Rocket Propulsion Capstone
Initial Design Report

Shannon Comstock: Project Manager, Primary Financial Manager, Primary Manufacturing Engineer, Secondary Safety Manager, Secondary CAD Manager

Remington Dasher: Primary Test Engineer, Primary CAD Manager, Secondary Nozzle Design Lead, Secondary Propellant Design Lead, Secondary Website Developer

Andrew King: Primary Club Liaison, Primary Nozzle Design Lead, Primary Website Developer, Secondary Test Engineer, Secondary CAD Manager, Secondary Logistics Managers

Grace Morris: Primary Safety Lead, Primary Propellant Design Lead, Primary Logistics Manager, Secondary Financial Manager, Secondary CAD Manager, Secondary Manufacturing Engineer

Fall 2023-Spring 2024

Project Sponsor: Gore

Faculty Advisor: Dr. Carson Pete

Sponsor Mentor: [Note: if any of these categories are the same person, delete the repeats]

Instructor: Dr. David Willy

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

This project's mission is to design and develop a 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, with a creative component such as color, to propel the rocket to its maximum potential altitude. The rocket is intended to achieve a maximum thrust of 5120Newton 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 38mm and 54mm 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 is currently building a specialized test stand. By collaborating with an Electrical Engineering team, this stand will allow for calculations of thrust curves, impulse, and burn rate for the developed motors. These metrics will provide key insights into the performance and efficiency of the rocket’s propulsion system. The data collected will help to optimize the rocket's performance characteristics and ensure its safety.

One of the core components of this project involves designing and building a motor casing capable of withstanding the extreme pressures that the rocket motor will experience. This casing is critical to the rocket's safety and successful launch for the final 76mm motor. The team has currently developed a MATLAB code which is able to calculate design components such as motor casing thickness, allowable stress, and allowable pressures depending on material strength and motor casing dimensions. This code will allow the team to iterate different materials and dimensions to determine what the optimal design is before determining a final design. The team will ensure the final design of the motor casing is able to handle the demands of the high pressures, temperatures and forces of the motor without compromising safety.

Currently, the team is in the process of chemical orders to begin the mixing and casting of the small scale 38mm motor grains motors to begin testing. The team will first test that their process of grain casting is correct by comparing burn rates and thrust curves of a sample grain made by the team to a professionally made grain of the same formula. If it is determined that the team's process of mixing and casting returns similar data to the professionally developed grain, then the team will move forward with testing a unique formula made by the team. This process is scheduled to occur throughout November and to have a well-tested and optimized formula by mid-December. Once the unique formula is determined to be optimized, the team will begin casting 54mm motors to ensure the formula's scalability. With the current projected timeline, the team will begin casting 76mm motors in mid-January 2024 to prepare for a launch date of the final 76mm motor in March 2024. This timeline allows for a in depth refining process of the propulsion formula and time to optimize the rocket's performance to reach its full potential.

The team is excited about the challenges and opportunities this project presents and committed to pushing the boundaries of rocketry. The dedication to creating a unique rocket propulsion system will allow for optimal performance of the rocket as well as showing its uniqueness with a component of color. With the process set in place of testing, data collection, and design efforts, the team is confident in the ability to achieve the project's objectives and deliver a successful Level Two rocket launch in March 2024.

TABLE OF CONTENTS

Contents

1 BACKGROUND

For the first part of this report, important metrics and descriptions will be given which lay the foundation for the bulk of the project and its requirements. First, an in-depth description of the project will be given which lays out what we need to do, our budget to be working within, and the greater purpose that this project serves.

Next, the project deliverables will be defined which our team must meet. These deliverables are often a week or two apart from each other, which makes sure that our project is well defined as well as finishing all the material needed to complete our project fully. At the time of this report, we are over halfway done with the first part of our senior capstone.

Finally, there are the design success metrics. These metrics are key to being able to define how this project is to be successful. These metrics include testing protocols, pressure and burn-rate calculations, and important design requirements that must be met to ensure our project succeeds with our client and other potential end users.

1.1 Project Description

The team's goal for this project is to construct a high-power level 2 rocket propulsion system 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). To ensure the safety and efficacy of the propulsion system, a dedicated rocket test stand will be 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 thrust and impulse data allowing for the team to understand how the motor will perform during a launch.

The team has been provided with a budget of $2,000 by GORE and $500 for the electronic components in order to complete these tasks. Additionally, there is a targeted fundraising goal of $1,000 with a current standing of $350 raised. In relation to the rocket motors, the team is scheduled to conduct at least two small-scale motor tests of diameters 38mm and 54mm 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 76mm motor. This 76mm motor is the final goal, with a targeted scheduled launch in March 2024.

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

1.3 Success Metrics

1.3.1 Test Stand Success Metrics

The test stand's success hinges on several key components. First and foremost, it must be capable of effectively accommodating a variety of motor sizes. Specifically, it should securely support motors ranging from at least 38mm to 76mm in diameter and from 7 inches to 36 inches in height. Second, the test stand's performance relies on its ability to accurately capture all important data of the motor including burn rates, thrust curves, and impulse measurements. 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 5120N*s of impulse. 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, based on these simulation findings, it is evident that the bottom plate must be designed to withstand the most stress of the structure, 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 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 16,000ft 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:

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

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 derived from the specific demands of our client, Dr. Carson Pete, as well as the closely aligned needs of the NAU Rocket Club. Additionally, the team will discuss the engineering requirements of the project which have been 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.

- Functionality – Our project must satisfy the major engineering requirements that physically measure the success of our project. These requirements can be found in Section 2.2.
- Cost – 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 their budget as well.
- On-Time – Because this project has a strict time to be complete by (Early March), we need to make sure that our research, development, and testing is completed by this time frame. By this time, we need to have our full-scale 76mm motor done and tested to make sure the Rocket Club is able to use it in their rocket.
- Scalable – 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 29mm-75mm. Our testing will comprise mostly of 38mm until an appropriate propellant mixture is found.
- Compliance – 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.

- Reach Minimum Altitude- During the final launch, the rocket must reach an altitude of 10km, roughly 32,000ft.
- Stay within Budget of the Project- It is important to our client that we keep the project within budget. The project in total must cost less than the $2000 provided. If we fundraise, we can expand the budget. However, we cannot spend more money than we have.
- Dimensions meet Constraints of the Rocket Size- 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 75mm. So, the propellent and casing must fit within the 75mm's of the rocket. It may be slightly smaller but should be close to 75mm in diameter since the client requested a motor of that size.
- Test Stand Withstands the Impulse of Rocket Testing- 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.
- 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 weight of the fuel. 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.
- 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.
- Casing Material is Non-Ferrous and Ductile- 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.

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

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 begin designing a unique test stand for the individual needs of this project. 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.

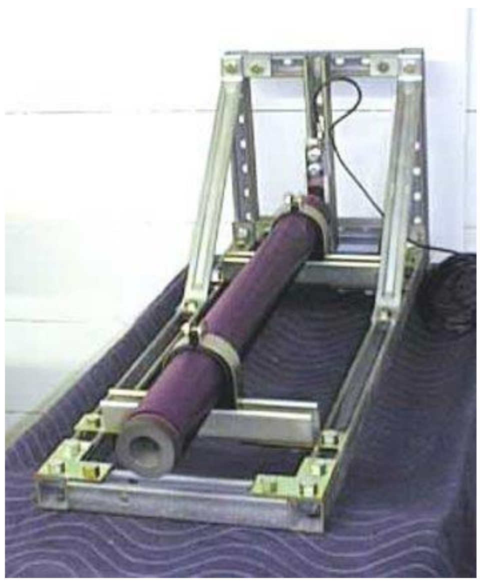


Figure 2. Aerocon Systems Horizontal/Vertical Test Stand [1]

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.

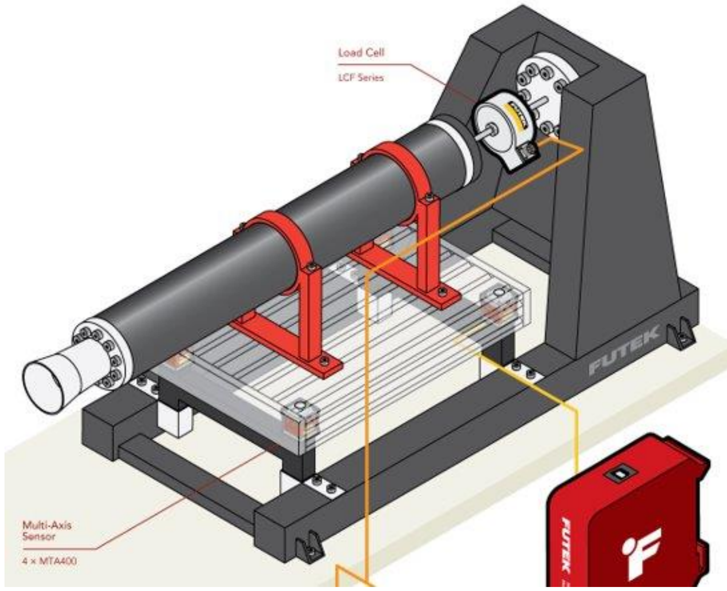


Figure 3. FUTEK Rocket Engine Thrust Measurement Stand [2]

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.

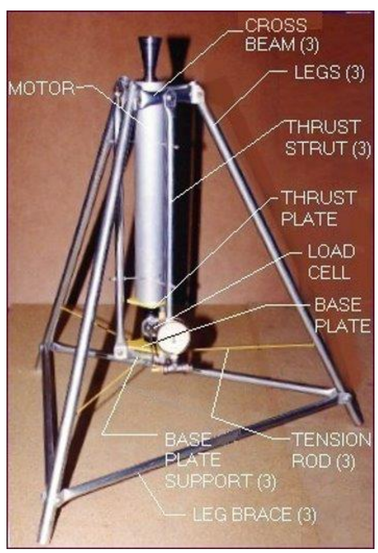


Figure 4. Richard Nakka's STS-5000 Static Test Stand [3]

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, as well as the unique demands of the specific rocket motor testing project.

3.1.2 Propellant Benchmarking

The first benchmark that the team look at for the propellent was the AeroTech RMS 75/1280 Motor [4]. This motor follows the safety standards set by the manufacture however it is unclear if these standards are in compliance with the Tripoli standards. This motor meets the size requirements. Unfortunately, this motor is not affordable, 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 75mm 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 75mm Motor [5]

The final benchmark that the team looked at was the Aerotech High-Power L875DM-PS 75mm [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 has to 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 75mm 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.

3.2.2 Andrew King: A Focus on Nozzle Design/Manufacture

[14]

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.

[15]

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.

[16]

“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 that is used in the design of the diverging portion of the nozzle. It allows for a better understanding of the motion of gas through nozzles.

[17]

“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.

[18]

“Gas Dynamics and Thermodynamics of Solid-Propellant Rockets”

This textbook contains a large number of 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.

[19]

“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.

[20]

“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 in conjunction with CFD to optimize nozzle design.

[21]

“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.

[22]

“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.

[23]

“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 conditions of the ambient air pressure such as pressure have a large effect on nozzle performance. The team can use this info to optimize the design for either Flagstaff or Phoenix elevation.

3.2.3 Grace Morris: A Focus on Propellent Design and Safety

[24]

“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.

[25]

“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.

[26]

“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 more or less set, the only thing that can be changed is the additives and the ratios.

[27]

“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.

[28]

“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.

[29]

“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 but not limited to the rocket’s constructions and stability. We also need to focus on section 10, which talks about motor limitations.

[30]

“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.

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

[32]

“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.

[33]

“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.

[34]

“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.

[35]

"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.

[36]

"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.

[37]

"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 goes on to describe how to be safe around testing and how to secure the stand in place. Their example was much larger than ours, but it is important to keep similarity between the two regardless.

[38]

"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, but analyzing other solid rocket formulas and cross-referencing with other formulations can help us tremendously when it comes to mixing our own, specialized batch.

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”[**] 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 factors 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 - 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.

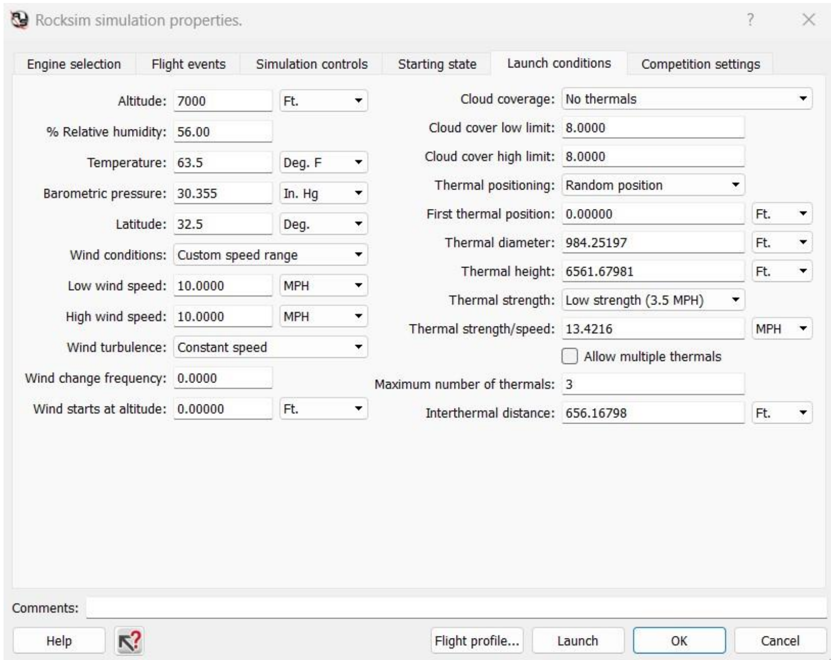


Figure 8: Rocksim Simulation Properties

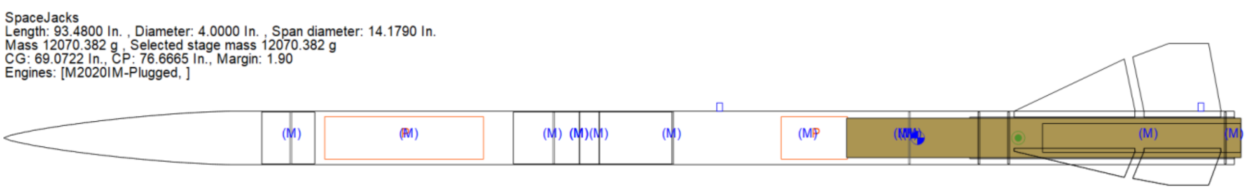


Figure 9: Rocksim Display Model

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 XX, 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.

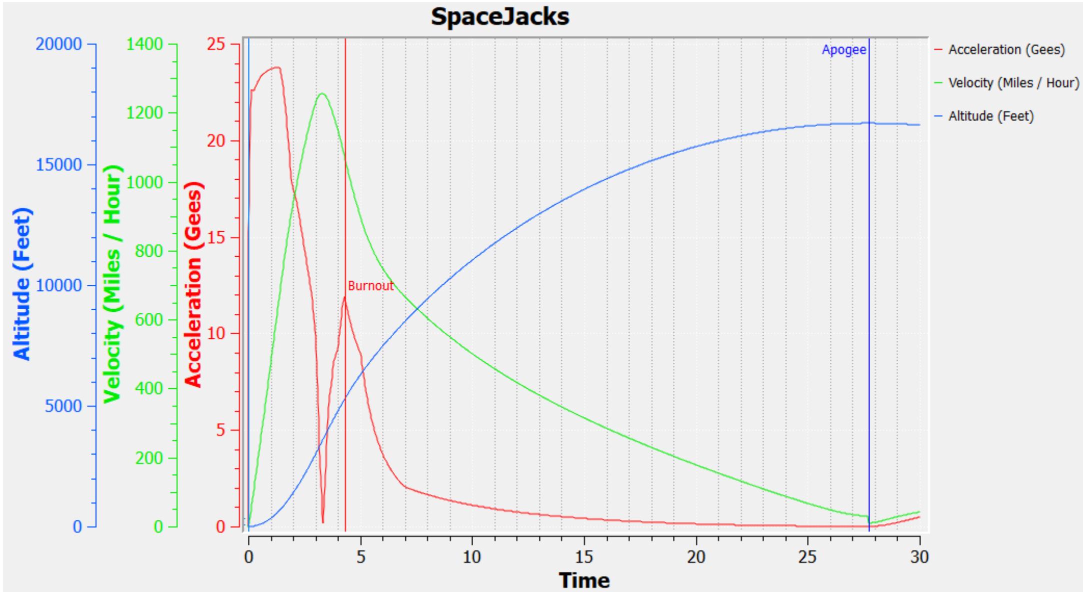


Figure 10: Rocksim Graph

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.

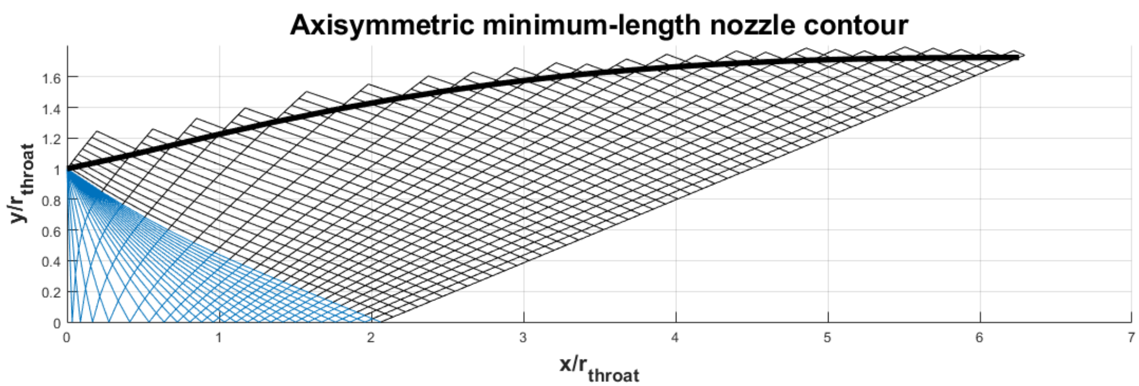


Figure 11: MOC Nozzle Contour

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 - 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.

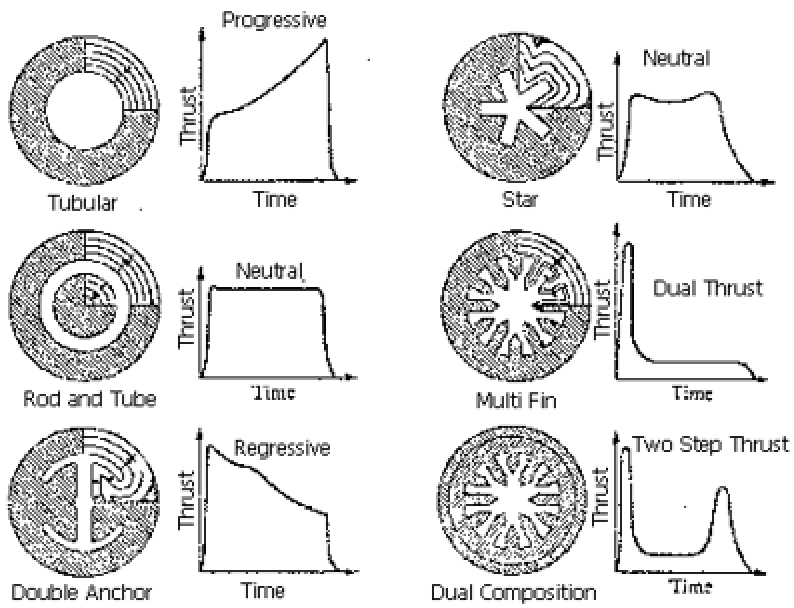


Figure 12. Grain Geometry and Thrust curves [Nakka Rocketry]

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

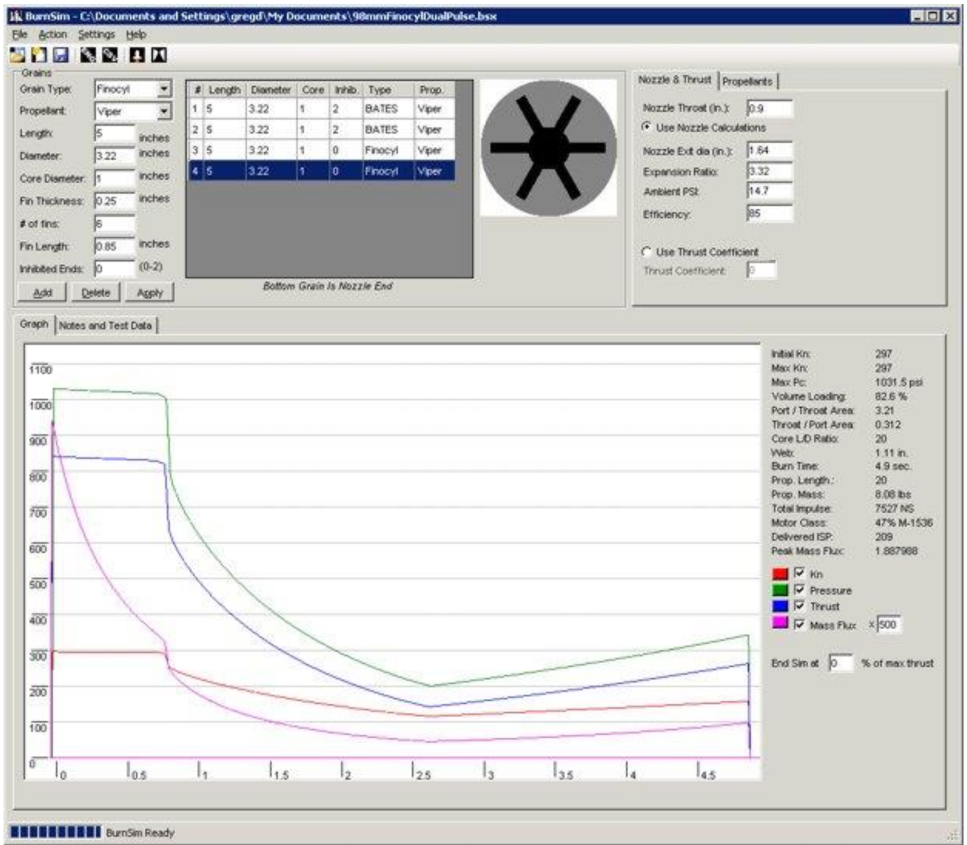


Figure 13. BurnSim Example

The above figure 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 of 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.

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. 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. 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.

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.

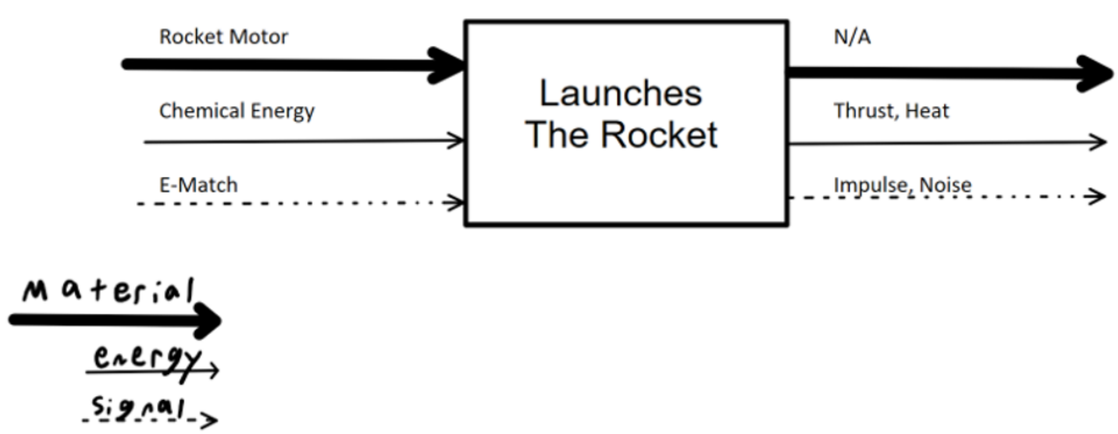


Figure 14. Black Box Model for Rocket Propulsion System

In order 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 that this model brought to our attention was that the motor needs to carry a significant amount of chemical energy in order for the rocket to lift off.

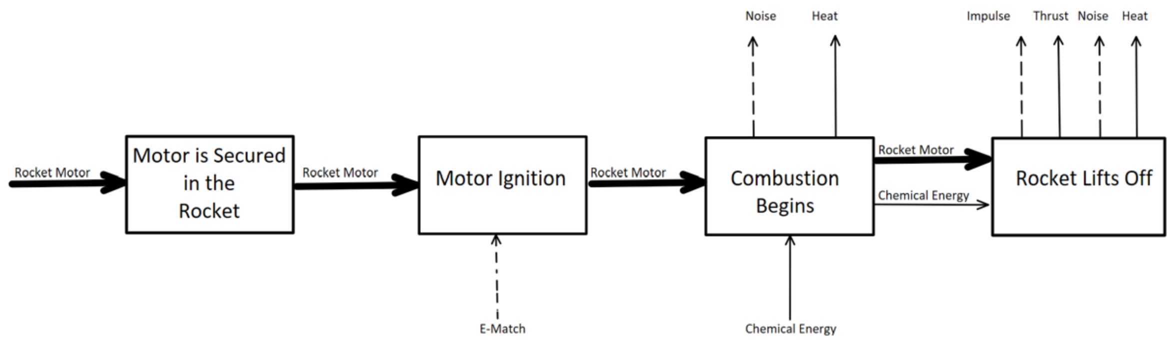


Figure 15. Functional Flow Model for Rocket Motor

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

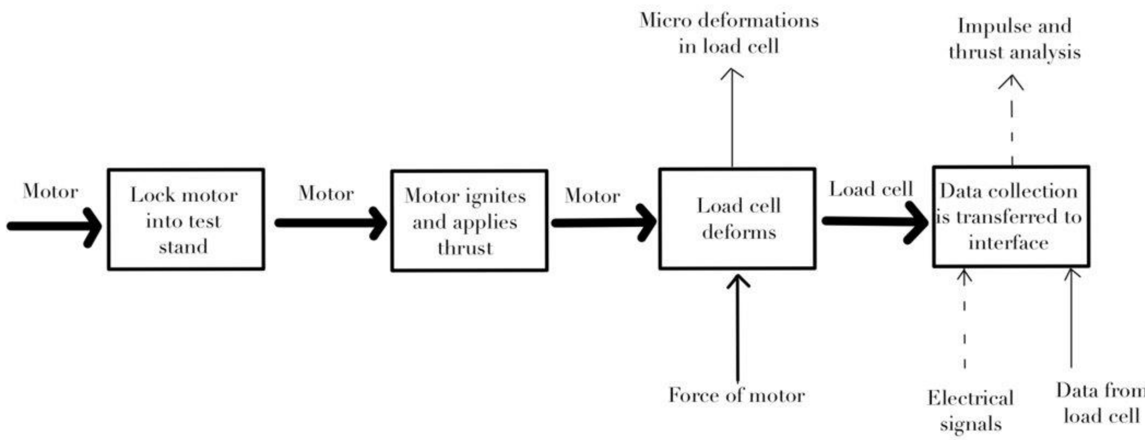


Figure 17. Functional Flow Model for Test Stand

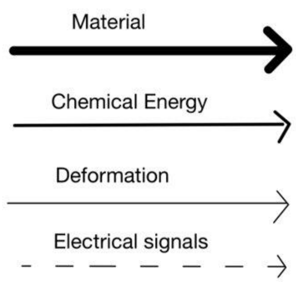


Figure 18. Model Correlation Key

4.2 Concept Generation

4.2.2 Test Stand Concept Generation

First Vertical Test Stand Design:

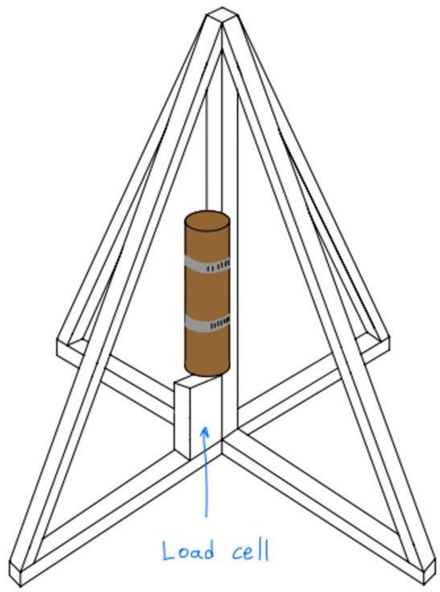
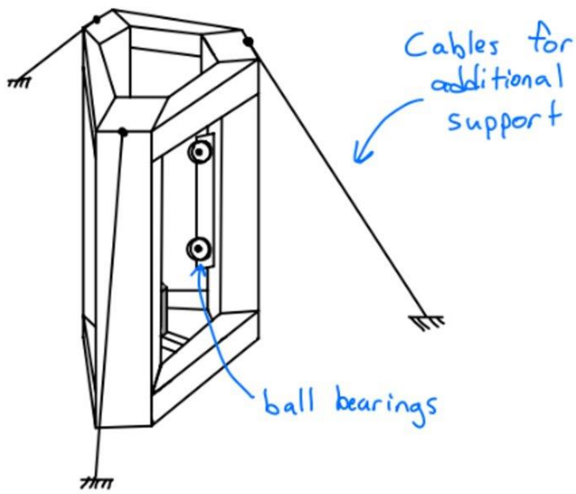


Figure 19. Vertical Test Stand 1

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:



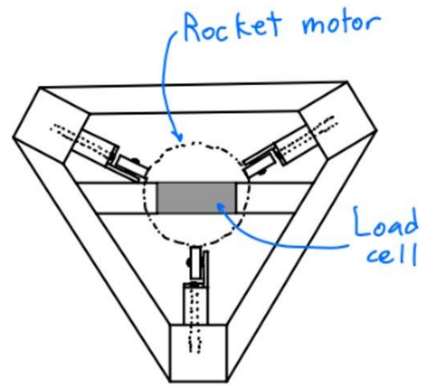


Figure 20. Isometric View of Vertical Test Stand 2 Figure 21. Top View

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. It is possible that we would be required to buy additional hardware or order parts from multiple websites, increasing the costs of shipping.

Third Vertical Test Stand Design:

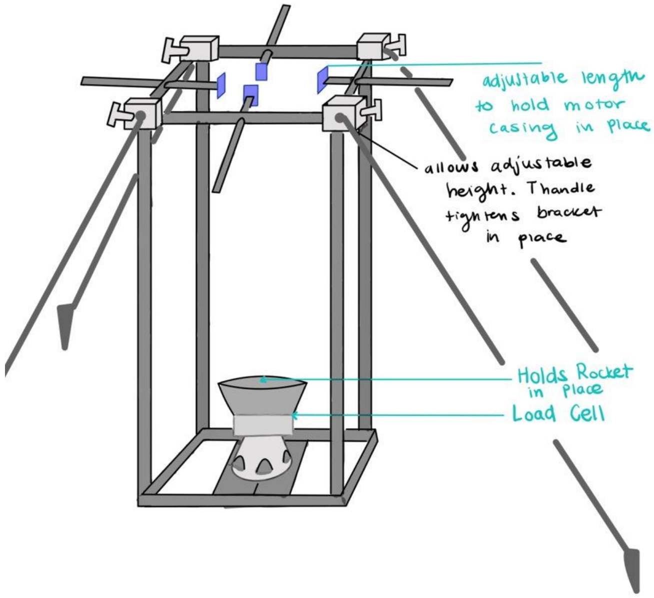


Figure 22. Vertical Test Stand 3

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:

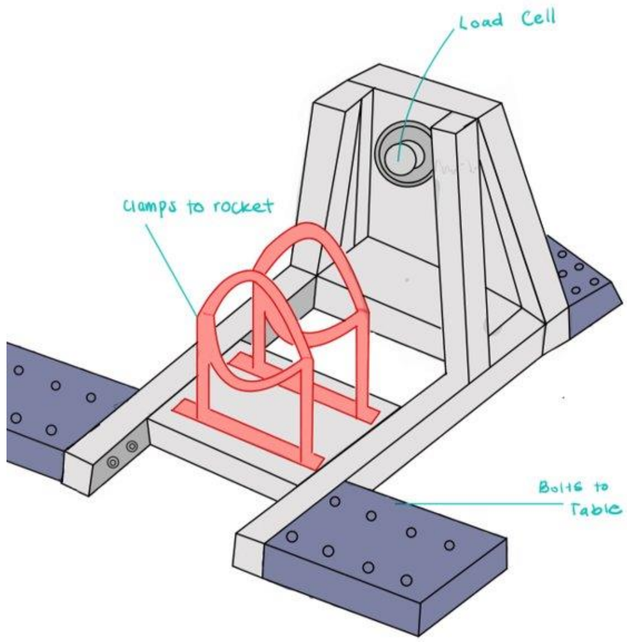


Figure 23. Horizontal Test Stand 1

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:

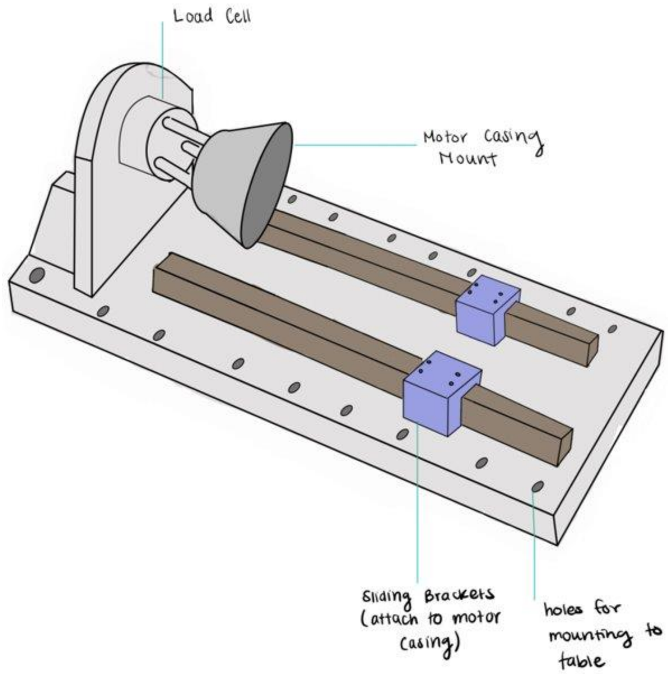


Figure 24. Horizontal Test Stand 2

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.

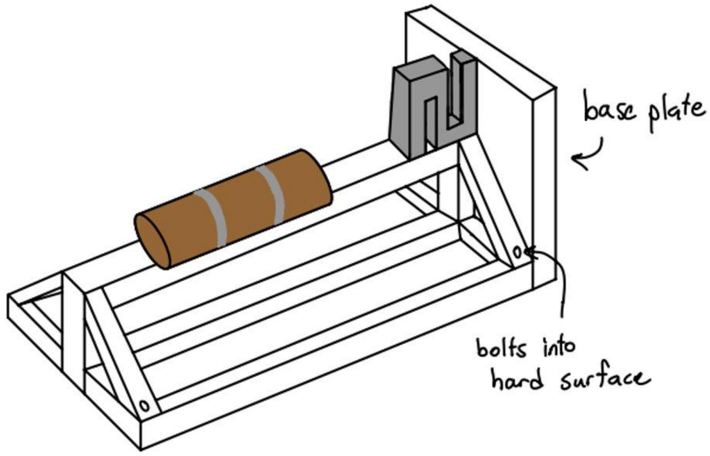


Figure 25. Horizontal Test Stand 3

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

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

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

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.

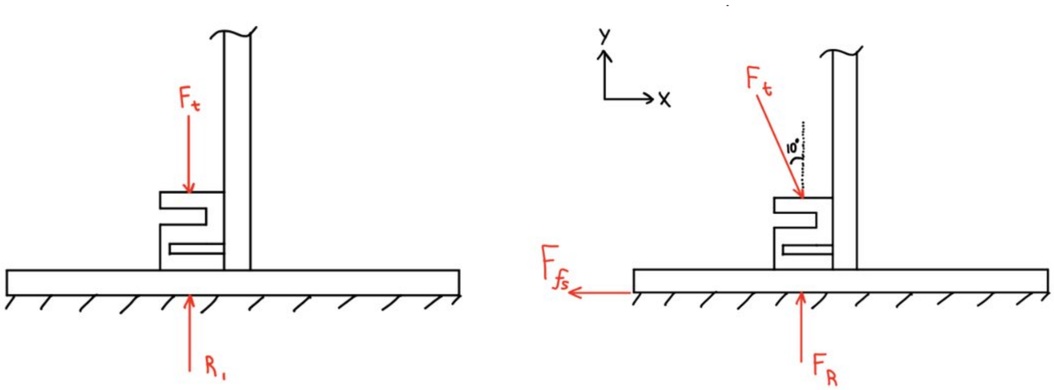


Figure 29. Case A (left) and Case B (right), Vertical Stand 1

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).

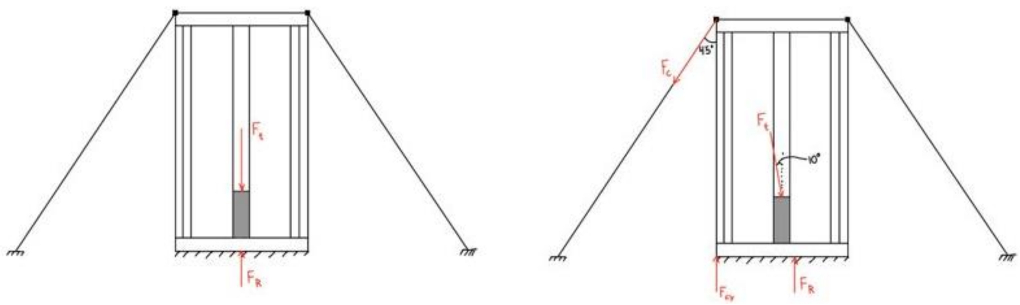


Figure 30. Case A (left), Case B (right), Vertical Stand 2

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 287.8lbf 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 381.7psi. 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 572.6psi.

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.

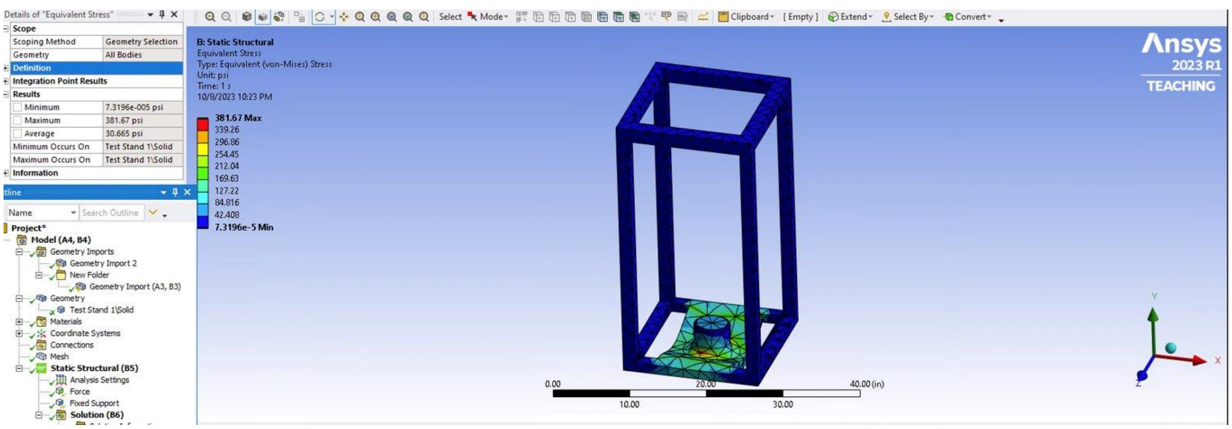


Figure 31. Ansys for Vertical Test Stand 3

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 that member EB needs to be significantly reinforced in order 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 409.8lbf. 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 409.8lbf by this factor, we get 614.7lbf, much higher than the horizontal design concepts to follow.

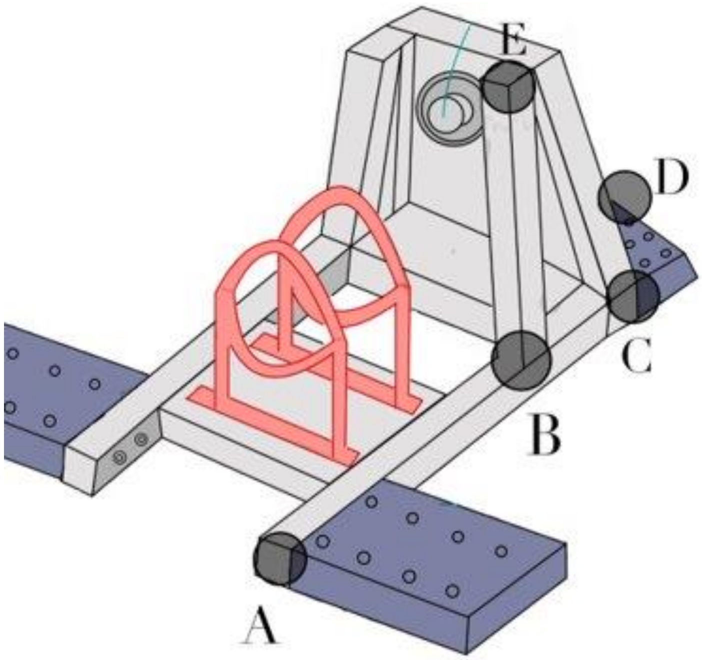


Figure 32. Critical Points for Horizontal Test Stand 1

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

Where 4 seconds is the approximate burn time

$+ \circlearrowleft \sum M_D = 0$

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

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

$R_1 = 204.9lbf$ ↓

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

$R_{Dy} = 204.9lbf$

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

$R_{Dx} = 287.8lbf$ ↑

$+ \circlearrowleft \sum M_B = 0$

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

$M_D = 53.2\ lbf * in$ ←

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

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

$R_{Ay} = 409.8lbf$ ↺

Figure 33. Stress Calculations for Horizontal Test Stand 1

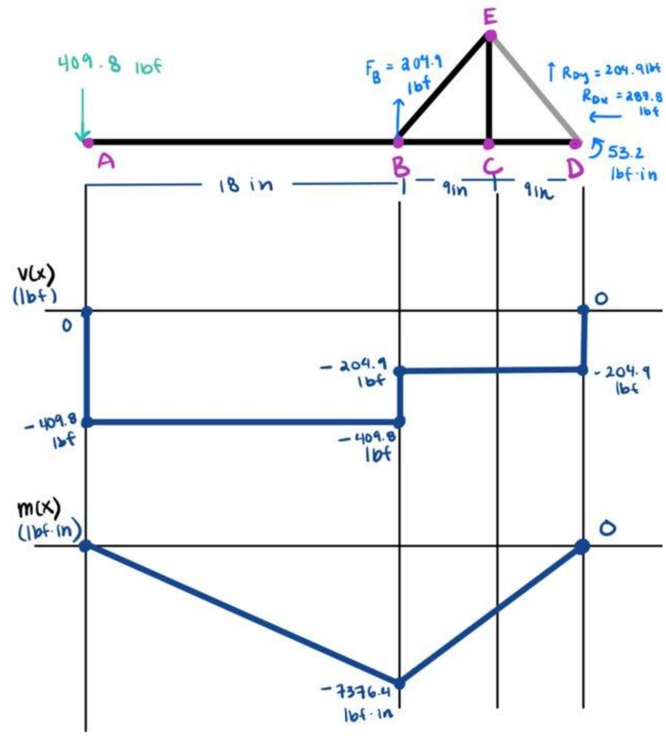


Figure 34. Shear and Bending Moment Diagrams for Horizontal Test Stand 1

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 488.5psi 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 732.8psi. 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.

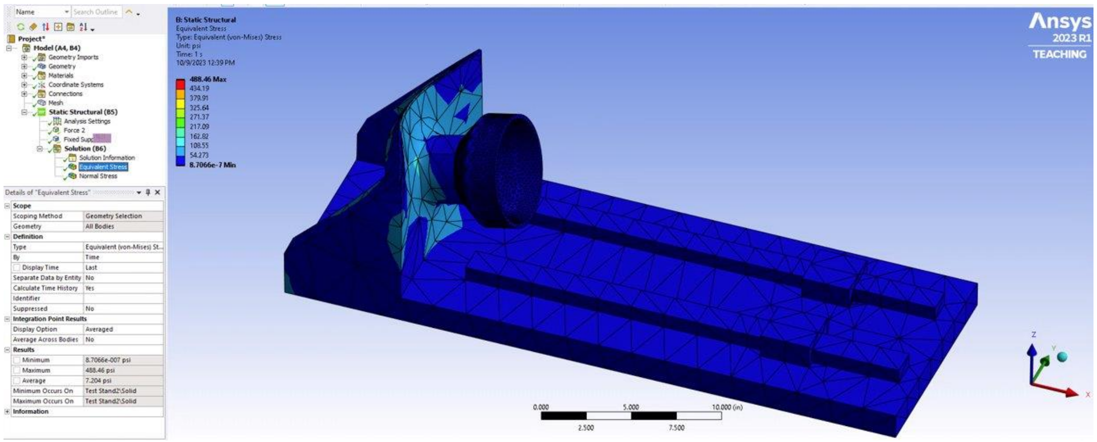


Figure 35. Ansys for Horizontal Test Stand 2

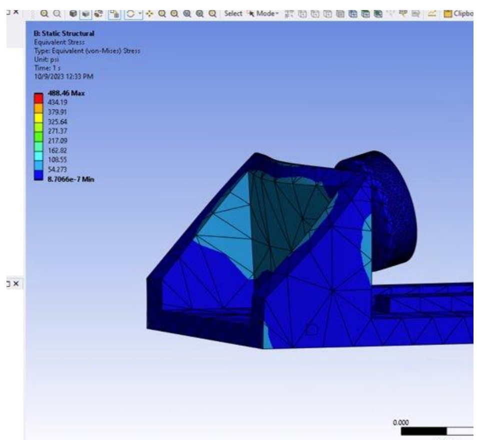
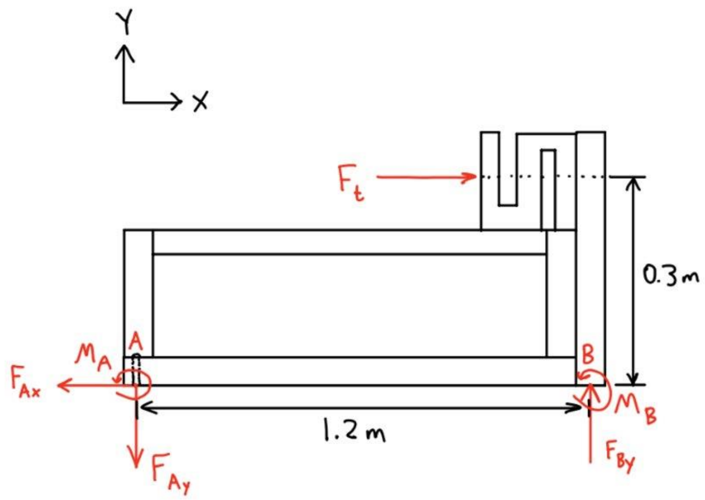


Figure 36. Close-Up of Figure 35.

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.



Equations:

$$I = F_t * t$$

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

$$\sum M = 0$$

$$\sum F_x = 0$$

$$\sum F_y = 0$$

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 of these values are 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.

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

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 5190ft/s.

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

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

Full results for all these concepts are shown in 7.2 appendix B. in the same order as they are listed here.

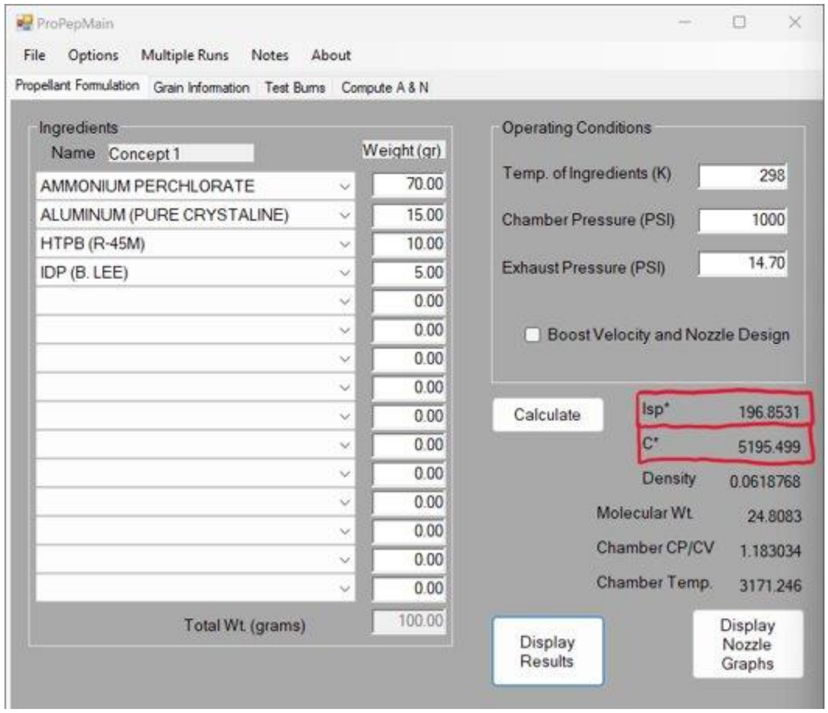


Figure 40. ProPep Results for Formula 1

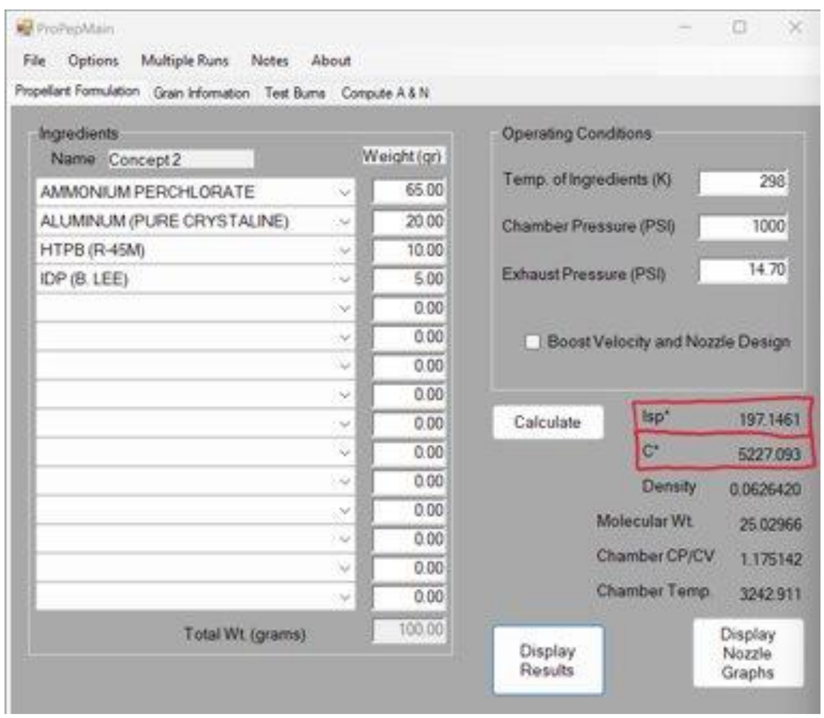


Figure 41. ProPep Results for Formula 2

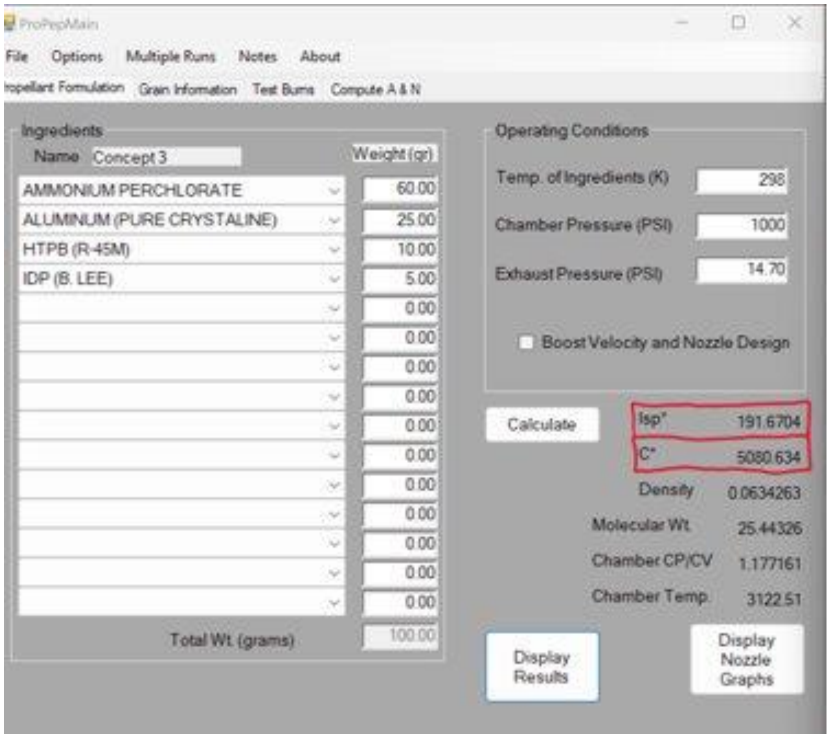


Figure 42. ProPep Results for Formula 3

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.

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

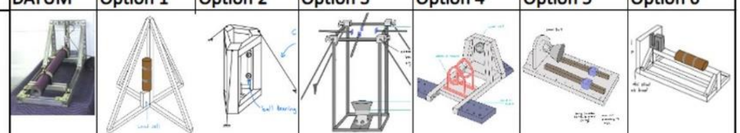
Table 9. Concept 3 Results

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



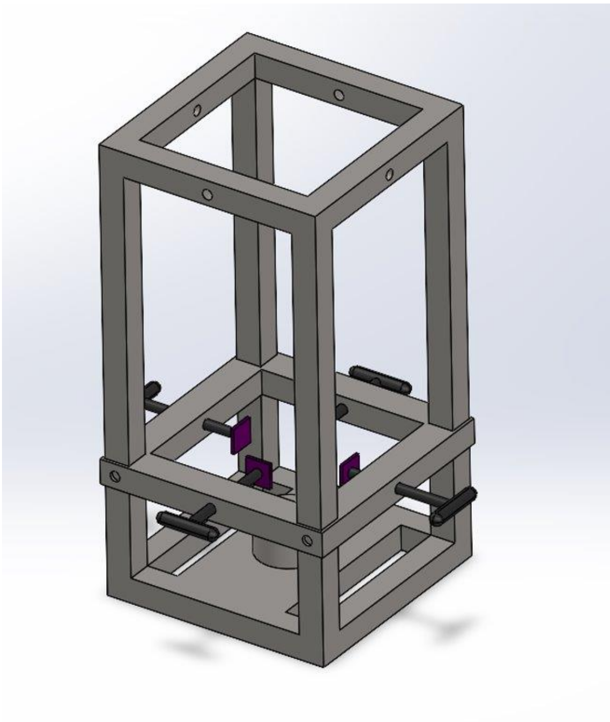
Criteria	Weight	DATUM	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Reach minimum altitude	2		0	0	0	0	0	0
Stay within Budget for the Project	2		+++	++	+	-	-	0
Dimensions meet constraints of rocket size	3	D	---	++	+++	--	0	+++
Stand withstands impulse of rocket testing	2	A	--	+	++	+++	++	+
Meet 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 was able to analyze 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.



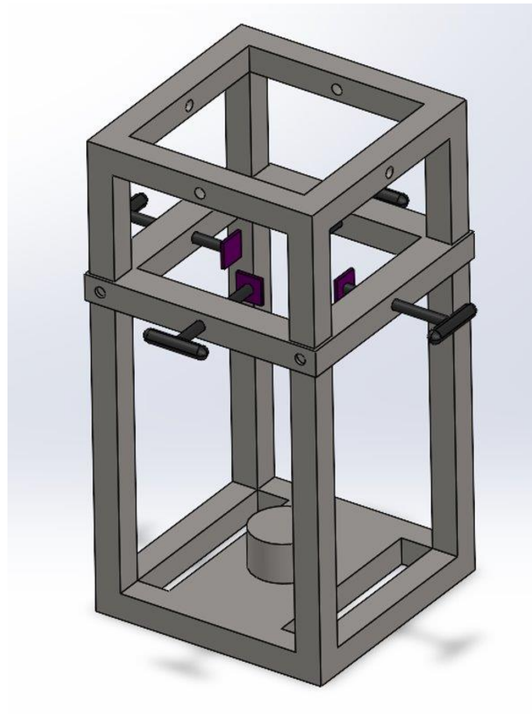


Figure 44. View 1 of Final Test Stand

Figure 45. View 2 of Final Test Stand

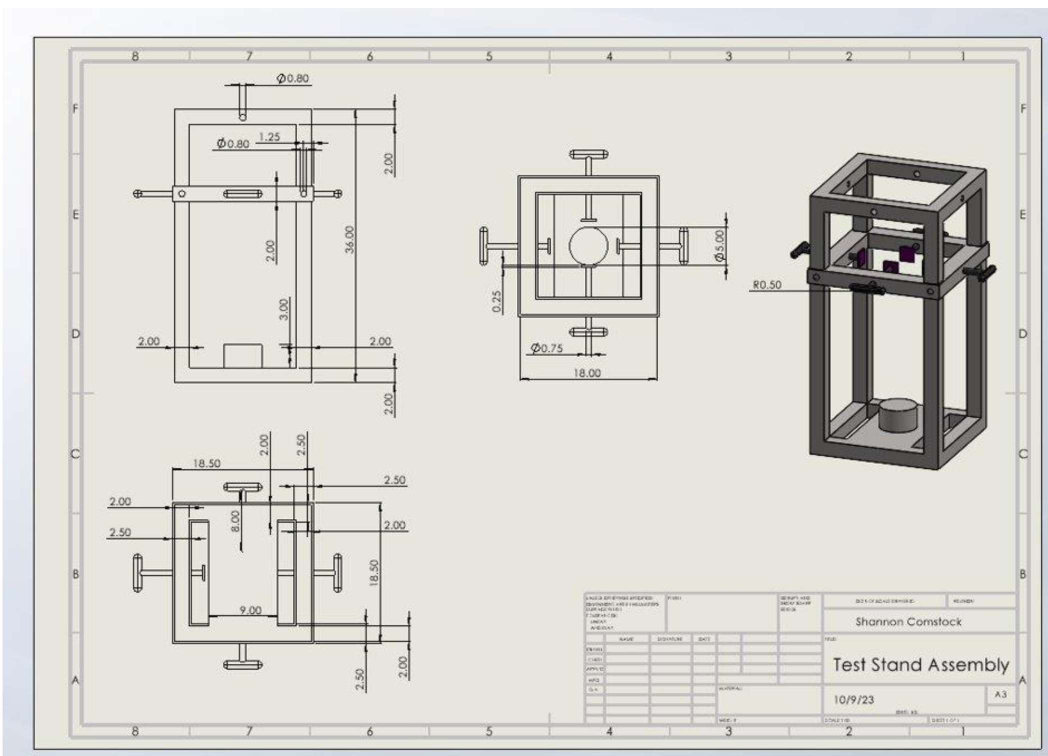


Figure 46. Drawing of Final Test Stand

4.4.2 Propellent Formulation Concept Selection

Criteria	Weight	DATUM 73% AP	Option 1 70% AP	Option 2 65% AP	Option 3 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

Criteria	Weight	Option 1 Competition Motor	Option 2 Uniform Concentric	Option 3 Varying Geometries	Option 4 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.

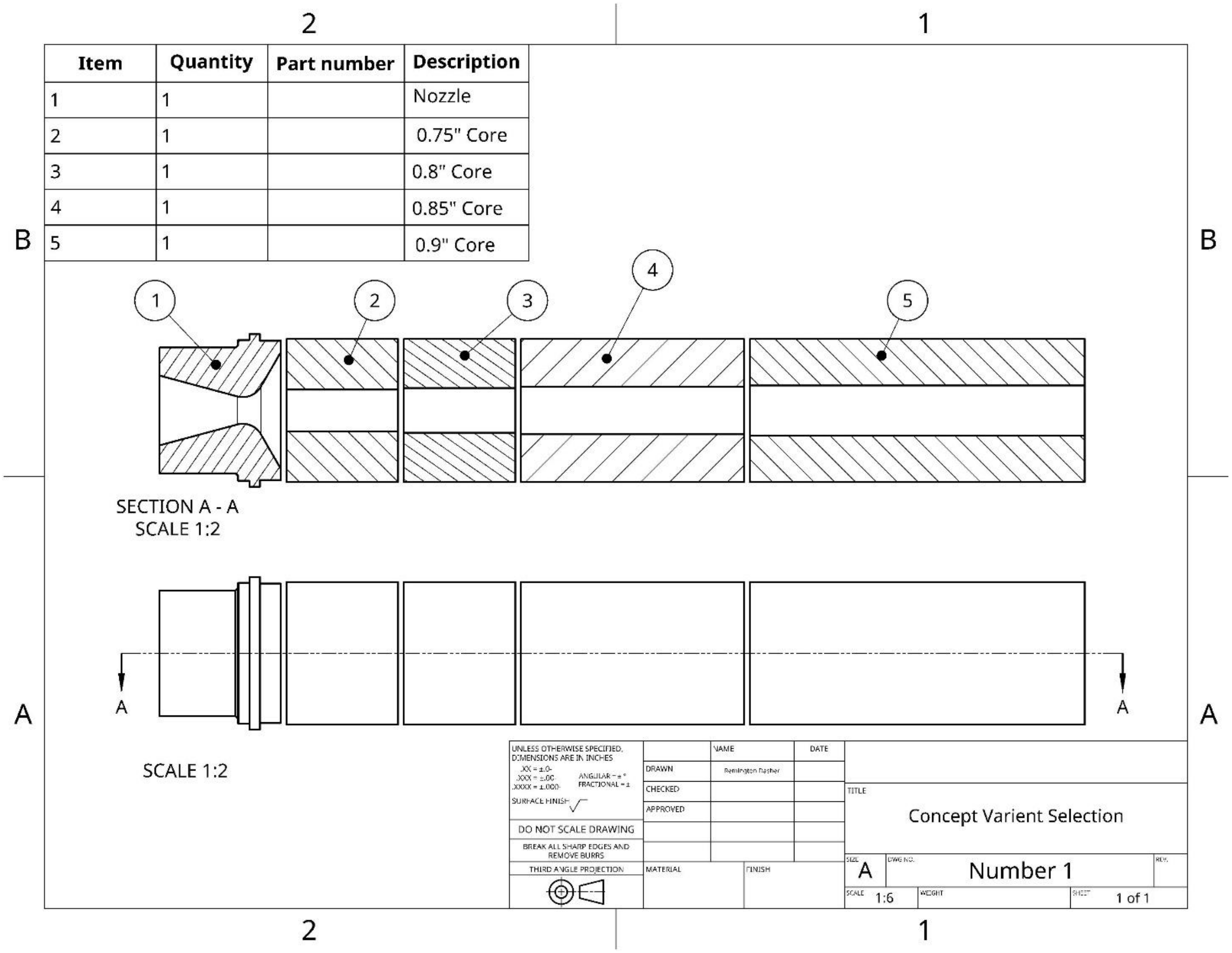


Figure 49. Drawing of Grain Geometries

[Discuss and show the selection process through Pugh charts, decision matrices, specification tables, and/or Factor -of-Safety (FoS) tables. Show the current state of the CAD drawing of the final concept selected with balloons and leader-line notes identifying the major sub-systems and components. Show and describe all other flow charts and/or diagrams as needed.]

5 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 78mm motor will be 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).

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.

Lastly, 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.

6 REFERENCES

Benchmarking

Test Stands:

[1] "Horizontal/vertical test stand to 1500 lb-F Thrust," Aerocon Systems Horizontal/Vertical Test Stand to 1500 LB-f Thrust, https://aeroconsystems.com/cart/motor-test-stands/horizontal/vertical-test-stand-to-1500-lb-f-thrust/ (accessed Sep. 17, 2023).

[2] "Rocket engine thrust measurement: Motor test stand," FUTEK, https://www.futek.com/applications/Rocket-Engine-Thrust-Stand (accessed Sep. 17, 2023).

[3] R. Nakka, "Richard Nakka's Experimental Rocketry Web Site," Richard Nakka's Experimental Rocketry Site, https://www.nakka-rocketry.net/sts5000f.html (accessed Sep. 17, 2023).

Propulsion:

[4] L. Sirius Rocketry, "Aerotech RMS 75/1280 Motor," AeroTech RMS 75/1280 Motor [ARO-7512M] - $377.99: Sirius Rocketry Online Store, For the Serious Rocketeer!, https://www.siriusrocketry.biz/ishop/aerotech-rms-75-1280-motor-886.html?gclid=Cj0KCQjwx5qoBhDyARIsAPbMagCoReHMnzQtyWaBR-ZfqKIePXhwDdmKJdkZ-XMiXdBLKVWZwqhSCeIaAkGvEALw_wcB (accessed Sep. 17, 2023).

[5] L. Sirius Rocketry, "Aerotech high-power M1350W-P 75mm dms hazmat - special order," Aerotech High-Power M1350W-P 75mm DMS HAZMAT - Special Order [ARO-13135P-SO] - $584.25: Sirius Rocketry Online Store, For the Serious Rocketeer!, https://www.siriusrocketry.biz/ishop/aerotech-high-power-m1350w-p-75mm-dms-hazmat-special-order-1584.html?gclid=Cj0KCQjwx5qoBhDyARIsAPbMagDFx_H0N8b7341OseZcTPIa_smTtYCrcjxMofvCjn68zWy89L1RlUcaAoitEALw_wcB (accessed Sep. 17, 2023).

[6] L. Sirius Rocketry, "Aerotech high-power L875DM-PS 75mm DMS HAZMAT," Aerotech High-Power L875DM-PS 75mm DMS HAZMAT [ARO-12875P] - $759.99 : Sirius Rocketry Online Store, For the Serious Rocketeer!, https://www.siriusrocketry.biz/ishop/aerotech-high-power-l875dm-ps-75mm-dms-hazmat-1585.html?gclid=Cj0KCQjwx5qoBhDyARIsAPbMagBcu_87ekCEw_0D9yzfd3lAR1woEgd3QNf2EZ30NEN8PwQvAkdZJXgaAngkEALw_wcB (accessed Sep. 17, 2023).

Literature Review

3.2.1 Shannon Comstock

Scholarly Articles:

[7] B. Niharika and B. B. Varma, "Design and analysis of composite rocket motor casing," *IOP Conference Series: Materials Science and Engineering*, vol. 455, p. 012034, 2018. doi:10.1088/1757-899x/455/1/012034
[8] D. Kumar B and S. Nayana B, "Design and structural analysis of solid rocket motor casing hardware used in aerospace applications," *Journal of Aeronautics & Aerospace Engineering*, vol. 5, no. 2, 2016. doi:10.4172/2168-9792.1000166
[9] J. A. Hendron, "Nondestructive testing of high-strength steel rocket motor cases," *Symposium on Recent Developments in Nondestructive Testing of Missiles and Rockets*. doi:10.1520/stp44520s

Textbooks:
[10] R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design*. New York, NY: McGraw Hill LLC, 2024.
[11] F. P. Beer, E. R. Johnston, J. T. DeWolf, and D. F. Mazurek, "Chapter 4 Design Concepts," in *Mechanics of Materials*, New York: McGraw-Hill Education, 2020

Online Resources:
[12] Glenn research center | NASA, https://www1.grc.nasa.gov/wp-content/uploads/Rocket-Lab-Safety-Manual-1959.pdf (accessed Sep. 17, 2023).
[13] EHS – EHS, https://ehs.mit.edu/wp-content/uploads/2020/01/Rocket_Safety_Plan_Template.docx (accessed Sep. 17, 2023).

3.2.2 Andrew King

Textbooks:
[14] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*. Hoboken, NJ: Wiley, 2017.
[15] R. C. Hibbeler, *Fluid Mechanics*. Hoboken, NJ: Pearson, 2015.
[16] M. J. Moran, H. N. Shapiro et al., *Fundamentals of Engineering Thermodynamics*. Hoboken, NJ: Wiley 2014
[17] R. D. Archer, M. Saarlas, *An Introduction to Aerospace Propulsion*. Upper Saddle River, NJ: Prentice-Hall, inc., 1996
[18] R. E. Sorkin, Gas Dynamics and Thermodynamics of Solid-Propellant Rockets. Jerusalem: Israel Program for Scientific Translations Ltd., 1967
Scholarly Articles:
[19] J. C. Restrepo, A. F. Bolaños-Acosta, and J. R. Simões-Moreira, "Short nozzles design for real gas supersonic flow using the method of characteristics," Applied Thermal Engineering, vol. 207, pp. 1–14, May 2022. doi:10.1016/j.applthermaleng.2022.118063
[20] K. N. Kumar, M. Gopalsamy, D. Antony, R. Krishnaraj, and C. B. Viswanadh, "Design and optimization of aerospike nozzle using CFD," IOP Conf. Series: Materials Science and Engineering, vol. 247, 2017. doi:10.1109/icraae.2017.8297246
[21] N. Önder and C. Tola, "Effects of Nozzle Throat and Combustion Chamber Design Variables on Divergent Portion of the Nozzle," 2019 9th International Conference on Recent Advances in Space Technologies (RAST), pp. 223–230, Jun. 2019. doi:10.1109/rast.2019.8767796
Online Materials:
[22] N. Hall, Ed., "Short index of propulsion slides," NASA, https://www.grc.nasa.gov/WWW/K-12/airplane/shortp.html (accessed Sep. 18, 2023).
[23] "NASA Technical Reports Server (NTRS)," NASA, https://ntrs.nasa.gov/api/citations/19770009539/downloads/19770009539.pdf (accessed Sep. 18, 2023).

3.2.3 Grace Morris

Textbooks:
[24] J. White, B. Anderson, B. Green, and M. Hall, Interactive General Chemistry. New York: Macmillan Learning, 2019.
[25] T. W. McCreary, Experimental Composite Propellant an Introduction to Properties and Preparation of Composite
Propellants - Design, Construction, Testing, and Characteristics of Small Rocket Motors. Murray, Ky: Eigenverl., 2014.

Scholarly Papers:
[26] A. B. Aziz, R. Mamat, W. K. W. Ali, and M. R. M. Perang, "Review on typical ingredients for ammonium perchlorate
based solid propellant," Applied Mechanics and Materials, https://www.scientific.net/AMM.773-774.470 (accessed Sep. 17,
2023).
[27] Author links open overlay panelM.S. McClain a et al., "Additive manufacturing of ammonium perchlorate composite
propellant with high solids loadings," Proceedings of the Combustion Institute, https://www.sciencedirect.com/science/article/pii/S1540748918300531 (accessed Sep. 17, 2023).
[28] S. Jain et al., "Size and shape of ammonium perchlorate and their influence on properties of composite propellant,"
Defence Science Journal, vol. 59, no. 3, pp. 294–299, 2009. doi:10.14429/dsj.59.1523
Online Sources:

[29] High-power safety information - tripoli rocketry association, https://www.tripoli.org/safety (accessed Sep. 17, 2023).
[30] "APCP solid propulsion development," Brandon Fallon, https://brandonfallon.com/apcp-solid-propulsion-development/ (accessed Sep. 17, 2023).
[31] "Solid Rocket Motor Theory -- GUIPEP," Richard Nakka's Experimental Rocketry Site, https://www.nakka-rocketry.net/th_imp.html (accessed Oct. 12, 2023).

3.2.4 Remington Dasher

Textbooks:
[32] W. Anderson, M. Beckstead, and R. Behrens, Solid Propellant Chemistry, Combustion, and Motor
Interior Ballistics, vol. 185. Reston, VA: American Institute of Aeronautics and Astronautics, Inc, 2000.
[33] J. D. Anderson, Fundamentals of Aerodynamics, 6th ed. New York, NY: McGraw-Hill Education, 2017.

Scholarly Articles:
[34] R. R. Sobczak, "Ammonium Perchlorate Composite Basics ," Journal of Pyrotechnics, no. 3, pp. 1–12,
1993.
[35] G. Lengelle, J. Duterque, and J. F. Trubert, "Combustion of Solid Propellants," Internal

Aerodynamics
in Solid Rocket Propulsion/STO Educational Notes, pp. 27–31, May 2002.
[36] Ji Dai, Fei Wang, Chengbo Ru, Jianbing Xu, Chengai Wang, Wei Zhang, Yinghua Ye, and Ruiqi
Shen, The Journal of Physical Chemistry C 2018 122 (18), 10240-10247, DOI: 10.1021/acs.jpcc.8b01514
Online Resources:
[37] "APCP solid propulsion development," Brandon Fallon, https://brandonfallon.com/apcp-solid-propulsion-development/ (accessed Sep. 17, 2023).
[38] B. Dunbar, "Solid rocket boosters," NASA, https://www.nasa.gov/returntoflight/system/system_SRB.html (accessed Sep. 17, 2023).

7 APPENDICES

7.1 *Appendix A: House of Quality (QFD)*

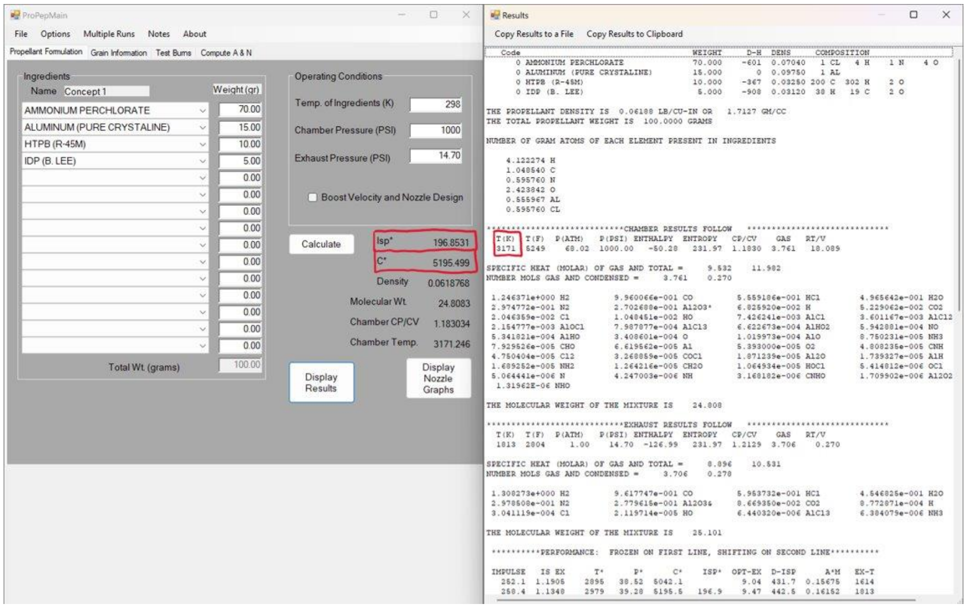
System QFD	Project:	Rocket Club CAPSTONE
	Date:	10/21/23

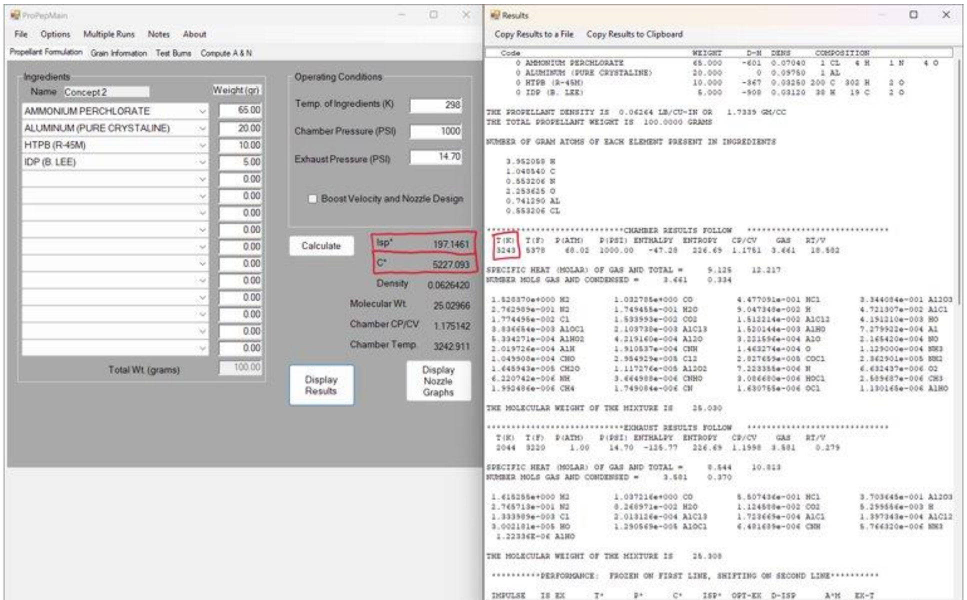
Legend	
A	Aerocon
B	FUTEK
C	Richard Nakka's
D	75/1280 Motor
E	M1350W
F	L875DM

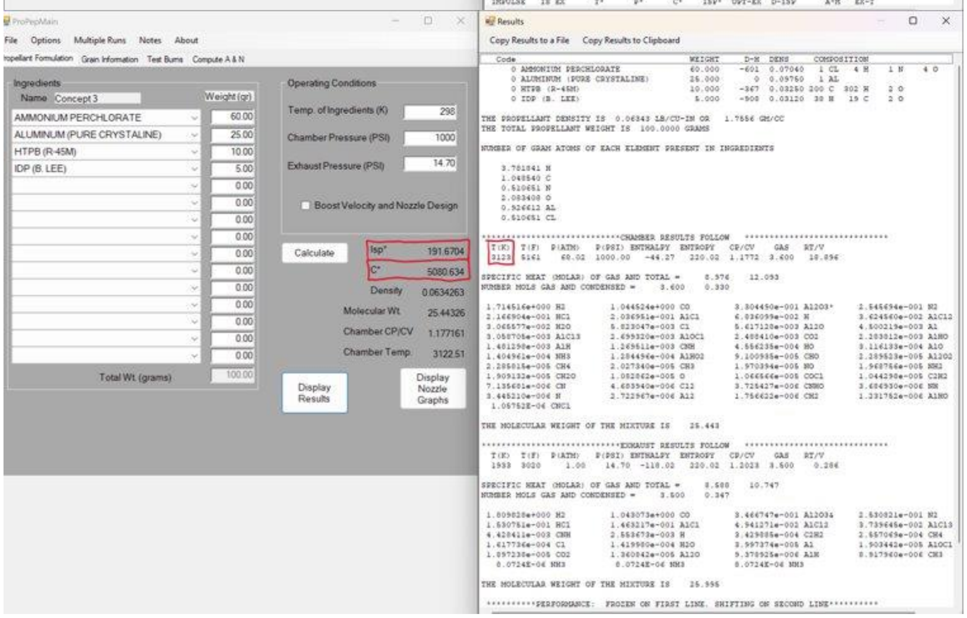
#	Technical Requirement	Reach minimum altitude	Stay within Budget for the Project	Dimensions meet constraints of rocket size	Stand withstands impulse of rocket testing	Meet Minimum Thrust to Weight Ratio Set by Tripoli	Complete final launch by march 2024
1	Reach minimum altitude						
	Stay within Budget 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
			Technical Requirements							**Customer Opinion Survey**				
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					

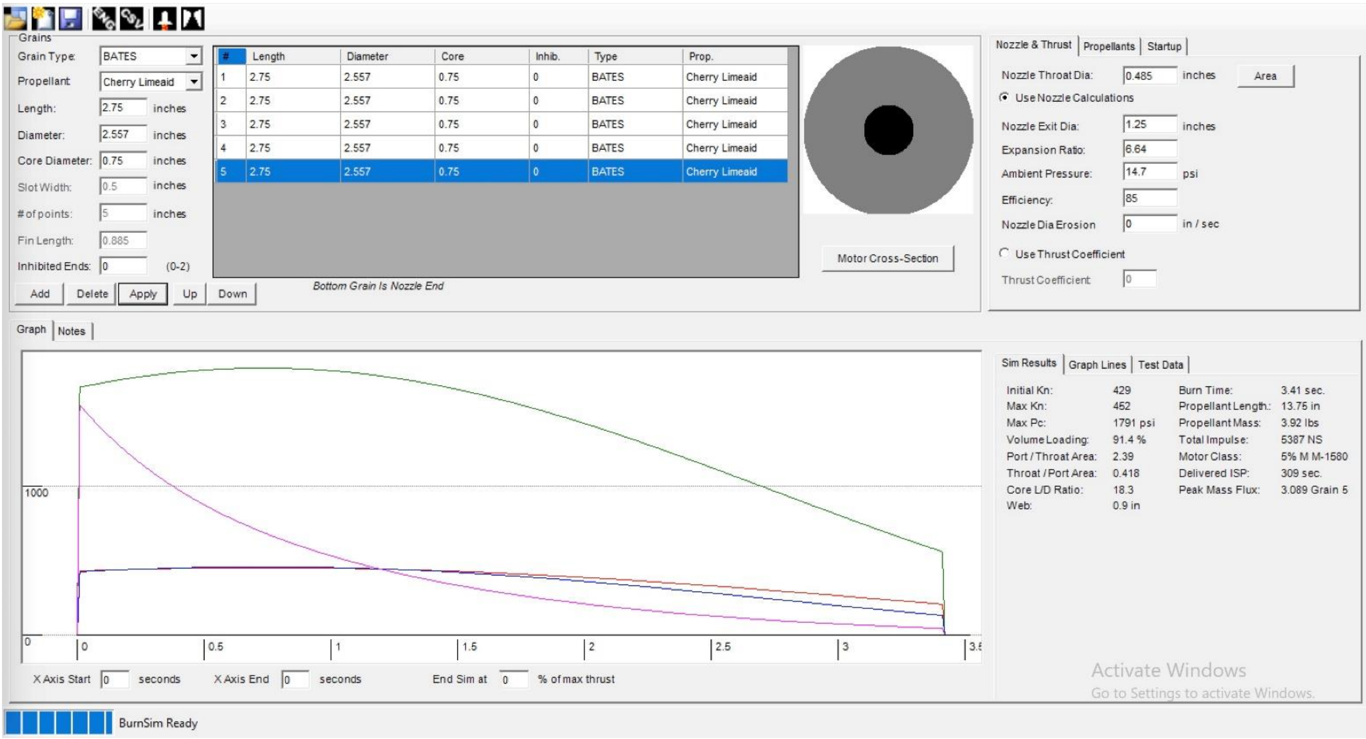
7.2 *Appendix B: ProPep3 Results*

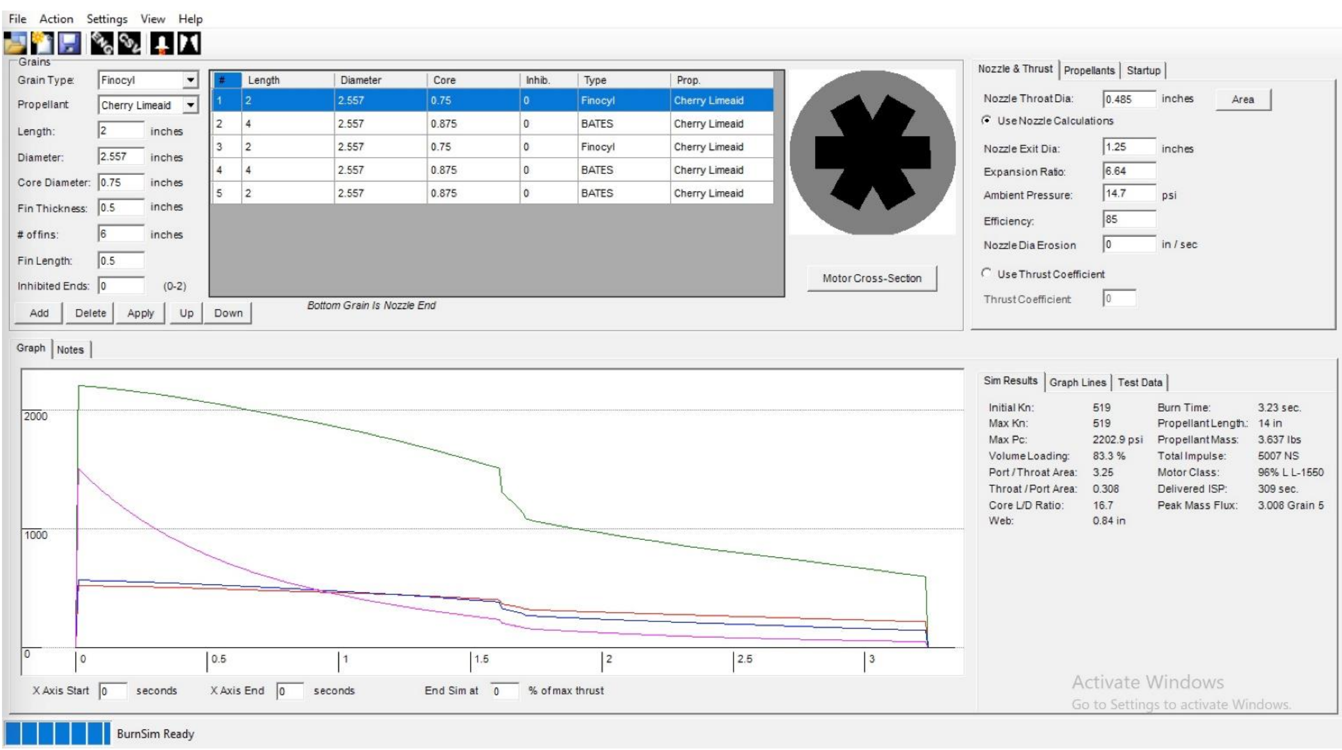


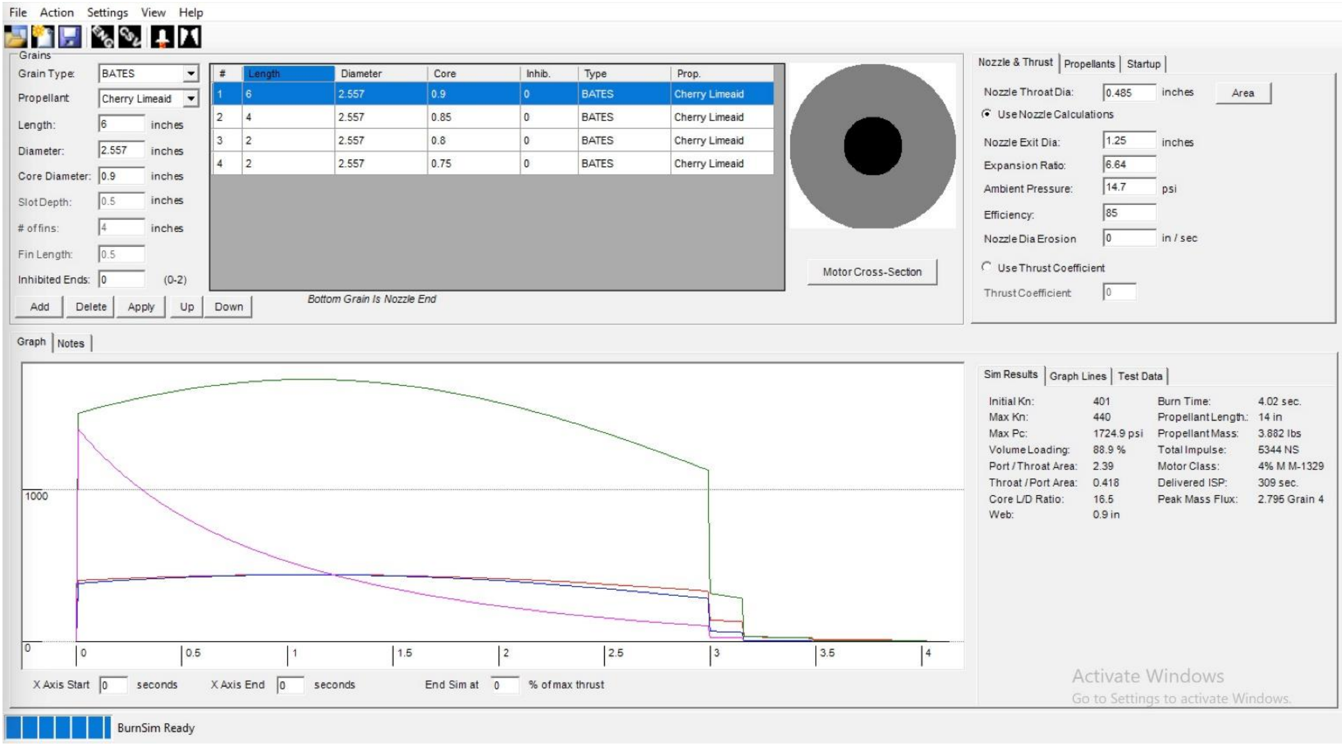

ProPepMain
File Options Multiple Runs Notes About
Propellant Formulation Grain Information Test Burns Compute A & N
Ingredients
Name Concept 2
Weight (gr)
AMMONIUM PERCHLORATE 65.00
ALUMINUM (PURE CRYSTALINE) 20.00
HTPB (R-45M) 10.00
IDP (B. LEE) 5.00
Total Wt. (grams) 100.00
Operating Conditions
Temp. 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

7.3 Appendix C: BurnSim Results






File Action Settings View Help
Grains
Grain Type: BATES
Propellant: Cherry Limeaid
Length: 6 inches
Diameter: 2.557 inches
Core Diameter: 0.9 inches
Slot Depth: 0.5 inches
# of fins: 4 inches
Fin Length: 0.5
Inhibited Ends: 0 (0-2)
Add Delete Apply Up Down
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
Bottom Grain Is Nozzle End
Motor Cross-Section
Nozzle & Thrust Propellants Startup
Nozzle Throat Dia: 0.485 inches Area
Use Nozzle Calculations
Nozzle Exit Dia: 1.25 inches
Expansion Ratio: 6.64
Ambient Pressure: 14.7 psi
Efficiency: 85
Nozzle Dia Erosion 0 in / sec
Use Thrust Coefficient
Thrust Coefficient 0
Graph Notes
1000
0
0 0.5 1 1.5 2 2.5 3 3.5 4
X Axis Start 0 seconds X Axis End 0 seconds End Sim at 0 % of max thrust
Sim Results Graph Lines Test Data
Initial Kn: 401
Max Kn: 440
Max Pc: 1724.9 psi
Volume Loading: 88.9 %
Port / Throat Area: 2.39
Throat / Port Area: 0.418
Core L/D Ratio: 16.5
Web: 0.9 in
Burn Time: 4.02 sec.
Propellant Length: 14 in
Propellant Mass: 3.882 lbs
Total Impulse: 5344 NS
Motor Class: 4% M M-1329
Delivered ISP: 309 sec.
Peak Mass Flux: 2.795 Grain 4
Activate Windows
Go to Settings to activate Windows.
BurnSim Ready