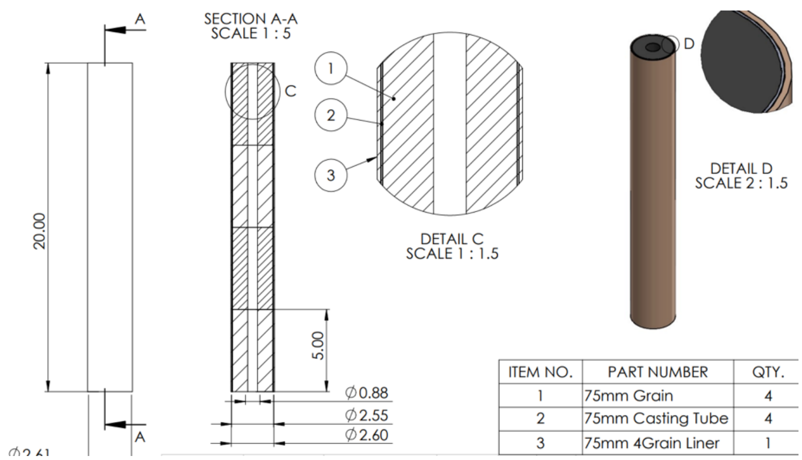


Figure 71. Propellant Green

Figure 72. Propellant grain CAD model

The propellant grains were finalized using a formula which was optimized through testing. We tested 38 mm motors, 54 mm motors and finally 75 mm motors in the order to determine that the propellant was stable and safe for use during launch.

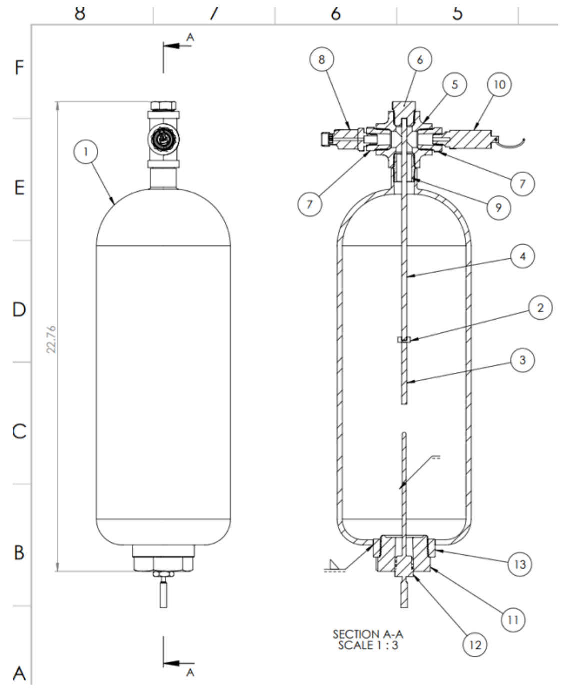


Figure 73. Strand burner

Figure 74. Strand burner CAD

The strand burner was tested multiple times during the beginning of the semester, however weather conditions and electronic issues consistently created issues during testing. The final design was determined to have a factor of safety of 2.5 and was safe to use if it had function functioned properly. Future research should be done to complete the pressure vessel in order to finalize its design.

Figure 75. Final nozzle design

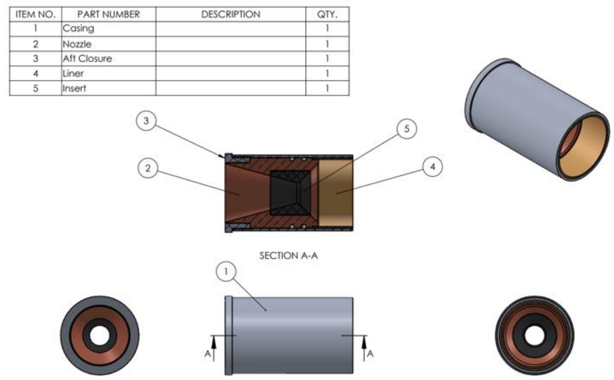


Figure 76. Final nozzle CAD

The nozzle was then designed a few different ways depending on the way that the snap ring fit into the motor casing. After doing testing, we decided that the snap ring design worked best. We finalized the card based off of the testing results and the final nozzle was determined as shown above. Additional nozzle design was tested for undergraduate research but not used in the final launch of the motor.

Figure 78. Final motor casing

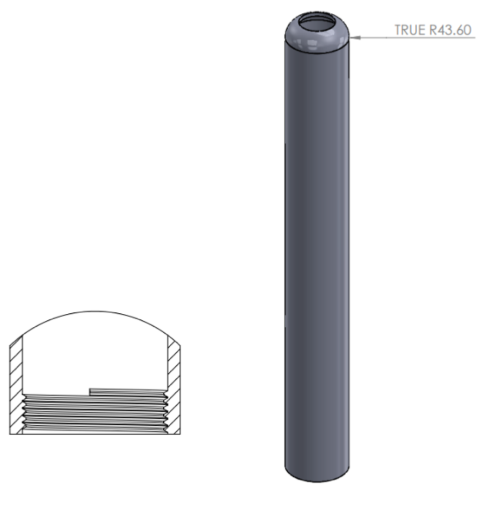


Figure 79. Final motor casing CAD

The motor casing card was made from an aluminum cylindrical hollow stock and welded at the end to create an edge which the casing can rest on inside of the rock body. Threads were initially designed on the motor casing to allow for the nozzle to thread into the motor casing, however it was determined during testing that the best design for this was to use snap rings and bulkheads which held the nozzle and motor greens in place. The CAD model and final motor casing are shown above and figures 48 in 49 above.

Figure 79. Final test stand

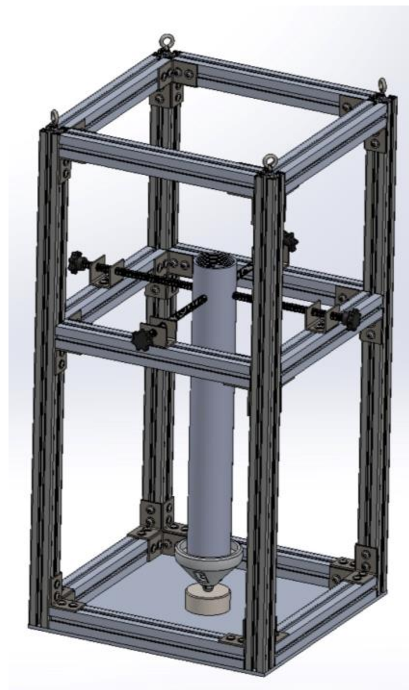


Figure 80. Final test stand CAD

The test stand was finalized using extrusion bar aluminum and a steel base plate. We found that the vertical test stand model worked best as it held the motor vertically such as if it were during launch and accounted for gravities effects. Aluminum extrusion was used horizontally to allow the test stand to alter the height at which it can hold motors. Brackets made from angle iron were cut in order to save money and ensure that the brackets were the dimensions which we needed for the extrusion. All-threads were used to apply pressure to the motor as it stood vertically in the test stand, along with a motor holder which was designed to hold different sized motors securely on the load cell.

8 Final Testing

8.1 Top Level Testing Summary Table

Experiment 1: Known Thrust Curve Apogee 38 mm Motor Testing

Experiment 2: Disposable Casing Don White Propellant Formula 38 mm Testing
Experiment 3: Disposable Casing Experimental Propellant Formula's 54 mm Testing
Experiment 4: Reusable Casing 54 mm Final Formula Determination Testing
Experiment 5A: Final Propellant Formula 75 mm Motor Testing
Experiment 5B: Depending on Results of 5A, Option for Another 75 mm Motor Testing if Needed

Table 12. Test Summary Table

Experiment	Engineering Requirements	Customer Requirements
1	ER1: A, B, C and D	CR1, CR8, CR9
2	ER1: A, B, C and D	CR1, CR8, CR9
3	ER1: A, B, C and D ER2: A, B ER3: B	CR1, CR2, CR6, CR8, CR9
4	ER1: A, B, C and D ER2: A ER3: B ER4: A, B	CR1, CR2, CR6, CR8, CR9
5A	ER1: A, B, C and D ER2: A, B ER3: A, B, C ER4: A, B	CR1, CR2, CR6, CR3, CR5, CR7, CR8, CR9
5B	ER1: A, B, C and D ER2: A, B ER3: A, B, C ER4: A, B	CR1, CR2, CR6, CR3, CR4, CR7, CR5, CR8, CR9

8.2 Detailed Testing Plan

Experiment 1: Known Thrust Curve - Apogee 38 mm Motor Testing

This experiment focuses on the test stand instruments, such as the load cell, and determining if the data collection method is accurate. Also, it will ensure that the test stand will hold the motors securely during testing and test its structural integrity. This is performed by using a 38 mm motor purchased through a professional rocketry source, called Apogee Rocketry, which includes a precise thrust curve for the motor. By testing this motor on the test stand and analyzing the data to obtain the thrust curve, we can confirm that the load cell and test stand are performing correctly if the thrust curves match.

Experiment 2: Disposable Casing Don White Propellant Formula 38 mm Testing

The second experiment is designed to test the propellant formulation procedure of the team by casting 38 mm motors of a well proven and tested propellant formula. This allows the team to see the propellant's performance to ensure the casting method does not have errors causing the propellant to malfunction when ignited. Additionally, it will test that the data collection procedure provides reliable data by analyzing if the thrust curves are very similar for the two-motor testings.

Experiment 3: Disposable Casing Experimental Propellant Formula's 54 mm Testing

Experiment 3 is catered towards homing in on a propellant choice that best fits our engineering requirements. Specifically, reaching maximum apogee and thrust-to-weight ratio. This will be our first test of our own formulation of propellant which comparing against our other data, we can select the best propellant choice. Comparing thrust curves from other sized and available motors will let us determine if our propellant is superior to the existing propellant formulations.

Experiment 4: Reusable Casing 54 mm Final Formula Determination Testing

Experiment 4 will mostly focus on nozzle design and propellant casting techniques. Being able to reliably cast our motors is incredibly important for the success of the project and our total apogee. This disposable casing will also have a pressure transducer attached to it which will allow for further data collection and design of the final nozzle. Both the load and pressure data will allow us to make an informed decision about what formula, nozzle, and core diameter to use. We can also use this data to simulate the burn characteristics which will allow for idealized selections.

Experiment 5A: Final Propellant Formula 75 mm Motor Testing

Our final motor burn will tell us much about what our max apogee will be as well as any indications of pressure leaks or critical pressures. It is known that with a 1000 psi maximum casing pressure, the casing should have a factor of safety of 2.3. This test will determine if our snap ring design is adequate, and our O-ring selection is appropriate. Much analysis has been done in these two areas but making sure the analysis stands up to the design is critical. Lastly, this test will underline the importance for safe testing and overall propellant grain design. If we see the pressure gets too high, we must adjust the grain core or nozzle throat diameter to reduce the internal pressure. We intend to stay above a factor of safety of 2.0 throughout the entirety of the experimental process.

Experiment 5B: Depending on Results of 5A, Option for Another 75 mm Motor Testing if Needed

This option is here in case we have a casing failure or need to test different nozzle throat or propellant grain core diameters. As said in the description of Experiment 5A, if we are seeing pressures that fall below our factor of safety of 2.0, adjustments to either or both diameters must be made. We will likely have more than one 75mm test, but this test is here just in case we need to do more than intended.

Equipment, isolated variables, and procedures are laid out in Appendix 12.6. This is our test stand static firing safety checklist and it highlights the importance of remaining safe during the testing as well as tabulating all required equipment to complete the testing. The safety checklist was amended from an earlier safety checklist submitted to the Tripoli Safety Community for the NAU Rocket Club's launch. The checklist also offers a safe distance table that is directly taken from the Tripoli Safety Code which allows us to remain a safe distance from the motor when testing. The results taken will determine our propellant, nozzle, and grain design selection which is why this testing procedure is so important.

In conclusion, this is a rather dangerous project which means safety is our upmost concern. Ensuring safe processes will allow us to continue our work without harm. Starting small and working up to our full scale is imperative to our project's success and safety. We have already begun propellant testing on the 38 mm motors and have learned from the mistakes made. This weekend, we intend to test our first motor with our own formulated propellant. This will show us if our process is correct and how we can better the formulation if needed. Once we get to the reusable motor casing, we can hone in on our nozzle design which will transfer over to the full-scale 75 mm test and final motor.

8.2.1 Test 1: *Known Thrust Curve - Apogee 38 mm Motor Testing*

8.2.1.1 Summary (Questions to Answer)

Is the equipment on the test stand functioning and calibrated correctly?

Equipment: Test Stand, Rocket Motor, Electronics Box, Safety Checklist, Fire Extinguisher

Variable: Force in the Z-Direction

8.2.1.2 Procedure

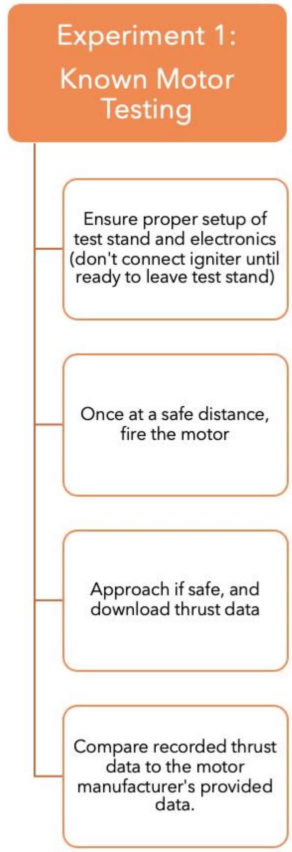


Figure 81. Test one procedure

8.2.1.3 Results

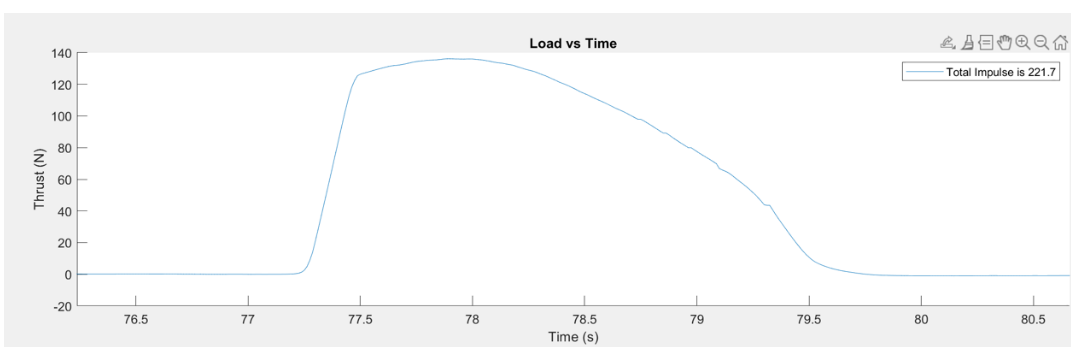


Figure 82. Testing results

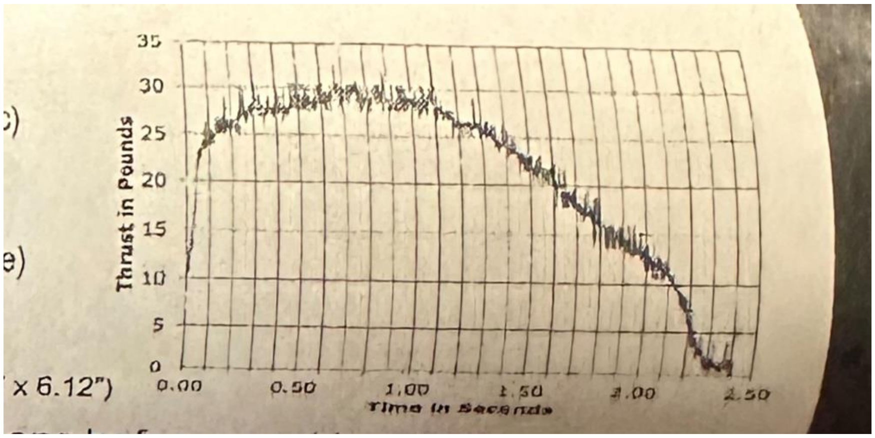


Figure 83. Thrust curve which we expect

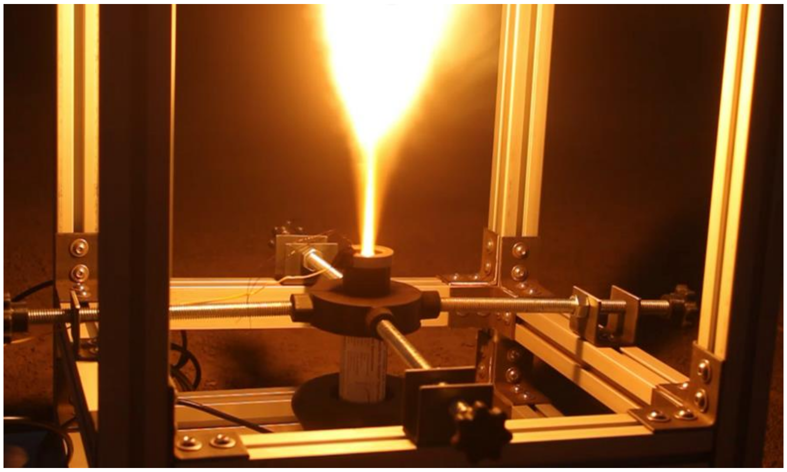


Figure 84. Motor during test

The results from this testing were successful as the data collected from the loadcell showed the exact thrust her which we had been expecting. There's determined that the loadcell another equipment were calibrated and functioning correctly as well as the method for testing was determined to be accurate.

Figures 82 and 83 above show the thrust curve which we received during testing as well as the thrust curve which we expected, showing the same thrust curve when converting from pounds to newtons.

8.3.1 Test 2: *Disposable Casing Don White Propellant Formula 38 mm Testing*

8.3.2 Summary (Questions to Answer)

Is the casting process producing good motors?

- Equipment: Test Stand, Rocket Motor, Electronics Box, Safety Checklist, Fire Extinguisher
- Variable: Force in the Z-Direction

8.3.3 Procedure

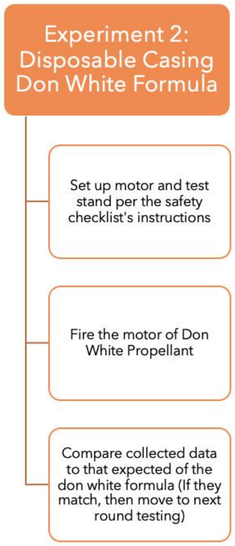


Figure 85. Test two procedure

Figure 86. Experimental set up

8.3.4 Results

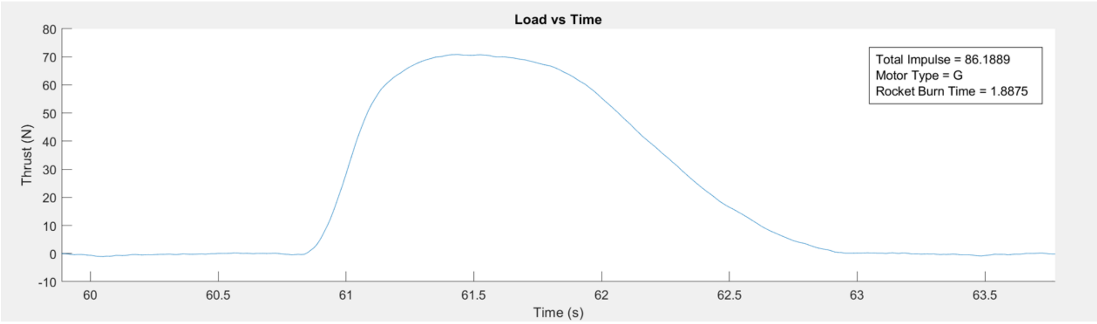


Figure 87. Data collected from experiment

Figure 88. Experimental set up

This experiment was successful in determining that the propellant formulation was correct for the Dan White formula. This determined that our method forecasting propellants motors was accurate and that we could continue forward in using different formulas with the same casting method.

8.4.1 Test 3 *Disposable Casing Experimental Propellant Formula's 54 mm Testing*

8.4.2 Summary (Questions to Answer)

Is the test stand functioning for larger motors?

Equipment: Test Stand, Rocket Motor, Electronics Box, Safety Checklist, Fire Extinguisher

Variable: Force in the Z-Direction, Internal Pressure

Calculate: Thrust curve, Max altitude

8.4.3 Procedure

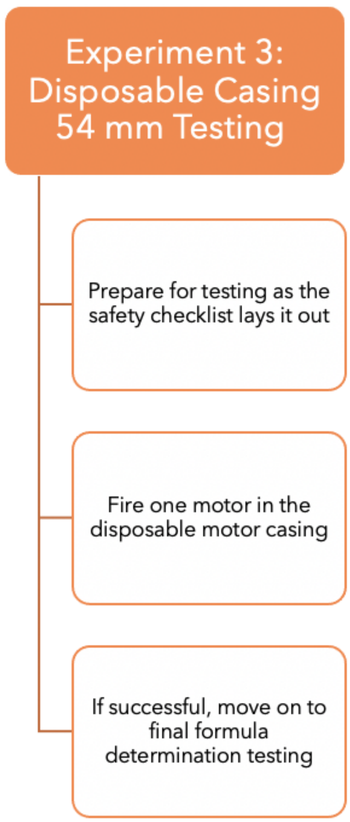


Figure 89. Test three procedure

8.4.4 Results

Figure 90. Image from live testing

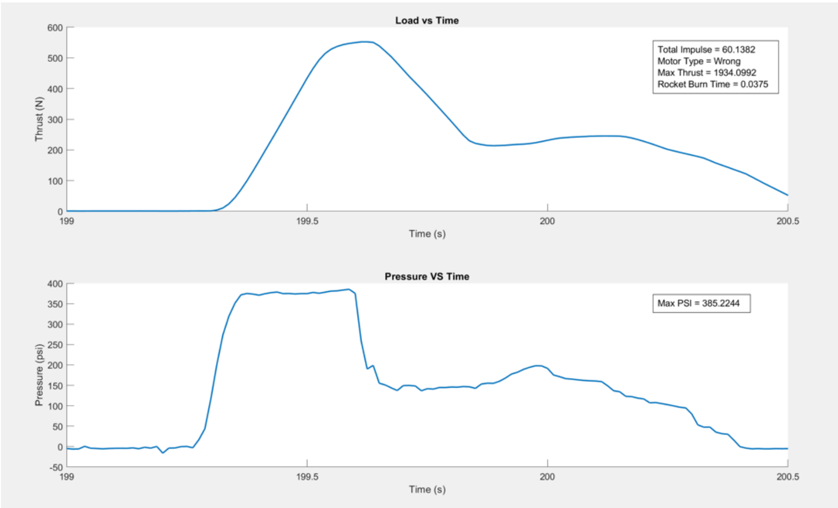


Figure 91. Data collected from testing

This testing was not successful as the pressure within the motor casing did not hold, we found that the bulkhead had issues in the way that it was assembled. Additionally this was the second formula which we had casted, not allowing for multiple iterations of formulation. It was determined that different bulkheads would need to be used in order to hold in the pressure

8.5.1 Test 4 *Reusable Casing 54 mm Final Formula Determination Testing*

8.5.2 Summary

Which formula do we use?

- Equipment: Test Stand, Rocket Motor, Electronics Box, Safety Checklist, Fire Extinguisher
- Variable: Force in the Z-Direction, Internal Pressure
- Calculate: Thrust curve, Max altitude

8.5.3 Procedure

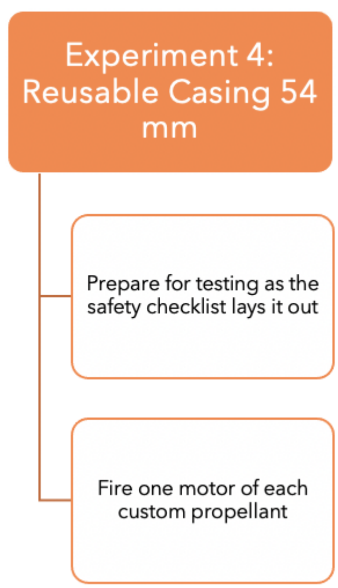


Figure 92. Test four procedure

8.5.4 Results

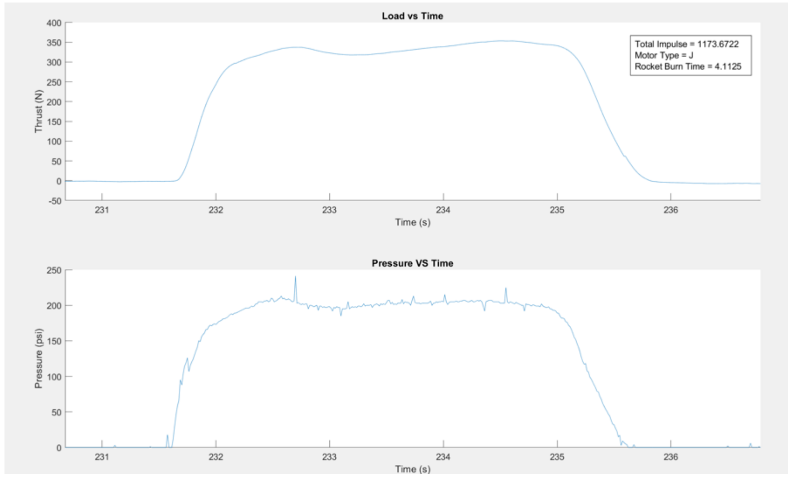


Figure 93. Test four data collection

Figure 94. Image from experiment 4

This testing was successful and showed that the rocket propellant formula was stable and functioned properly during testing. Additionally we saw that the nozzle function properly and even allowed for mock diamonds to form. We were able to collect a accurate thrust curve which determined the max impulse and what type of motor it would be defined as. We were able to then use this thrust curve to input into the simulation software for further use and simulation of launch.

8.6.1 Test 5: *Final Propellant Formula 75 mm Motor Testing*

Test 5 has not been completed yet and will be done Wednesday, April 24th and will be presented during the UGRADS presentation on Friday, April 26th.

8.6.2 Summary

Is the 75 mm Motor functioning for final launch?

- Equipment: Test Stand, Rocket Motor, Electronics Box, Safety Checklist, Fire Extinguisher
- Variable: Force in the Z-Direction, Internal Pressure
- Calculate: Thrust curve, Max altitude, Thrust to weight ratio

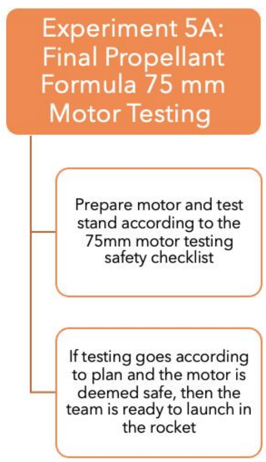


Figure 95. Test 5 procedure

Table 13. Specification Sheet ER's

Engineering Requirements	Target	Tolerance	Measured	ER Met? (Y/N)	Client Acceptable?
ER1A-Lightweight Test Stand	<60 lbs	+ 5 lbs	45 lbs	YES	YES
ER1B- Accommodate Size Ranges	Dia: 38-75mm Length: 10-30in	Dia: +0.00/-0.05mm Length: -5/+10in	Dia: 38-75mm Length: 5-40in	YES	YES
ER1C- Securely Hold Motor	Runout <1mm	+0.00/-0.10mm	0.75mm	YES	YES
ER1D- Collects Data	300lb (136kg)	<= 1102.3lb (500kg)	287.8lb	YES	YES
ER2A- Optimized Propellant	5120 Ns	<5120Ns (Tripoli L2)	Experimental	---	YES
ER2B- Propellant Tested in Multiple Sizes	5120 Ns	<5120Ns (Tripoli L2)	Experimental	---	YES
ER3A-Casing Fit	75mm	+/- 0.1mm	0.01mm	YES	YES
ER3B- Use O-RIngs and Snap RIngs	54 & 75mm Bulkheads	+0.00/-0.010mm	54.90/74.90mm	YES	YES
ER3C- FOS on Bulkhead	<1000 psi	<=1.5 FOS	2.3 FOS @ 1000 psi	YES	YES
ER4A- Use CFD	Ensuring Choked Flow	M=1 +/-0.00	M=1 (CFD Analysis)	YES	YES
ER4B- Test Nozzle	2 Motor Tests	+1 Motor / -0 Motor	2 Motors	YES	YES

9 Future Work

Next steps for this project would be to focus on the propellant strand burner and its functioning. The strand burner had many issues when it came to using it in the field, mainly related to the electronics and the data collection equipment. When bringing the strand burner and associated equipment into the field, we often times found that the reading of the thermocouples or pressure transducer would read as zero or a very far off value. These issues which continuously occurred could likely be fixed by using the PCB board which was designed later on in this project to attach the thermocouples and pressure transducer to. When we previously tested, the electrical engineering team had been using a breadboard which would often times have wires come loose during testing, causing most of these issues. Once having implemented the custom PCB we had designed, we believe most of these issues would be fixed.

Once the pressure vessel is functioning properly, different propellant formulas can be quickly and easily iterated through to determine the performance of the formula. The formula can be altered by changing the percentage of Ammonium Perchlorate and Atomized Aluminum used in the overall mixture of chemicals. Other additives can also be added to the formula such as chemicals which increase impulse and chemicals which can change the color of the exhaust gas or add sparkles to the motors exhaust during launch.

After having iterated through different formulas using the strand burner, the performance of the propellant formulas can be evaluated using the simulation software's Propep, BurnSim, and RockSim to use the temperature and pressure data to determine the thrust curve, max impulse, and conduct the flight simulation to find variables such as apogee. Once a desired formula has been optimized and simulated, a testing of this motor should be conducted using the motor test stand we have built and designed. Finally, after having had a successful testing, the propellant formula can be casted into 54- or 75-mm motors using the casting table we have built to launch the rocket using this new formula.

10 Conclusions

In this report, we begin by describing the project we were given, designing, mixing, and testing our own formulation of a solid rocket motor. Our full-scale 76 mm motor is tested on a test stand of our design and creation to make sure it is suitable for use in the rocket for the NAU Rocket Capstone launch. We then defined our project and derived important requirements that must be met to succeed in our endeavors. We obtained our customer requirements, which helped align with our measurable engineering requirements. These demands then were analyzed in a House of Quality (QFD) shown in appendix 12.1.

After these different analyses we each found multiple resources that increase our understanding in this area of focus. It was imperative for the project to research our project's area of focus because it offers us key details into what we need to succeed and remain safe while completing our tasks. We then defined important mathematical models and tools that will help us numerically solve these problems we are dealing with.

To determine a reasonable design, we created a functional decomposition of our system which helped us generate potential concepts. We then generated specific selection criterion which was evaluated within a decision matrix to get us to our final design. Propellant formulas and geometries were also defined and evaluated which gave us our ideal propellant characteristics. These selections are already being used further in our project and have promising results.

To further ensure the safety of our design, the team performed FMEA analyses on each of the subsystems (test stand, APCP mixture, motor casing/combustion chamber, and nozzle assembly). Such analyses allowed the team to determine the most likely modes of failure and how they can be mitigated. Another way the team ensured the safety of the design is through engineering calculations. For example, the ANSYS FEA simulation performed on the test stand shows that mathematically, the design is safe. The MATLAB calculations performed on the nozzle assembly help to validate its performance. The shear force calculations performed on the solid propellant allow the team to avoid issued identified in the propellant FMEA. The hoop stress calculations performed on the motor casing allows the team to recognize the maximum allowable chamber pressure and helps to avoid catastrophic failure of the propulsion system.

Finally, the team was able to have a successful 54 mm rocket launch made from their own propellant formula. The launch showed that the motor is stable, and this formula can be used in future launches. Future work can be done to complete the functioning of the strand burner in order to optimize other propellant formulas. A final 75 mm rocket motor will hopefully be launched this weekend, April 27 of 2024, at a launch site located past Phoenix. This project has helped to create equipment and research which future NAU Rocket Club members can use to create their own propellant formulas and complete their own experimental motor launches.

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12 Appendices

12.1 Appendix A: House of Quality (QFD)

System QFD

Project: Rocket Club CAPSTONE
Date: 10/21/23

Legend

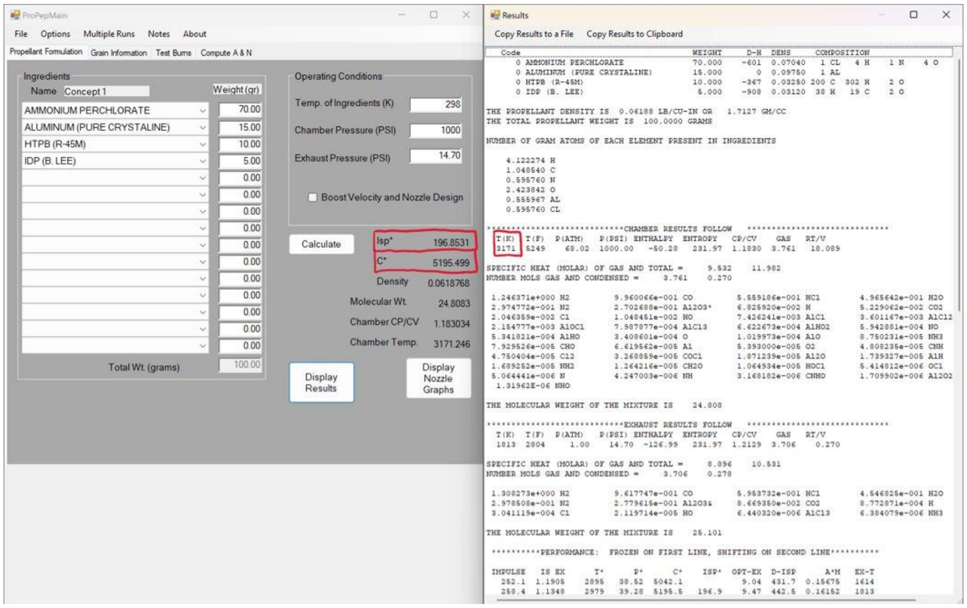
A	Aerocon
B	FUTEK
C	Richard Nakka's
D	75/1280 Motor
E	M1350W
F	L875DM

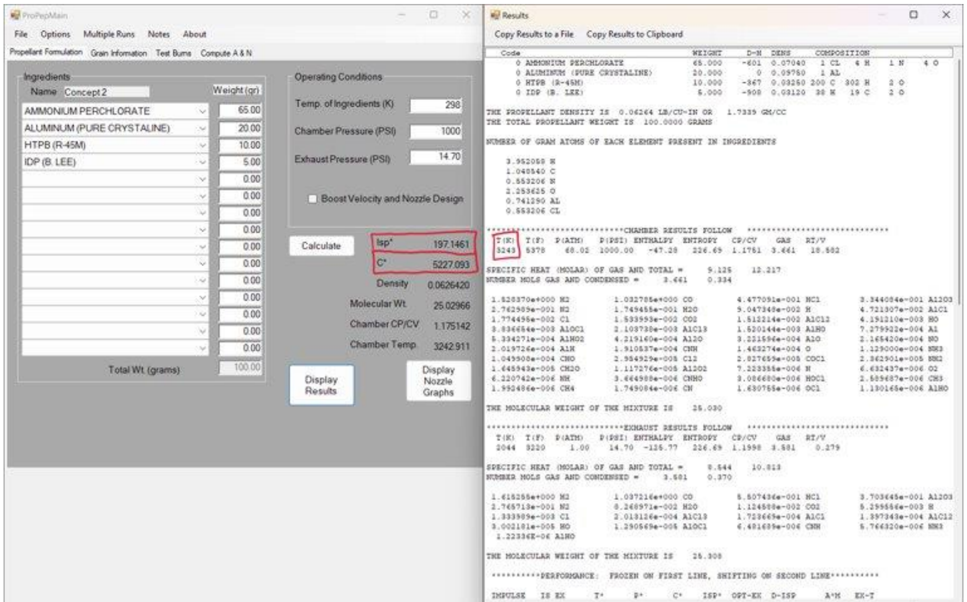
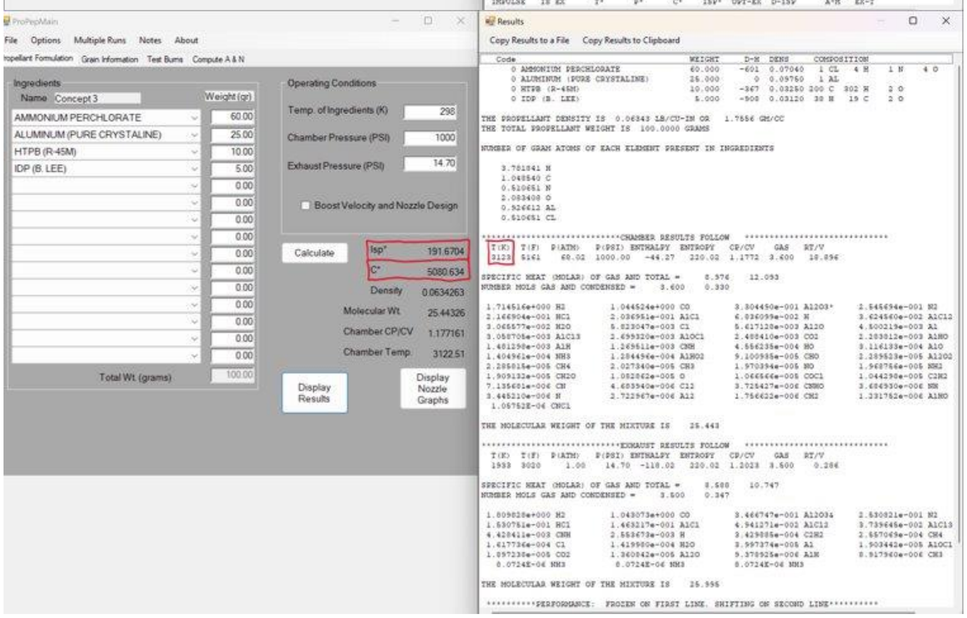
1	Reach minimum altitude						
	Stay within Budget for the Project	0					
2	Dimensions meet constraints of rocket size	9	0				
3	Stand withstands impulse of rocket testing	3	0	3			
4	Meet Minimum Thrust to Weight Ratio Set by Tripoli	9	3	6	6		
5	Complete final launch by march 2024	3	3	3	3	3	
	Non-Ferrous Ductile Casing	3	0	3	3	6	3

	Customer Needs	**Customer Weights**	Reach minimum altitude	Stay within Budget for the Project	Dimensions meet constraints of rocket size	Stand withstands impulse of rocket testing	Meet Minimum Thrust to Weight Ratio Set by Tripoli	Complete final launch by march 2024	Non-Ferrous Ductile Casing	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
1	Functionality	4	9	3	6	9	3	3	3		A B C	F	E	D
	Low Cost	4	0	9	3	0	6	3	0	B E F		D	A	C
2	Scalable	3	3	3	9	6	6	3	3		C		A B	D E F
3	Sturdy Test Stand	4	3	3	6	9	3	3	3	C D E F	A			B
4	Comply with Tripoli Rocketry Association safety standards	5	3	3	6	6	9	3	9	C	A D	E		B F
5	Timely Completion	3	3	3	3	3	3	9	3	B	C	A D E F		
	Technical Requirement Units		km	$	mm	N-s	N/N	Months	Y/N					
	Technical Requirement Targets		10	2000	75	5120	5:1	3	Y					
	Absolute Technical Importance		81	57	114	129	96	75	87					
	Relative Technical Importance		4	3	5	5	5	4	5					

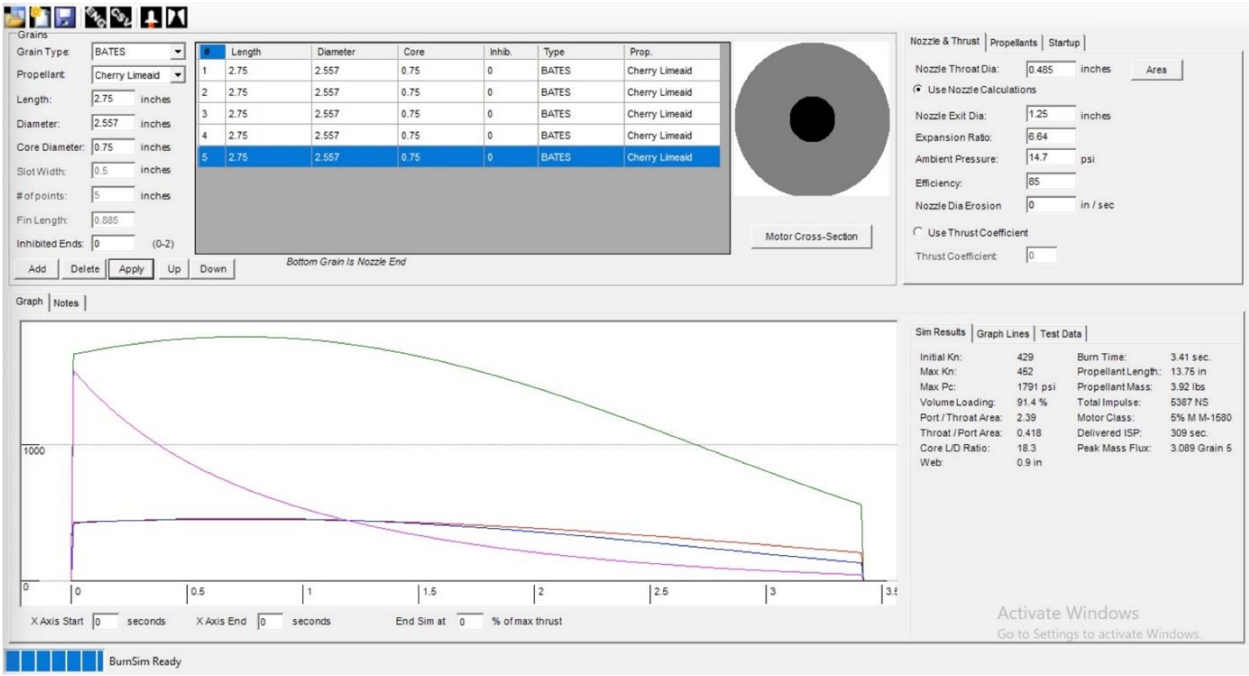
Technical Requirements spans the seven technical-requirement columns; Customer Opinion Survey spans columns 1–5.

12.2 Appendix B: ProPep3 Results

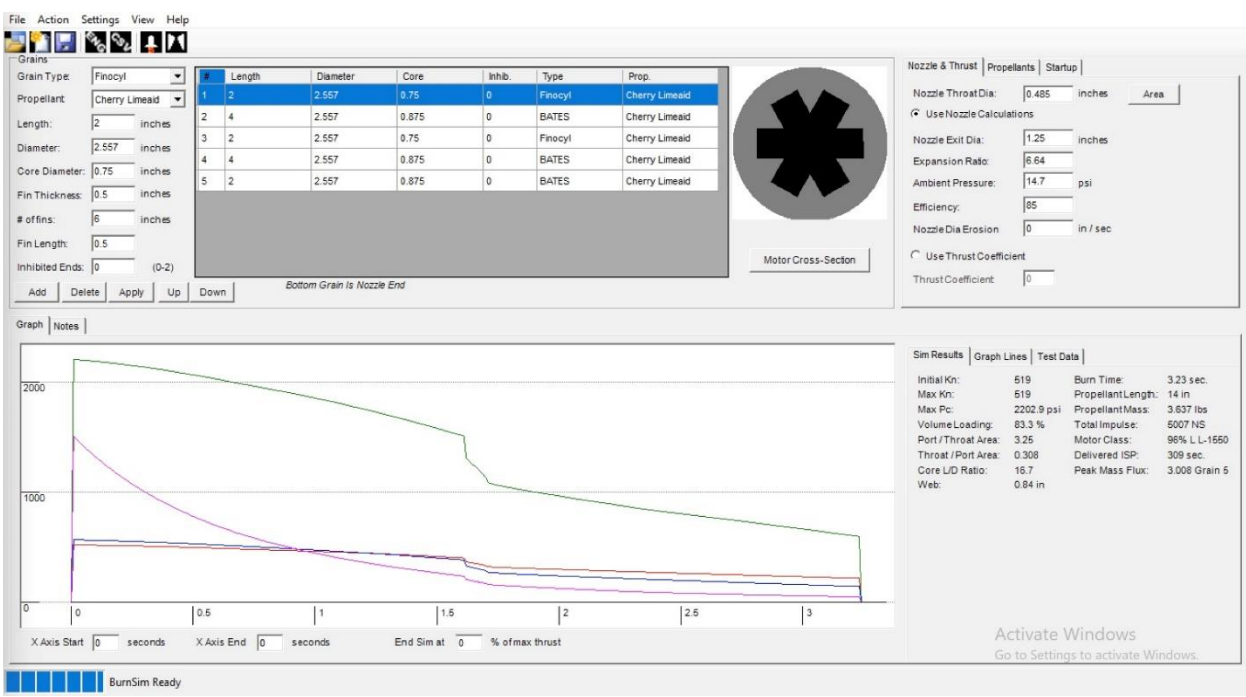



ProPepMain
File Options Multiple Runs Notes About
Propellant Formulation Grain Information Test Burns Compute A & N
Ingredients
Name Concept 2
Weight (gr)
AMMONIUM PERCHLORATE 65.00
ALUMINUM (PURE CRYSTALINE) 20.00
HTPB (R-45M) 10.00
IDP (B. LEE) 5.00
Total Wt. (grams) 100.00
Operating Conditions
Temp. of Ingredients (K) 298
Chamber Pressure (PSI) 1000
Exhaust Pressure (PSI) 14.70
Boost Velocity and Nozzle Design
Calculate
Isp* 197.1461
C* 5227.093
Density 0.0626420
Molecular Wt. 25.02966
Chamber CP/CV 1.175142
Chamber Temp. 3242.911
Display Results
Display Nozzle Graphs
Results
Copy Results to a File Copy Results to Clipboard

ProPepMain
File Options Multiple Runs Notes About
Propellant Formulation Grain Information Test Burns Compute A & N
Ingredients
Name Concept 3
Weight (gr)
AMMONIUM PERCHLORATE 60.00
ALUMINUM (PURE CRYSTALINE) 25.00
HTPB (R-45M) 10.00
IDP (B. LEE) 5.00
Total Wt. (grams) 100.00
Operating Conditions
Temp. of Ingredients (K) 298
Chamber Pressure (PSI) 1000
Exhaust Pressure (PSI) 14.70
Boost Velocity and Nozzle Design
Calculate
Isp* 191.6704
C* 5080.634
Density 0.0634263
Molecular Wt. 25.44326
Chamber CP/CV 1.177161
Chamber Temp. 3122.51
Display Results
Display Nozzle Graphs
Results
Copy Results to a File Copy Results to Clipboard

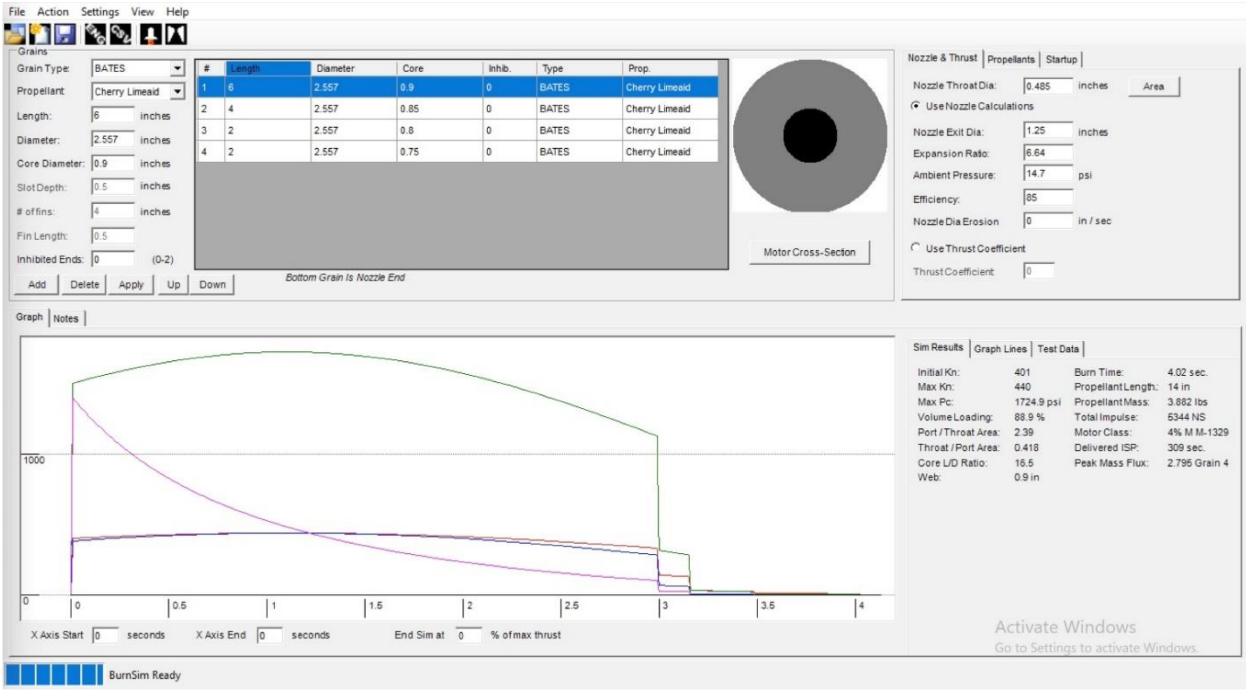
12.3 Appendix C: BurnSim Results9



#	Length	Diameter	Core	Inhib.	Type	Prop.
1	2.75	2.557	0.75	0	BATES	Cherry Limeaid
2	2.75	2.557	0.75	0	BATES	Cherry Limeaid
3	2.75	2.557	0.75	0	BATES	Cherry Limeaid
4	2.75	2.557	0.75	0	BATES	Cherry Limeaid
5	2.75	2.557	0.75	0	BATES	Cherry Limeaid



#	Length	Diameter	Core	Inhib.	Type	Prop.
1	2	2.557	0.75	0	Finocyl	Cherry Limeaid
2	4	2.557	0.875	0	BATES	Cherry Limeaid
3	2	2.557	0.75	0	Finocyl	Cherry Limeaid
4	4	2.557	0.875	0	BATES	Cherry Limeaid
5	2	2.557	0.875	0	BATES	Cherry Limeaid



#	Length	Diameter	Core	Inhib.	Type	Prop.
1	6	2.557	0.9	0	BATES	Cherry Limeaid
2	4	2.557	0.85	0	BATES	Cherry Limeaid
3	2	2.557	0.8	0	BATES	Cherry Limeaid
4	2	2.557	0.75	0	BATES	Cherry Limeaid

12.4 Appendix D: FMEA

12.4.1 Appendix D: FMEA Test Stand

Product Name: Motor Test Stand	Development Team: Shannon Comstock, Remy Dasher, Andrew King, Grace Morris	Page No of
System Name: Motor Testing		FMEA Number
Subsystem Name: Thrust and Impulse Analysis		Date 11/1/2023
Component Name: Test Stand		

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Top Brackets	Temperature Deformation	Top extrusion bars and brackets will loosen due to expansion from motor exhaust heat, decreasing the structural interity over time	3	Motor exhaust reaches high temperature	4	Maintenance requirement to tighten all bolts	2	24	None
	Thermal Fatigue from the expansion and contraction from the exhaust heat on the brackets	Crack propogations can cause brackets to fail, decreasing the structural integrity	4	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	3	24	None
Bottom Brackets	Force Deformation	The brackets warp causing the structural integrity to decrease.	2	Impact loading from thrust force	2	Designed to withstand max loading	3	12	None
Top Extrusion Bars	Temperature Deformation	The aluminum extrusion warps from heat exposure, causing structure to deform and potentially effect grip on motor	6	Motor exhaust reaches high temperature	5	Coat/ cover the parts exposed to heat with thermal sheilding	4	120	Simulate thermal analysis of these components and detemrine if design needs to be altered
	Thermal Fatigue from the expansion and contraction from the exhaust heat	The aluminum extrusion fractures/ fails, causing motor to lack support in its fixed position	3	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	3	18	None
Bottom Extrusion Bars	Force Deformation	Instability in motor mounting during testing may cause motor to become disloged and become a projectile	9	Impact loacing from thrust force	4	Designed to withstand max loading	5	180	Simulate structural analysis of these components and determine if design needs to be altered
Bolts	Force deformation (Shearing)	Bolts shear during testing, potentially causing bracket to be unsupported	4	Impact loacing from thrust force	5	Designed to withstand max loading	4	80	None
	Force Deformation (Normal Stress)	Bolts buckle from compressive stress causing lack in structural integrity	4	Impact loacing from thrust force	5	Designed to withstand max loading	3	60	None
	Temperature Deformation	Bolts come loose from the structure, causing instability, potentially lack of support for motor	4	Motor exhaust reaches high temperature	2	Maintenance requirement to tighten all bolts	2	16	None
	Thermal Fatigue from the expansion and contraction from the exhaust heat	Bolts crack during tesing, decreasing structural integrity	2	Motor exhaust reaches high temperature	2	Coat/ cover the parts exposed to heat with thermal sheilding	2	8	None
T-Nuts	Force Deformation (Normal Stress)	Loosens from bolts, compromising the strength of the brackets hold on the extrusion	2	Impact loacing from thrust force	1	Maintenance requirement to tighten all bolts	2	4	None

12.4.2 Appendix D: FMEA Nozzle

Product Name	NAU Rocket Club Capstone	Development Team: Shannon Comstock, Remington Dasher, Andrew King, Grace Morris				Page No of			
System Name	Carbon Rocket					FMEA Number			
Subsystem Name	Propulsion Subsystem					Date: 11/3/2023			
Component Name	75mm Rocket Nozzle								
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
graphite insert for throat	Overpressurization of motor casing - Ductile Fracture	Explosion of motor casing, mounting points of nozzle are sheared off	10	Cross-sectional area of throat is too small	3	Measure precise throat diameter with micrometers	1	30	Pay special attention during design process, and ensure the insert has been machined to the correct diameter
	Throat area experiences extreme erosion	Decreased thrust performance	5	High temp. exhaust, abrasive granules present in exhaust gas	4	Simulations, and small scale experimental burn	3	60	Pick isotropic graphite, pick low-temperature propellant.
	Mechanical vailure via crack propogation	Fracturing of graphite insert, rapid decrease in thrust	8	Thermal expansion	2	Ensure proper fitting, and FEA simulations	3	48	Choose temperature resistant graphite, and consider adding insulation to reduce thermal expansion. Ensure the diameter is the same as the height of the insert
	Insert is ejected out of nozzle due to force of exhaust gas	The insert becomes a high-velocity projectile and the rest of the propulsion assembly may fail	10	If the step-down that holds the insert in place is too weak	1	Perform FEA on parts to ensure required strenth	2	20	Include step-down geometry, precicely machine graphite for a press-fit, Heat up metal nozzle during press fit.
Converging-Diverging nozzle	Ductile failure of diverging section	Explosion of motor casing, rapid decrease in thrust	10	Nozzle diverges at too steep of an angle and the flow separation causes inintentional side-loading	2	CFD simulations in Ansys, and small scale test firings	2	40	Pay special attention during design process, and ensure the nozzle has been machined correctly
			9	The extreme temperatures weakens the design	3	Heat transfer simulations and hand calculations	2	54	Select nozzle material that has a high thermal conductivity and is resistant to melting
O-ring Seals	Force and/or temperature deformation	Increased likelihood of catastrophic motor failure, decrease in thrust performance, components that are not meant to experience extreme temperature will be affected by the escape of exhaust gas	10	Incorrectly sized O-rings; too small	2	ensure proper O-ring groove dimensions with calipers or micrometer	1	20	Choose temperature resistant o-rings or implement additional insulation
			10	Incorrect installation	3	attached O-ring Diameter with inner diameter of casing	1	30	Ensure that the O-rings fit securely in the machined grooves in nozzle fitting
	Chemical and thermally induced corrosion	Chamber pressure will escape and have catastophic effects on motor and rocket parts	10	Manufacturer defect; did not cure properly in factory	1	Elastic strength tests	1	10	Implement quality assurance plan guring motor assembly

12.4.3 Appendix D: FMEA Propellant

Product Name		Development team: Shannon, Remy, Andrew, Grace					Page No 1 of 1			
System Name							FMEA Number			
Subsystem Name							Date 11/3/23			
Component Name	Motor									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action	
Propellant Grain	Force Deformation	Propellant falls out of rocket either before or during combustion depending on severity, this leads to unsafe conditions for spectators and decreased altitude performance	9	Incorrect propellant formulation; Propellant is not fully cured	4	Hardness checks	2	72	Two or more team members should look over the grains prior to launch	
	Accelerated Burn Rate	Pressure builds and the rocket explodes, or the fuel burns too fast and decreases altitude performance	10	Propellent contains voids due to errors in manufacturing processes	3	Density checks	2	60	Include a shake table in manufacture to reduce size and occurrence of voids	
	Decelerated Burn Rate	Minimum thrust-to-weight ration is not meet and rocket can not lift off	7	Incorrect propellant formula	7	Iterative formula testing and analysis	1	49	Double check final iterations with a mentor prior to launch	
Casting Tubes	Inconsistent Part Quality	The propellant grain does not fit properly in the liner and needs to be trimmed down	2	Casting tube is ripped during manufacturing	1	Rough quality control of incoming parts	2	4	None	
Motor Liners	Inconsistent Part Quality	The motor does not fit properly in the casing	6	Incorrect Tolerances	1	Rough quality control of incoming parts	2	12	None	
E-Matich	Short Circuit	Ignition would fail and nothing would happen	5	Manufacturer error	1	Rough quality control of incoming parts	6	30	None	

12.4.4 Appendix D: FMEA Casing

Product Name	NAU Rocket Capstone	Development Team: Shannon Comstock, Remington Dasher, Andrew King, Grace Morris							
System Name									
Subsystem Name									
Component Name	Motor Casing								
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Aluminum Casing	Casing rupture	Explosive decompression caused by rapid gas fluxuation	10	Voids in propellant grains, inconsistant aluminum rounds, incorrect milling	5	Grain analysis, Aluminum checks	4	200	Assign 1-2 teammembers to analyze each grain for voids, make sure during milling that aluminum is sound
Bulkheads	Bulkhead rupture	Rapid decompression which causes harm to the casing	4	Incorrectly machined parts, Faulty O-rings	3	Consistant dimension checks during machining	3	36	Make sure that consistant checks on the bulkhead dimensions are done, ensuring o-rings are consistant
0	Radial Bolt Failure	Destroys casing and bulkhead is no longer secure	5	Impropper bolt selection	4	Load analysis of the bulkead/casing interaction	4	80	Ensure that the load analysis gives accurate results to ensure proper bolt selection
0	Pressure Transducer Thread Failure	Destroys bulkhead and pressure transducer	3	Incorrect thread tapping, teflon tape use	4	Ensuring threads are fully cut	2	24	Make sure with machine shop managers that threads are adequetly cut
Nozzle	Nozzle Improperly Secured	Nozzle unseats or falls out which would ruin compression and thrust	5	Incorrect seating, loose nozzle fit	3	Move the nozzle and look out for any slop or other signs of incorrect seating	1	15	Prepare an accurate CAD model to make sure nozzle seats correctly

12.5 Appendix E: Budget

		Expected Expenses			Actual Expenses To-Date		
Source	Amount	Subsystem	Products Needed	Amount	Item Bought	Cost	
Gore Fund	2000	Nozzle	Graphite	125			
Go Fund Me	1000		Steel	150			Note: all red funds can only be used for specific things
Undergrad Research	700		Lathe	450			
		Casing	Prototype Casings	25			
			Retaining Rings	40			
			Material for Final Casing	100			
		Test Stand	Steel Tubing	50	Aluminum Extusion	150	
			Aluminum Stock	50	Angle Iron	30.82	
			Connectors	50	T-Nuts	81.56	
			Bearings or Wheels	100	Screws	45.03	
					Washer	32.93	
EE Team	500	Test Stand Electronics	Load Cell	300	Load Cell	157.78	
			Arduino	50			
			Other EE Components	525			
		Strand Burner	Steel Pipe	100			
			End Caps	50			
			Thermocuples	40			
			Pressure Tranducer	40			
			Assembaly Tools	50			
		Test Rocket Motors	Ammonium Perchlorate	200	Aluminum Powder	29.41	
			Aluminum Powder	100	Binders	27.75	
			Binder	150	Additives	71.62	
			Additives	75	Liners	66.95	
			Fuses	15	Casting Materals	154.1	
		75mm Final Motor	Ammonium Perchlorate	250			
			Aluminum Powder	125			
			Binder	175			
			Additives	100			
			Fuses	15			
		PPE	Gloves	10	Gloves	24	
			Eye Protection	5			
			Resperators	60			
Total	4200			3500		847.95	

12.6 Test Stand Safety Checklist

Test Stand Safety Checklist

Materials:

Test Stand	Ignitor	Ignition System	Electronics Box
Motor	Fire Extinguishers	Safety Glasses	Motor Holder
Motor Guide	Water	Shovel	Level (If Needed)

Air Temperature________ Wind Speed_________ Gusting_________ Direction_______

Air Humidity___________ Barometric Pressure___________________

- 1. Fill out air data and wind speeds to ensure safe operation
- 2. Set up the test stand in an area free from any brush or flammable debris
- 3. Adjust the gantry height to be around 3-4 inches from the nozzle end of the motor; secure the screws to lock into place
- 4. Ensure that the motor holder is correctly secured onto the load cell nipple. Use a level if necessary
- 5. Plug in the load cell wires into the electronics box
- 6. Place the motor through the motor guide on the gantry and slot into the correct motor holder ring
- 7. Plug in the pressure transducer and thread the wire through the motor holder. Plug into the electronics box
- 8. PRESS THE OFF BUTTON, SWITCH OFF THE IGNITION REMOTE, AND TAKE THE BATTERY OUT
- 9. Thread the ignitor through the electronics box (DO NOT CONNECT TO SYSTEM)
- 10. Thread the ignitor all the way down into the motor until it stops. Place tape on the top of the motor; out of the way of the nozzle
- 11. With fire extinguishers nearby and safety glasses on, secure the ignition wire into the electronics box
- 12. After all systems are ready, walk back to the distance given by the Tripoli Safety Standard (Table 1).

Table 1. Safety Data For Distance According to Max Impulse From Tripoli Safety Standard

Motor Designation	**Total (MAX) Impulse (Nm)**	**Distance in Feet**
A-G	0.01	100
H-J	160.01	100
K	1280.01	200
L	2560.01	300
M	**5120.01**	**500**
N	10240.01	1000

- 13. Put the battery back into the remote and switch on the ignition remote
- 14. Count down from five (5) to ensure everyone is ready and alert. Ignite
- 15. Keep an eye on the burn. If after the burn brush catches fire, rush to put it out using the fire extinguishers/water
- 16. After the burn has concluded, turn the ignition remote off, take out the battery, then approach the stand and take the motor out; being cautious of the motor heat

12.7 Manufactured Bill of Materials

SUBSECTION	ITEM NO.	PART	DESCRIPTION	MATERIAL	MANUFACTURING LOCATION	MACHINIST	TIME (hr.)	IMAGE	QTY.	TOTAL TIME COMPLETED	TOTAL TIME ESTIMATED	
TEST STAND	6	10' 2x2x1/8 Angle Iron	Brackets	Steel	Machine Shop	Team	10		64	10	10	
	9	Steel Plate	Secures Load Cell	Steel	Machine Shop	Remy and Andrew	6		1	6	6	
	10	Knobs	Easy to turn Motor Aligners	PETG Plastic	Machine Shop	Remy	1		4	4	4	
	13	2"x1/8" Flat Bar	Stock for Motor Alignment Threads	Steel	Machine Shop	Remy	1		4	4	4	
	14	5" Aluminum Round	Stock for Motor Holder	6061 Aluminum	Machine Shop	Remy	2		2	2	2	
STRAND BURNER	21	3/4in NPT Plug	Seals Pressure and Holds Transducer	Steel	Machine Shop	Team	1		3	3	3	
	27	1/2in Steel Tube	Brings Strand to Middle of Vessel	Steel	Machine Shop	Remy	4		1	4	4	
	30	3/4in Steel Round Stock	Stock for Strand Holding Platform	Steel	Machine Shop	Remy	1		2	2	2	
CASING	34	3in 0.125 Thick Aluminum Tube	Metalic Casing for Holding Pressure	6061 T6 Aluminum	Machine Shop	Team	4		2	8	8	
	38	3in Aluminum Round	Used to Make the Forward Bulkhead	6061 T6 Aluminum	Machine Shop	Team	2		2	4	4	
NOZZLE	42	Isomolded Graphite Rod	Used as an Insert For Max Temperatures	Graphite	Solar Shack	Andrew	4		4	12	12	
	44	Phenolic	For The Body of The Nozzle	Phenolic Resin	Solar Shack	Andrew	4		4	15	15	
PROPELLANT	63	Two Part Silicone Mold Mix	For Casting Propellant Strands	Silicone	Machine Shop	Remy and Shannon	3		1	3	3	
				Quantity								
		not manufactured							85			
			motor casing	1						0.5	0.5	
			75mm motors	2						0	3	
			54 mm motors	2						3	3	
			Count	5								
										TOTAL HOURS Completed	TOTAL HOURS ESTIMATE	PERCENT HOURS COMPLETE
										80.5	83.5	96.41
					Percentage manufacuted by number	0.9551						
					Percentage manufacuted by time	0.9641						